Soil & Tillage Research 136 (2014) 61–69

Contents lists available at ScienceDirect

Soil & Tillage Research

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

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

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

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

ARTICLE INFO

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

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

ABSTRACT

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

1. Introduction

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

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

---

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

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

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

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

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

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

2. Materials and methods

2.1. Site and soil description

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

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

2.2. Experimental design, treatments and field operations

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

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

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