Plant Soil
DOI 10.1007/s11104-009-0223-7

REGULAR ARTICLE

Penetration of cover crop roots through compacted soils

Guihua Chen · Ray R. Weil

Received: 23 July 2009 / Accepted: 3 November 2009

Abstract Tap-rooted species may penetrate compacted soils better than fibrous-rooted species and therefore be better adapted for use in "biological tillage". We evaluated penetration of compacted soils by roots of three cover crops: FR (forage radish: *Raphanus sativus* var. *longipinnatus*, cv. 'Daikon'), rapeseed (*Brassica napus*, cv. 'Essex'), two tap-rooted species in the Brassica family, and rye (cereal rye: *Secale cereale L.*, cv. 'Wheeler'), a fibrous-rooted species. Three compaction levels (high, medium and no compaction) were created by wheel trafficking. Cover crop roots were counted by the core-break method. At 15–50 cm depth under high compaction, FR had more than twice and rapeseed had about twice as many roots as rye in experiment 1; FR had 1.5 times as many roots as rye in experiment 2. Under no compaction, little difference in root vertical penetration among three cover crops existed. Rapeseed and rye root counts were negatively related to soil strength by linear and power functions respectively, while FR roots showed either no (Exp.1) or positive (Exp. 2) relationship with soil strength. We conclude that soil penetration capabilities of three cover crops were in the order of FR > rapeseed > rye.

Keywords Brassica cover crop · Root penetration · Biological drilling · Soil compaction

Responsible Editor: Len Wade.

Electronic supplementary material The online version of this article (doi:10.1007/s11104-009-0223-7) contains supplementary material, which is available to authorized users.

G. Chen · R. R. Weil
Department of Environmental Science and Technology,
University of Maryland,
Room 1109, H. J. Patterson Hall,
College Park, MD 20742, USA
4998 Battery Lane, Apt. 317,
Bethesda, MD 20814, USA
e-mail: gchen06@gmail.com

Introduction

Poor plant growth and reduction of crop yields due to soil compaction have been recognized as early as plowing was practiced and encouraged (Bowen 1981). Soil compaction is known to restrict plant root growth, reduce water and nutrient uptake, and thereby impede plant development (Carr and Dodds 1983; Ishaq et al. 2001). These detrimental effects subsequently reduce crop yields (de Willigen and van Noordwijk 1987). Tillage is often used as a solution to soil compaction. However, in the long-term, tillage may not be a good solution for compaction because it encourages decomposition of organic matter, breaks down soil aggregates and weakens soil structure (Brady and Weil 2008). Subsoil compaction is very persistent and there are few options for natural or artificial loosening (Vepraskas and Miner 1986) Some deep tillage practices may even worsen soil structure and hasten soil degradation (McGarry and Sharp 2001).

Published online: 19 November 2009

Partly to reduce soil erosion and water pollution associated with conventional tillage, conservation tillage systems (e.g. reduced-till and no-till) have been gaining acceptance in the USA since the 1970s. More recently, leaching of post-harvest residual soil nitrogen has been shown to be a major source of water contamination. In the Mid-Atlantic region of USA, the use of winter cover crops has been encouraged as a cost-effective means to remove residual soil nitrogen and reduce the potential for nitrogen leaching to sensitive water bodies such as the Chesapeake Bay (Coale et al. 2001; Ritter et al. 1998). Rye (*Secale cereale L.*) is a commonly used and widely studied cover crop for this purpose in Maryland (Staver and Brinsfield 1998).

However, even with the use of cereal cover crops, problems of soil compaction still remain. The use of "plant roots as a tillage tool" (Elkins 1985) may offer a practical solution to soil compaction. The term "bio-drilling" (Cresswell and Kirkegaard 1995) refers to the creation of bio-pores by deeply penetrating tap roots and the subsequent use of these biopores as low resistance pathways by the roots of succeeding crops. Such "bio-drilling" may be especially effective in no-till farming because the root channels are not destroyed by tillage (Stirzaker and White 1995; Williams and Weil 2004). Roots of different species differ in capacity to penetrate compacted soils where the sizes of soil pores are smaller than their diameters (Bengough and Mullins 1990; Clark et al. 2003), and it has been suggested that roots with greater diameter may be better able to penetrate compacted soils than roots with smaller diameters (Materechera et al. 1991; Misra et al. 1986). Studies by Ishaq et al. (2001) suggested that incorporating species with a deep tap root system in the rotation was desirable to minimize the effects of soil compaction.

Two tap-rooted species in the Brassica family: forage radish (*Raphanus sativus* var. *longipinnatus*, cv. 'Daikon') (FR) and rapeseed (*Brassica napus*, cv. 'Essex'), have recently been introduced in the Mid-Atlantic region. Their potential for capturing residual nitrogen has been determined to be as great as or greater than rye (Dean and Weil 2009). The goal of this study was to determine if these two tap-rooted species could alleviate soil compaction better than rye on coastal plain soils under no-till management in the Mid-Atlantic region. The main objective of this study was to compare the effects of soil compaction on vertical root penetration by the two Brassica cover crops (FR and rapeseed) and rye, and determine the relative effectiveness of these cover crops for compaction alleviation by bio-drilling.

Materials and methods

Experimental sites and soils

Two experiments were 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 ecoregion in Maryland, USA (39°01′N, 76°55′ W). The annual precipitation (1971–2000) is 1,125 mm, of which 42% is in August to December, a period of decreasing potential evapotranspiration. The precipitation from August to December in 2006 and 2007 was 110.5% and 79.2%, respectively, of the 30 year average (Table 1).

Prior to our experiments, conventional tillage consisting of moldboard plow followed by disking was used in both fields. The near-term cropping history for the Exp. 1 field was potato (S. *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—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) in the east end with 0–5% slope in the east-west direction. The soils in 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. Table 2 describes two distinct soil profiles in each experimental site.

Experimental design and treatments

A randomized complete block design was used for both fields. There were four blocks in each field which were blocked against soil texture and slope. Each block in Exp. 1 contained nine plots and in Exp.

Table 1 Monthly mean temperature and total precipitation during fall/winter cover crop growing season in 2006, 2007 and 30 years' average (1971–2000) at the experiment sites

	Temp. (°C)					Prec.(mm)				
	Aug	Sep	Oct	Nov	Dec	Aug	Sep	Oct	Nov	Dec
Avg.	23.4	19.8	13.5	8.3	2.7	96.3	103.6	93.3	86.4	93.4
2006	16.4	18.8	13.0	9.8	5.9	7.4	201.9	133.4	142.0	38.1
2007	24.9	20.7	17.1	7.9	3.6	81.0	14.2	155.7	39.6	84.1

2 contained six 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 turning the tractor and equipment during creation of the compaction treatments and crop planting. In Exp.1, three levels of compaction (high, medium and no compaction) and three levels of cover crops (FR, rapeseed and rye) were combined in a factorial arrangement to provide a total of nine treatments. Exp. 2 included all three compaction levels but only two cover crops (FR and rye) for a total of six treatment combinations.

Experiment 1 was established in August 2006 and continued until September 2008. Experiment 2 used some of the same treatments as Exp. 1 and was conducted for 1 year (August 2007 to September 2008) (Table 3). Prior to establishment of the compaction treatments, both fields were deep-ripped to an average depth of 45 cm at the moisture status slightly drier than the plastic limit, then moldboard plowed to an average depth of 32 cm and finally disked to approximately 8 cm depth. In middle to late August 2006 (Exp. 1) and 2007 (Exp. 2), the two fields were irrigated to saturation and then allowed to drain to near field capacity before compaction was applied. For Exp. 1, a John Deere 544C tractor (Deere & Company, Moline, IL) (axle load 11.88 Mg with solid rubber tires and a rear tire contact area of 1,652 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 no compaction received no tractor pass. 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 (Deere & Company, Moline, IL) (axle load 5.83 Mg with pneumatic tires and a rear tire contact area of 1,610 cm^2) was used to create the medium compaction, and no tractor traffic occurred for the no compaction treatment. Right after the compaction

Table 2 Soil profile characteristics for the two experiments. For each experiment, opposite ends of the field had distinctly different soil profiles

Horizon	Depth (cm)	Clay (%)	Soil texture	Horizon	Depth (cm)	Clay (%)	Soil texture	Coarse fragments, cobbles (%)
Exp. 1, West end (Block I)				Exp. 1, East end (Block IV)				
Ap	20	12.5	SL[a]	Ap	20	18.2	L	
AE	30	12.6	SL	AE	40	16.6	L	
Bt1	40	18.0	SL	Bt1	57	24.2	L	
Bt2	60	18.3	L	CB	75	12.1	SL	
Bt3	80+	20.9	L	C	85+	10.0	SL	
Exp. 2, Southeast end (Block IV)				Exp. 2, Southwest end (Block III)				
Ap	20	11.0	SL	Ap	20	5.1	CSL	5–10%
AE	30	10.0	SL	AC	40	3.8	VCS	50%
Bt	70	16.0	SL	C1	75	4.4	VCS	50%
CB	90	10.0	SL	C2	80+	4.4	CS	>50%

[a] L, SL, CLS, VCS and CS stand for loam, sandy loam, coarse loamy sand, very coarse sand and coarse sand, respectively

Table 3 Time line for field preparation, compaction application, cover crop sowing and management, and sample collection during the experimental period

Exp.	Field preparation[a]	Compaction & surface disking	Cover crop sowing	Fertilization	Irrigation	Biomass sampling	Core break root sampling
1	June–mid-Aug. 2006	Mid-late Aug. 2006	26 Aug. 2006	22 Sep. 2006	16 Oct. 2006	Mid-Nov., 2006	Early Dec., 2006
			29 Aug. 2007	29 Aug. 2007			Late Nov., 2007
2	July–mid-Aug. 2007	Mid-late Aug. 2007	29 Aug. 2007	29 Aug. 2007	5 Sep. & 6 Oct. 2007	none	Late Nov. 2007

[a] Including deep ripping, moldboard plowing and surface disking to loosen soils along the profiles, and irrigation to saturate soils two days prior to compaction was applied

treatments were imposed, the soil in both experiments was disked to a depth of approximately 8 cm to establish a suitable seedbed.

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 long 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 4 cm/s rate and mean penetration resistance was recorded in kPa for every 5 cm depth increment to 45 cm. Penetration resistance was measured at 10 randomly selected locations per plot. In Exp. 2, because of the high content of cobble-gravel in block III (Table 2), a dynamic cone penetrometer was used (Herrick and Jones 2002). Concurrent with measuring soil strength, ten undisturbed soil cores per plot were taken to 40 cm depth with a 1.85-cm diameter JMC soil bulk density probe (JMC Soil Samplers, Newton, IA, USA). To reduce the possibility of sample compaction, the probe was first pushed to 20 cm to take the upper 20 cm soil core, and was then placed back to the same hole and pushed down to 40 cm depth to get the 20 to 40 cm soil core. There was no observable soil compression during coring. In block III of Exp. 2, because of the gravelly soil, samples were taken using a drop-hammer corer with inside diameter of 6. 4 cm. All cores were divided into 5 cm increments, weighed, dried and re-weighed to determine soil bulk density and soil moisture content. Soil strength and bulk density measurements were taken immediately after application of compaction in August 2006 (Exp. 1) and August 2007 (Exp. 2) and again in March 2008 (both experiments) when the soil moisture was close to field capacity (0.26–0.33 cm^3 cm^{-3} in Exp. 1 and 0.22–0.32 cm^3 cm^{-3} in Exp.2).

Soil bulk densities from the two measuring times did not differ in most cases, except that in Exp. 1 bulk density for no compaction was greater in spring 2008 than in fall 2006 for most depths. Figure 1 presents the values of soil bulk density and penetration resistance in spring 2008. Considering both bulk density and penetration resistance, the compacted zones for medium and high compaction treatments in Exp. 1 existed mainly at 5–25 cm depth, and the soil was more compacted in high compaction than in medium compaction. In Exp. 2, however, the bulk density differed among three compaction treatments from 5–30 cm, while the differences of penetration resistance were only at 15–30 cm depth. Though the compaction treatments increased bulk densities of high and medium compaction above 10 cm, they did not increase penetration resistance significantly at the same depth because of the coarse soil texture and surface disking.

Crop management

Cover crops were seeded in the late August of 2006 (Exp. 1) and of 2007 (Exp. 1 and 2) using a no-till drill with 16 cm row spacing. Cover crop seeding rates were 14 kg ha^{-1} for FR, 9 kg ha^{-1} for rapeseed and 134 kg ha^{-1} for rye. On 22 September, 2006, nitrogen fertilizer (urea ammonium nitrate) was applied at a rate of 28 kg N ha^{-1} because of the observed nitrogen deficiency. To ensure vigorous growth, the cover crops in 2007 in both experiments were planted with the use of urea ammonium nitrate (UAN) at a rate of 22 kg N ha^{-1} as a starter fertilizer.

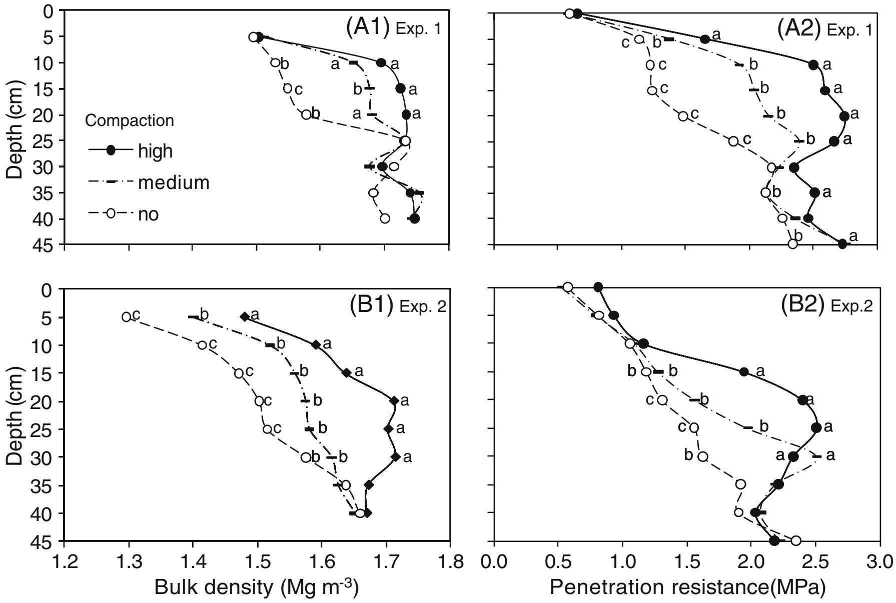


Fig. 1 Variation of soil bulk density (*left*) and penetration resistance (*right*) along depth for three compaction treatments in the two experimental sites, spring 2008. * Values within the same depth followed by the same letter(s) are not significantly different (F-protected LSD, $P<0.05$)

Because of the unusual short dry period after cover crops were planted in 2007, about 30 mm water was irrigated on 16 October in Exp. 1 and on 5 September and again 16 October in Exp. 2.

The rapid fall growth allowed FR to achieve a high shoot and root biomass within 2 months. Forage radish at vegetative stage was frost-killed in winter when air temperature dropped below −4°C for several nights in a row. In Exp. 1, rapeseed and rye were killed on 11 April, 2007 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.). On 16 April, maize was planted with a no-tillage planter in four 76-cm rows per plot at an average population of 74,000 seeds ha^{-1}. 22 kg N ha-1 as granular ammonium nitrate was applied with planting as a starter fertilizer. Weeds in maize were controlled with glyphosate (1.85 L ha^{-1} a.i.) on 9 May. On 6 June, 112 kg N ha^{-1} as a UAN solution dribbled on the soil surface between rows. Maize silage 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.

Cover crop above- and below-ground biomass and root penetration

Cover crop biomass at vegetative stage was sampled on 11 November, 2006 (75 days after planting). A golf cup cutter with an inner diameter of 10.44 cm was inserted to a depth of 16 cm to collect samples for assessment of relative cover crop root distributions. Three samples per plot were taken. Each sample was divided into two segments: 0–8 cm (layer loosened by disking) and 8–16 cm (compacted layers for medium and high compaction). Before taking the soil cores, the shoot biomass (shoots for rapeseed and rye; and shoots and the aboveground portion of roots for FR) in the sampling area of 85.6 cm^2 was collected. Shoot and root samples were washed and dried prior to recording the dry weight. The ratio of root dry biomass in the upper and lower layers was calculated as: [(root dry weight at 0–8 cm): (root dry weight at 8–16 cm)]; while the proportion of dry matter of roots to the dry matter of roots and shoots was calculated as: [(root dry weight): (root + shoot dry weight)].

Vertical root penetration under the different compaction treatments was assessed using the core-break method (van Noordwijk et al. 2000). Soil cores were collected on 1–4 December 2006 and 24–30 November 2007 to a depth of 50 cm using a tractor-mounted direct-drive hydraulic soil coring machine (Giddings, Inc., Windsor, CO) with a sampling tube of 6.4 cm inner diameter. In each plot, three cores were collected from an area occupied by one or more cover crop plants following removal of plant shoots by cutting them at the soil surface. The cylindrical soil cores collected were laid in horizontal holding troughs made of PVC plastic. Each core was broken by hand every 5 cm along its length. The number of roots protruding from both break faces was recorded. Because roots broke some distance (1 to 15 mm) from the core break plane and therefore a given root could show on only one of the break surfaces, the root counts from both surfaces were added together and reported as the sum for the two break surfaces. For one of the three cores in each plot, the soil from each segment was collected and stored at −12°C. These core samples were later thawed and manually washed with water using a sieve of 0.8 mm diameter opening (US standard sieve series no. 20). All roots in a core segment were collected with tweezers and dried at 65°C to determine root dry matter.

Statistical analysis

Analysis of variance was performed using PROC MIXED (SAS v. 9.1, SAS Institute, Cary, NC). Treatment effects were considered significant when *P* value was less than 0.05 and mean separation was done using PDIFF option of the LSMEANS statement. Mean comparison was made using Fisher's protected least significant difference (LSD). Proc Model (SAS v. 9.1, SAS Institute, Cary, NC) was used to explore relationships between root dry matter and root counts, and between root counts and soil strength based on the maximum R square.

Results

Effects of compaction on cover crop biomass

The ratio of root biomass in the upper, loosened (0–8 cm) to that in the lower, unloosened (8–16 cm) soil layers was 43:1 under high compaction. This ratio was significantly greater than the ratios of 16:1 and 8:1 under medium and low compaction, respectively. There was no interaction between compaction and cover crop treatments nor was there a main effect of cover crop on this ratio. Thus, the high compaction treatment caused more extensive rooting in the upper (loosened) layer while greatly restricting rooting in the unloosened layer.

Table 4 presents the shoot and root (0–16 cm) dry matter and the ratio of root weight to the total weight of root plus shoot for each treatment combination from Exp. 1, in November 2006. Rapeseed shoot dry matter was greater under no compaction than under high and medium compaction. Although there was a trend of decreased shoot dry matter for FR and rye with compaction, the compaction effect on shoot dry matter was not significant (P=0.12 for FR; P=0.10 for rye). Root dry matter also tended to be lower as compaction increased, but the reductions were not significant (P=0.09, 0.08 and 0.36 for rapeseed, FR and rye respectively). However, there were significant compaction and cover crop effects of on roots as a fraction of whole plant dry matter. This root fraction was greatest for rye under medium and high compaction and smallest for rapeseed under no compaction. The root fractions for rye under medium and high compaction were greater than for rye under no compaction, FR under medium compaction and rapeseed under no compaction.

Cover crop root counts at 0–50 cm depth

Soils from late fall to the next spring are relatively moist in the Mid-Atlantic region because of the considerable precipitation received and the low evaporation potential (Table 1). In Sept., 2007, irrigation was applied to maintain enough soil moisture for good cover crop growth (Table 3). Thus it is unlikely that during the cover crop growing season soils dried enough to have major effects on soil strength.

Cover crop root counts at depths between 0 and 50 cm for three Exp.-years are shown in Fig. 2. In Exp. 1, 2006, under high soil compaction, FR had more roots than rye at 10–50 cm depth except at 20 cm and had more roots than rapeseed at 35–50 cm depth; rapeseed had more roots than rye at 25–35 cm depth (Fig. 2-A1). Under medium soil compaction, rye had more roots than FR at 5 cm; FR had more roots than rye and rapeseed at 15–30 cm and more than rye at 40–45 cm depth, while rapeseed had more roots than rye at 40–45 cm depth (Fig. 2-A2). Under no compaction, rye and rapeseed had more roots than FR at 5–20 cm depth; FR had more roots than rapeseed and rye at 45 cm depth (Fig. 2-A3).

In Exp. 1, 2007, roots at 5 cm were in the order of rye > rapeseed > FR for all compaction treatments (Fig. 2-B). Under high compaction, FR had more roots than rye at 20–50 cm depth and more than rapeseed at 20 and 45 cm depths; rapeseed had more roots than rye at 30–50 cm depth except at 45 cm

Table 4 Cover crop root and shoot dry matter (g), and the ratio of root to the whole plant (root + shoot) dry matter in Exp. 1, December, 2006

Cover crop	Compaction	Shoot (g)	Roots (g)	Roots: (roots ± shoot)[a]
Forage radish	High	18.7b*	8.7a	0.31ab
	Medium	23.4b	6.9a	0.23bc
	no	27.2b	11.9a	0.29ab
Rapeseed	High	16.4bc	4.9a	0.28ab
	Medium	18.1b	8.2a	0.31ab
	no	44.2a	9.8a	0.18c
Rye	High	18.9b	11.4a	0.38a
	Medium	18.6b	10.0a	0.36a
	no	27.8b	8.9a	0.25bc

[a] Root was sampled in 85.6 cm^2 area at 0–16 cm depth; shoot of plants in the rooting area was sampled

*Values within the column followed by the same letter(s) are not significantly different (Fisher's protected LSD $P<0.05$)

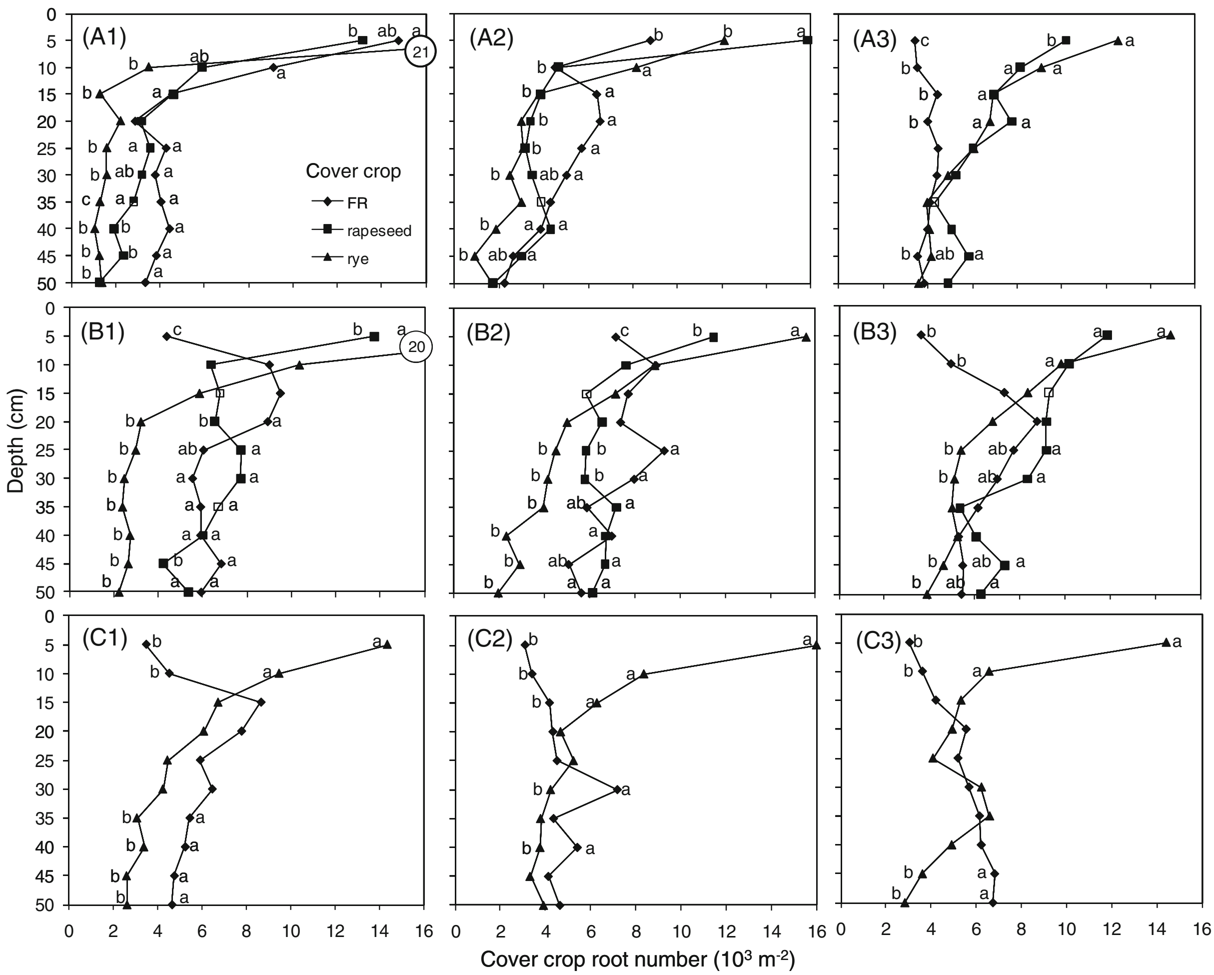


Fig. 2 Root penetrations of three cover crops under high, medium and no compaction in three Exp.-years. A1, A2, A3 are results for Exp. 1, 2006, B1, B2, B3 are results for Exp. 1, 2007, and C1, C2 and C3 are results for Exp. 2, 2007 under high, medium and no compaction, respectively. * Values within the same depth followed by the same letter(s) are not significantly different (F-protected LSD, $P<0.05$)

(Fig. 2-B1). Under medium compaction treatment, there were more FR roots than rye roots at 25–50 cm depth while rapeseed had more roots than rye at 40 and 50 cm depths (Fig. 2-B2). Under no compaction, rapeseed had more roots than rye at 25–30 cm and 45–50 cm depths (Fig. 2-B3).

In Exp. 2, 2007, the differences in root numbers among the three cover crops under soil compaction were less frequent and smaller than in Exp. 1 (Fig. 2-C). Rye roots were more numerous than FR roots at 5–10 cm for all three compaction treatments. Under high soil compaction, FR had more roots than rye at 35–50 cm depth (Fig. 2-C1). Under medium compaction, FR had more roots than rye only at 30 cm and 40 cm depths (Fig. 2-C2). Under no compaction, FR had more roots than rye at 45–50 cm depth (Fig. 2-C3).

Relationships between root counts, penetration resistance, and root dry matter

The relationships between cover crop root counts and soil penetration resistance are presented in Figure 3. There were highly significant ($P<0.001$) relationships between roots and penetration resistance for all three cover crops in both experiments except for FR in Exp. 1. Forage radish roots in Exp. 2 increased by a power function with penetration resistance (Fig. 3-A), while rye roots decreased with soil penetration resistance by power functions for both experiments (Fig 3-C). Rapeseed roots decreased linearly with penetration resistance (Fig. 3-B).

Correlations between root counts and root dry matter are presented in Table 5. Because root dry matter near the soil surface was usually greater by a magnitude of 100 times or more than root dry matter at deeper depths (below 15 cm for FR and rapeseed and below 5 cm for rye), two depth intervals for each cover crop species were evaluated. At 10–50 cm depth, rye root counts were positively related to root dry matter by logarithm functions in all three Exp.-years. Rapeseed root counts and root dry matter were positively related by logarithm functions at two depth intervals for all Exp.-years. Forage radish root counts and dry matter at 0–15 cm depth were negatively correlated by either logarithm functions (Exp. 1, 06 & Exp. 2, 07) or linear functions (Exp. 1, 07 & all three Exp.-years). Below 20 cm, FR root counts were positively related to root dry matter by logarithm functions in the separate and pooled data in the three Exp.-years.

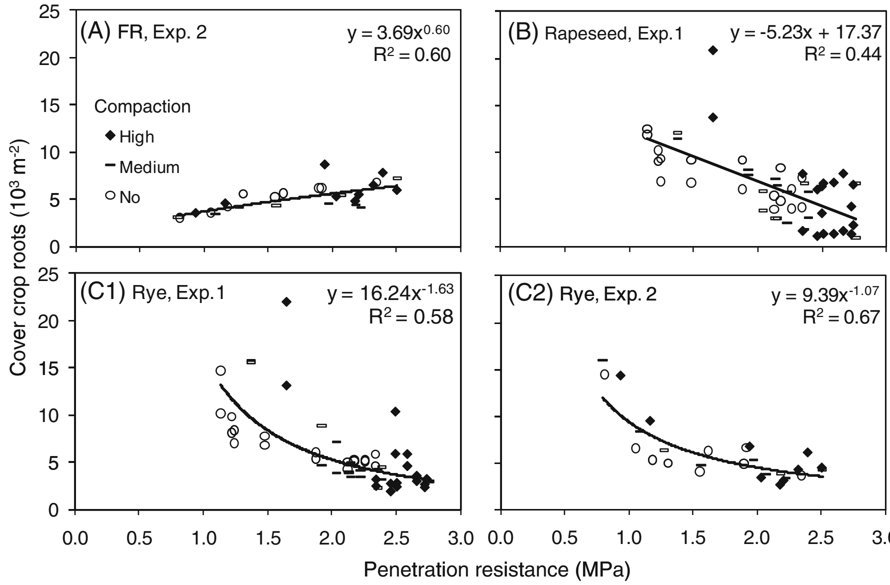
Discussion

Effects of compaction on root (0–16 cm depth) and shoot biomass of three cover crops

Root behavior for all three cover crops at the interface of the loose (upper 8 cm) and compacted (8–16 cm) soil layers was similar. The ratio of root biomass at the upper to the lower layers for high compaction was about 5 times as that for no compaction. The compaction effect on root biomass was due to the thickness of primary roots and proliferation of branch/lateral roots in the loose soil layer above a high soil strength layer, as have been previously reported (Atwell 1988; Misra and Gibbons 1996). The increased proliferation of branch/lateral roots above a homogeneous compacted layer may be due to the increased ethylene production by the stressed roots (Kays et al. 1974) and the higher availability of carbohydrates when the growth of main axes is restricted (Thaler and Pagès 1999). Taking the two layers (0–16 cm) as a whole, only the root biomass of rapeseed under high compaction was reduced (Table 4). This is in agreement with the finding by Steen and Hakansson (1987). Studies on fleshy/storage type roots like those of FR are rare. Maduakor (1993) reported that compaction decreased weight of the storage root of cassava (*Manihot esculenta*, Crantz) at early but not late growth stages.

As reviewed by Greacen and Sands (1980), restrictions of root growth do not necessarily reduce shoot growth, as long as the resource availability and root extension are not limiting to shoot growth. In our study, the significant reduction of rapeseed shoots under high compaction (Table 4) was probably due to its relatively limited root extension, assuming the availability of nutrient and water resources was the same for all three cover crops. Figure 2-A1 illustrates that rapeseed had fewer roots than rye at 5 cm and fewer roots than FR at most deeper depths. Changes in the ratio of root: whole plant dry matter have been explained by source/sink relationships (Thornley 1972) and by hormone regulation (Tardieu 1994), and are species dependent. The influence of adverse below ground environmental conditions on plant

Fig. 3 Correlations between cover crop root number (10^3 m^{-2}) and soil strength (MPa) in the two experiments



growth is usually greater on shoot than on root growth (Brouwer 1962; Kjellstrom and Kirchmann 1994) and this was also the case in our study. For example, the ratio of root: whole plant dry matter for rye and rapeseed was greater under high and medium compaction than under no compaction (Table 4), suggesting that shoot growth was inhibited more by compaction than root growth. This may be the result of compaction inducing greater dry matter allocation to roots, as was reported for barley (*Hordeum vulgare*

Table 5 Correlations between root number and root dry matter for the three experiment-years

Cover crop	Exp.-year	(0–5/15) cm Depth[a]			(10/20–50) cm Depth[a]		
		r[b]	p	n[c]	r	p	n
Rye	Exp.1, 06	0.14	0.671	12	0.73[d]	<.001	106
	Exp.1, 07	0.09	0.773	12	0.79[d]	<.001	104
	Exp.2, 07	0.43[d]	0.166	12	0.54[d]	<.001	108
	Overall	0.15[d]	0.372	36	0.71	<.001	322
Rape	Exp.1, 06	0.60[d]	<0.001	35	0.58[d]	<.001	75
	Exp.1, 07	0.45[d]	0.006	36	0.51[d]	<.001	79
	Overall	0.53[d]	<.001	71	0.59[d]	<.001	153
FR	Exp.1, 06	−0.17[d]	0.359	32	0.21[d]	0.061	81
	Exp.1, 07	−0.40	0.009	36	0.26[d]	0.017	82
	Exp.2, 07	−0.53[d]	0.001	34	0.17[d]	0.136	77
	Overall	−0.40	<.001	102	0.20[d]	0.002	240

[a] Rye roots were divided into groups of (0–5) cm and (10–50) cm; FR and rapeseed roots were divided into groups of (0–15) cm and (20–50) cm

[b] r-correlation coefficient, p-*P* value, n-sample size

[c] Sample sizes for FR or rapeseed at 0–15 cm depth smaller than 36 were due to rapid decomposition of several fleshy roots during cold storage. Sample sizes at 10–50 cm for rye and 20–50 cm for FR and rapeseed less than 108 and 84, respectively, were due to high gravel contents that prevented core penetration to sufficient depth

[d] Nonlinear relationship between root counts and dry matter as: root counts = LN (root dry matter); r value was for the nonlinear correlation

Prisma) by Bingham and Bengough (2003) and Braim et al. (1992). Among the three cover crop species studied, only forage radish exhibited no effect of compaction on root dry matter, shoot dry matter, and root: whole plant dry matter ratio. We found no studies in the literature on plants similar to forage radish with which we could compare our results.

Root penetration in and below the compacted soils

The root numbers obtained by the core break method further verified root proliferation in the upper loose layer right above the compacted layer, especially for rapeseed and rye. However root changes in numbers in and below the compacted layer differed greatly among three species (Fig. 2). At depth of 15–50 cm, rye under no compaction had 3.3, 1.8 and 1.1 times as many roots as it had under high compaction in Exp. 1–06, Exp. 1–07 and Exp. 2–07, respectively. Comparable values were 1.1, 1.0 and 1.0 for FR in Exp. 1–06, Exp. 1–07 and Exp. 2–07, respectively, and 2.0 and 1.2 times for rapeseed in Exp. 1, 2006 and 2007. When comparing roots of three species at 15–50 cm depth, in Exp. 1, 2006 under high, medium and no compaction respectively, FR had 2.65, 1.86 and 0.81 times as many roots as rye did, and rapeseed had 1.95, 1.36 and 1.14 times as many as rye. In Exp. 2 2007, FR had a mean of 1.47, 1.10 and 1.21 times as many roots as rye under high, medium and no compaction, respectively. In Exp. 1, 2006, forage radish had more than twice and rapeseed had about twice the number of roots as rye in and below the highly compacted soil layers. The data suggest that FR root counts were rarely decreased; rapeseed roots were moderately decreased, while rye roots were severely decreased by compacted soils. The results are in agreement with the findings by Materechera et al. (1992, 1993) that species with greater root diameters had greater root density in compacted soils than did species with smaller root diameters.

The difference in root penetration observed in this study might be explained by the findings of Misra et al. (1986) that maximum axial root growth pressure (σ_{max}) increased by a power function with an increase in root diameter. However, later studies suggest that roots with greater diameters (dicotyledons) do not always generate greater maximum root growth pressure compared to roots of smaller diameters (monocotyledons) (Clark and Barraclough 1999). Whalley and Dexter (1993) found no relation between the σ_{max} and the ability to penetrate strong soils. It has been suggested that the ability of roots to penetrate strong soils is directly related to root diameter (Clark et al. 2003). As was measured by Whiteley and Dexter (1981), fine penetrometers need to exert greater pressure to enter soil than coarse pentrometers. Shierlaw and Alston (1984) suggested that the same might apply to roots. It is reported that root strength (in terms of tension) tends to decrease with diameter according to a power law (Bischetti et al. 2005), and that thicker roots have a greater potential to relieve peak soil-root friction stress at the root tip (Kirby and Bengough 2002). Therefore, greater diameters would favor root penetration because roots with greater diameters need to overcome less friction pressure of the soil and less tension in the cell wall, compared roots with smaller diameters. It was also found that roots with greater diameter were more resistant to buckling (Whiteley et al. 1982). Clark et al. (2008) reported log-log positive relationships between root diameters and bending stiffness.

If we integrate all of the preceding concepts, we can suggest that roots with greater diameter may exhibit good penetration of strong soils because of a combination of reduced overall friction, fewer tendencies to be deflected sideways or buckling. In our study, though FR and rapeseed are both tap-rooted species, FR has a single dominant cylindrical-shaped fleshy taproot with thick branch roots, while rapeseed may have several main taproot branches with a fibrous near-surface root system and many fine laterals coming out of the main root branches. These differences in their root systems are consistent with the difference in root penetration observed between the two species. As a fibrous rooted species, rye was the one that was most sensitive to soil compaction.

It is worth mentioning that rye root growth in Exp. 2 2007 was less inhibited by compaction than in Exp. 1 2006. As is described in "Materials and methods", for the same compaction level, soils in Exp. 2 had higher sand content (and gravel content in Block III) and received less axel load, therefore they should have relatively larger pore sizes than soils in Exp. 1. On the other hand, the greater clay content in Exp. 1 may also have led to greater frictional resistance experienced by roots (Iijima et al. 2004). Studies have demonstrated that mechanical resistance to the growth of thin roots is a limiting factor only in fine and densely compacted soils because the diameters of the thin roots are often smaller than the pore diameters in coarse textured soils, even under some types of compaction. The fine roots may therefore elongate into the pores of some compacted sandy soils (Pietola and Smucker 1998; Scholefield and Hall 1985; Warnaars and Eavis 1972; Wiersum 1957).

Increase of root penetration following cover crop-corn rotation

In Exp. 1 which had cover crops planted in fall of both 2006 and 2007 and maize planted in summer of 2007, cover crop root counts were generally greater in the second year (Fig. 2A and B), and the increase of rye root counts were most pronounced under the high compaction treatment (Fig 2 A1 vs. B1). We did not find any significant changes in soil bulk density or penetration resistance in Exp. 1 between the first year and second year for soils with high and medium compaction treatments. The increase in root penetration in the second year was therefore likely due to the formation of root channels by the cover crop and maize that grew in the year since the compaction was applied. These root channels could have provided easier access through the compacted soils for the second-year cover crop roots, especially for rye roots which were greatly inhibited in the first year. Evidence that root channels created by one crop can be used by succeeding crops has been previously reported (Rasse and Smucker 1998; Stirzaker and White 1995; Williams and Weil 2004).

Relationships between soil strength and root penetration, root number and dry matter

Figure 3 shows the relationships betweens soil strength and root growth for each cover crop. It is well known root growth decreases as soil strength increases (Taylor and Ratliff 1969). There are widely reported negative curvilinear relationships between root growth and soil strength for different species such as cotton (*Gossypium spp.*) and peanuts (*Arachis hypogaea*) (Taylor and Ratliff 1969), barley (*Hordeum vulgare* L.) (Goss 1977), wheat (*Triticum aestivum*) (Merrill et al. 2002) and maize (Panayiotopoulos et al. 1994). For an individual root, the elongation rate has been reported to decrease linearly as soil strength increases (Tardieu 1994; Taylor et al. 1966). Because rye has a typical fibrous root system and rapeseed has a finely branched root system, the relationships we observed between their root growth and soil strength were in agreement with the common findings just cited (Fig. 3). The difference of root penetration between rapeseed (as a dicot) and rye (as a monocot) was that rye roots decreased more rapidly than rapeseed roots as soil strength increased.

The exception was that FR roots increased with soil strength. As demonstrated by Goodman and Ennos (1999), in response to soil strength, sunflower (*Helianthus annuus* L.) had greater increases in the angle of spread of its root system and the thickness of roots than maize (*Zea mays* L.). Pietola and Smucker (1998) reported that in response to compaction, carrot (*Daucus carota* sativus) had an increase in number of fine roots in natural soil profiles to 50 cm depth. It appears that in our study the FR root system responded to soil compaction in a manner similar to that reported for sunflower and carrot. Root growth in Exp. 2 was generally less inhibited than in Exp. 1 for the reasons previously discussed. Thus, it is not surprising that FR root number, which was not affected by soil compaction in Exp. 1, actually increased with soil strength in Exp. 2 (Fig. 3A). We did not find any reports of similar findings in the literature.

The lack of correlation between rye root number and dry matter at 0–5 cm might be due to small sample size and/or the take-over effect of the thickened primary roots in the compacted plots. Compaction increased FR (branch) root number (Fig. 2-A) but decreased its root dry matter (Table 4). Forage radish root dry matter was negatively correlated with root number at shallow depths (Table 5), probably because of the huge difference in dry matter for a FR tap root and a FR branch root. Below 5 cm (for rye) and 15 cm (for rapeseed), root size for both rye and rapeseed might be less variable, and root dry matter and number were better correlated. Because of the thick branch roots and greater penetration ability, the diameters of FR roots below 15 cm were still highly varied. This fact is reflected by the weak correlations between root counts and dry matter for FR in Exp. 1, and lack of correlation in Exp. 2.

Conclusion

In this study, we demonstrated that among the three cover crops examined, soil penetration by FR roots was least affected by compaction while penetration by rye roots was most inhibited by compaction, especially where soil clay content was relatively high and when pre-existing root channels were not available. The ranking for number of root penetration in compacted soils was FR > rapeseed > rye. Forage radish and rapeseed, therefore, can be expected to perform better than rye when used as a biological tillage tool. We suggest that the use of a Brassica fall/winter cover crop, especially FR, may be useful in alleviating the effects of soil compaction in no-till farming systems. Mixing rye with forage radish might provide both bio-drilling and mulching benefits, and this system is now under study.

Acknowledgements This study was partially funded by USDA NE-SARE program (grant LNE03-192) and the Harry R. Hughes Center for TAgroT-TEcology. We thank Dr. Robert Hill (Univ. of Maryland) for his insightful suggestions during the research design, Kevin Conover (Univ. of Maryland) for help in taking deep soil cores.

References

Atwell BJ (1988) Physiological responses of lupin roots to soil compaction. Plant Soil 111:277–281

Bengough AG, Mullins CE (1990) Mechanical impedance to root-growth—a review of experimental-techniques and root-growth responses. Eur J Soil Sci 41:341–358

Bingham IJ, Bengough AG (2003) Morphological plasticity of wheat and barley roots in response to spatial variation in soil strength. Plant Soil 250:273–282

Bischetti GB, Chiaradia EA, Simonato T, Speziali B, Vitali B, Vullo P, Zocco A (2005) Root strength and root area ratio of forest species in Lombardy (Northern Italy). Plant Soil 278:11–22

Bowen HD (1981) Alleviating mechanical impedance. In: Taylor HM, Arkin GF (eds) Modifying the root environment to reduce crop stress. ASAE, St. Joseph, pp 21–57

Brady NC, Weil RR (2008) Soil water: Characteristics and behavior. In: Brady NC, Weil RR (eds) The nature and properties of soils. Prentice Hall, New Jersey, pp 177–217

Braim MA, Chaney K, Hodgson DR (1992) Effects of simplified cultivation on the growth and yield of spring barley on a sandy loam soil.2. Soil physical properties and root growth, root shoot relationships, inflow rate of nitrogen water use. Soil Tillage Res 22:173–187

Brouwer R (1962) Nutritive inlfuence on the distribution of dry matter in the plant. Neth J Agric Sci 10:361–376

Carr MKV, Dodds SM (1983) Some effects of soil compaction on root-growth and water-use of lettuce. Exp Agric 19:117–130

Clark LJ, Barraclough PB (1999) Do dicotyledons generate greater maximum axial root growth pressures than monocotyledons? J Exp Bot 50:1263–1266

Clark LJ, Whalley WR, Barraclough PB (2003) How do roots penetrate strong soil? Plant Soil 255:93–104

Clark LJ, Price AH, Steele KA, Whalley WR (2008) Evidence from near-isogenic lines that root penetration increases with root diameter and bending stiffness in rice. Funct Plant Biol 35:1163–1171

Coale FJ, Costa JM, Bollero GA, Schlosnagle SP (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

Cresswell HP, Kirkegaard JA (1995) Subsoil amelioration by plant roots—the process and the evidence. Aust J Soil Res 33:221–239

de Willigen P, van Noordwijk M (1987) Roots, plant production and nutrient use efficiency. In: Agricultural concepts of roots: From morphogenetic to functional equalibrium between root and shoot growth. Onerzoek Uitgevoerd op het Instituut voor Bodemvruchtbaarheid, The Netherlands

Dean JE, Weil RR (2009) Brassica Cover Crops for N Retention in the Mid-Atlantic Coastal Plain. J Environ Qual 38:520–528

Elkins CB (1985) Plant roots as tillage tools. In: International conference on soil dynamics, Auburn, pp 519–523

Goodman AM, Ennos AR (1999) The effects of soil bulk density on the morphology and anchorage mechanics of the root systems of sunflower and maize. Ann Bot 83:293

Goss MJ (1977) Effects of mechanical impedance on root-growth in barley (Hordeum-vulgare-L).1. Effects on elongation and branching of seminal root axes. J Exp Bot 28:96–111

Greacen EL, Sands R (1980) Compaction of forest soils—A review. Aust J Soil Res 18:163–189

Herrick JE, Jones TL (2002) A dynamic cone penetrometer for measuring soil penetration resistance. Soil Sci Soc Am J 66:1320–1324

Iijima M, Higuchi T, Barlow PW (2004) Contribution of root cap mucilage and presence of an intact root cap in maize (Zea mays) to the reduction of soil mechanical impedance. Ann Bot 94:473

Ishaq M, Ibrahim M, Hassan A, Saeed M, Lal R (2001) Subsoil compaction effects on crops in Punjab, Pakistan: II. Root growth and nutrient uptake of wheat and sorghum. Soil Tillage Res 60:153–161

Kays SJ, Nicklow CW, Simons DH (1974) Ethylene in relation to response of roots to physical impedance. Plant Soil 40:565–571

Kirby JM, Bengough AG (2002) Influence of soil strength on root growth: experiments and analysis using a critical-state model. Eur J Soil Sci 53:119–127

Kjellstrom CG, Kirchmann H (1994) Dry-matter production of oilseed rape (Brassica napus) with special reference to the root-system. J Agric Sci 123:327–332

Maduakor HO (1993) Effect of soil compaction on leaf, stem and fibrous root-growth of Cassava (*Manihot-ssculenta*, Crantz). Soil Tillage Res 26:69–78

Materechera SA, Dexter AR, Alston AM (1991) Penetration of very strong soils by seedling roots of different plant-species. Plant Soil 135:31–41

Materechera SA, Alston AM, Kirby JM, Dexter AR (1992) Influence of root diameter on the penetration of seminal roots into a compacted subsoil. Plant Soil 144:297–303

Materechera SA, Alston AM, Kirby JM, Dexter AR (1993) Field evaluation of laboratory techniques for predicting the ability of roots to penetrate strong soil and of influence of roots on water sorptivity. Plant Soil 149

McGarry D, Sharp G (2001) A rapid, immediate, farmer-usable method of assessing soil structure condition to support conservation. In: Garcia-Torres L, Benites J, Marttinez-Vilela A (eds) First world congress on conservation agriculture, 1–5 October 2001. Natural Resource Sciences, Madrid, pp 209–214

Merrill SD, Tanaka DL, Hanson JD (2002) Root length growth of eight crop species in haplustoll soils. Soil Sci Soc Am J 66:913–923

Misra RK, Gibbons AK (1996) Growth and morphology of eucalypt seedling-roots, in relation to soil strength arising from compaction. Plant Soil 182:1–11

Misra RK, Dexter AR, Alston AM (1986) Maximum axial and radial growth pressures of plant roots. Plant Soil 95:315–326

Panayiotopoulos KP, Papadopoulou CP, Hatjiioannidou A (1994) Compaction and penetration resistance of an alfisol and entisol and their influence on root-growth of maize seedlings. Soil Tillage Res 31:323–337

Pietola L, Smucker AJM (1998) Fibrous carrot root responses to irrigation and compaction of sandy and organic soils. Plant Soil 200:95–105

Rasse DP, Smucker AJM (1998) Root recolonization of previous root channels in corn and alfalfa rotations. Plant Soil 204:203–212

Ritter WF, Scarborough RW, Chirnside AEM (1998) Winter cover crops as a best management practice for reducing nitrogen leaching. J Contam Hydrol 34:1–15

Scholefield D, Hall DM (1985) Constricted growth of grass roots through rigid pores. Plant Soil 85:153–162

Shierlaw J, Alston AM (1984) Effect of soil compaction on root-growth and uptake of phosphorus. Plant Soil 77:15–28

Staver KW, Brinsfield RB (1998) Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. J Soil Water Conserv 53:230–240

Steen E, Hakansson I (1987) Use of in-growth soil cores in mesh bags for studies of relations between soil compaction and root-growth. Soil Tillage Res 10:363–371

Stirzaker RJ, White I (1995) Amelioration of soil compaction by a cover-crop for no-tillage lettuce production. Aus J Agric Res 46:553–568

Tardieu F (1994) Growth and functioning of roots and of root systems subjected to soil compaction—towards a system with multiple signaling. Soil Tillage Res 30:217–243

Taylor HM, Ratliff LF (1969) Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. Soil Sci 108:113–119

Taylor HM, Roberson GM, Parker JJ (1966) Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Sci 102:18–22

Thaler P, Pagès L (1999) Why are laterals less affected than main axes by homogeneous unfavourable physical conditions? A model-based hypothesis. Plant Soil 217:151–157

Thornley JH (1972) Balanced quantitative model for root—shoot ratio in vegetative plants. Ann Bot 36:431–441

van Noordwijk M, Brouwer G, Meijboom F, do Rosaerio M, Oliveira G, Bengough AG (2000) Trench profile techniques and core break methods. In: Smit AL, Bengough AG, Engels C, van Noordwijk M, Pellerin S, van de Geijn SC (eds) Root methods: A handbook. Springer-Verlag, Berlin, pp 211–234

Vepraskas MJ, Miner GS (1986) Effects of subsoiling and mechanical impedance on tobacco root-growth. Soil Sci Soc Am J 50:423–427

Warnaars BC, Eavis BW (1972) Soil physical conditions affecting seedling root growth. 2. Mechanical impedance, aeration and moisture availability as influenced by grain-size distribution and moisture-content in silica sands. Plant Soil 36:623–634

Whalley WR, Dexter AR (1993) The maximum axial growth pressure of roots of spring and autumn cultivars of lupin. Plant Soil 157:313–318

Whiteley GM, Dexter AR (1981) The dependence of soil penetrometer pressure on penetrometer size. J Agric Eng Res 26:467–476

Whiteley GM, Hewitt JS, Dexter AR (1982) The buckling of plant roots. Physiol Plant 54:333–342

Wiersum LK (1957) The relationship of the size and structural rigidity of pores to their penetration by roots. Plant Soil IX (1):75–85

Williams SM, Weil RR (2004) Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci Soc Am J 68:1403–1409