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Root growth and yield of maize as affected by soil compaction and cover crops

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ABSTRACT

The yield of rainfed crops is commonly limited by the availability of soil water during the summer growing season. Channels produced by cover crop roots in fall/winter when soils are relatively moist may facilitate the penetration of compacted soils by subsequent crop roots in summer when soils are relatively dry and hard. Our objective was to determine the effects of fall cover crops on maize (*Zea mays*) growth and soil water status under three levels (high, medium, and no) of imposed traffic compaction. The study was conducted on coastal plain soils (fine-loamy Typic/Aquic hapludults and siliceous, Psammentic hapludults) in the mid-Atlantic region of the United States from 2006 to 2008. Cover crop treatments were FR (forage radish: *Raphanus sativus* var. *longipinnatus*, cv. 'Daikon'), rapeseed (*Brassica napus*, cv. 'Essex'), rye (cereal rye: *Secale cereale* L., cv. 'Wheeler') and NCC (no cover crop). Maize under high compaction achieved more deep-roots following FR and rapeseed than following rye or NCC. However, maize had greater yield following all cover crops than NCC control regardless of compaction levels and soil texture. Compaction reduced maize yield only under the high compaction in the lightly textured soils. During 24 June–24 July 2008, soils at 15 and 50 cm depths were drier under no compaction than high compaction and drier following FR than other cover crop treatments. Our results suggest that FR benefited maize root penetration in compacted soils while rye provided the best availability of surface soil water; rapeseed tended to provide both benefits. However, as rapeseed is relatively difficult to kill in spring, a mixture of FR and rye cover crops might be most practical and beneficial for rainfed summer crops under no-till systems in regions with cool to temperate, humid climates.

1. Introduction

The ability of plants to obtain water and mineral nutrients from the soil is related to their capacity to develop extensive root systems. Soil compaction, especially in subsoil layers, may restrict deep root growth and adversely affect plant access to subsoil water from the middle to late growing season when rainfall is usually sparse and evapotranspiration is high. The resulting increase in drought stress may limit plant growth and yield. Deep ripping has been used to alleviate soil compaction (Schmidt et al., 1994), but the benefits of deep tillage may be short-living (Calonego and Rosolem, 2010; Hall et al., 1994) and costly in terms of energy and time. Use of deep tillage to alleviate compaction also disrupts the surface mulch that develops after years of no-till management, increasing the soil's susceptibility to erosion and sealing (Wiermann et al., 2000; Zhang et al., 1998).

Crop rotation is an important tool for maintaining long-term productivity and environmental quality (Ball et al., 2005). The crop rotation system chosen may profoundly influence soil physical properties, especially with respect to the development and distribution of root channels. The possibility of using "plant roots as tillage tools" was first proposed by Elkins (1985). More recently, Cresswell and Kirkegaard (1995) suggested the term "biological drilling" to describe the process by which root channels left by previous crops may ameliorate the effects of subsoil compaction on subsequent crop root growth. Among the few studies published (Materechera et al., 1992; Merrill et al., 2002), there is general agreement that roots with greater diameter (often tap-rooted dicots) are more capable of penetrating compacted soil layers than roots with smaller diameter (usually fibrous-rooted monocots), although the mechanisms for this difference are not clearly understood (Chen and Weil, 2010; Clark et al., 2003). Rasse and Smucker (1998) found that maize after alfalfa achieved a higher number of roots in the subsoil than maize after maize, a finding which is in agreement with Materechera et al. (1991). However, Cresswell and Kirkegaard (1995), after finding that a canola (*Brassica rapa* L.) crop did not improve rooting depth in a following wheat crop, suggested that perennials might be more capable of

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providing root channels in compacted soils than annuals. In contrast, Williams and Weil (2004) observed soybean [*Glycine max* (L.) Merr.] roots growing through compacted plowpan soil using channels made by roots of a previous canola cover crop. This suggests that the benefit from a given cover crop species may depend on the following cash crop species and environmental conditions.

In the mid-Atlantic region of the USA, erratic precipitation and high evapotranspiration during the summer crop growing season typically results in plant water stress that causes yield reduction where irrigation is not available. This is especially true where compacted soils prevent crops from growing deep root systems, but instead promotes extensive shallow roots. Subsoil horizons often store enough water to potentially meet crop requirements and avoid drought stress between rain events, provided roots can actually access this stored subsoil water (Talsma and Gardner, 1986).

Rye (cereal rye: *Secale cereale* L., cv. 'Wheeler') winter cover crop has been widely used for conservation of post-harvest residual soil nitrogen in the mid-Atlantic Coastal Plain (Coale et al., 2001). Forage radish (FR) (*Raphanus sativus* var. *longipinnatus*, cv. 'Daikon') and rapeseed (*Brassica napus*, cv. 'Essex'), both cover crops in the Brassica family, were recently introduced to the mid-Atlantic region. Unlike rye and rapeseed, planting date is critical for FR in order to catch up significant amounts of soil nitrogen before it is frost-killed in the mid-Atlantic climate (Weil et al., 2009). As dairy farming is a major cropping system in this region, planting Brassica cover crops can fit at the optimum window after harvest of maize silage at late August–early September. Although drilling the seeds ensures decent plant population, broadcasting seeds into soybean or maize canopies that are beginning to senesce is also used to establish these cover crops.

The use of Brassica cover crops may provide multiple benefits when used in maize–soybean rotations and maize silage systems in the mid-Atlantic region (Lawley et al., 2011; Weil and Kremen, 2007). Dean and Weil (2009) reported that Brassica cover crops were more effective than rye in reducing the leaching loss of nitrogen. Jones (2008) reported extension trials in Virginia in which FR and legume cover crops equally increased maize yields compared to maize with no preceding cover crop. He suggested that the increase in maize yields may have been due to the "biodrilling" effect provided by FR. Though rye cover crop has been reported to reduce post-harvest soil nitrogen leaching (Coale et al., 2001; Rasse et al., 2000), no studies have been conducted on if rye could benefit subsequent summer crops, especially in compacted soils. Our hypotheses were that the two Brassica cover crops (FR and rapeseed) would better alleviate soil compaction for summer crops than rye by providing more root channels and enhancing subsoil water uptake. The objectives were (1) to compare the effects of four cover crop treatments, FR, rapeseed, rye and NCC on the vertical distribution of maize roots in soils with three levels of traffic compaction; (2) to determine soil water potential during the maize growing season at 15 cm (the interface of loosened and compacted layers) and 50 cm (below the compacted layer) depths as affected by preceding cover crops; and (3) to evaluate the effects of cover crops and levels of soil compaction on maize yield.

2. Materials and methods

2.1. Site description

Two experiments (Exp. 1 and Exp. 2) were located in two fields next to each other on the north farm of the USDA-ARS Beltsville Agricultural Research Center in Beltsville, MD in the coastal plain ecoregion (39°01′N, 76°55′W, and altitude of 41 m). The size for Exps. 1 and 2 was 0.28 and 0.23 ha, respectively. The two fields had a long history of conventional tillage practices. Prior to the start of Exp. 1, potatoes (*Solanum tuberosum* L.) and green beans (*Phaseolus vulgaris* L.) were grown in 2005 and 2006, respectively, and rye cover crop was established in the fall of 2005. Near-term cropping history for the field used for Exp. 2 included green beans and Zucchini (*Cucurbita pepo* L.) in the summers of 2005 and 2006, respectively, rye cover crop in fall 2005 and cereal rye from fall 2006 to summer 2007. The soils in Exp. 1 sloped slightly (0–5%) to the east, such that the predominant soil series was Elsinboro (fine-loamy, mixed, semiactive, mesic Typic hapludults) with a sandy loam in the A horizon (12.5% clay and 22.9% silt), and the eastern most block was dominated by the Woodstown series (fine-loamy, mixed, active, mesic Aquic hapludults) with a loam soil in the A horizon (18.2% clay and 36.8% silt). The soils in Exp. 2 had a 0–5% slope from the northeast toward the southwest, and consisted of a complex of Elsinboro series and Galestown series (siliceous, mesic Psammentic hapludults;) with a coarse loamy sand soil (5.1% clay and 11% silt) in the A horizon. The field of Exp. 2 had a gravelly variant in the southwest quadrant of the field. In both fields, the pH_{H_2O} of the A and B horizon soils ranged from 5.6 to 6.1. The organic matter content of the A horizons ranged from 1.0 to 1.8% (by loss on ignition), and the A horizon soil test values for P and K (Mehlich 3 extract) were near optimal (86.6–112.7 mg kg^{-1} and 67.2–78.4 mg kg^{-1}, respectively).

2.2. Experimental design and compaction treatments

A randomized complete block design was used for both fields. There were four blocks in each field, which were blocked against soil properties and slope. Each block in Exp. 1 contained 12 plots; however, due to the smaller field size, each block in Exp. 2 contained only nine plots. The plot dimensions were 3.0 m $\times$ 9.0 m, and 3.3 m $\times$ 12.2 m for Exps. 1 and 2, respectively. Blocks within the fields were separated by alleys (10.7 and 12.2 m wide in Exps. 1 and 2, respectively) to allow equipment maneuvering room during creation of the compaction 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. In Exp. 1, three levels of compaction (high, medium and no) and four levels of cover crops (FR, rapeseed, rye and NCC) were combined in a factorial arrangement to provide a total of 12 treatment combinations. Experiment 2 included three compaction levels and three cover crops (FR, rye and NCC) for a total of nine treatments. High, medium and no compaction treatments are abbreviated as HC, MC and NC, while compaction-cover crop treatment combinations are abbreviated as HC-FR for high compaction with forage radish, NC-NCC for no compaction with no cover crop, etc.

Prior to establishment of the compaction treatments, both fields were deep-ripped to an average depth of 45 cm when the soil was slightly drier than the plastic limit (the lowest soil water content at which the soil remains plastic), then moldboard plowed to 32 cm and finally disked to approximately 8 cm depth. In mid-late August 2006 (Exp. 1) and 2007 (Exp. 2), the 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 m^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 a total axle load of 12.91 Mg. Medium compaction was established by one pass of the tractor without rocks in the bucket. For Exp. 2, a single pass of the John Deere 544C tractor was used to create the HC, 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 m^2) was used to create the MC. No tractor traffic occurred for the NC treatment for both experiments. Immediately after the compaction treatments were imposed, the soils in both experiments were 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. Penetration resistance was measured at 10 randomly selected locations per plot. At each location, the penetrometer was pushed by hand at 4 cm s^{-1} rate and mean penetration resistance was recorded in kPa for every 5 cm depth increment to 45 cm. 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 20–40 cm soil core. There was no observable soil compression during coring. All cores were divided into 5 cm increments, weighed, dried and re-weighed to determine soil bulk density and water content. Soil strength and bulk density measurements were taken immediately after application of compaction but prior to surface disking in August 2006 (Exp. 1) and 2007 (Exp. 2) and again in March 2008 (both Exps. 1 and 2) when soil water content 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).

2.3. Cover crop management and biomass sampling

Cover crops were planted on 31 August, 2006 (Exp. 1) and 27 August 2007 (Exps. 1 and 2) using a no-till drill with 16 cm row spacing. The seeding rates for FR, rapeseed and rye were 14, 9 and 134 kg ha^{-1}, respectively. On 22 September, 2006, 28 kg N ha^{-1} as urea ammonium nitrate (UAN) granular was surface applied because of observed nitrogen deficiency in the cover crops. In 2007 in Exp. 1, prior to planting second year cover crops, weeds were controlled with glyphosate (N-(phosphonomethyl)-glycine) (1.85 L ha^{-1} active ingredient (a.i.)). Concurrent with cover crop planting in 2007, 22.4 kg N ha^{-1} as UAN granular was applied in both experiments as a starter fertilizer for the cover crops to ensure adequate growth. Forage radish was frost-killed in the winter when air temperature dropped below −4 °C for several nights in a row. Rye, rapeseed and weeds on no cover plots were killed on 11 April 2007 (Exp. 1) by spraying paraquat dichloride (0.68 L ha^{-1} a.i.) and on 16 April 2008 (Exps. 1 and 2) by spraying glyphosate (1.85 L ha^{-1} a.i.) and 2,4-D (2,4-dichlorophenoxyacetic acid) (1.05 L ha^{-1} a.i.).

Cover crop shoots were sampled on 30 November 2007 before FR was frost-damaged and on 10 April 2008 before rye and rapeseed were spray-killed. Samples were taken in a 0.5 m × 0.5 m area at both ends of the plot, rinsed with water and dried prior to recording the dry matter.

2.4. Maize management

Four 75-cm rows of maize (Pioneer, 34B62, glyphosate tolerant) were planted per plot with a no-till planter at a seeding rate of 74,000 seeds ha^{-1} on 24 April 2007 (Exp. 1) and 5 May 2008 (Exps. 1 and 2). As a starter fertilizer 22 kg N ha^{-1} as granular UAN was applied at planting in a band 5 cm to the side of and 5 cm deeper than the seed furrow. Maize was sidedressed with 112 kg N ha^{-1} as a UAN solution dribbled on the soil surface between rows on 7 June 2007 and 10 June 2008. In 2007, glyphosate (1.85 L ha^{-1} a.i.) and 2,4-D (1.05 L ha^{-1} a.i.) were sprayed on 9 May, to control weeds and kill rapeseed that had not been killed in the earlier application. In 2008 weeds were controlled in the maize crop with glyphosate (1.85 L ha^{-1} a.i.) on 18 June 2008.

For Exp. 1 in 2007, 23 mm of water was sprinkler applied on 2 July to moisten the soil to allow planned measurement of surface soil structure; 51 mm of water was sprinkler applied on 23–25 July to allow for deep soil core sampling. In 2008, both Exps. 1 and 2 received a total of 102 mm of irrigation water to make possible deep soil coring, but the irrigation was delayed until July 30 so that the treatment effects on soil water tension could be monitored during July, a critical period for maize growth.

Maize silage was harvested by hand on 14 August 2007 and 2008. Plants in 3-m length of the two central rows in each plot were cut 1 cm above the soil surface. The fresh weight and total plant counts in the harvest area (6 m × 0.75 m) were recorded. Three plants were randomly selected to determine dry matter percentage and this value was used to calculate the dry weight of silage maize per unit area.

2.5. Root vertical distribution measurement

Vertical distribution of maize roots was measured in late July to early August 2008 using the core break method which counts only non-brittle living roots (Noordwijk et al., 2000). Soil cores were collected using a tractor-mounted direct-drive hydraulic soil coring machine (Giddings Inc., Windsor, CO) with a sampling tube of 6.4 cm inner diameter and 90 cm long. In some plots, gravels or dense clay in the B horizon limited core penetration (causing the rig to lift off the ground) at 60–70 cm. Therefore soil cores were collected to 60 cm to provide a consistent core depth. In each plot, three cores were collected in the two central inter-rows (no wheel trafficking after compaction was applied) 5 cm away from representative maize plants. The cylindrical soil cores collected were laid in horizontal holding troughs. Each soil 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 (1–15 mm) from the 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.

2.6. Soil water tension measurement

From 21 June to 28 July 2008, a pair of granular matrix electrical resistance sensors (Watermark™, Irrometer Co., Riverside, CA) were installed between the two central maize rows in plots under combinations of HC/NC-FR, HC/NC-NCC and HC/NC-rye treatments at 15 and 50 cm depth, respectively. In plots of HC/NC-rapeseed treatments (Exp. 1) sensors were installed only at 50 cm depth. The electrical resistance readings were automatically corrected for soil temperature and converted by dataloggers (Watermark monitor 3.1, Irrometer Inc., Riverside, CA) using factory calibration to hourly readings of soil water tension in units of kPa. The purpose of these measurements was to monitor soil water tension under the different compaction/cover crop treatments to help interpret plant and soil responses to these treatments. Although readings from granular matrix sensors can be somewhat variable among individual sensors (Intrigliolo and Castel, 2004), these sensors are considered to be satisfactory for indicating relative soil wetness (Haman et al., 2000; Hanson et al., 2003; Shock et al., 1998).

2.7. Statistical analysis

Analysis of variance was performed using PROC MIXED (SAS v. 9.1, SAS Institute, Cary, NC). For soil bulk density, data in spring 2008 were analyzed by depth using compaction and cover crop as fixed factors, and block as a random factor. When cover crop effect on bulk density were insignificant at all depths, data collected right after compaction application (fall 2006 for Exp. 1 and fall 2007 for Exp. 2) and in spring 2008 were pooled using sampling time and compaction as fixed factors, depth as a split-plot factor, and blocks remained as the random factor. For soil penetration resistance, data were analyzed separately by sampling time and depth, using compaction and cover crop (only for data in spring 2008) as fixed factors, block and sample location as random factors. Maize root distribution was analyzed using block and location as random factors, compaction and cover crop as fixed factors and depth as a split-plot factor. The same approach was used to analyze daily mean soil water tension except that separate analyses were performed on each depth. However, mean comparisons for soil bulk density, penetration resistance, and maize root distribution were restricted to within each site and depth because soil texture varied greatly among sites and down the soil profiles as described by Chen and Weil (2010). Analyses of maize yield and population density were also performed separately by site. In Exp. 1, year was treated as a fixed factor because of the potential cumulative effect of cover crops from the previous year. Mean comparison was performed using Fisher's protected least significant difference (LSD) when the ANOVA indicated a statistically significant effect ($P \leq 0.05$).

3. Results and discussion

3.1. Soil bulk density and penetration resistance

The ANOVA showed that in spring 2008 in both experiments there was no interaction effect of compaction and cover crop on soil bulk density ($P > 0.06$ and >0.12 for Exps. 1 and 2, respectively) or penetration resistance ($P > 0.07$ for both Exp. 1 and 2). Cover crop itself had no effect on bulk density in either experiment ($P > 0.10$ and >0.09 for Exp. 1 and 2, respectively). However, there was cover crop effect on penetration resistance at 0–10 cm in Exp. 1 ($P < 0.02$). The penetration resistance at 0–10 cm depth of Exp. 1 was greater in plots of FR and NCC than in plots of rye and rapeseed, which was probably because the soil water content was 2% greater in plots of rye and rapeseed. Though FR and rapeseed were observed to grow more roots than rye in the compacted soil layers (Chen and Weil, 2010), there was no detectable difference of soil bulk density or penetration resistance among different cover crop treatments. This lack of effect on these parameters was expected because small (<1 mm diameter) root channels would not change gross soil bulk density as the root simply moved soil small distances laterally. Nor would small root channels be expected to influence the resistance to penetration by a conical tip order of magnitude wider than those channels unless the conical tip encountered several root channels within its 10 mm diameter. Given the taprooted cover crop population densities of 10–20 plants m^{-2}, more years of cover cropping than just the one to two years in this study would be required to achieve a density of root channels such that the cone might encounter several channels at once. Chan and Heenan (1996) reported that tap-rooted species reduced bulk density and penetration resistance more than fibrous-rooted species after four-season crop rotations, which agrees with Jokela et al. (2009) who suggested that it might take 4 or more years of cover crops for some soil quality indicators to fully respond.

The ANOVA for soil bulk density indicated a significant interaction of compaction × time × depth, with the greatest F-value for compaction, followed by depth in both experiments (Table 1). Fig. 1 presents soil bulk density values from 0 to 40 cm depth at two sampling times and different compaction levels. Compared to measurements taken immediately after compaction application (fall 2006 for Exp. 1 and fall 2007 for Exp. 2), soil bulk density in spring 2008 had increased for NC at 0–25 cm in Exp. 1 and at 5–20 cm in Exp. 2 and decreased for MC and HC at 0–5 cm in Exp. 1 and 0–15 cm in Exp. 2. This reduction in bulk density was probably due to the surface (~0–8 cm) disking performed prior to planting the first cover crops. There was no difference in bulk density among the three compaction levels at 0–5 cm for Exp. 1 in spring 2008; however, bulk density was greater at HC than MC and NC at 0–10 cm for Exp. 2. Regardless of the above changes, bulk density was in the order of HC > MC > NC at 5–25 cm depth for Exp. 1 and at 15–25 cm depth in Exp. 2 at both sampling times.

Table 1
F-statistic significance for compaction, time and depth effects on soil bulk density in Exp. 1 and Exp. 2.

Source of variance	NDF[a]	Exp. 1		Exp. 2	
		F value	Pr > *F*[b]	*F* value	Pr > *F*
Compaction (Com)	2	453.56	<0.0001	135.64	<0.0001
Time (T)	1	4.90	0.0272	1.05	0.3068
Depth (D)	7	159.95	<0.0001	87.30	<0.0001
Com × T	2	63.48	<0.0001	16.89	<0.0001
Com × D	17	28.31	<0.0001	4.39	<0.0001
T × D	7	8.40	<0.0001	10.28	<0.0001
Com × T × D	14	8.97	<0.0001	2.44	0.0026

[a] NDF is numerator degree of freedom.
[b] Values indicate the probability of a greater *F*-value.

Because soil penetration resistance is highly influenced by soil texture and water content, as well as by bulk density (Abdalla et al., 1969; Vazques et al., 1991), we did not attempt to compare penetration resistance at different sampling times or different depths. Penetration resistance right after compaction application was greater at HC and MC than at NC at 0–25 cm in Exp. 1 and at 0–35 cm in Exp. 2; the difference between HC and MC was significant at 0–5, 15–20 and 35–40 cm in Exp. 1, and at 0–5, 10–15, 20–35 cm in Exp. 2 (Fig. 2). In spring 2008, the compaction effect was significant at 0–25 cm in Exp. 1 and 10–30 cm in Exp. 2, and penetration resistance was in the order of HC > MC > NC at 0–25 cm in Exp. 1 but in Exp. 2 only at 15–25 cm as penetration resistance did not differ between MC and NC at 10–15 cm or between HC and MC at 25–30 cm (Fig. 2).

The data for both bulk density and penetration resistance show that zones of compaction were created for the MC and HC treatments in Exp. 1 mainly in the 5–25 cm layer, and that, as expected, the soil was more compacted in HC than in MC plots. In Exp. 2, the bulk density differed among three compaction treatments from 5 to 30 cm, while compaction treatment affected penetration resistance only at 15–30 cm depth. These results were expected as it is known that the first pass causes much more compaction than subsequent passes, and increasing the number of passes does increase soil compaction (Bakker and Davis, 1995; Seker and Isildar, 2000). Our data also agree with observations made by Horn et al. (1998) and Servadio et al. (2005) that increasing the number of wheeling events increased bulk density at shallow (above 30 cm) depths. Apparently, for Exp. 2 at 0–10 cm the HC and MC treatments increased the bulk density, but the penetration resistance did not change because of shallow disking operation and the coarse soil texture.

3.2. Vertical distribution of maize roots

For corn root number in Exp. 1, the compaction × cover crop × depth and cover crop × depth interaction effects were not significant, however, there were the significant compaction × depth and compaction × cover crop interactions (Table 2). The three-way compaction × cover crop × depth interaction effect on root number was significant in Exp. 2 (Table 2). Vertical distribution of maize roots in late July, 2008 is presented in Fig. 3. In Exp. 1, maize under HC treatment had the most roots in rapeseed treatment and differed in root number from maize in other cover crop treatments at the 10–15 and 25–40 cm depths; maize had more roots in FR treatment than in NCC at 45 cm depth (Fig. 3 (1));

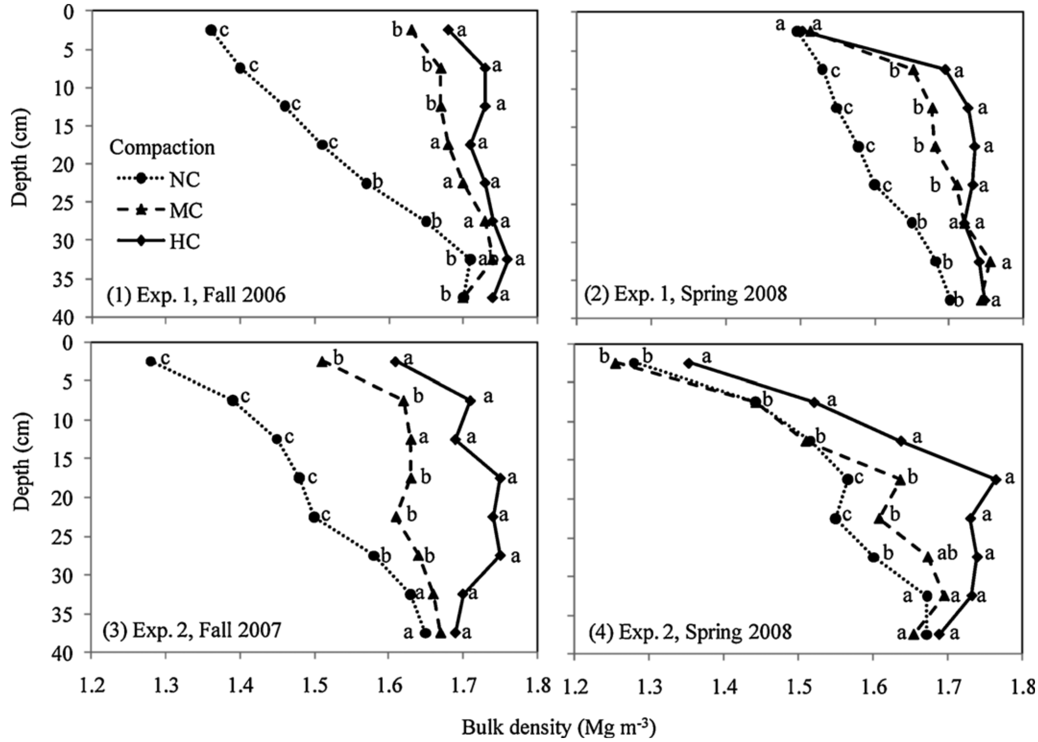

Fig. 1. Soil bulk density for three compaction treatments in Exp. 1 (upper) and 2 (lower) in the soil profiles right after compaction application (left) and in spring 2008 (right). Values within the same depth followed by the same letter(s) are not significantly different (*F*-protected LSD, $P \leq 0.05$). HC, MC, and NC stand for high, medium and no compaction, respectively.

maize under MC treatment had more roots in FR treatment at 5, 15, 30 and 35 cm, in rye at 5, 10 and 15 cm, and in rapeseed at 5 and 10 cm depths, compared with maize in NCC treatment (Fig. 3 (2)); maize for NC treatment had more roots in rapeseed than in NCC at 20 and 25 cm and in rye than in NCC at 20 and 30 cm (Fig. 3 (3)). In Exp. 2, maize had nearly twice as many roots below the 20 cm depth in HC-FR treatment compared to HC-Rye or HC-NCC (Fig. 3 (4)); maize had more roots in MC-FR than in MC-NCC treatment at

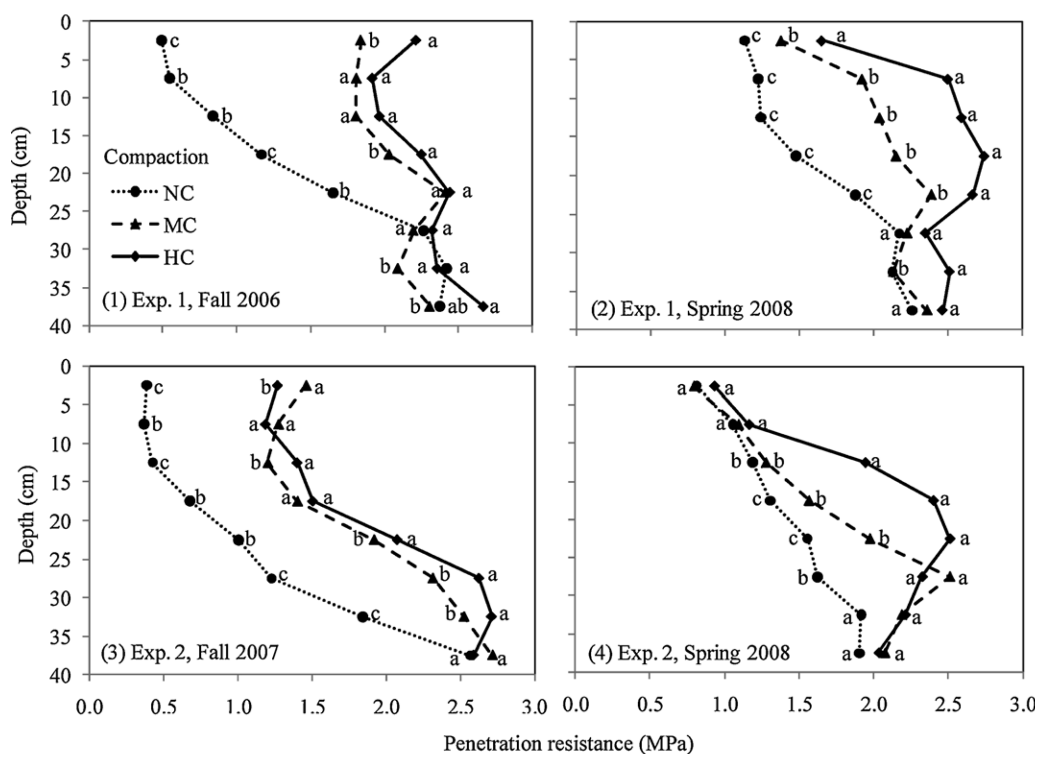

Fig. 2. Soil penetration resistance for three compaction treatments in Exp. 1 (upper) and 2 (lower) in the soil profiles right after compaction application (left) and in spring 2008 (right). Values within the same depth followed by the same letter(s) are not significantly different (*F*-protected LSD, $P < 0.05$). HC, MC, and NC stand for high, medium and no compaction, respectively.

Table 2
F-statistic significance for compaction, cover crop and depth effects on root number (log transformed) in Exp. 1 and Exp. 2 in 2008.

Source of variance	Exp. 1			Exp. 2		
	NDF[a]	*F* value	Pr > *F*[b]	NDF[a]	*F* value	Pr > *F*[b]
Compaction (Com)	2	49.44	<0.0001	2	56.70	<0.0001
Cover crop (CC)	3	58.91	<0.0001	2	51.94	<0.0001
Depth (D)	11	64.24	<0.0001	11	40.97	<0.0001
Com × CC	6	8.37	<0.0001	4	16.72	<0.0001
Com × *D*	22	3.58	<0.0001	22	3.09	<0.0001
CC × D	33	1.19	0.2180	22	1.82	0.0121
Com × CC × D	66	1.06	0.3460	44	1.47	0.0252

[a] NDF is numerator degree of freedom.
[b] Values indicate the probability of a greater F-value.

15, 35 and 40 cm depths, and more roots in MC-FR than in MC-rye at the 35 cm depth (Fig. 3 (5)). However, under NC in Exp. 2, maize had almost twice as many roots in rye compared to FR or NCC between 15 and 40 cm depths, and more roots in both rye and FR than in NCC from 45 to 60 cm (Fig. 3 (6)).

At the 20–60 cm depth, compared to root counts in the HC-NCC treatment, mean maize root counts in the HC-FR, HC-rapeseed and HC-rye treatments were 1.8, 3.2 and 1.7 times greater, respectively, in Exp. 1. At this depth in Exp. 2, root counts in the HC-FR and HC-rye treatments were 2.3 and 1.2 times greater, respectively, than root counts in the HC-NCC treatment. The effect of cover crops on the vertical distribution of maize roots for MC was similar to that for HC, though less pronounced. It is clear that cover crops increased maize root growth in and below compacted soil layers, though the magnitude differed among cover crops. Chen and Weil (2010) reported that FR and rapeseed grew more deep-roots than rye did in compact soils. Root channels left by the cover crops may facilitate the growth of subsequent crop roots in high strength soils (Hirth et al., 2005; Williams and Weil, 2004). Our data also suggest that the enhanced maize root penetration of compacted soil in HC and MC treatments was due to cover crop root channels, rather than mulch or organic matter influences as the enhancement was greater for FR and rapeseed than for rye. This result is in agreement with the finding that maize after alfalfa produced more roots in the subsoil than maize after maize (Rasse and Smucker, 1998). Though maize in HC-rapeseed of Exp. 1 and HC-FR of Exp. 2 achieved the most roots in and below the compacted layers, maize in Exp. 1 had more roots in HC-rapeseed than in HC-FR at most depths. Both Brassica cover crops were most effective in ameliorating the effects of soil compaction treatments on maize root growth; however the data do not conclusively determine which Brassica cover crop, FR or rapeseed, had greater ability to enhance maize root penetration

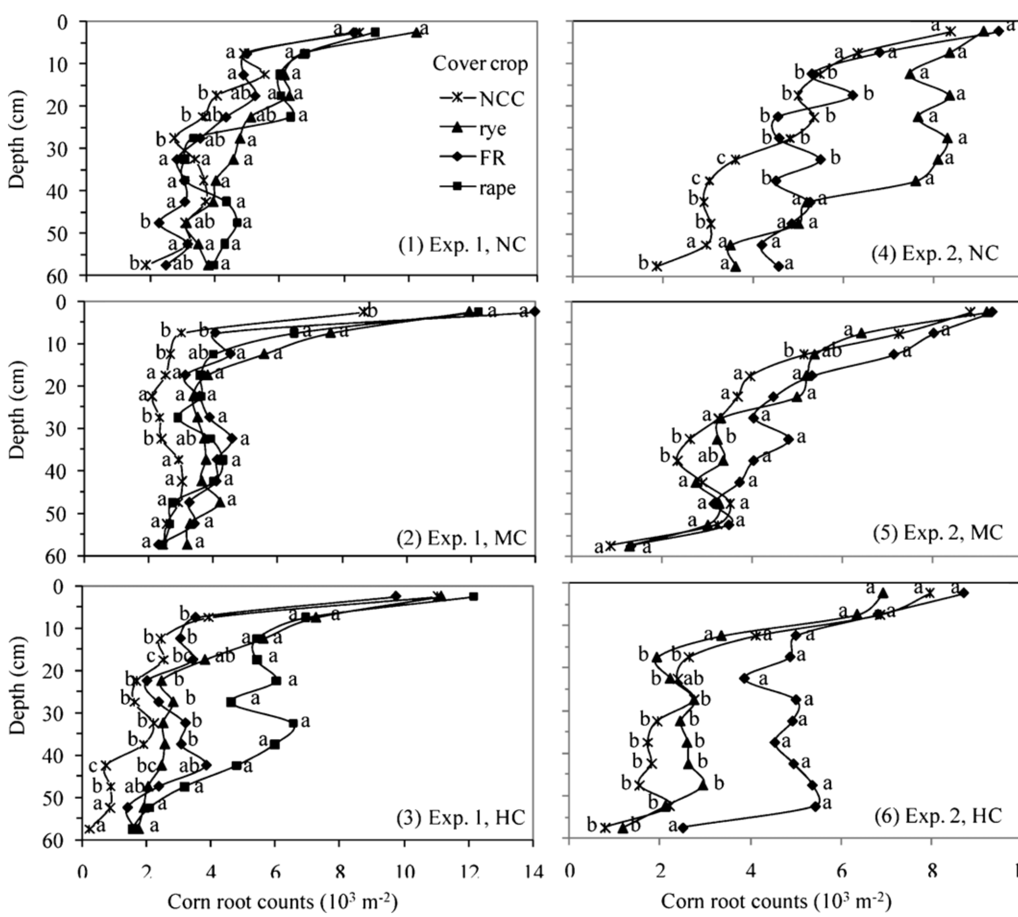

Fig. 3. Maize root number in Exp. 1 (left) and 2 (right) under high (HC), medium (MC) and no compaction treatments following no cover crop (NCC), rye, forage radish (FR) and rapeseed cover crop treatments in 2008. Values within the same depth followed by the same letter(s) are not significantly different (*F*-protected LSD, $P < 0.05$).

Table 3
Cover crop shoot dry matter (kg ha^{-1}) at termination.

Exp.	Cover crop season	Compaction	FR[a]	Rye[a]	Rapeseed[a]	Weeds (NCC)[a]
			Winter	Spring	Spring	Winter/spring
1	First (2006–2007)	High	3825cd[b]	3051d	2466de	678g
		Medium	4627bc	4134c	1857ef	1212fg
		No	5583a	4177c	5067ab	1629ef
	Second (2007–2008)		4699c	7011b	7949a	<600d
2	First (2007–2008)	High	4604b	4927b	NA[c]	<400c
		Medium	4688b	6567a	NA	<400c
		No	4936b	7148a	NA	<400c

[a] Forage radish was sampled on 30 November 2006 and 2007 before it was damaged by frost. Rapeseed and rye were sampled on 8 and 11 April, 2007 and 2008, respectively, before being spray-killed. Weeds in no cover crop plots were sampled only on 30 November 2006 in Exp. 1 and estimated for spring 2008.
[b] For each experiment, means within the same cover crop season followed by the same letter(s) are not different (*F*-protected LSD, $P < 0.05$).
[c] Not applicable as there was no rapeseed cover crop in Exp. 2.

through compacted soils. We conclude that the cover crop treatments improved maize root growth through compacted soils in the order of NCC < rye < Brassica crops (FR and rapeseed).

3.3. Surface mulch, precipitation, and soil water tension

Table 3 presents cover crop dry matter at termination. High compaction reduced dry matter of all cover crops (and weeds in NCC treatment) in Exp. 1 and dry matter of rye cover crop in Exp. 2 for the first cover crop season. For Exp. 1 in the second cover crop season, compaction did not affect cover crop dry matter and dry matter was in the order of rapeseed > rye > FR. The effect of compaction on cover crop growth was previously discussed (Chen and Weil, 2010). Regardless of compaction affects on FR dry matter in the winter, frost-killed FR had decomposed almost completely by early spring and left only a very thin, discontinuous film-like mulch on the soil surface prior to corn planting. The dry matter of spring weeds in NCC plots was not measured, but the weed biomass was estimated to be less than 10% of the spring-killed cover crops. During the corn growing seasons, the surface mulch was observed to be much greater in plots following rye and rapeseed cover crops than in FR or NCC treatments.

Fig. 4 shows cumulative precipitation from mid-April to mid-August for 2007, 2008, and the 30-year average. The normal annual precipitation (1971–2000 average) for this location is 1125 mm, of which 355 mm occurs during the maize growing season (early May to mid-August). The maize growing season was relatively dry in 2007 (202 mm less than normal) and relatively wet in 2008 (135 mm more than normal). In 2008, there were five major rainfall events which were 203, 87, 22, 34, and 32 mm on 8–12 May, 31 May–4 June, 28–29 June, 13–14 July and 23 July, respectively. These rainfall events, together with the presence of evaporation-inhibiting surface mulch and the magnitude of water

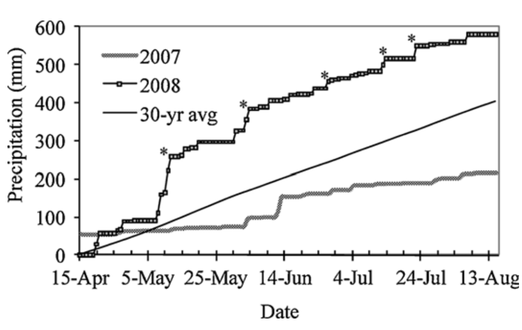

Fig. 4. Cumulative precipitation in Beltsville, Maryland from mid-April to mid-August, 2007 and 2008, and 30-year average. *Indicated the five major rainfall events during the 2008 maize growing season, four of which were discussed in Section 3.

uptake by maize roots, should have influenced soil water status in the maize growing season.

Fig. 5(a) and (b) presents daily mean soil water tension at 15 and 50 cm depths in Exp. 1 from 24 June to 28 July, 2008. At the 15 cm depth, the plots of HC-NCC and NC-NCC exhibited the lowest and highest soil water tensions, respectively, during most of the period except for 27 June–1 July and 24–25 July when soil water tension in the HC-rye dropped dramatically in response to two rainfall events. Soil water tension in HC/NC-FR treatments were slightly lower than those in NC-NCC, except in late July when they were in the middle of the range for all treatments. Soil water tension in HC/NC-rye dropped dramatically on 28 June in response to a rain event, but increased rapidly thereafter and closely paralleled the trend of FR treatments after 11 July.

At the 50 cm depth in Exp. 1, soil water tension for all treatments increased during the entire observation period, but differences among treatments and effects of individual rain event were less pronounced than at the 15 cm depth. During 21–29 June, plots of HC/NC-rapeseed, NC-NCC, and HC-FR exhibited the greatest soil water tensions, while plots of HC/NC-rye and HC-NCC exhibited the lowest soil water tensions, and plots of NC-FR showed intermediate values between these groups of treatments. On 28 June, soil water tension in HC-rapeseed dipped in response to a moderate rainfall event and remained in the mid-range of the treatments thereafter. After 8 July, soil water tensions in NC-rapeseed treatment began increasing more rapidly than in NC-NCC and HC-FR and thereafter soil in NC-rapeseed was considerably drier than in all other treatments. Soil water tensions in all treatments increased rapidly during 17–23 July and then leveled off, except that values in HC-NCC showed less increase and values in HC-rapeseed declined rapidly after 23 July. The HC-NCC and HC-rye were the treatments exhibiting the lowest soil water tensions throughout the period.

Fig. 5(c) and (d) shows mean daily soil water tensions at 15 and 50 cm depths in Exp. 2 during 24 June–28 July, 2008. With very coarse textured soil, water tension at 15 cm in all treatments responded dramatically to rainfall events. At 15 cm depth, soil water tensions in NC-FR were consistently the highest and exhibited the widest fluctuations of any treatment. Soil water tensions in HC-FR was the second highest among the six treatments, but fluctuated less widely than those in NC-FR. Soil water tensions in NC-NCC were similar or slightly lower than in HC-FR throughout the measurement period. Soil water tensions in plots of HC-NCC and HC/NC-rye treatments were similar to each other and lower than the other three treatments throughout the period.

At 50 cm depth in Exp. 2, soil water tensions on 24 June were in the order of HC-FR > NC-FR = NC-NCC > HC-NCC > HC-rye = NC-rye treatments. During the whole period, soil water tensions increased quite steadily and were consistently greatest in the HC/NC-FR treatments. Soil water tensions in NC-NCC began near

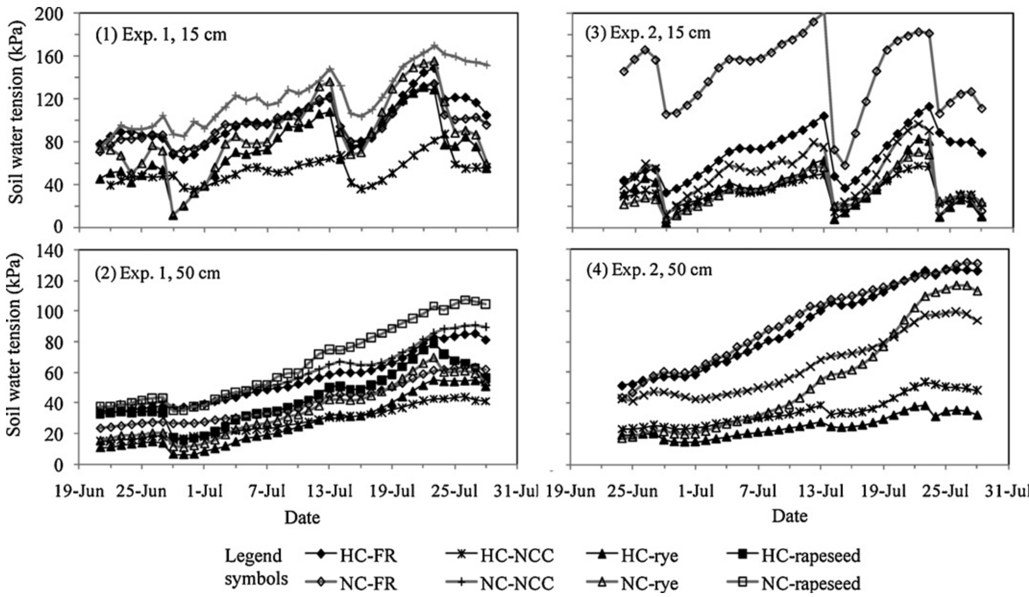

Fig. 5. Soil water tension at 15 (upper) and 50 (lower) cm depths in Exp. 1 (left) and 2 (right) during maize growing season, 2008. HC and NC = high and no compaction; NCC, FR, rye and rapeseed = no cover crop, forage radish, rye and rapeseed, respectively.

40 kPa (similar to the NC-FR), but did not change much until 9 July and were considerably lower than in the FR treatments for most of the period. Soil water tensions in HC/NC-rye and HC-NCC were all quite low and relatively stable (near 20 kPa) for the first two weeks of the measurement period, however, values in NC-rye increased much faster than in all other treatments after 9 July and were nearly as high as the HC/NC-FR treatments during the last few days measured.

Soil water tension at 15 cm depth dipped significantly after most rainfall events in both experiments in all treatment combinations (Fig. 5). However, at 50 cm depth, soil water tension in both experiments dipped only after the first rainfall event and the dip was deeper in plots of rapeseed (Exp. 1) and rye treatments (Exps. 1 and 2) than in FR or NCC treatments (Fig. 5(b) and (d)). Forage radish decomposed very quickly in spring and left little to no surface residue but did leave large open root channels in the surface soil by early May, which could encourage infiltration but also promote fast evaporation, especially for coarse-textured soils in Exp. 2. The killed rapeseed and rye cover crops produced a large amount of shoot dry matter (Table 3) and these residues provided thick surface mulch during the summer, which could conserve soil water by decreasing evaporation and increasing infiltration. Weeds in NCC produced substantial (70–80%) ground cover prior to maize planting (Lawley et al., 2011) but very little dry matter (Table 3), which may explain why the NCC treatment often had an intermediate impact on soil water tension at 15 cm. The effect of different amounts of surface mulch on soil water content at this shallow depth was similar to observations reported by Ampofo (2006) and Gicheru et al. (2005).

Irrespective of the effects of precipitation and cover crop treatments, HC soils usually had lower water tension than NC soils in both experiments and at both depths (15 and 50 cm) during the monitored period. This is in agreement with the findings of Assouline (2006) and Fernandez-Galvez and Barahona (2005) who reported that compaction decreased the volume of larger drainage pores but increased the volume of smaller water retention pores. The difference in soil water tension between HC and NC treatments could also be related to the difference of plant water uptake as there were fewer maize roots under HC than NC treatments (Fig. 3). This role of plant water uptake was consistent with the very small effect of compaction on both soil water tension and maize roots in the FR treatment plots, especially in Exp. 2 (Figs. 3 and 5). The rapid increase of soil water tension at 50 cm in NC-rye plots in Exp. 2 after mid-July may be also related to more active plant water uptake. Similar trends were observed in Exp. 1 in rapeseed and rye treatments at 50 cm. On the contrary, the lower soil water tension at 50 cm in HC-NCC in Exps. 1 and 2 and in HC-rye in Exp. 2 could be due to less plant water uptake as root growth was inhibited by compaction. Similar inhibition of maize root distribution and soil water extraction under subsoil compaction were reported by Himmelbauer et al. (2010).

3.4. Maize silage yield and plant population density

Table 4 summarizes the ANOVA results for the effects of cover crop and compaction on corn silage yield and population density. For Exp. 1, only the main effects of cover crop and year were significant on silage yield, while both the main effect of cover crop and the compaction × year interaction effect were significant on plant population density. For Exp. 2, both cover crop and compaction treatments affected yield significantly while no treatment had a significant effect on population density. Maize yield was greater following FR, rapeseed, and rye than NCC in Exp. 1 and greater following FR and rye than following NCC treatment in Exp. 2 (Table 5). Using an orthogonal comparison of all cover crops to the NCC control, it was determined that corn yield was 1.60 (P = 0.0001) and 2.43 Mg ha^{-1} (P = 0.0025) greater following cover crops than following no cover crop for Exps. 1 and 2, respectively. Yield of maize for Exp. 1 was greater in 2008 than in 2007, most likely because of the greater rainfall in 2008.

Maize population density in Exp. 1 was greater in FR and rapeseed than NCC and rye treatments; and it was not affected by compaction treatments in 2007, however, it was greater under MC than NC treatment in 2008. Yields of maize in Exp. 2 were 11.02, 10.04, and 8.71 Mg ha^{-1} for NC, MC, and HC, respectively with the yield under NC being significantly greater than that under HC treatment.

Non-leguminous cover crops can improve subsequent crop yields by numerous mechanisms, mainly alleviation of compaction by biodrilling, suppression of weeds, diseases and nematodes and enhancement of nutrient cycling (Weil and Kremen, 2007). In our study, however, nutrient cycling and weed suppression were

Table 4
F-statistic significance for cover crop and compaction treatment effects on maize yield and population density in Exp. 1 in 2007–2008 and Exp. 2 in 2008.

Exp.	Source of variance	Yield			Plant population		
		NDF[a]	*F* value	Pr > *F*[b]	NDF	*F* value	Pr > *F*
1	Cover crop (CC)	3	7.07	0.0004	3	9.55	<0.0001
	Compaction (Com)	2	0.36	0.7024	2	2.96	0.0597
	Year (Y)	1	33.31	<0.0001	1	3.80	0.0559
	CC × Com	6	1.38	0.2397	6	1.62	0.1582
	CC × Y	3	2.74	0.0517	3	2.02	0.1215
	Com × Y	2	0.94	0.3979	2	3.24	0.0466
	CC × Com × Y	6	0.80	0.5756	6	1.04	0.4096
	MSE		2.25			54.13	
2	CC	2	7.96	0.0022	2	1.78	0.1899
	Com	2	4.37	0.0241	2	1.34	0.2799
	CC × Com	4	2.10	0.1122	4	1.06	0.3991
	MSE[c]		3.68			31.70	

[a] NDF is numerator degree of freedom.
[b] Values indicate the probability of a greater *F*-value.
[c] Means square error.

unlikely to have had much influence on maize yields as we used recommended fertilizer and the herbicide practices used gave effective weed control. Furthermore, no disease or nematode problems were evident. We therefore ascribe the cover crop effects on yields observed in our study mainly to enhanced availability of soil water to the maize.

The contributions of cover crops to greater soil water uptake by maize could include both surface mulch and root channels. The thick rye residue could be expected to conserve soil water by reducing evaporation and increasing infiltration, as suggested by the soil water tension (Fig. 5) which showed soils at both 15 cm and 50 cm to be wetter following rye than following the other cover crop treatments. Although the dead rapeseed plants remained upright throughout the summer, the rapeseed residue appeared to have also conserved water, but to a less extent than did the decumbent rye residues.

The greater number of deep maize roots following FR and rapeseed treatments, especially under soil compaction (Fig. 3), suggests that subsoil water may have been more available to the maize plants following these two tap-rooted cover crops than in the other cover crop treatments. It seems that the rapeseed cover crop was able to provide both a mulch effect and a biodrilling effect with deep root channels. However, since we have observed that, compared to rye, it is much more difficult to completely kill rapeseed with either tillage or herbicides (see Section 2.3), rapeseed may be less attractive for adoption by farmers.

Crop yield reduction due to soil compaction is widely reported and most often related to limited root growth and water uptake (Freddi et al., 2007; Sadras et al., 2005; Vrindts et al., 2005). This is in agreement with our data for Exp. 2. The reduction in maize yield with compaction in Exp. 2 was most likely related to limited root growth in the compacted soils. It is not clear why compaction did not affect maize yield in Exp. 1, but there are several possible explanations. First, soil water availability may have been less of a limiting factor in Exp. 1 than in Exp. 2 because the A-horizon soils in Exp. 1 could hold more water as they contained almost twice as much clay (12.5–18.2%) as those in Exp. 2 (5.0–11.0%). Second, the supplemental irrigation on 2 and 23–25 July, 2007 in Exp. 1 (see Section 2.4) might have alleviated drought stress for maize under HC and/or MC treatments.

Successful germination and seedling establishment of maize may be affected by soil physical and chemical conditions that are influenced by the preceding cover crops. In our study, maize population densities were greater following the two Brassica cover crops than following the NCC and rye treatments, but only in Exp. 1 (which had higher soil clay contents). The effect of cover crop effects on maize plant density was, therefore, probably due to the different soil physical properties such as surface soil water content and temperature, and soil-seed contact. Unlike the rye cover crop, FR was winter-killed and left very little residue in spring, but it did leave large root channels (1–5 cm in diameter and 20–30 cm deep) open to the soil surface. These two features of the no-till seedbed following FR typically result in a significantly warmer surface soil than with most other cover crops (Lawley et al., 2011; Weil et al., 2009). In Exp. 1, rapeseed residue remained erect through the summer, which would also allow soil to warm up easier than rye residue. Incomplete closure of the no-till seed furrows and resulting poor soil-seed contact was observed in several of the plots that had a thick surface mulch of rye residue. Teasdale et al. (2008) reported that thick cover crop residue reduced sweet corn population density in two out of three years. The surface residue of spring weeds in the NCC plots was <10% of that in the rye plots and did not resulted in the poor soil-seed contact and seed furrow closure that was observed in the rye plots.

About 200 mm of rain fell during 8–12 May, 2008 and corn was planted on May 7 (Fig. 4). This heavy rainfall would have resulted in more water logging in the NCC plots where few channels existed, compared to the plots of FR and rapeseed treatments for the finer textured soils in Exp. 1 (Weil et al., 2009). The improved soil drainage and warmer soil temperatures induced by tap-rooted cover crops could explain why maize plant population was greater in plots of FR and rapeseed treatments than in NCC treatment. Nonetheless, in our study, maize achieved the same yield following rye as following FR and rapeseed, most likely because of water conservation by the thick rye residue mulch later in the growing season that appeared to have compensated for the lower plant density. Similar observations were reported by Teasdale et al. (2008). However, without the benefits of either water conserving

Table 5
Maize silage yield and population density as affected by cover crop treatments for each experiment (means of two years for Exp. 1).

Exp.	Cover crop treatment			
	FR	NC	Rapeseed	Rye
Dry matter[†] ($Mg\ ha^{-1}$)				
1	10.54 a	8.74 b	9.84 a	10.66 a
2	10.04 a	8.30 b	–	11.42 a
Population[‡] (10^3 plants ha^{-1})				
1	67.7 a	60.6 b	67.0a	58.0 b
2	70.1 a	71.0 a	–	66.9 a

[†] Within each experiment, values of dry matter followed by the same letter(s) are not significantly different (*F*-protected LSD, $P < 0.05$).
[‡] Within each experiment, values of population density followed by the same letter(s) are not significantly different (*F*-protected LSD, $P < 0.05$).

surface mulch or enhanced access to subsoil water from cover crop biodrilling or improved drainage by large root channels in the seedbed, maize yields following NCC treatment were reduced because of both the reduction in plant density and in available soil water.

Undoubtedly, the higher yield in 2008 in Exp. 1 was largely due to the greater amount and better distribution of precipitation during the maize growing season in 2008 than in 2007 (Fig. 4). Our previous results showed that the cover crop roots in the compacted soil layer were more numerous in the late fall in 2007 than in 2006 (Chen and Weil, 2010). Therefore, there would have been more cover crop root channels available to maize roots in 2008 than in 2007, which would also have made subsoil water more available to maize plants in the summer of 2008 than 2007.

4. Conclusion

The plant availability and accessibility of surface and subsurface soil water during middle to late summer growing season (when rainfall is usually sparse and evapotranspiration is high) is critical for crop production in the mid-Atlantic region of USA. Our data suggest that surface mulch and deep root channels left by winter cover crops can be advantageous for summer crop growth, particularly when soils are highly compaction. Tap-rooted FR and rapeseed cover crops enhanced maize roots to access subsurface soil water by providing deep root channels in compacted soils. Fibrous-rooted rye cover crop benefited maize growth by conserving soil water through surface mulch. Alleviation of soil compaction effects by these cover crops was at least partly responsible for greater maize yield following these cover crops. However, the thick surface mulch of rye residue interfered with seeding operations resulting in suboptimal maize population densities, though the reduction in plant density was compensated for by the water conservation effects of this mulch. Although this study did not include such a mixture, we suggest that cover crop benefits might be maximized by using a mixed cover crop of rye with either FR or rapeseed planted in separate rows. The rows of FR or rapeseed could be located to coincide with the summer crop planting rows to provide "biological subsoil tillage" effects and to allow earlier planting and better stands of the summer crop. The rows of rye cover crop would provide a thick mulch in the summer crop inter-rows to improve conservation of surface soil water during the summer growing season. We suggest that further research into such improved cover crop systems be undertaken in environmental similar to those in this study.

Acknowledgements

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References

Abdalla, A.M., Hettiaratchi, D.R.P., Reece, A.R., 1969. The mechanics of root growth in granular media. J. Agric. Eng. Res. 14, 236–248.

Ampofo, E.A., 2006. Soil moisture dynamics in coastal savanna soils in the tropics under different soil management practices. Hydrol. Sci. J.-J. Sci. Hydrol. 51, 1194–1202.

Assouline, S., 2006. Modeling the relationship between soil bulk density and the water retention curve. Vadose Zone J. 5, 554–563.

Bakker, D.M., Davis, R.J., 1995. Soil deformation observations in a vertisol under field traffic. Aust. J. Soil Res. 33, 817–832.

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.

Calonego, J.C., Rosolem, C.A., 2010. Soybean root growth and yield in rotation with cover crops under chiseling and no-till. Eur. J. Agron. 33, 242–249.

Chan, K.Y., Heenan, D.P., 1996. The influence of crop rotation on soil structure and soil physical properties under conventional tillage. Soil Till. Res. 37, 113–125.

Chen, G.H., Weil, R.R., 2010. Penetration of cover crop roots through compacted soils. Plant Soil 331, 31–43.

Clark, L.J., Whalley, W.R., Barraclough, P.B., 2003. How do roots penetrate strong soil? Plant Soil 255, 93–104.

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.

Cresswell, H.P., Kirkegaard, J.A., 1995. Subsoil amelioration by plant roots—the process and the evidence. Aust. J. Soil Res. 33, 221–239.

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.

Elkins, C.B., 1985. Plant roots as tillage tools. In: International Conference on Soil Dynamics, Auburn, AL, pp. 519–523.

Fernandez-Galvez, J., Barahona, E., 2005. Changes in soil water retention due to soil kneading. Agric. Water Manage. 76, 53–61.

Freddi, O.D., Centurion, J.F., Beutler, A.N., Aratani, R.G., Leonel, C.L., 2007. Effect soil compaction on root growth and maize yield. Rev. Bras. Cienc. Solo 31, 627–636.

Gicheru, P.T., Gachene, C.K.K., Mbuvi, J.P., 2005. Effects of soil management practices and tillage systems on soil moisture conservation and maize yield on a sandy loam in semiarid Kenya. J. Sustain. Agric. 27, 77–92.

Hall, D.J.M., McKenzie, D.C., MacLeod, D.A., Barrett, A., 1994. Amelioration of a hardsetting Alfisol through deep mouldboard ploughing, gypsum application and double cropping. 1. Soil physical and chemical properties. Soil Till. Res. 28, 253–270.

Haman, R.B., Orloff, S., Peters, D., 2000. Monitoring soil moisture helps refine irrigation management. Calif. Agric. 54, 38–42.

Hanson, B.R., May, D.M., Schwankl, L.J., 2003. Effect of irrigation frequency on subsurface drip irrigated vegetables. HortTechnology 13, 115–120.

Himmelbauer, M.L., Loiskandl, W., Rousseva, S., 2010. Spatial root distribution and water uptake of maize grown on field with subsoil compaction. J. Hydrol. Hydromech. 58, 163–174.

Hirth, J.R., McKenzie, B.M., Tisdall, J.M., 2005. Ability of seedling roots of *Lolium perenne* L. to penetrate soil from artifical biopores is modified by soil bulk density, biopore angle and biopore relief. Plant Soil 272, 327–336.

Horn, R., kretschmer, H., Baumgartl, T., Bohne, K., Neupert, A., Dexter, A.R., 1998. Soil mechanical properties of a partly reloosened (split plough system) and a conventionally tilled overconsolidated gleyic luvisol derived from glacial till. Int. Agrophys. 12, 143–154.

Intrigliolo, D.S., Castel, J.R., 2004. Continuous measurement of plant and soil water status for irrigation scheduling in plum. Irrig. Sci. 23, 93–102.

Jokela, W.E., Grabber, J.H., Karlen, D.L., Balser, T.C., Palmquist, D.E., 2009. Cover crop and liquid manure effects on soil quality indicators in a corn silage system. Agron. J. 101, 727–737.

Jones, B., 2008. Agronomy Extension Research Update—Cover Crop Effects on Corn Silage [Online]. Virginia Tech. University, Extension.

Lawley, Y., Weil, R.R., Teasdale, J., 2011. Forage radish winter cover crops suppress winter annual weeds in fall and before corn planting. Agron. J. 103, 137–144.

Materechera, S.A., Alston, A.M., Kirby, J.M., Dexter, A.R., 1992. Influence of root diameter on the penetration of seminal roots into a compacted subsoil. Plant Soil 144, 297–303.

Materechera, S.A., Dexter, A.R., Alston, A.M., 1991. Penetration of very strong soils by seedling roots of different plant-species. Plant Soil 135, 31–41.

Merrill, S.D., Tanaka, D.L., Hanson, J.D., 2002. Root length growth of eight crop species in haplustoll soils. Soil Sci. Soc. Am. J. 66, 913–923.

Noordwijk, M.V., Brouwer, G., Meijboom, F., do Rosaerio, M., Oliveira, G., Bengough, A.G., 2000. Trench profile techniques and core break methods. In: Smit, A.L., Bengough, A.G., Engels, C., van Noordwijk, M., Pellerin, S., van de Geijn, S.C. (Eds.), Root Methods: A Handbook. Springer-Verlag, Berlin, Heidelberg, Germany, pp. 211–234.

Rasse, D.P., Ritchie, J.T., Peterson, W.R., Wei, J., Smucker, A.J.M., 2000. Rye cover crop and nitrogen fertilization effects on nitrate leaching in inbred maize fields. J. Environ. Qual. 29, 298–304.

Rasse, D.P., Smucker, A.J.M., 1998. Root recolonization of previous root channels in corn and alfalfa rotations. Plant Soil 204, 203–212.

Sadras, V.O., O'Leary, G.J., Roget, D.K., 2005. Crop responses to compacted soil: capture and efficiency in the use of water and radiation. Field Crop. Res. 91, 131–148.

Schmidt, C.P., Belford, R.K., Tennant, D., 1994. Effect of different direct drilling and conventional sowing techniques on soil strength, root growth and grain yield of wheat on sandplain soils in Western Australia. Aust. J. Agric. Res. 45, 547–564.

Seker, C., Isildar, A.A., 2000. Effects of wheel traffic porosity and compaction of soil. Turk. J. Agric. For. 24, 71–77.

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 Till. Res. 84, 87–100.

Shock, C.C., Feibert, E.B.G., Saunders, L.D., 1998. Onion yield and quality affected by soil water potential as irrigation threshold. Hortscience 33, 1188–1191.

Talsma, T., Gardner, E.A., 1986. Soil-water extraction by a mixed eucalypt forest during a drought period. Aust. J. Soil Res. 24, 25–32.

Teasdale, J.R., Abdul-Baki, A.A., Park, Y.B., 2008. Sweet corn production and efficiency of nitrogen use in high cover crop residue. Agron. Sustain. Dev. 28, 559–565.

Vazques, L., Myhre, D.L., Hanlon, E.A., Gallaher, R.N., 1991. Soil penetration resistance and bulk density relationships after long term no tillage. Commun. Soil Sci. Plan. 22, 2101–2117.

Vrindts, E., Mouazen, A.M., Maertens, K., Maleki, M.R., Ramon, H., Baerdemaeker, J.D., 2005. Management zones based on correlation between soil compaction, yield and crop data. Biosyst. Eng. 92, 419–428.

Weil, R., White, C., Lawley, Y., 2009. Forage radish: a new multi-purpose cover crop for the mid-Atlantic. Fact sheet. Maryland Cooperative Extension, College Park. Available at http://extension.umd.edu/publications/pdfs/fs824.pdf (verified 20 Feb. 2010).

Weil, R.R., Kremen, A., 2007. Thinking across and beyond disciplines to make cover crops pay. J. Sci. Food Agric. 87, 551–557.

Wiermann, C., Werner, D., Horn, R., Rostek, J., Werner, B., 2000. Stress/strain processes in a structured unsaturated silty loam Luvisol under different tillage treatments in Germany. Soil Till. Res. 53, 117–128.

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.

Zhang, X.C., Miller, W.P., Nearing, M.A., Norton, L.D., 1998. Effects of surface treatment on surface sealing, runoff, and interrill erosion. Trans. ASAE 41, 989–994.