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DIVISION S-6—NOTES

CROP COVER ROOT CHANNELS MAY ALLEVIATE SOIL COMPACTION EFFECTS ON SOYBEAN CROP

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Abstract

Deep-rooted cover crops may help alleviate effects of soil compaction, especially in no-till systems. We evaluate compaction-alleviating ability of three Brassica cover crops and cereal rye (*Secale cereale* L.). Using a minirhizotron camera, we observed soybean [*Glycine Max* (L.) Merr.] roots growing through compacted plowpan soil using channels made by decomposing cover crop roots. Soybean yield response to the preceding cover crops was most pronounced at the site with most severe drought and soil compaction. At this location, with or without deep tillage, soybean yields were significantly greater following a "forage radish + rye" combination cover crop. Rye left a thick mulch, resulting in conservation of soil water early in the season. Root channels left by forage radish (*Raphanus sativus* L. 'Diachon') may have provided soybean roots with low resistance paths to subsoil water. Due to lower than normal winter precipitation, this study was a conservative test of the cover crops' ability to alleviate the effects of soil compaction.

Soil compaction continues to be a major problem for farmers in intensely cropped areas of the eastern USA. The urgency of timely field operations, often accompanied by unpredictable precipitation, often results in heavy equipment traffic on wet soils (Bowman et al., 2000). Due to the yield-reducing secondary effects of soil compaction, growers often purchase expensive tillage equipment to deep till their compacted soils. Deep tillage is expensive and energy intensive, and benefits are short-lived (Horn et al., 2000). Resorting to tillage in a no-till cropping system can also set back the development of improved soil quality and increase the susceptibility to erosion.

Buttery et al. (1998) reported that limited root penetration on compacted soils aggravated the effects of drought in reducing soybean yields. Soil strength increases with compaction (Eavis, 1972), especially during the summer when compacted layers in the soil become dry and hard, therefore, roots are less able to penetrate deeply enough to access the water and nutrients stored in the subsoil.

While much is known about the negative effects of soil compaction on the growth and yields of soybean and other crops, non-tillage methods to alleviate compaction problems have not been extensively researched. Deep-rooted cover crops are one possible solution to compaction problems, especially in no-till farming systems (Unger and Kaspar, 1994). The deep growing tap roots of the perennial alfalfa (*Medicago sativa* L.), can increase infiltration rate on compacted no-till soils (Meek et al., 1990), and recolonization of root channels left by alfalfa have been shown to benefit corn (*Zea Mays* L.) root systems that follow (Rasse and Smucker, 1998). Stirzaker and White (1995) showed a doubling of yield for lettuce (*Letuca sativa* L.) grown on compacted soil following a cover crop of subterranean clover (*Trifolium subterraneum* L.). They speculated that the yield increase was due to biopores made by the cover crop roots. It has been proposed that biopores produced by cover crop roots might be used by the roots of later crops as low resistance pathways, a process dubbed "biodrilling" (Cresswell and Kirkegaard, 1995).

The objectives of this study were: (i) to observe soybean roots penetrating compacted soil layers during the summer via root channels made a preceding Brassica cover crop; and (ii) to compare the effects of various cover crops and deep tillage on the yield of soybeans on soils of differing compaction severity. We report direct observations of the proposed "biodrilling" process and a preliminary evaluation in no-till fields of the compaction-alleviating ability of three Brassica cover crops: canola, oilseed radish, and forage radish.

Materials and Methods

Sites and Soil Conditions

Experiments were conducted at the University of Maryland Wye Research and Education Center (WREC) on a Mattapex silt loam (fine-silty, mixed, active, mesic Aquic Hapludults) and at the USDA Beltsville Agricultural Research Center (BARC) on an Elkton silt loam (fine-silty, mixed, active, mesic Typic Endoaquults).

Undisturbed soil cores were collected in 10-cm increments to a depth of 40 cm to determine soil bulk density and soil water content at the time of penetration resistance measurement (Table 1). Particle-size analysis was performed on the same samples, using a modified hydrometer method (Day, 1965). To characterize soil compaction levels and distribution, a recording cone penetrometer with a 25 by 15 mm tip and 10-mm diameter shaft (Spectrum Technologies, Plainfield, IL) was used to measure soil penetration resistance. Measurements were taken on a 6 by 6 m grid on 28 Feb. 2001 at WREC and 9 Mar. 2001 at BARC (Barone and Faugno, 1996). At each grid point, mean penetration resistance (kPa) was recorded in 5-cm increments to a depth of 45 cm by pushing the penetrometer tip into the soil at a constant rate.

Crop Treatments and Management

Four winter cover crops were used in the study (canola, oilseed radish, forage radish, and cereal rye). The radishes

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Abbreviations: BARC, Beltsville Agriculture and Research Center; WREC, Wye Research and Education Center.

Table 1. Selected properties of the soils used at the Wye Research and Education Center (WREC) and Beltsville Agricultural Research Center (BARC) in 10-cm increments to 40 cm.

Site	Depth	Clay	Sand	Bulk density	Water content†	pH
	cm	— g kg^{-1} —		Mg m^{-3}	g kg^{-1}	
WREC	0–10	119	244	1.38	160	6.0
WREC	10–20	125	269	1.48	180	5.7
WREC	20–30	118	243	1.55	190	5.2
WREC	30–40	187	203	1.40	210	5.1
BARC	0–10	132	299	1.32	230	6.8
BARC	10–20	163	328	1.55	230	6.7
BARC	20–30	133	388	1.58	210	6.5
BARC	30–40	277	279	1.58	240	5.4

† Mass water content at time of penetrometer readings.

were chosen because of their large taproots. Rye was used because it is the cover crop most commonly grown in the mid-Atlantic region. Additionally, two treatments of combined forage radish and rye, with and without deep tillage, were included. No-cover treatments, with and without deep tillage, were included as controls (Table 2). At each site, the experiments utilized a randomized complete block design with four replicates. Block layout maximized the homogeneity of compaction within blocks, based on the observed spatial distribution of soil penetration resistance. Individual plot size was 9 m long by 3 m wide. Penetration resistance was measured within each plot during the grid sampling described above.

Cover crops were planted on 7 Sept. 2001 at BARC and 10 Sept. 2001 at WREC in 19 cm rows with a no-till drill at the seeding rates listed in Table 2. Two treatments were chisel plowed to a depth of 35 cm before planting the cover crops (Table 2). To ensure vigorous cover crop growth, both sites received 45 kg ha^{-1} N as ammonium nitrate by surface application 1 d after cover crop planting. The cover crops were killed with 900 g ai ha^{-1} of glyphosate [(N-phosphonomethyl) glycine] on 21 May 2002 at WREC and on 24 May 2002 at BARC.

Dekalb brand DKB44-51 (glyphosate-resistant) soybeans (Monsanto Co., St. Louis, MO) were planted no-till on 31 May 2002 at WREC and on 10 June 2002 at BARC in 76 cm rows at a rate of 20 seeds m^{-1}. Total plant biomass (aboveground excluding senesced leaves) and grain yield were measured by harvesting representative samples from each plot on 28 Oct. 2002 at WREC and on 8 Nov. 2002 at BARC. At each site, 3 m lengths of the center two rows were cut 1 cm above the soil surface and weighed to obtain the fresh weight for each plot. Moisture content and seed to whole plant ratio were determined on a 10-plant subsample and used to calculate seed yield per plot area.

Minirhizotron Root Observations

A minirhizotron camera (Model XYZ123, Bartz Technology, Santa Barbara, CA) was used to monitor root growth of both cover crops and soybeans throughout the 2002 growing season. In March 2002, clear cellulose acetate butyrate observation tubes (1 m in length and 50.8 mm in outside diameter) were installed at a 45° angle (as recommended by Ephrath et al., 1999) in Treatments 1 to 6 in one replicate at each location. To avoid damaging the installation equipment, the most compacted replicate at each site was not be used for this purpose. Because the soil at BARC was too dry in February 2002 to insert the observation tubes, approximately 4 cm of irrigation water was applied in early March to soften the soil before insertion of the tubes. A close fit between minirhizotron tube and soil was assured by use of a drop hammer driven corer and reamer. The corer was designed to prevent compaction of the soil lining the hole. The hole was then slightly enlarged by a reaming device, allowing the tubes to be easily slid into place with a close fit but minimal smearing. Images of the cover crop root zones were recorded biweekly during April and May 2002 by inserting a minirhizotron camera into the tube and saving images every 12 mm down the tube from the soil surface to 90 cm (a vertical depth of approximately 63 cm). Index holes every 12 mm in the camera handle assured that observations on each date were made of the same 75 locations within the root zone along each tube. To avoid damaging the tubes during soybean planting, the minirhizotron tubes were located where there would be a non-wheel track soybean interrow. Wheel traffic was restricted to the outside interrows between plots during the study (however wheel traffic had not been controlled in previous experiments on these sites). A 1.5-m long row of soybean seed was planted by hand directly over the minirhizotron tubes to assure a uniform plant stand and to assure that the tubes would be in the root zone of the soybean crop. The soybean root zone was observed biweekly from July–September 2002.

Soil Water Content

Cylindrical gypsum electrical resistance blocks (24 mm long × 30 mm diameter) were used to monitor soil moisture at 20- and 50-cm depths in Treatments 1, 4, 7, and 8 at both sites. One block was installed at each depth in each monitored plot. Resistance readings were recorded weekly for the period of June–September 2002 using a digital resistance meter (Delmhorst, Towaco, NJ, model KS-D1), calibrated to read 97 to 100 in saturated soil. Block readings were calibrated to volumetric soil water content by regressing resistance readings for blocks buried in the study soils over a range of known water contents. Electrical resistance blocks are considered less accurate in soils approaching or reaching saturation, but are well suited for measuring soil water in drier soils (Brady and Weil, 2002, p. 191–195.).

Statistical Analysis

Statistical analyses were performed using SYSTAT 9 software (SPSS Inc., 1999). For each 5-cm soil layer at each experiment site, maps of the horizontal spatial variation in penetration resistance were generated using the non-rotated kriging

Table 2. Treatments included at Beltsville Agricultural Research Center and Wye Research and Education Center.

Treatment no.	Cover crops	Scientific names	Deep tillage	Seeding rate
				kg ha^{-1}
1	Forage radish	*Raphanus sativus* L.	No	17
2	Oilseed radish	*Raphanus sativus* L.	No	17
3	Canola	*Brassica rapa* L.	No	9
4	Rye	*Secale cereale* L.	No	60
5	Forage radish + rye	*Raphanus sativus* L. + *Secale cereale* L.	No	17 + 30
6	Forage radish + rye	*Raphanus sativus* L. + *Secale cereale* L.	Yes	17 + 30
7	None	–	Yes	–
8	None	–	No	–

option of the plot command in SYSTAT 9, which is an independent implementation of kriging with a trend model (Deutsch and Journel, 1998). Penetration resistance data on these maps were used to increase block homogeneity in the experimental design and as a covariate in the analysis of variance (ANOVA) used to test for treatment effects on soybean aboveground dry matter and seed yield. Treatment differences were considered significant by F-protected LSD at the 0.10 probability level. To examine the rye × forage radish interaction and the deep tillage × cover crop interaction, we ran 2 × 2 factorial ANOVAs on Treatments 1, 4, 5, and 8 and Treatments 5, 6, 7, and 8, respectively (Table 2). For WREC, where the effect of deep tillage was not significant, the data were pooled for the no-till and deep tilled plots of the no-cover and forage radish + rye treatments (Treatments 5 and 6).

Results and Discussion

Soil Compaction

The vertical (Fig. 1) and horizontal (data not shown) spatial distribution of penetration resistance at WREC and BARC showed that, under nearly water saturated conditions (0.22 cm^3 cm^{-3} at WREC and 0.27 cm^3 cm^{-3} at BARC), both fields contained some areas with penetration resistance ≥2000 kPa, which is commonly considered to be root-restricting (Bengough and Mullins, 1990; Loboski et al., 1998; Materechera et al., 1991). Penetration resistance ranged from 70 to 6919 kPa at WREC and 175 to 3756 kPa at BARC. Since penetration resistance is inversely related to soil water content, the penetration resistance on these fields would therefore greatly exceed 2000 kPa under drier conditions that generally characterize the soybean growing season (Eavis, 1972).

Compaction was spatially variable within each site, with the most highly compacted conditions at the corner where machinery usually entered and exited. The pattern of relative horizontal distribution of penetration resistance (data not shown) was similar at all depths. The areas of the field with the greatest compaction in the deeper layers also showed the greatest compaction in the surface soil, suggesting that the compaction was due to surface traffic and tillage, rather than to a naturally occurring clay pan layer. Had a clay pan layer been the cause of the increased penetration resistance below the surface, the spatial pattern of high penetration resistance would not have been observed in the surface layer.

At WREC, the compacted zone began at approximately the 15-cm depth, with penetration resistance becoming greatest at the 35-cm depth and several individual readings exceeded 6900 kPa (Fig. 1). Penetration resistance data at BARC showed a similar trend, with the layer of highest resistance found between 25- and 30-cm depth but with a maximum resistance just slightly >2000 kPa (Fig. 1). The higher bulk density observed at BARC is due to the higher clay content in the subsoil at that site. Despite the greater bulk density at BARC, however, the WREC site still shows greater penetration resistance in the subsoil. Therefore, the WREC soil was considerably more severely compacted than the BARC soil.

Minirhizotron Root Images

Cover crop roots were visible in 35% of the minirhizotron images obtained at WREC and in 31% of the images at BARC. All other images showed only soil. Images obtained documented that soybean roots did follow channels left by the decomposition of cover crop roots. The set of images that best documented this phenomenon were recorded of canola roots in early May in plots at BARC (Fig. 2, bottom, left) and WREC (Fig. 2, top, left). By observing the progress of cover crop roots from one date to the next (figures not shown), we were able to determine that these roots were creating new channels as they grew, rather than using pre-existing channels. Later in the summer, soybean roots were observed growing in the same channels (found by returning to the exact same frame with the minirhizotron camera) that the canola roots had produced and left behind as they decomposed. This was observed both above the highly compacted layer (Fig. 2, bottom), and below the compacted layer (Fig. 2, top). The observations indicated that some cover crop roots did penetrate the compacted layer, despite the unusually dry conditions during the 2001–2002 winter cover crop growing season. Fur-

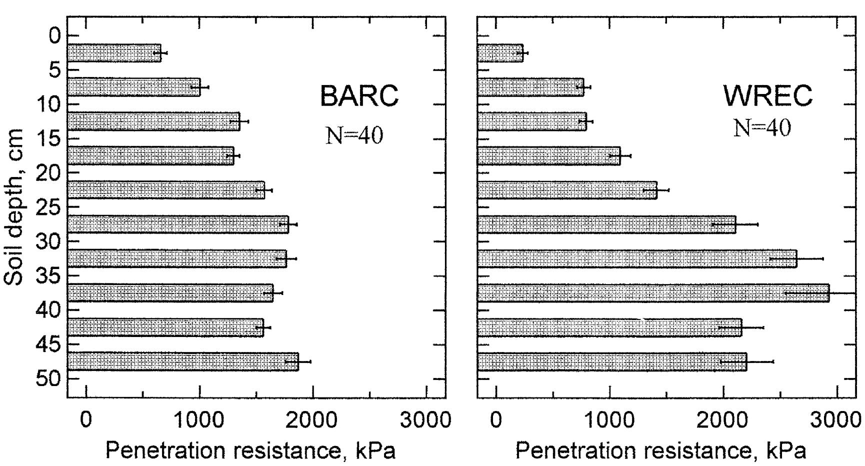


Fig. 1. Penetration resistance (kPa) with depth (cm) at Beltsville Agricultural Research Center (BARC) and Wye Research and Education Center (WREC). Average volumetric water content at time of penetration resistance measurement was 0.22 cm^3 cm^{-3} (WREC) and 0.27 cm^3 cm^{-3} (BARC) in the surface soil (0–20 cm) and 0.29 cm^3 cm^{-3} (WREC) and 0.39 cm^3 cm^{-3} (BARC) in the subsoil (20–40 cm).

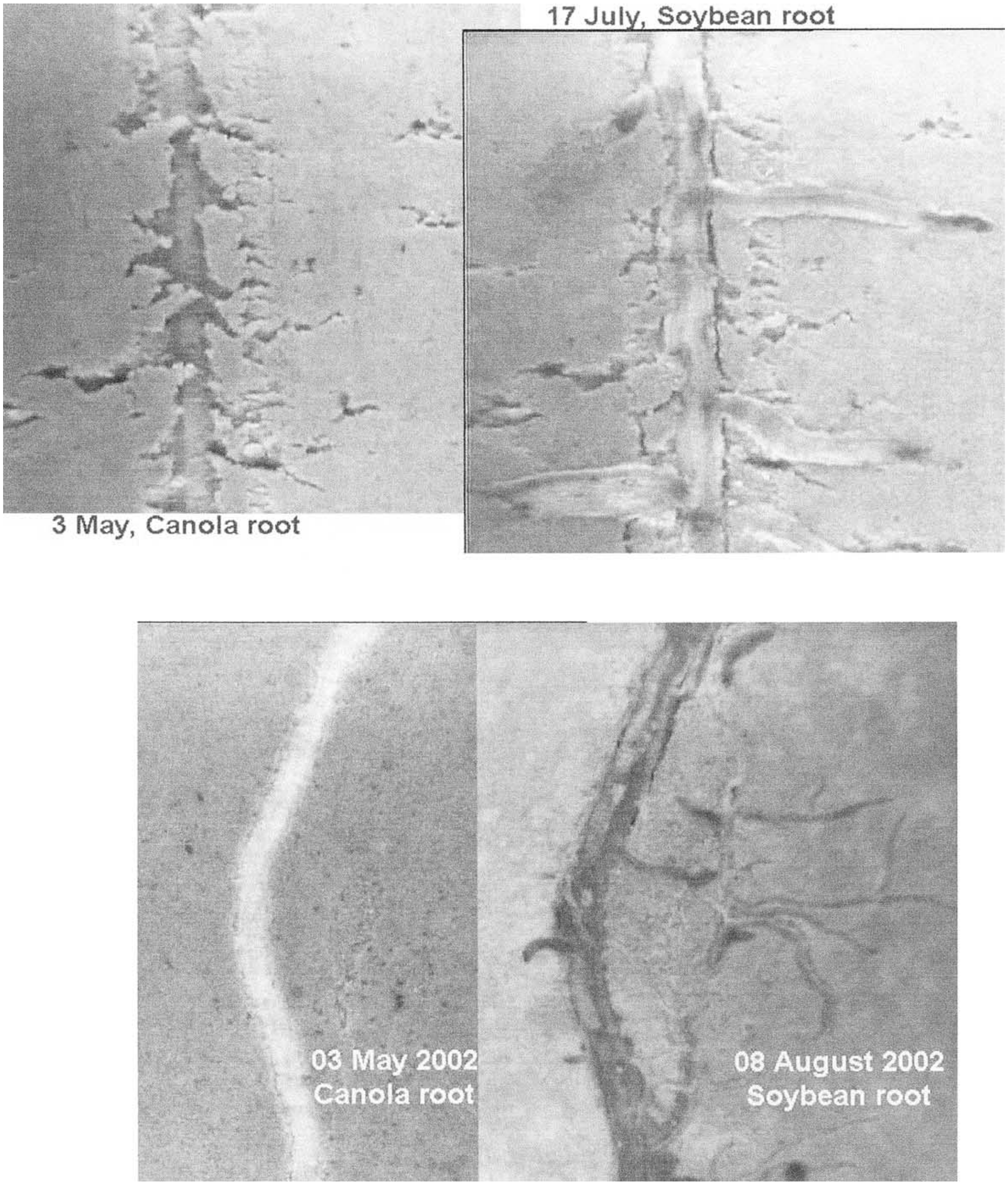
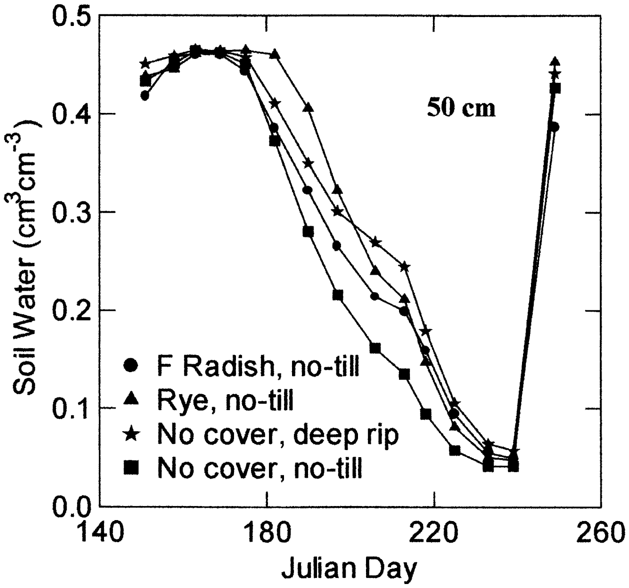


Fig. 2. Minirhizotron images showing canola roots growing in May (left) and soybean roots observed in July and August (right) following the channels made by the preceding canola cover crop at 38.2 cm (at WREC) (top) and 18 cm (at BARC) (bottom) depth. Bulk density was 1.55 and 1.61 and penetration resistance was 2247 and 2176 kPa for the upper and lower soils, respectively.

thermore, the observation of soybean roots growing in these same channels later in the season suggested that roots of summer crops could follow existing root channels to gain access to the subsoil when the compacted layer is driest and penetration resistance is highest.

Precipitation and Soil Water Conditions

Both sites received much lower than normal rainfall during the experimental period, but the drought conditions were more severe at WREC (122 mm total precipitation from September 2001 to March 2002, the cover crop growing season, and 96 mm total precipitation from June to September 2002, the soybean growing season) than at BARC (255 mm of precipitation + 40 mm irrigation from September 2001 to March 2002 and 244 mm from June to September 2002). The long-term average precipitation in Maryland is 589 mm from September to March and 409 mm from June to September. The rye cover crop, no-till treatment had the wettest soil at the 20-cm depth for the first half of the growing season at both sites. This was due to the thick mulch left by the rye cover crop, which limited surface evaporation



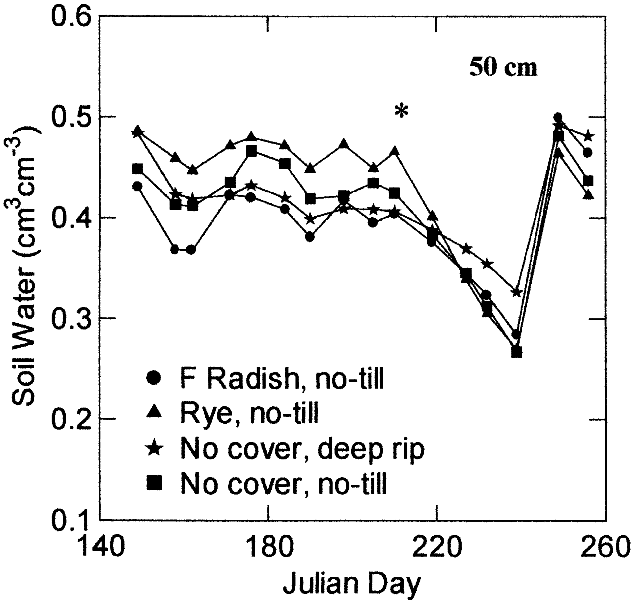


Fig. 3. Soil volumetric water content (cm^3 cm^{-3}) at the 50-cm depth at Wye Research and Education Center (top) and Beltsville Agricultural Research Center (bottom), May–September 2002. * Denotes days on which differences in soil water content were significant at the 0.05 probability level (Bonferroni). ANOVA performed on soil moisture meter readings.

and may have enhanced infiltration. A significant difference in soil water content below the compacted layer at BARC was observed on only 1 d, with the forage radish cover crop being the driest treatment (Fig. 3). The BARC site was slightly wetter, as it received closer to normal precipitation during the soybean growing season, as well as an irrigation in March 2002 (to enable the installation of the minirhizotron observation tubes). The higher clay content in the subsoil at BARC may also have contributed to the wetter conditions in the BARC subsoil. No significant differences in soil water content below the compacted layer were observed at WREC. The extremely dry conditions that persisted throughout the winter of 2001/2002 and following summer of 2002 at WREC probably limited the amount of cover crop root penetration through the compacted layer.

In March 2002, eight randomly selected canola and forage radish cover crop plants in plots adjacent to the main study at WREC were excavated to a 25-cm depth. Their roots were observed to grow vertically only as deep as 10 to 15 cm, at which depth the root diameter became greatly reduced and growth became horizontal. In several instances, after 5 to 10 cm of horizontal growth, root growth became vertical once more, suggesting that a pre-existing channel was encountered. The same cover crop species growing on the same site in 2003 (a year with normal winter precipitation levels) were observed to have roots that grew vertically to a depth of more than 30 cm. These observations suggest that cover crop root penetration into the subsoil during 2002 was less than normal, though it did occur in some instances, as documented in the minirhizotron images.

Soybean Yield Response

Deep ripping tillage did not significantly affect soybean yield at WREC. Therefore, data for the deep tilled and untilled treatments were pooled for the no cover and forage radish + rye treatments to compare the cover crop effect regardless of tillage. At WREC, soybean seed yield following forage radish + rye cover crop was significantly higher than those following all other treatments except forage radish cover crop alone (Fig. 4). The results in Fig. 4 suggest that the forage radish had a positive effect on soybean yield, and that this effect was enhanced by the presence of the rye in a mixed cover crop. Soybean yields following the rye cover crop were significantly lower than yields following forage radish + rye cover crop. Soybean yields following the canola and oilseed radish cover crops did not significantly differ from those following no cover (data not shown).

When the complete factorial of no-till treatments at WREC involving two levels of rye (present or absent) and two levels of forage radish (present or absent) were considered, it was observed that individually, both rye and forage radish increased soybean yields over the no-cover treatment (the main effects were significant) (Fig. 4). This analysis further showed that the combination of rye and forage radish gave the highest soybean yields (the rye × forage radish interaction was significant).

At BARC, orthogonal contrasts indicated a significant tillage effect between the two 'no cover' treatments, but not between the two forage radish + rye treatments. Therefore, tillage treatments were not pooled for the BARC data (Fig. 4). The treatments without deep tillage had higher yields than those with deep tillage. The no-till rye cover crop treatment had higher soybean yields than any other treatment. At BARC, soybean yields following the canola cover crop were significantly lower than all other treatments (data not shown), due to competition from volunteer seeded canola and limited effectiveness of the herbicide treatment in killing the canola cover crop.

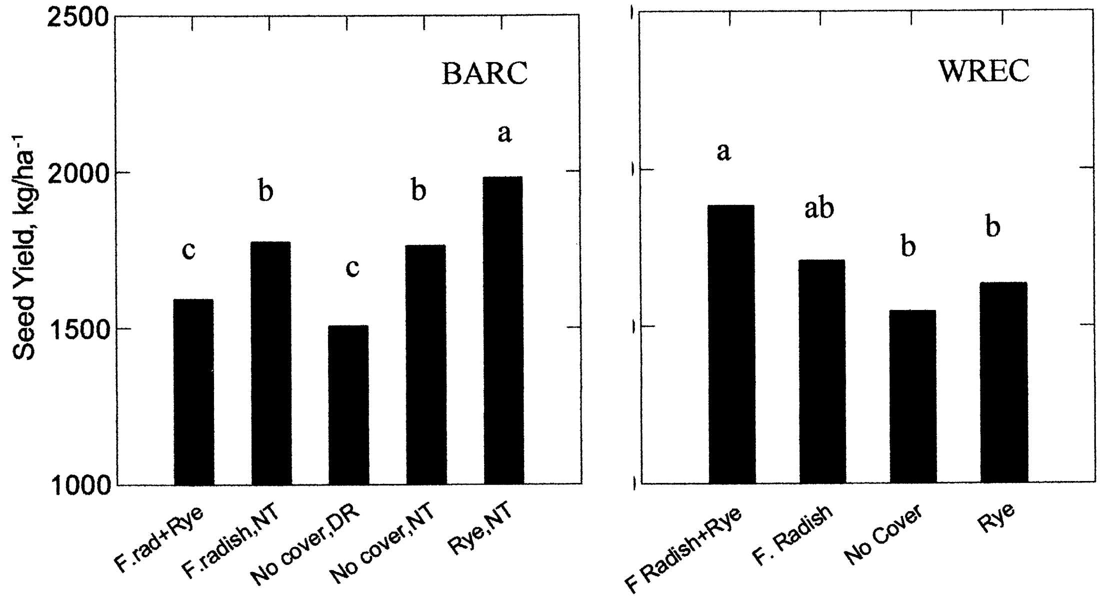


Fig. 4. Soybean seed yield (kg ha^{-1}) following no-till, no cover; no-till rye; no-till forage radish; or no-till forage radish + rye cover crop treatments at Beltsville Agricultural Research Center (BARC) and Wye Research and Education Center (WREC). Mean separation within each site by LSD at the 0.10 probability level.

During the study year, BARC was the wetter of the two sites, as it received more than twice as much water during the cover crop and soybean growing seasons. The higher clay content in the subsoil at BARC may also have contributed to the wetter conditions in the BARC subsoil. The wetter conditions at BARC may have led to less moisture stress in soybean plants during the summer of 2002 and less soybean response to any root channels created by the cover crops. However, the later planting date may have prevented the attainment of expected higher yields at BARC.

We speculate that the forage radish + rye cover crop treatment may have benefited the following soybean crop by a combination of two mechanisms: the forage radish provided low-resistance paths into the subsoil and the rye provided a mulch that limited evaporation from the soil surface and increased infiltration early in the growing season. The benefits afforded by the forage radish and forage radish + rye cover crop treatments that were observed at WREC, however, were not observed at BARC. We attribute this difference in the effect of cover crop treatment to differences in the level of plant moisture stress experienced during the soybean growing season as a result of different severity of compaction and precipitation at the two sites.

CONCLUSIONS

Soybean roots were directly observed to take advantage of the root channels left by decomposition of cover crop roots. While this "biodrilling" phenomenon was observed at both sites, the yield response to the cover crops was most pronounced at WREC where the drought conditions were more severe and the soil was more compacted. At this location, soybean yields were significantly greater following a 'forage radish + rye' combination cover crop than following no cover crop, regardless of tillage. The rye cover crop left a thick mulch, which resulted in higher surface soil moisture during the first half of the soybean growing season. The root channels left by the forage radish may also have benefited the soybean crop later in the summer by providing low resistance paths by which roots could obtain water stored in the subsoil. The effects of these cover crops were less pronounced at BARC, where the soil was less compact and more precipitation occurred.

The highly unusual winter drought in the Maryland coastal plain from Fall 2001 to Spring 2002 probably had a major impact on the results of this study. The hypothesis that the cover crop roots should be able to penetrate the compacted layer during the winter hinges on the fact that soil moisture is normally very high (and penetration resistance low) throughout the winter. However, since the sites received very little precipitation during the winter of 2001/2002, this lessening of penetration resistance never occurred to the degree expected. The results reported here, should therefore be considered an extremely conservative test of the cover crops' ability to effectively alleviate the effects of soil compaction.

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