

## ABSTRACT

Title of Dissertation: ALLEVIATION OF SOIL COMPACTION BY  
BRASSICA COVER CROPS

Guihua Chen, Doctor of Philosophy, 2009

Dissertation directed by: Professor, Dr. Ray R. Weil  
Department of environmental Science and  
Technology

Soil compaction is a worldwide problem in modern agriculture associated with overuse of heavy machinery and intensification of cropping systems. Though tillage is traditionally used to alleviate compaction effect, increasing concerns about environmental impacts of tillage have led to interest in conservational tillage systems and incorporation of cover crops into crop rotations. Previous study showed soybean (*Glycine Max* L.) roots grew through a plowpan soil using channels left by canola (*Brassica napus*) cover crop roots, a process termed “biodrilling” to alleviate compaction effect. However, this study did not provide any quantitative data to support the observational conclusion. We studied “biodrilling” abilities of three cover crops and the effects of “biodrilling” on corn (*Zea mays*)/soybean growth by conducting three experiments. The first two experiments included three surface horizon compaction treatments (high, medium and no compaction), four cover crops [FR (forage radish: *Raphanus sativus* var.

*longipinnatus*, cultivar ‘Daikon’) and rape (rapeseed: *Brassica napus*, cultivar ‘Essex’) (tap-rooted species in the Brassica family), rye (cereal rye: *Secale cereale* L., cultivar ‘Wheeler’) (fibrous-rooted species) and NC (no cover crop)] in Exp. 1, and three cover crops (FR, rape and NC) in Exp. 2. The third experiment was conducted on field with a legacy plowpan (subsoil compaction) using FR, rye and NC cover crops.

Roots of FR were least inhibited by compaction, while rye roots were severely arrested by compaction. The order of “biodrilling” ability was FR > rape > rye. Soil bulk density, strength and least limiting water range were controlled by compaction treatments. Soil air permeability was greatly reduced by compaction. Air permeability was greater in rape/FR treatments than in rye/NC treatments under high/medium compaction. Corn/soybean root penetrations, subsoil water uptake in the compacted soils were enhanced by FR/rape treatments but not by rye/NC treatments. Compaction decreased corn yield only in Exp. 2 where soil sand fraction was greater. The yield of corn was greater in three cover crop treatments than in NC control. In terms of “biodrilling”, Brassica cover crops (FR and rape) were more effective than rye cover crop, would alleviate effects of soil compaction on plant growth in no-till farming systems.

ALLEVIATION OF SOIL COMPACTION BY BRASSICA COVER CROPS

By

Guihua Chen

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Advisory Committee:

Professor Ray R. Weil, Chair

Professor Robert L. Hill

Associate Professor Robert Kratochvil

Professor (Emeritus) Richard Weismiller

Professor Joseph Sullivan

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“人要结实，土要疏松。”

Human beings should be firmly built, while soil need to be loosely structured.

Chinese proverb

## Dedication

To my mother, Shenxiu Gao, who has only one career experience in her life - farming and taught me from her actions that persistence is essential for successes, and to my son, William Zeng, who uses the word 'soil' instead of 'dirt' more often in his talk.

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## Chapter 1: Introduction

### **1. Background and Problem Definition**

Soil compaction is a worldwide problem associated with agriculture. The ever-increasing of world's population necessitates the intensification of farming and cropping systems to meet the demand for more food. As a consequence, it has become common in the world to increase heavier farming machinery and have more animals per land surface area. Soil compaction is, thus, primarily caused by wheel traffic associated with intensive cropping, overuse of heavy equipment on wet soils, and a limited number of species in crop rotations or monoculture production (Servadio *et al.*, 2001; Hamza and Anderson, 2005; Servadio *et al.*, 2005), and also caused by animal trampling associated with intensive grazing (Van Haveren, 1983). Soil compaction 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). Compaction changes packing arrangement, size and shape of aggregates and clods, and therefore the total porosity, pore shape and pore size distribution.

Soil compaction can be divided into two types: surface horizon compaction and subsoil compaction. Surface horizon compaction is usually induced by wheel trafficking during field operations. It also includes surface crusting that results from impact of raindrops on weak aggregates and any other compaction that occurs between the soil surface and the tillage depth. Though this

kind of compaction restricts seedling emergence and water infiltration, it can usually be loosened by normal tillage and biological activities of soil fauna and flora; hence, it is relatively easily managed. Subsoil compaction refers to any type of compaction deeper in the soil profile than the surface horizon. Examples are plow pans, deep compaction, and inherent hardpans (Soil Quality Institute, 2003). A plow pan is a dense layer (often 5-10 cm thick) beneath the normal tillage depth that forms when the tillage depth does not change over years. It is possible to break a plow pan with appropriately timed deep ripping. Deep compaction is usually found below the level of tillage (deeper than a plow pan). It occurs because the ground contact pressure and/or the axle load is so great that the effect reaches a greater depth (Hadas, 1994). This kind of compaction is not easy to alleviate and may exist permanently. Finally, inherent dense layers, such as fragipans and claypans, are formed during the process of soil formation and are caused by internal factors. They are deep in the soil profile (lower part of B horizon) and very difficult to alter by management.

Soil compaction is not necessarily detrimental to the soil microbial community because the relationship between the two is complex based on the various responses results from various field or laboratory studies (Landina and Klevenskaya, 1984; Stovold *et al.*, 2004; Shestak and Busse, 2005). However, compaction can affect plant growth by impacting soil physical, chemical and biological properties, and the primary effects are physical. Changes in soil physical properties (increase in penetration resistance and bulk density) induced by compaction are usually detrimental to plant root growth (Saqib *et al.*, 2004;



Foloni *et al.*, 2006), water availability (Smittle and Williamson, 1977; Kristoffersen and Riley, 2005) and nutrient accessibility (Smittle and Williamson, 1977; Ishaq *et al.*, 2001; Rosolem *et al.*, 2002). Usually there is a negative correlation between root elongation rate and soil penetration resistance, regardless of whether changes in resistance were brought about by variations in either soil water content or soil density (Masle, 2002). The reduction in root elongation rate or root number with an increase in soil penetration resistance has been widely reported; as an exponential function (Goss, 1977; Zou *et al.*, 2001), as a power function (Panayiotopoulos *et al.*, 1994; Busscher and Bauer, 2003), as a linear function (Ehlers *et al.*, 1983) and as a quadratic function (Taylor and Ratliff, 1969); depending on plant species and range of resistances studied. Root growth parameters are also usually negatively related to soil bulk density (Shierlaw and Alston, 1984; Stirzaker *et al.*, 1996; Hirth *et al.*, 2005).

When a root system encounters a compacted soil layer, lateral root formation increases and root hair proliferates in the above loose soil layer (Schuurman, 1965; Goss, 1977; Shierlaw and Alston, 1984; Atwell, 1988; Misra and Gibbons, 1996). This has been determined to be a compensatory-type growth of roots (Misra and Gibbons, 1996; Bingham and Bengough, 2003) or to support the rear of elongation zone in compacted soils (Hettiaratchi and Ferguson, 1973). The proliferation of shallow roots and reduction of deep roots caused by soil compaction may not reduce crop yield if supply of water and nutrients is made available (Kristoffersen and Riley, 2005). However, since only 17 percent of the world's agriculture land is irrigated (Droogers *et al.*, 2001), the majority of the

world's agriculture land is rain-fed. Reduction of crop production in rain-fed agriculture is caused by either deficient rainfall (Cooper *et al.*, 2008) and/or adverse soil conditions (Passioura, 2002). Retardation of plants growth and yield reduction under soil compaction have been widely reported to be associated with drought stress (Tardieu and Katerji, 1991; Bengough and Young, 1993; Tardieu, 1994; Young *et al.*, 1997). Despite being severely drought-stressed, many crops usually leave substantial amounts of water in the subsoil at maturity. It is, therefore, important to find ways to make subsoil water available to plants in order to mitigate drought stress and increase crop yield.

## **2. Justification for Research**

Tillage has been used to effectively alleviate soil compaction (Schmidt *et al.*, 1994), but the benefits of tillage, especially deep tillage, may be short-lived (Hall *et al.*, 1994) and costly in terms of energy, capital and time. Increasing concerns about environmental impacts of tillage have led to interest in reduced- or no-tillage farming systems and incorporation of cover crops into crop rotations to reduce soil erosion, water pollution and greenhouse gas emissions. No-till management can also improve soil quality and health by increasing soil organic matter content (Weil and Magdoff, 2004). The use of deep ripping disrupts the surface mulch that develops after years of no-till management.

The needs to maintain sustainable crop production and a healthy environment re-establish the important role of crop rotation (Ball *et al.*, 2005) though it has been practiced for thousands of years. The importance of crop

rotation, which is the sequential production of different plant species on the same land, has been recognized for thousands of years. Crop rotation systems profoundly affect the soil physical environment, especially in the development and distribution of root channels. The idea of using “plant roots as tillage tools” was first proposed by Elkins (1985). Later, Cresswell and Kirkegaard (1995) called this “biodrilling” and suggested the terminology be used to describe cases where biopores left by previous crop roots can provide low resistance pathways for subsequent crop roots. Research on the biodrilling effect can be divided into two categories: annual and perennial crops. The results from the few studies conducted with perennial crops are more conclusive than those conducted with annual cover crops.

It was demonstrated by Elkins (1985) that the yield of cotton grown in rotation with perennial pensacola bahiagrass (*Paspalum notatum* Flugge) was 1.5 to 3.0 times greater than that of continuous cotton. His finding was later confirmed in a report by Katsvairo *et al.*(2007). They both concluded that the better performance of subsequent crop roots was attributed to the deep-rooted bahiagrass. The yield of oats (*Avena sativa* L.), sorghum hay (*Sorghum vulgare* Pers.) and corn (*Zea mays* L.) following three-year growth of kudzu (*Pueraria thumbergiana* Benth) increased 47, 77 and 131%, respectively, compared to continuous cropping (Sturkie and Grimes, 1939). Using minirhizotron technique, Rasse and Smucker (1998) found that corn grown after the cool season perennial alfalfa (*Medicago sativa* L.), achieved a higher percentage of roots in subsoil than corn

grown after corn. Even though there are not many studies in the literature, the biodrilling effect of perennial species appears to be quite conclusive.

Henderson (1989) reported that lupin (*Lupinus angustifolius* L. cv. Illyarrie) had no effect on root growth of the following wheat crop (*Tritium aestivum* L. cv. Gutha) and concluded that the increase in wheat yield was likely due to some other benefits from the cover crop. His finding was very similar to what Cresswell and Kirkegaard (1995) reported, that canola crop (*Brassica napus* L.) did not improve rooting depth for the following wheat crop, though it did increase wheat grain yield. They suggested that perennial species might be more capable of providing root channels in compacted soils than annual species. By including subterranean clover (*Trifolium subterraneum*) as a cover crop, Stirzaker and White (1995) found that lettuce (*Lactuca sativa*) yield increased; however, they stated a very broad conclusion that included all the possible benefits a cover crop could provide including changes in soil temperature, strength and biopores. In a recent study using a minirhizotron technique, Williams and Weil (2004) observed that soybean (*Glycine Max* L.) roots grew through a compacted plowpan soil using channels made by decomposing canola cover crop roots. However, their study did not provide any quantitative data to support their observation.

The biodrilling effect of annual cover crops still remains in question. More research is needed to provide solid and conclusive information on the differential ability for penetration through compacted soils by roots of various cover crop species. A better understanding is also need on the effects of winter cover crops and soil compaction on summer crop root penetration, subsoil water use and yield.

### 3. General Research Approach

There were three field experiments in the research project. Experiment 1 and 2 were conducted on soils of surface horizon compaction created by wheel trafficking. Experiment 3 was conducted on a field with preexisting subsoil compaction (an old plow pan).

Experiment 1 was established in fall 2006 and continued till fall 2008 with no-till farming system, at field NF-2B, BARC, Beltsville, USDA, a site that is in the coastal plain ecoregion in Maryland (39°01'N, 76°55' W). Experiment 2 located the adjacent field NF-2C was conducted from fall 2007 to fall 2008 to repeat aspects of Exp. 1. Randomized complete block design with factorial treatment structure was used in both experiments. In Exp. 1, there were three compaction levels created by driving tractors with different axle load or number of passes: high compaction (two passes), medium compaction (one pass) and no compaction (no pass); four cover crops treatments: forage radish (*Raphanus sativus* var. *longipinnatus*, cultivar 'Daichon') (FR), rapeseed (*Brassica napus*, cultivar 'essex') (rape), rye (cereal rye: *Secale cereale* L., cultivar 'Wheeler') and NC (no cover crop). In Exp. 2, there were three compaction levels (the same as in Exp. 1) but only three cover crops: FR, rye and NC.

Experiment 3 was conducted on the field site of University of Maryland Central Maryland Research and Education Center at Beltsville facility [CMREC], where an old plowpan was detected at 30-35 cm depth. Randomized complete block design was used in this experiment. The experiment continued from fall 2004 to fall 2006. Cover crops (FR, rye and NC) were rotated with corn/full-

season soybean in the study. Forage radish and rape cover crops are tap-rooted species in the Brassica family, while rye has fibrous root system.

A recording cone penetrometer (Spectrum Technologies, Plainfield, IL) was used to measure soil strength. At each location, the penetrometer was pushed by hand at a constant rate down to the depth of 45 cm. Mean penetration resistance was recorded in kPa for every 5 cm depth increment to 45 cm. In field of Exp. 2, because of the high content of gravels in block III, a dynamic cone penetrometer that is designed for gravelly soils (Herrick and Jones, 2002) was used. Concurrent with measuring soil strength, undisturbed soil cores were taken per plot (40 cm depth) using a soil probe. In block III of Exp. 2, soil samples were taken using a handle corer with the inside diameter of 6.4 cm for the same reason described above. The cores were divided into 5 cm increments, weighed, dried and re-weighed to determine soil bulk density and soil moisture content.

In Exp. 1 and 2, in order to find the effects of compaction and cover crops on least limiting water range, soil samples at 10-15 cm depth (where the differences of compaction treatments existed) were used to determine soil water contents at various water potentials. The known weights of soil was packed into the steel rings to achieve the desired bulk densities corresponding to those measured in the fields at the same depth and corresponding to the high, medium and no compaction treatments. Soil water contents at low suctions were determined in the tension table, the procedure described by Topp and Zebchuk (1979). Soil water contents at greater suctions were determined at the pressure plate apparatus using the method described by Dane (2002).

A field air permeameter that is based on concepts described by Jalbert and Dane (2003) was used to measure soil air permeability in early to middle June 2008 in Exp. 1 and 2. To make the field measurements, a 16 cm long PVC cylinder with an inside diameter of 10.16 cm was pushed steadily into the soil. A cylindrical PVC chamber sealed at one end was then fitted over the inserted cylinder. The measurement was taken at 0-3, 0-6, 0-9 and 0-12 cm depth intervals. For each depth interval, air temperature, back pressure, and air flow rate were recorded. After air permeability was measured at all 4 depths, the volumetric soil moisture content was measured at 1.5, 4.5, 7.5 and 10.5 cm using horizontally-inserted capacitance soil moisture probe (EC-5, Decagon, Inc. Measurements were taken at 3 locations per plot.

In Exp. 1 and 2, vertical root penetration of cover crops under different compaction treatments and vertical root penetration of corn under different compaction and cover crop treatment combinations were examined using the core break method (Noordwijk, 2000). Soil cores of cover crop root samples were taken in November/December before FR was frost-killed, directly under the plants after shoots were removed. Soil cores of corn root samples were taken 5 cm away from corn plants in the two central rows of each plot to examine corn root penetration after corn was mature in late July –early August, 2007 (Exp. 1) and 2008 (Exp. 1 and 2). Soil cores were collected to a depth of 50 to 60 cm (maximum depth based on machine capability in these soils) using a tractor-mounted direct-drive hydraulic soil coring machine (Giddings, Inc., Windsor, CO) with a sampling tube of 6.4 cm inner diameter. The cylindrical soil cores collected

were laid in horizontal holding troughs made of PVC plastic. Each soil core was broken by hand every 5 cm along its length. The number of roots protruding from both break faces was recorded.

In Exp. 3, corn/soybean root penetration was examined by both core break method and minirhizotron technique, while cover crop root penetration in the fall of 2005 was studied by minirhizotron technique only. One minirhizotron tube (1.8 m long) was installed at 45° angle at the end of each plot in early June 2005. The minirhizotron camera (Model BTC-2, Bartz Technology, Santa Barbara, CA) was inserted into the tube, and images (13.5 x 18.0 mm) were taken and saved to a computer drive at 13.5 mm intervals starting at the soil surface progressing downwards. The camera position was precisely controlled by the camera handle apparatus so that the same soil zone could be imaged repeatedly. Images were taken to the bottom of each tube or to a vertical depth around 95 to 100 cm. Corn/soybean root images were taken periodically from late June to early August 2005 and 2006, respectively. Cover crop root images were taken on October 3, and November 4, 2005. Root numbers of corn, cover crops and soybean were counted in each image starting at the plow pan soil depth (20 cm) to 50 cm. Root numbers for every 5 cm depth increment were summed and expressed as root counts per m<sup>2</sup> based on the actual area covered in the summed images. The core break method used in Exp. 3 was the same as described above for Exp. 1 and 2. The only difference was that soil cores were taken using a 30 cm long drop-hammer driven corer with a cutting diameter of 6.3 cm. Core-break enumeration



was performed from late July to early August for corn (2005) and for soybean (2006).

Variation of surface and subsoil water content during corn/soybean growing season was monitored at all three experiments. Granular matrix electrical resistance sensors (Watermark™, Irrrometer Co., Riverside, CA) were installed at 15, 50 cm depths. The electrical resistance readings were adjusted for soil temperature and converted by dataloggers (Watermark monitor 3.1, Irrrometer, Inc., Riverside, CA) to hourly readings of soil water tension in units of kPa. Laboratory calibration was conducted for soils at each experimental site to convert soil water tension to volumetric soil water content.

Corn silage was harvested by hand in mid-August 2005, 2007 and 2008. Corn plants in 3 m-length of the two central rows per plot were cut 1 cm above the soil surface. The fresh weight and total plant counts in the harvest area (6 m x 0.76 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 corn per unit area.

#### **4. General Research Objectives and Hypotheses**

The overall aim of whole research project was to study the degree to which the use of fall cover crops (forage radish, rapeseed and rye can alleviate the restrictions on root growth caused by soil compaction and therefore substitute for the traditional use of deep tillage on middle Atlantic coastal plain soils under no-till management. The first hypothesis was that the tap rooted species, FR and /or

rape could send more roots into deep compacted soil layers than rye in fall and winter when the soil is relatively moist and therefore soil strength is relatively low. The second hypothesis was that soil bulk density, penetration resistance and least limiting water range (at 10-15 cm depth) would only be affected by compaction treatments but not by cover crop treatments, soil air permeability would be affected by both compaction and cover crop treatments; The third hypothesis was that corn (*zea mays*, cultivar 'Pioneer' 34B62) and soybean grown after FR or rape would produce more deep roots that penetrate compacted soil layers by recolonizing cover crop root channels. The fourth hypothesis was that the greater degree of deep rooting by corn/soybean after FR and rape would result in increasing in subsoil water use, thus reducing drought stress and increasing yields.

## Chapter 2: Literature Review

### Soil Compaction, Root Penetration and Water Uptake

#### **Abstract**

Soil compaction is a worldwide problem for modern agriculture. Plant growth is subjected to mechanical impedance when the pore size is too small for roots to extend further into the compacted zones. This chapter is a brief review of the parameters characterizing soil compaction; the mechanisms of root penetration in compacted soils; evidence and possible mechanisms why some plant species penetrate better in compacted soils than others; and relationships between root growth and soil water uptake.

Quantitative characterization of soil compaction can be divided into two aspect groups: static and dynamic. Soil bulk density, total/macro porosity and degree of compactness are static parameters described on a volume basis. Soil penetration resistance, water/air permeability, gas diffusivity and soil aeration are dynamic parameters described on a plant and root growth restriction basis. Among the above parameters, soil air permeability is the most sensitive to soil compaction. It reflects not only the pore size, but also the pore continuity. A recently introduced concept, the least limiting water range, integrates the effects of soil aeration, water potential and penetration resistance on plant growth into one parameter. Therefore, it may be a potential index of soil physical quality for crop production.

The effect of mechanical impedance on root penetration is reviewed on an individual root basis. A descriptive root extension model explains the mechanism

of apex geometric changes when a root encounters mechanical impedance. Cell expansion is crucial for a root to overcome pore space confinement, while the extensibility of cell wall microfibrils plays a vital role in controlling the change of cell shape. A quantitative root elongation model, based on the theory of cell division and elongation, integrates the effects of soil water potential and mechanical impedance. However, neither of the above models can fully explain the mechanisms of root growth in compacted soils. Root penetration of compacted soils is a dynamic and physiological process that involves not only physical responses, but also hormone regulation.

The possible mechanisms for why roots with greater diameter penetrate compacted soils better than those with smaller diameter are discussed based on the present knowledge. “Biodrilling”, the phenomena that biopores left by previous crop roots can provide low resistance pathways for subsequent crop roots, is discussed for perennial and annual crops. The efficiency of soil water uptake depends on root distribution. Root parameters such as root length density, surface area and rooting depth are thought to correlate with water uptake. In the summer when soil water in the surface layer is depleted, the deeper the roots can penetrate, the more subsoil water the plants can take up. Therefore, plant uptake of soil water is often found to be better correlated to rooting depth.

## **1. Introduction**

Soil compaction 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; Soil Quality Institute, 2003). Compaction changes packing arrangement, size and shape of aggregates and clods, and therefore the total porosity, pore shape and pore size distribution. Soil compaction can be divided into two types: surface horizon compaction and subsoil compaction. Surface horizon compaction is usually induced by wheel trafficking during field operations. It also includes surface crusting that results from impact of raindrops on weak aggregates and any other compaction that occurs between the soil surface and the tillage depth. Though this kind of compaction restricts seedling emergence and water infiltration, it can usually be loosened by normal tillage and biological activities of soil fauna and flora; hence, it is relatively easily managed. Subsoil compaction refers to any type of compaction deeper in the soil profile than the surface horizon. Examples are plow pans, deep compaction, and inherent hardpans (Soil Quality Institute, 2003). A plow pan is a dense layer (often 5-10 cm thick) beneath the normal tillage depth that forms when the tillage depth does not change over years. It is possible to break a plow pan with appropriately timed deep ripping. Deep compaction is usually found below the level of tillage (deeper than a plow pan). It occurs because the ground contact pressure and/or the axle load is so great that the effect reaches a greater depth (Hadas, 1994). This kind of compaction is not easy to alleviate and may exist permanently. Finally, inherent dense layers, such as fragipans and claypans, are formed during the process of soil formation and are caused by internal factors. They are deep in the soil profile (lower part of B horizon) and very difficult to alter by management.

Soil compaction is a worldwide problem associated with agriculture. It is primarily caused by wheel traffic associated with intensive cropping, overuse of heavy equipment on wet soils, and a limited number of species in crop rotations or monoculture production (Servadio *et al.*, 2001; Hamza and Anderson, 2005; Servadio *et al.*, 2005). It may also be caused by animal trampling associated with intensive grazing. Compaction problems are similar in different cropping systems because of the similarities in the types of farm vehicle traffic (Soane and van Ouwerkerk, 1994) and in the field operation cycles of land preparation, soil cultivation, pesticide and fertilizer applications, harvesting and commodity transport operations (Figure 2.1). The duration of the cycle varies depending on the crop, e.g., only a few months for vegetables to almost a century for some forest crops (Masle, 2002).

Soil compaction can affect plant growth by impacting soil physical, chemical and biological properties, but the primary effects are physical. Compaction is not necessarily detrimental to the soil microbial community because the relationship between the two is complex based on the various responses results from various field or laboratory studies (Landina and Klevenskaya, 1984; Stovold *et al.*, 2004; Shestak and Busse, 2005). However, changes in soil physical properties induced by compaction are usually detrimental to plant root growth, water availability and nutrient accessibility.

## 2. Characterization of Soil Compaction

Unlike erosion and salinization which give surface evidence of soil degradation, soil compaction (or soil structure degradation) is not easily recognized without physically monitoring and examining the soil below the surface. Compared to non-compacted soils, compacted soils tend to have higher bulk density, lower porosity, lower infiltration rate, lower saturated hydraulic conductivity, poorer aeration (because of a reduction in the macro and meso pores) and greater soil strength. Parameters often used to quantify/characterize soil compaction are soil bulk density and soil strength (penetration resistance). Other parameters such as water infiltration rate or hydraulic conductivity, total and/or macro porosity, and gas diffusivity are also used to monitor soil compaction status. Among these parameters, bulk density and soil water content are key components.

Although the impact of soil compaction on plant growth has usually been examined with regard to one or two separate parameters, it is actually controlled by dynamic and complex interactions among soil properties among which soil moisture is a key variable. It was not until 1985 that Letey introduced a new concept, the non-limiting water range (NLWR) (Letey, 1985), which integrates as one index the effects on plant growth of water potential, aeration and mechanical impedance. In 1994, da Silva *et al.* (1994) proposed the least limiting water range (LLWR) concept based on NLWR. This new concept received considerable attention and is now widely applied.

### *2.1 Static parameters characterizing soil compaction*

Soil bulk density is the mass of dry soil per unit volume; it reflects the capacity of a soil to store and transport water and air and is inversely related to total soil porosity (Masle, 2002). Because soil bulk density varies with soil texture and organic matter content, Håkansson (2000) proposed a parameter termed the *degree of compactness* (D) as an effective description of plant response to machinery traffic. This parameter may also be useful for very loose soils where no mechanical resistance or aeration problems exist to limit root growth, but incomplete root-soil contact and lower hydraulic conductivity are limiting factors. Håkansson (2000) defined the degree of compactness (D) as the dry bulk density of a soil as a percent of a reference bulk density. The reference bulk density is determined by a standardized uniaxial compression test on large samples at a stress of 200 kPa. The use of this parameter to describe soil compaction status can be explained by a schematic diagram (Figure 2.2). This diagram has some similarities to the relationship between LLWR and soil bulk density, as described below.

### *2.2 Dynamic parameters characterizing soil compaction*

Soil strength is a measure of the force required to push a cone-tipped probe through the soil. The measurement reflects the degree to which a soil is resistant to root penetration because roots need to generate a force that can overcome the mechanical resistance of soil aggregates to displacement and deformation. Soil strength is also referred to as penetration resistance. It is



influenced by soil texture, organic matter content, bulk density and water content. Penetration resistance in a given soil varies with water content and bulk density. The variation of penetration resistance is well correlated with the variation in the overall resistance to root penetration. (Unger and Kaspar, 1994). Soil penetration resistance has a high positive correlation with soil bulk density and a negative relationship to soil water content. As reviewed by Unger and Kaspar (1994). Soil strength increases exponentially with bulk density, and the rate of increase is greater at lower water potentials (Figure 2.3 from Shierlaw and Alston, (1984)). Panayiotopoulos *et al.* (1994) reported that penetration resistance increased linearly with bulk density for two soils (an Entisol and an Alfisol). It is well established that soil strength increases as a function of bulk density, but the relationship will differ for different soils and at different soil water potentials. Soil penetration resistance also increases exponentially as soil water content decreases, as presented in Figure 2.4 (Bengough, 1997). Pagliai and Jones (2002) proposed a linear relationship between soil porosity and penetration resistance using their data and data from Marsili *et al.* (1998). However, an exponential function fits the data better than a linear one (Figure 2.5).

Soil air permeability ( $k_a$ ) is a parameter that describes pore geometry in terms of its effects on transport processes. The geometric factors include total porosity ( $\epsilon_a$ ), pore size distribution (radius of pores), pore continuity (inverse to tortuosity (T)) and shape. Pore space and continuity in the soil govern the content and movement of gas and water. Air movement can be assumed to be laminar flow and Darcy's law is also applicable (Ball, 1981a). By combining Darcy's law

and Poiseuille's law, air permeability was given by Ball (1981a) as:  $k_a = n\pi r^4 / 8T\pi r_s^2$ , where  $n$  is the number of channels that conduct air,  $r$  is the radius of channel,  $r_s$  is the radius of soil column,  $T$  is pore tortuosity, equals ratio of the length of channel ( $l$ ) to the length of soil column. If the porosity of the channels ( $\epsilon_a$ ) is given as:  $\epsilon_a = n\pi r^2 / L\pi r_s^2 = nT\pi r^2 / \pi r_s^2$ , then  $k_a = (r^2 / 8T^2) \epsilon_a$ . This equation shows that air permeability will increase as air-filled porosity increases and/or pore size becomes larger but decrease as tortuosity increases.

Based on the above principles, indices of "pore organization efficiency" were given as  $k_a / \epsilon_a$  and  $k_a / \epsilon_a^2$  by Ball (1981a), where  $k_a$  is air permeability at a given air-filled porosity  $\epsilon_a$ . The pore sizes are comprised of the pore space and the connections between the pores and are different for different soils even at equal air-filled porosity ( $\epsilon_a$ ). A soil with a higher percentage of macropores and better pore connection usually has greater air permeability compared with a soil with less macro porosity and more tortuosity of pore connection at the same air-filled porosity. Thus, a soil with greater air permeability when equal air-filled porosity exists, is a soil with more efficient pore organization. The applications indicate that when air filled pore space is made up of pores with the same size distribution and continuity,  $k_a / \epsilon_a$  values should not differ; if the pore continuity is the same,  $k_a / \epsilon_a^2$  values should be the same. When  $k_a / \epsilon_a^2$  values are the same for two soils but  $k_a / \epsilon_a$  values are different, the difference for  $k_a / \epsilon_a$  values is due to the difference in pore size, which results in the difference of  $k_a$  (Ball, 1981b; Groenevelt et al., 1984). Applications on the efficiency of pore organization by comparing  $k_a$ ,  $k_a / \epsilon_a$  and  $k_a / \epsilon_a^2$  have been widely reported later on (Blackwell *et al.*, 1990b; Schjønning

and Rasmussen, 2000; Munkholm *et al.*, 2005b). Unfortunately, comparisons of  $k_a$ ,  $k_a/\epsilon_a$  and  $k_a/\epsilon_a^2$  are restricted to laboratory measurements because the  $k_a$  has to be measured either under equal air filled porosity or for soils at the same water potential. Other parameters relating  $k_a$  to pore geometric factors were given by Ball *et al.* (1988) using an empirical form of the Kozeny-Carman equation for air permeability as:  $\log k_a = M + N \log \epsilon_a$ . M and N are constants and can be got for different soils from best-fit equations. Greater M values are related to larger pore sizes, while larger N values are thought to reflect a greater proportion of open and continuous pore paths with increasing air-filled porosity. Roseberg and McCoy (1990) reported that soil with greater macro porosity had greater  $k_a$ , M and N values. N is more sensitive to pore continuity and hence a better index than  $k_a/\epsilon_a$  or  $k_a/\epsilon_a^2$  to characterize efficiency of pore organization. Soils may have the same  $k_a/\epsilon_a$  and/or  $k_a/\epsilon_a^2$  values but different  $k_a$ s can occur because some of air-filled pores may be dead pores which do not conduct air (Fedotov, 1990; Dörner and Horn, 2009).

The effect of compaction on oxygen movement in soils is crucial to living organisms. Compaction has been widely reported to significantly decrease oxygen content and oxygen diffusion rate (ODR) (Shierlaw and Alston, 1984; Agnew and Carrow, 1985; Gilman *et al.*, 1987; Watson and Kelsey, 2006). There is also a high correlation between soil bulk density and ODR. As observed by (Czyż, 2004), ODR decreases linearly as soil bulk density increases independent of soil texture, while the difference in the intercept (bulk density at which ODR = 0) is associated with soil water content during the measurement (Figure 2.6).

Soil water storage and movement also are affected by compaction. Water infiltration rate decreases with an increase in the number of track passes, tire inflation pressure or load (Abu-Hamdeh *et al.*, 2000; Abu-Hamdeh and Al-Widyan, 2000). Soil hydraulic conductivity not only decreases as the number of track passes increases, it also decreases linearly as the percentage of elongation pores in the soil decreases (Pagliai *et al.*, 2003) (Figure 2.7).

The least limiting water range (LLWR) concept is defined as “the range of soil water contents within which limitations to plant growth associated with water potential, aeration and mechanical resistance to root penetration are small” (da Silva and Kay, 2004). Outside the least limiting water range, plant growth is most limited either by poor aeration, high soil strength or low water potential. In this concept, the range of soil water contents over which plants can function adequately has lower and upper limits. Based on this concept, the LLWR can be diagrammed as shown in Figure 2.8 (Brady and Weil, 2008). The upper limit is arbitrarily chosen based on the water content at 10% air-filled pore space and field capacity (whichever is less), while the lower limit is arbitrarily chosen based on the water content at wilting point and penetration resistance of 2 MPa (whichever is greater). As bulk density increases, soil mechanical impedance becomes greater while soil total, macro-porosities become less. Accordingly, the upper limit would move down while lower limit move up, which results in a narrower range of LLWR. Thus, a wider range of 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 or mechanical impedance and will

be more productive, compared to a narrower range of LLWR. The critical bulk density at which LLWR equals zero can then be found. This concept of LLWR was applied to nitrogen mineralization (Drury et al., 2003) and crop production (da Silva and Kay, 1996; Lapen *et al.*, 2004; Beutler *et al.*, 2005). Corn shoot growth rate was found highly correlated to the proportion of the total number of measurements in which the water content fell outside the LLWR (da Silva and Kay, 1996). The above few applications of LLWR provide a good evidence that it is possible to use LLWR as an index of soil productivity. However, plant growth is a dynamic process. When selecting different values for the upper limit of penetration resistance and lower limit of air-filled porosity, it is necessary to take into account physiological and morphological adaptation by plants to environment stresses.

### **3. Root Growth and Soil Compaction**

#### *3.1 Root systems and structure*

Root systems differ from species to species, but can be divided into two major forms: the fibrous root system typical of monocots, and the tap root system typical of dicots. In monocots, there are usually three to six primary root axes from the germinating seed and adventitious (or brace) roots that develop later. In the fibrous root system, all the roots generally have the same diameter if there is no modification of adverse soil environmental conditions. In dicots, there is one single main root axis with lateral roots that develop later forming an extensively branched root system. Different from the root size similarity for monocots, dicots

have a major vertical root axis, and their roots will have widely different diameters (Taiz, 2006).

The root growth of both dicots and monocots depends on the activity of the root apical meristem and the production of lateral root meristems. The apical region of a root for all species is identical and has three active zones: meristematic, elongation and maturation (Taiz, 2006). In the root apex, the root cap also protects the delicate meristematic cells as the root explores the hostile soil environment. Behind the root cap lies the meristematic zone. In the quiescent center, cell division is relatively slow. The region of rapid cell division in the meristem is at about 0.1 mm from the apex. The elongation zone is at approximately 0.7-1.5 mm from the apex, and is the zone where cell elongation rapidly occurs and where a final round of cell divisions occurs to produce a central ring of cells called endodermis. Root growth is the combination of cell division in the meristematic zone and cell expansion in the elongation zone. In the maturation zone, fully developed xylem is found allowing water translocation and root hairs develop to anchor the rear of the root elongation zone to the soil.

### *3.2 Root responses to soil compaction*

When growing in soil, roots have to overcome axial and radial stresses as well as frictional forces. Although the relative magnitude of these components varies depending mostly upon the physical properties of the soil and to a lesser extent on root shape and diameter, the axial component is generally dominant (Masle, 2002). Roots can detect and respond to small changes in soil strength

(Barley, 1962). In order to grow through the soil, roots need to generate a force that can overcome the mechanical resistance caused by the soil volume, of which the most important factor is the resistance exerted by soil particles against displacement and deformation by the root tip. This resistance determines the pressure that the root tip needs to exert to push its way through the soil.

Compared to most roots, the probe of the penetrometer (with the tip diameter 1 cm) is usually greater in diameter, more rigid in size and shape, and has higher friction force. Therefore, the measured penetration resistance is generally greater than the force a root actually needs to exert for growth. However, a close relationship between measured penetration resistance and changes in root elongation rate has been reported (Taylor et al., 1966). Usually there is a negative correlation between root elongation rate and soil penetration resistance, regardless of whether changes in resistance were brought about by variations in either soil water content or soil density (Masle, 2002). The reduction in root elongation rate or root number with an increase in soil penetration resistance has been widely reported; as an exponential function (Goss, 1977; Zou et al., 2001), as a power function (Panayiotopoulos *et al.*, 1994; Busscher and Bauer, 2003), as a linear function (Ehlers et al., 1983) and as a quadratic function (Taylor and Ratliff, 1969); depending on plant species and range of resistances studied. Root growth parameters are also usually negatively related to soil bulk density (Shierlaw and Alston, 1984; Stirzaker *et al.*, 1996; Hirth *et al.*, 2005).

### *3.3 Morphological responses of roots to soil compaction*

The phenomena and mechanics of root response to increased soil strength have been widely studied (Bengough et al., 2006). Plants growing in compacted soils exhibit a range of physiological adaptations affecting morphological architecture. The morphological changes to roots induced by mechanical impedance are not only reduced elongation rate, but also a more rounded root cap and increased root diameter (Goss and Russell, 1980; Hanbury and Atwell, 2005). Impedance mostly affects cells within the root elongation zone, and the broadening and shortening of these cortical cells result in a thicker root axis (Atwell, 1993). It is widely reported that when a root system encounters a compacted soil layer, lateral root formation increases and root hair proliferates in the above loose soil layer (Schuurman, 1965; Goss, 1977; Shierlaw and Alston, 1984; Atwell, 1988; Misra and Gibbons, 1996) This has been determined to be a compensatory-type growth of roots (Misra and Gibbons, 1996; Bingham and Bengough, 2003) or to support the rear of elongation zone in compacted soils (Hettiaratchi and Ferguson, 1973).

### *3.4 Role of root cap mucilage in root penetration*

It is generally accepted that the plant root cap protects the root meristem and assists root penetration in a compacted soil environment (Taiz, 2006). By sloughing off the cap cells and mucilage, the friction force on the surface of the growing root is reduced. When encountering a soil with high strength, a root tends to secrete more exudates (Iijima et al., 2000; Masle, 2002). It is reported that a



root with an intact cap can penetrate faster and for a longer period of time into the compacted soil compared with roots that have been de-capped (Iijima et al., 2003). More specifically, the contribution of root penetration by the root border cells is greater than just by mucilage (Iijima et al., 2004). It is interesting to note that root growth pressure was smaller while root diameter was larger in the intact root cap compared with the decapped root (Iijima *et al.*, 2003; Iijima *et al.*, 2004). There must be some physiological responses of the root cap to soil compaction that has not yet been discovered.

### *3.5 Descriptive root extension model*

The mechanism of root growth in compacted soils was well documented by Hettiaratchi (1990). In the analogue model of a root apex as shown in figure 2.9, Hettiaratchi (1990) described the force that drives a root cap into the soil comes from the individual forces generated by the cells in the elongation zone. “These cells are organized in the form of a series-parallel array of ‘hydraulic jacks’” (Hettiaratchi, 1990) which is the energy source. The pressure  $p_a$  in the axial direction is induced by soil strength acting on the cells in the meristematic and elongation zones, while the pressure  $p_r$  in the radial direction is induced by the soil strength acting on the root epidermis. For a root to grow, the turgor pressure ( $p$ ) in the cell and cell wall elasticity must be greater than  $p_a$  in the axial direction in order to elongate or greater than  $p_r$  in the radial direction in order to enlarge.

In this model, Hettiaratchi (1990) divided root growth into three main steps based on the hypothesis proposed by Abdalla *et al.* (1969), during which root swelling was critical for roots to overcome mechanical impedance. First, when a root encounters a high strength surrounding the root cap, the elongation zone fails to advance the root cap in the axial direction. The root apex is still able to expand in the radial direction in a cylinder mode because the external pressure in the direction of elongation is always greater than those in the direction of expansion (Hettiaratchi and Ferguson, 1973). This allows root growth to change from the axial direction to the radial direction, which was termed “growth polarity” (Hettiaratchi, 1990). However, it seems that which is greater, root axial pressure or radial pressure, is species dependent (Atwell, 1993), but the difference is that radial pressures are exerted over a larger area while axial pressures are exerted only at the point of impact. Second, once the root radial expansion succeeds, the soil at both ends of the elongation zone will be displaced radially and fails as a result of tension cracking, and the constraints to the axial extension of the root cap are alleviated by radial expansion. Third, until the soil strength is less than the maximum cell pressure in the root cap, the axial growth of elongation zone resumes, as shown in figure 2.10. When the external stresses reach the maximum point of root pressure in both axial and radial directions ( $p_a = p_r = p$ ), root growth ceases because cell volume cannot increase. The microfibrils in the plant cells influence the radial expansion and control cell wall shape because they are relatively inextensible. The radial expansion of the cell must result in an axial contraction and an increase in fibril angle and vice versa. There

is a critical value of fibril angle. At the critical value, both axial and radial extension is arrested. The axial extension is the greatest at 90° and decreases rapidly as fibril angle reduces until it is arrested at the critical angle. The axial extension reduces as the fibril angle increases from zero to the critical angle and is arrested at the critical angle.

### 3.6 Quantitative root elongation model

The physical model of root growth was first proposed by Greacen and Oh (1972) as  $R = m_r (W - W_c)$ , where R is the rate of root elongation (mm/day),  $m_r$  is the parameter that reflects the extensibility of cell wall material, W is the cell wall pressure, and  $W_c$  is the threshold value of the cell wall pressure at which cell elongation ceases. This model was later modified by (Greacen, 1986) to include the factor of soil penetration resistance. The modified model is  $l^I (dl/dt) = m(\sigma) (P - Y(\sigma) - \sigma)$ , where l is the length of elongating root under consideration, m is the same as in the initial model, P is the turgor pressure, Y has the same meaning as  $W_c$  in the initial model. In the modified model, the parameter of wall extensibility and threshold of cell wall pressure are no longer constant, but vary as soil strength changes. Based on the above two models, Dexter (1987) proposed a third model that separates the effect of soil water potential from that of soil mechanical strength. The model is  $R/R_{max} = I - \psi_0/\psi_w - \sigma/\sigma_{max}$ . R is the actual elongation rate while  $R_{max}$  is maximum growth rate;  $\psi_0/\psi_w$  reflects the effect of soil water potential ( $\psi_0$  – actual soil water potential,  $\psi_w$  - soil water potential at wilting point); and  $\sigma/\sigma_{max}$  reflects the effect of soil mechanical resistance ( $\sigma$  –

growth pressure that root has to exert to deform the surrounding soil,  $\sigma_{\max}$  - maximum growth pressure a root can exert). This model suggests that in the condition of optimal soil water content, mechanical strength should be the only factor that controls root elongation, and plant roots with greater  $\sigma_{\max}$  would result in greater root elongation rate under the same soil strength.

### *3.7 Plant hormone regulation*

The response of plant root to environmental changes is an integration of physiological process. Any simple model may not fulfill the explanation of the complex of root responses to soil compaction. For example, roots that were impeded in the compacted layer elongated at a reduced rate even after left from the compacted layer towards the subsequent loose layer (Bengough and Young, 1993). It was also observed that high soil strength not only inhibited axial growth of primary roots and enhanced radial expansion of the root behind the apex, but also stimulated the abundance of lateral roots and root hairs (Atwell, 1988; Garcia et al., 1988; Misra and Gibbons, 1996). These cannot be interpreted by either of the above models. It is possible that plant hormones also play important roles in regulating root responses to soil compaction. Ethylene concentration in roots was found to increase upon compaction and it was suggested that endogenous ethylene might control the extension of primary roots but increase the formation of root hairs and lateral roots (Veen, 1982; Moss *et al.*, 1988; Taylor and Brar, 1991). Abscisic acid (ABA) concentration in xylem sap increased due to compaction (Tardieu and Katerji, 1991), which might facilitate root penetration because it

induced morphological and anatomical changes of roots (Hartung et al., 1994). However, the regulation of root growth upon compaction by hormones still remains to be elucidated, especially the antagonistic relationship between ethylene and ABA (Sharp, 2002; Karahara *et al.*, 2008).

Some other factors such as the supplement of carbon and oxygen to roots in compacted soils may also impact root elongation (Tardieu, 1994). The rapid consumption of oxygen of the impeded roots may suffer from oxygen deficiency and be more susceptible to compaction effects (Hanbury and Atwell, 2005). More research integrating the effects of hormone regulation, carbohydrate translocation and metabolism of roots under mechanical stress are needed.

#### **4. Ability of Roots to Penetrate Compacted Soils**

Root systems are genetically controlled and the amount of species-specific variability is great. It is known that tap-rooted species (dicots) generally have greater relative root diameters (RRDs) than fibrous-rooted species (monocots). There is evidence that different plant species or cultivars of the same species differ in their abilities to penetrate compacted soils (Taylor and Ratliff, 1969; Merrill *et al.*, 2002; Cairns *et al.*, 2004). Root length density in compacted soils was positively correlated to the root diameter, and roots having larger relative root diameters were found to have greater ability to penetrate through compacted soil layers (Materechera et al., 1991; Materechera et al., 1992). The authors suggested that roots with larger diameters may possess greater growth pressure ( $\sigma_{\max}$ ). Misra *et al.* (1986) reported that the maximum axial root growth pressure increased

curvilinearly with the increase of root diameter. However, a later study by Clark and Barraclough (1999) discovered that roots with greater diameters (dicotyledons) did not always generate greater  $\sigma_{\max}$  than roots with smaller diameters (monocotyledons). Therefore, besides  $\sigma_{\max}$ , some other physiological or physical mechanisms also regulate the ability for root penetration. By studying tree roots, Bischetti *et al.* (2005) found that root strength decreased with diameter by a power function; and roots with greater diameter may be more resistant to buckling (Whiteley *et al.*, 1982). These findings may help explain why thicker roots penetrate better in compacted soils. However, the mechanism that roots with greater diameters have greater ability to penetrate strong soils is still not very clear and more research needs to be done.

From a whole root system perspective, mechanical impedance restricts primary root development for dicots and seminal root elongation for monocots, while stimulating more branch growth for dicots and more adventitious root growth for monocots (Goss, 1977; Pietola and Smucker, 1998; Bingham and Bengough, 2003). Despite a similar stimulation effect caused by soil compaction, the distribution of lateral roots for dicots and monocots is different. Goss (1977) found that lateral roots of barley (*Hordeum vulgare* L.) were distributed mostly in the surface layer. Conversely, by growing carrots in soils where compaction and non-compaction treatments were at upper 25/30 cm, Pietola and Smucker (1998) found that branch roots of carrot (*Daucus carota* L. cv. Nantes Duke Notabene 370 Sv) had greater root length density in the compacted layer than in non-

compacted layer; below 25/30 cm where no differences of compaction existed, there were no differences in root length density as in the upper layers.

The mechanism of stimulation of lateral roots by mechanical impedance was explained by Thaler and Pagès (1999). They found that the availability of carbohydrates for the secondary/tertiary roots increases when the demands from the primary root zone are reduced because its growth is arrested by high soil strength. The difference of lateral root distribution between barley (monocots) and carrot (dicots) may be explained by the difference in their root diameters. However, because the information on the lateral diameter of barley was not available, no further inference could be drawn. Future research on the distribution and mechanism of branch roots under soil compaction between different species (dicots vs. monocots) is necessary.

## **5. Effect of “Biodrilling” on Root Growth**

The importance of crop rotation, which is the sequential production of different plant species on the same land, has been recognized for thousands of years. Crop rotation systems profoundly affect the soil physical environment, especially in the development and distribution of root channels. The research by Materechera *et al.* (1992) and Merrill *et al.* (2002) have shown that roots with greater diameters (often tap-rooted dicots) are more capable of penetrating strong soils than roots with smaller diameters (usually fibrous-rooted monocots), though the mechanisms causing this difference remain unknown (Clark *et al.*, 2003). This makes it possible to reduce the soil compaction effect on root penetration by

including some tap-root species in the crop rotation. The idea of using “plant roots as tillage tools” was first proposed by Elkins (1985). Later, Cresswell and Kirkegaard (1995) called this “biodrilling” and suggested the terminology be used to describe cases where biopores left by previous crop roots can provide low resistance pathways for subsequent crop roots. It was found that soybean (*Glycine max* L.) root distribution and shape were modified by pre-existing bio-pores (root channels and earthworm holes) (Wang et al., 1986). Research on the biodrilling effect can be divided into two categories: annual and perennial crops. The results from the few studies conducted with perennial crops are more conclusive than those conducted with annual cover crops.

### *5.1 Biodrilling effects of perennial crops*

It was demonstrated by Elkins (1985) that the yield of cotton grown in rotation with perennial pensacola bahiagrass (*Paspalum notatum* Flugge) was 1.5 to 3.0 times greater than that of continuous cotton. His finding was later confirmed in a report by Katsvairo *et al.*(2007) that cotton (*Gossypium hirsutum* L.) root penetration was improved in the cotton - bahiagrass rotation system but not in the peanut (*Arachis hypogaea* L.) - cotton rotation. They both concluded that the better performance of subsequent crop roots was attributed to the deep-rooted bahiagrass. The yield of oats (*Avena sativa* L.), sorghum hay (*Sorghum vulgare* Pers.) and corn (*Zea mays* L.) following three-year growth of kudzu (*Pueraria thumbergiana* Benth) increased 47, 77 and 131%, respectively, compared to continuous cropping (Sturkie and Grimes, 1939). Using minirhizotron technique,



Rasse and Smucker (1998) found that corn (*Zea mays* L.) grown after the cool season perennial alfalfa (*Medicago sativa* L.), achieved a higher percentage of roots in subsoil than corn grown after corn. Even though there are not many studies in the literature, the biodrilling effect of perennial species appears to be quite conclusive.

### *5.2 Biodrilling effect using annual cover crops*

Henderson (1989) reported that lupin (*Lupinus angustifolius* L. cv. Illyarrie) had no effect on root growth of the following wheat crop (*Triticum aestivum* L. cv. Gutha) and concluded that the increase in wheat yield was likely due to some other benefits from the cover crop. His finding was very similar to what Cresswell and Kirkegaard (1995) who reported that canola crop (*Brassica napus* L.) did not improve rooting depth for the following wheat crop, though it did increase wheat grain yield. They suggested that perennial species might be more capable of providing root channels in compacted soils than annual species. da Silva and Rosolem (2002) explored the effects of eight cover crops, black oat (*Avena strigosa*), pigeon pea (*Cajanus cajan*), pearl millet (*Pennisetum glaucum*), black mucuna (*Mucuna pruriens*), soybean (*Glycine max*), grain sorghum (*Sorghum molasses*) and lupin (*Lupinus angustifolius* L.) on subsequent soybean root penetration in a compacted soil, and found that only the first three favored soybean root growth in the compacted layer. By including subterranean clover (*Trifolium subterraneum*) as a cover crop, Stirzaker and White (1995) found that lettuce (*Lactuca sativa*) yield increased; however, they stated a very broad

conclusion that included all the possible benefits a cover crop could provide including changes in soil temperature, strength and biopores. In a recent study using a minirhizotron technique, Williams and Weil (2004) observed that soybean (*Glycine Max* L.) roots grew through a compacted plowpan soil using channels made by decomposing canola cover crop roots. However, this study did not provide any quantitative data to support their observational conclusion.

Perennials grow year around and their roots can penetrate the soil more easily whenever the soil is moist. In contrast to perennials, annual cover crops usually grow for only a few months. Most commonly, winter cover crops are planted in late summer or early fall, grow throughout the fall and winter and into early spring. In regions with either udic or xeric moisture regimes, this period is characterized by a positive balance of precipitation over evapotranspiration demand and soils are generally near or above field capacity water content for much of the period. Thus winter annual cover crops commonly grow when soil strength may be low enough for root penetration, even in relatively compacted soil layers. Under other conditions, growth of annual cover crops may be limited by soil moisture which is affected by the previous crop and precipitation levels. Under conditions in which the soil moisture is either too low or too high during the growing season, root penetration of cover crops may be prevented by high soil strength or poor soil aeration; hence the biodrilling effect may not occur. Therefore, studies on biodrilling performance under ideal controlled environmental conditions may not predict the behavior of cover crop roots in the field.

## **6. Root Growth and Water Uptake**

Roots not only physically support the above ground portion of a plant, but more importantly, supply it with water and nutrients. The uptake of water and nutrients depends on plant demand, the uptake ability of the root per unit length and the root distribution and soil water/nutrient conditions. The distribution of roots, however, interacts with soil structure and soil water status. Soil compaction restricts root growth, thus reducing the soil volume that plant roots can exploit. Compaction also modifies soil water status and reduces the availability of soil water for plants because least limiting water range is narrowed down by compaction. On the other hand, higher soil moisture content reduces the mechanical resistance and allows more roots to penetrate (Rasse and Smucker, 1998); while decreasing soil water content (or at a lower water potential) decreases the maximum root growth pressure and stops root elongation (Whalley et al., 1998). Hydrotropism, the physiological response of roots to water gradient, would direct growth of roots towards the higher soil water potential (Eapen et al., 2005). The evidence that more roots in the deep soil profile were found during the late growing season when surface soil water was depleted (Ellis et al., 1977) may result from both physiological and mechanical responses, if soil strength is not a limiting factor.

Because the three-way soil-root-water interaction is complicated, there are models at varying levels of complexity designed to compute soil water extraction rates by plant roots. In most models, per unit volume soil water uptake, as reviewed by Wang and Smith (2004), depends on rooting depth, root length

density, or root mass density of fine roots, which are often used to compute soil water uptake. Some field research shows that there is a positive relationship between the distribution of roots in the soil profile (whether in root length density, root number or other parameters) and the amount of soil water uptake (Ellis et al., 1977; Stone et al., 2001). However, because water uptake efficiency is species-dependent and also depends on the root age or morphology, the correlation between root parameter and water uptake may vary. Lipiec *et al.*(1993) found that the higher total water uptake from undisturbed horizons was related to the denser root system in the soil profile. Hamblin and Tennant (1987) reported that soil water loss during the growing season was better correlated to maximum rooting depth rather than root length density, which is in agreement with Parker *et al.*'s (1989) results. Stone *et al.*(2001), in a field experiment, also reported a better correlation between rooting depth and soil water uptake for grain sorghum [*Sorghum bicolor* (L.) Moench] and sunflower (*Helianthus annuus* L.).

Most cash crops grow in the summer. Generally a seasonal fluctuation of precipitation and high evapotranspiration during the summer crop growing season will cause short dry periods that may increase the risk of plant water stress and result in yield reduction where irrigation is not accessible. The water stress is compounded where the soil is too compacted for plants to grow deep root systems, leaving them instead to develop extensive shallow roots. On the other hand, water stored in the subsoil horizons is often usually more than enough to meet plant needs and avoid drought stress if it is available to plant roots. Since the uptake of water during the growing season is usually increasingly dependent on roots deep

in the subsoil, it is not surprising that in field studies a high correlation is often reported between rooting depth and soil water uptake.

## **7. Conclusion**

Soil compaction affects many aspects of plant growth. Root growth is directly controlled and modified by the soil environment. The physiological responses of roots to mechanical impedance are very complex and species/cultivar specific. Soil water uptake, an important function of roots, depends mostly on root distribution and soil water status. For most summer crops, rooting depth correlates better with soil water uptake than other root parameters.

Plants with greater root diameter (dicots) usually penetrate the compacted soils better than those with smaller root diameter (monocots). Biodrilling – the provision of root channels by one crop such that they can be used by a second crop as pathways for penetration through compact soil layers -- may provide a possible solution to soil compaction. But biodrilling effectiveness depends on plant characteristics and soil water availability, so research is needed in relevant environments to determine effective species or cultivars and management practices.

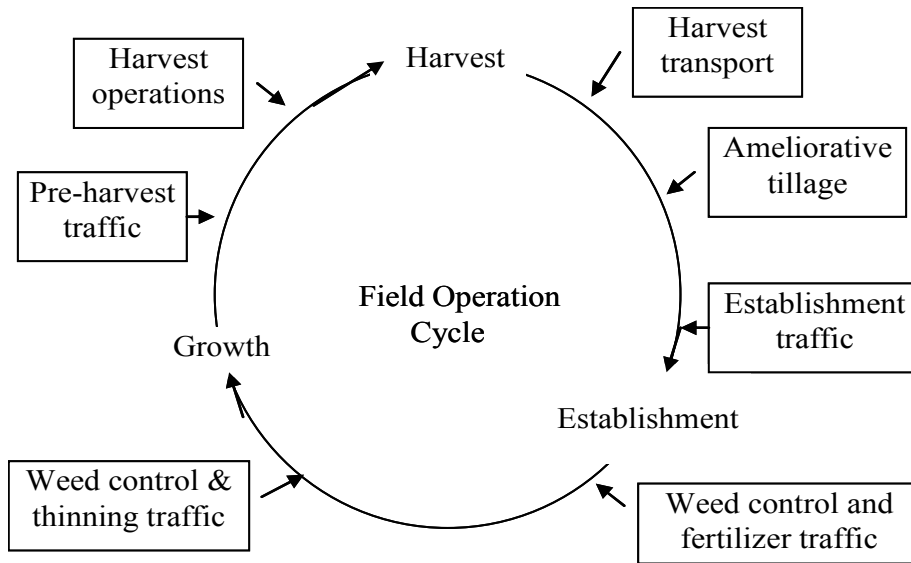


Figure 2.1 The cycle of field operations during the course of crop production where compaction is caused by trafficking (re-drawn from Soane, 1994). Change label to Weed control (not weeds)

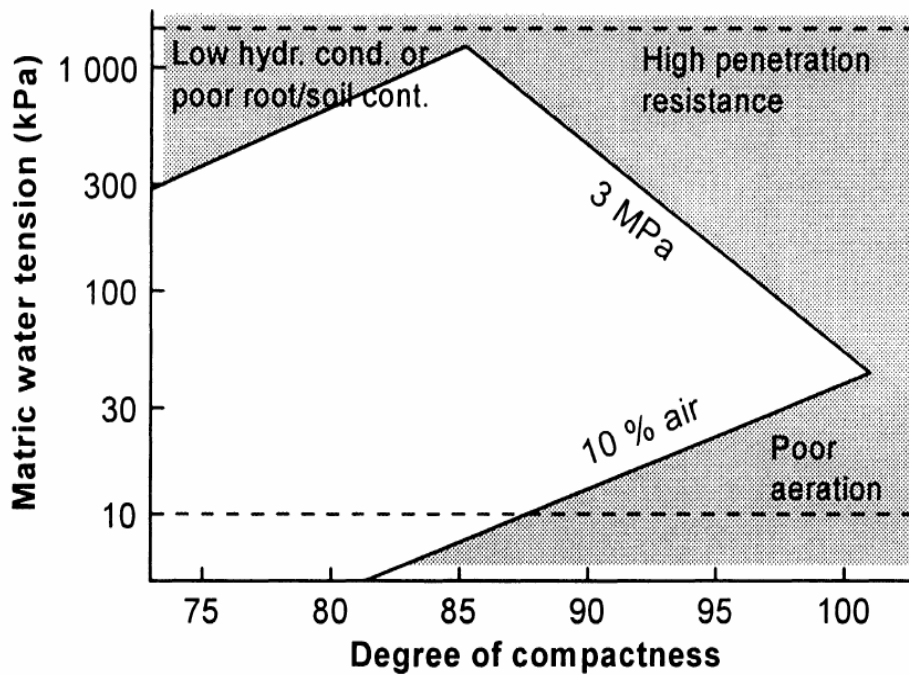


Figure 2.2 Schematic diagram showing how a soil air content of 10% (v/v) and a penetration resistance of 3 MPa (regarded by references as a critical limit with respect to plant growth ) are related to the degree of compactness and matric water tension of the plow layer (Håkansson, 2000).

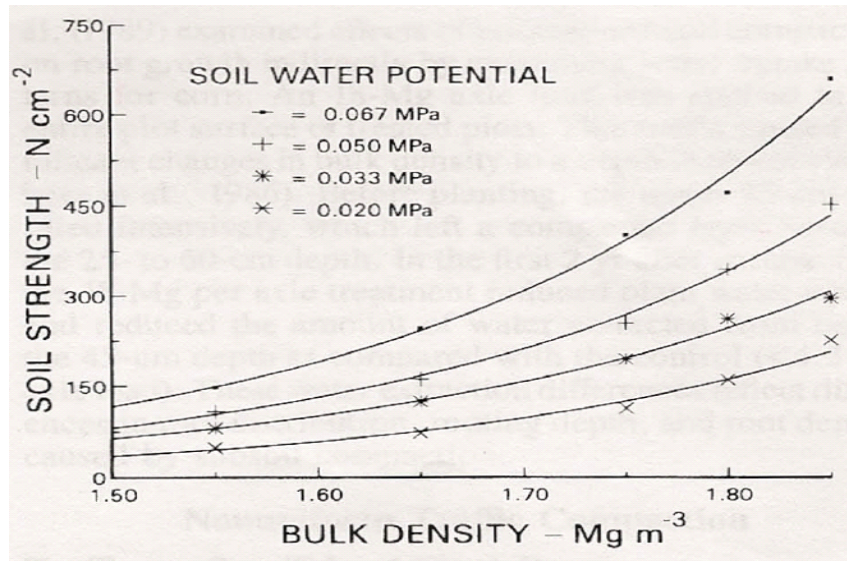


Figure 2.3 Relationship between soil bulk density and soil strength at different soil water matric potentials (Unger, et al., 1994).

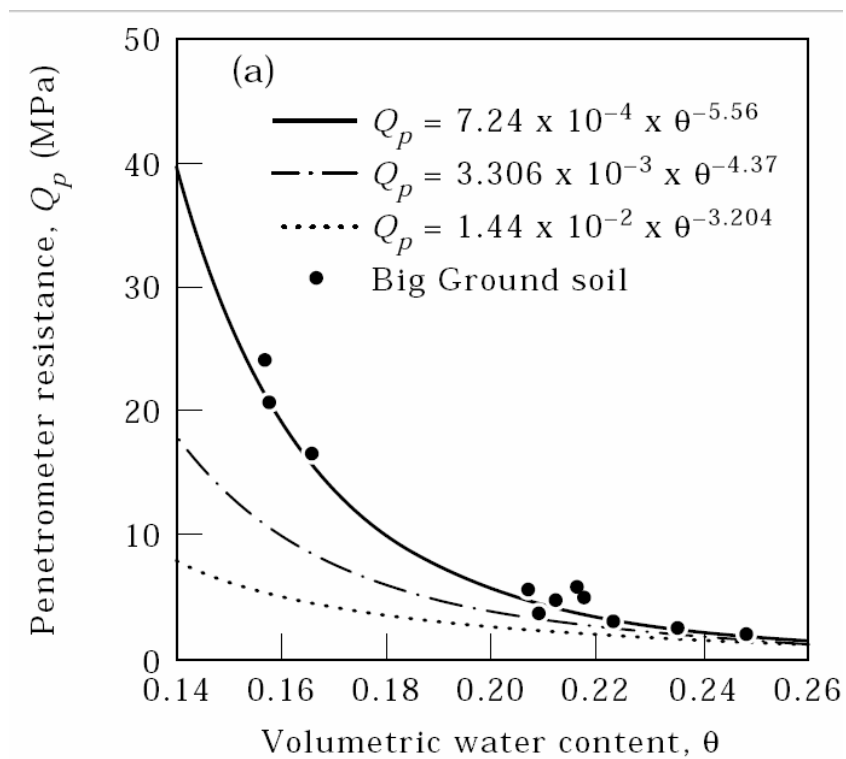


Figure 2.4 Penetration resistance ( $Q_p$ ) varied as a function of soil volumetric water content ( $\theta$ ) for a sandy loam soil (Big Ground soil) in three layers (different in bulk density) (Bengough, 1997).

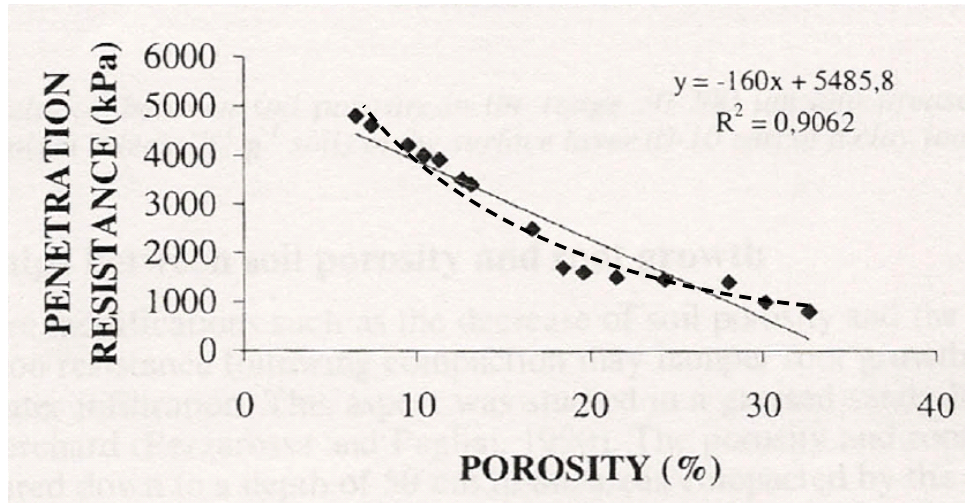


Figure 2.5 Relationship between porosity and soil strength proposed by (Pagliai, 2002). (The dashed line indicating an exponential relationship was proposed by the reviewer.)

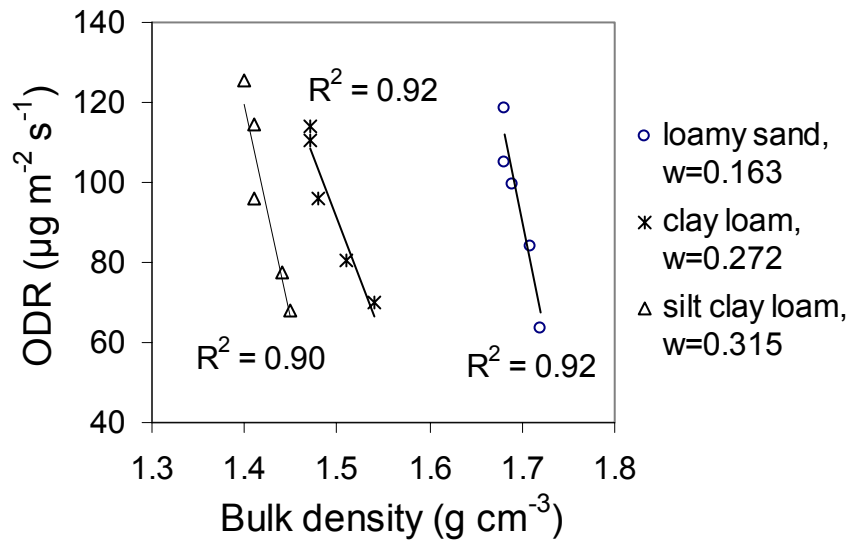


Figure 2.6 Correlations between soil bulk density and oxygen diffusion rate in three soils (from left to right: silt clay loam at  $\theta = 31.54\%$ , clay loam at  $\theta = 27.16\%$ , and loamy sand at  $\theta = 16.3\%$  (g/g)) (Graphed from data in Czyż, (2004)).



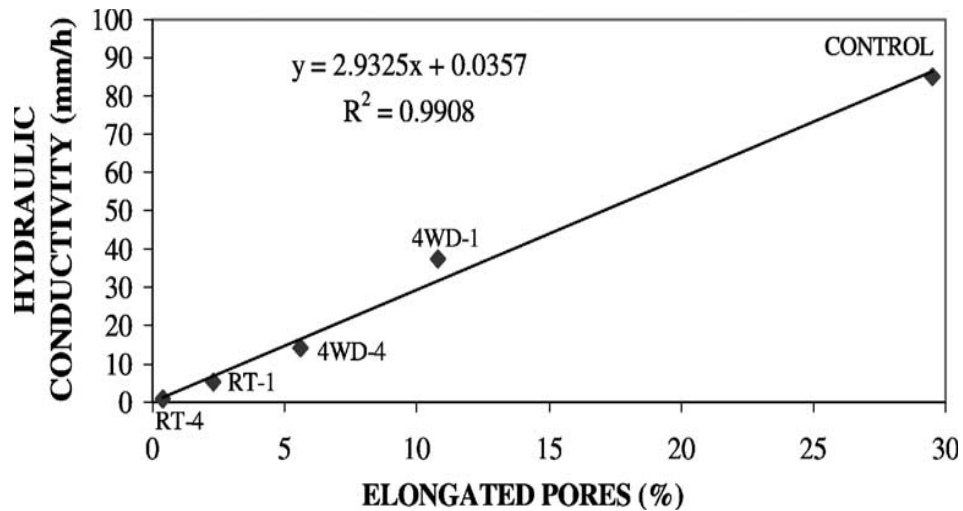


Figure 2.7 Relationship between hydraulic conductivity and elongated pores after 1-4 passes of wheeled (4WD) and rubber tracked (RT) in the surface layer (0-10 cm) (Pagliai, et al., 2003).

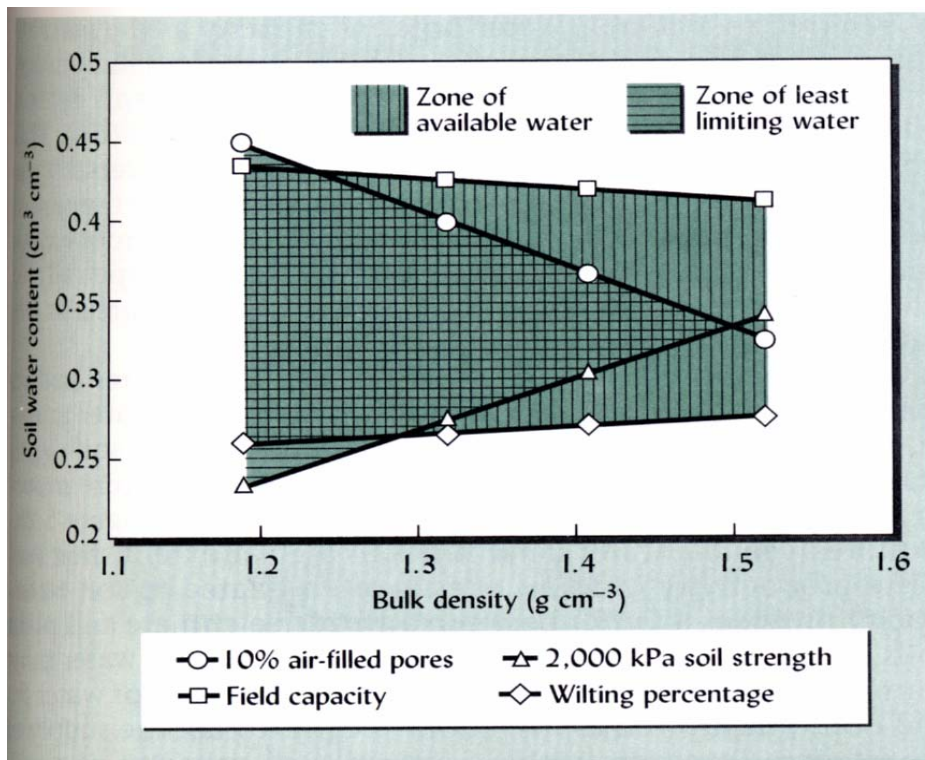


Figure 2.8 The least limiting water range as affected by soil compaction (Brady and Weil, 2002).

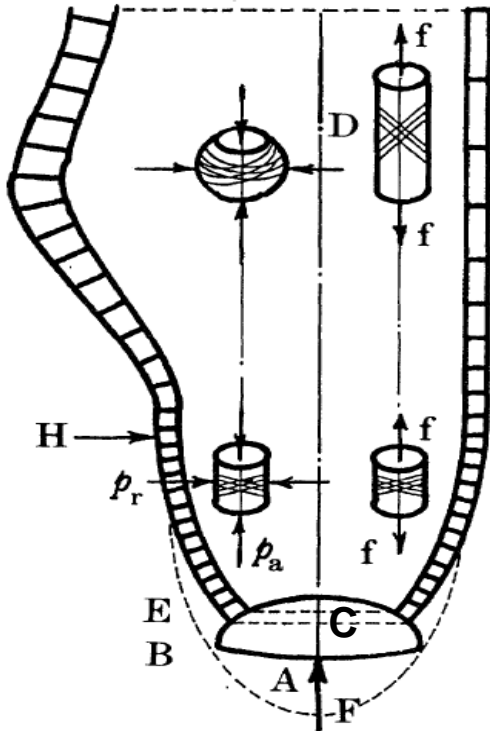


Figure 2.9 Mechanism analogue of root apex. Right half section: normal growth; left half section: influence of mechanical impedance A – root cap, B and E – distal and domed surfaces of C respectively, C – quiescent center, D – elongation zone, F and H – soil mechanical impedance acting on the root epidermis in axial and radial directions,  $p_a$  and  $p_r$  – axial and radial stresses generated by mechanical impedance on the cells,  $f$  – individual force generated by the elongation cells in zone D. (From Hettiaratchi, 1990).

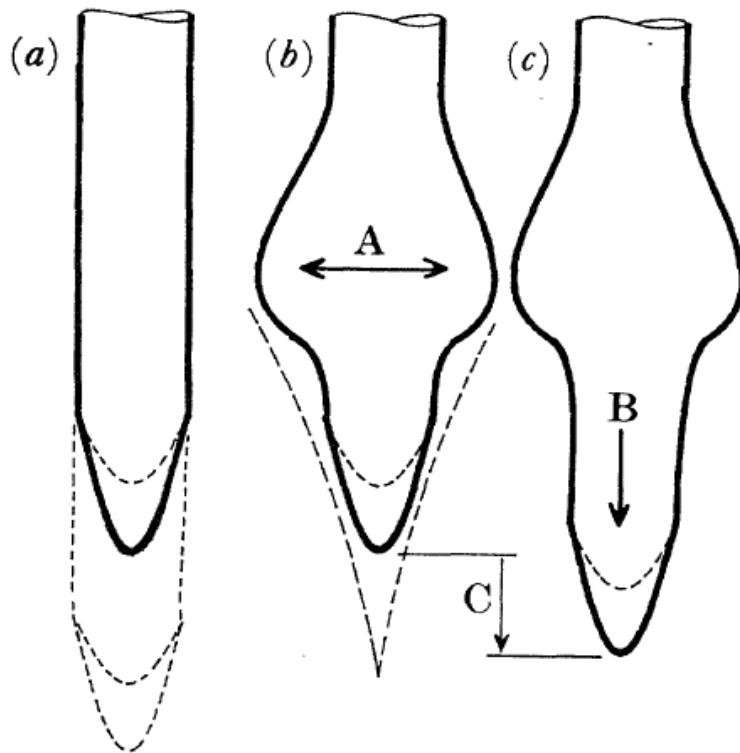


Figure 2.10 Hypothesis of “Root extension model” (a) Axial extension arrested by soil in root cap zone; (b) Radial expansion of region behind root tip weakening soil in root cap zone; (c) Axial extension resumed. (A – radial growth mode, B – axial growth mode, C – root extension increment.) (From Abdalla, 1969).

## Chapter 3: Effects of Compaction and Cover Crops on Least Limiting Water Range and Soil Air Permeability

### **Abstract**

Compaction affects soil properties by altering the arrangement of soil particles, which usually results in increased bulk density, greater penetration resistance, reduction of total and macro porosity, and an increase of pore tortuosity. Plant roots are able to improve soil structure by increasing macro porosity and pore continuity. The least limiting water range (LLWR), a potential index of soil physical quality, integrates the effects of bulk density, penetration resistance, aeration and water potential on plant growth. Soil air permeability is the most sensitive parameter for characterizing pore size distribution and continuity. In this study, we examined the effects of soil compaction and cover crops on LLWR and soil air permeability. There were three compaction treatments: high, medium and no compaction, and four cover crop treatments: FR (forage radish: *Raphanus sativus* var. *longipinnatus*, cultivar 'Daikon'), rape (rapeseed: *Brassica napus*, cultivar 'Essex') rye (cereal rye: *Secale cereale* L., cultivar 'Wheeler') and NC (no cover crop). Due to high content of sand in block I and high content of sand and gravel in block III of Exp. 2, the analysis for Exp. 2 was grouped into blocks I and III and blocks II and IV. There was no interaction effect of compaction and cover crop on LLWR. Compared to no compaction in Exp. 1, LLWR in high and medium compaction was reduced by 81.8% and 58.8%, respectively. Neither compaction nor cover crop had effect on LLWR in block I & III of Exp. 2. LLWR in high compaction was reduced by 45.6% compared to that in no compaction in

block II and IV of Exp. 2, and the LLWR was not changed by medium compaction. In block II & IV of Exp. 2, LLWR was increased by FR but not by rye cover crop. The reduction of LLWR was due to the limitations caused by poor aeration and high soil strength. In Exp.2, LLWR was reduced by the increased bulk density (soil strength) caused by compaction. LLWR was increased by FR because FR provided more root channels in the compacted zone which might reduce local soil strength and increase aeration. Air permeability was significantly reduced within the high and medium compaction treatments in Exp. 1 and this reduction was determined irreversible even though shallow depth tillage following compaction was applied with a disk. The differences observed for air permeability for the three compaction treatments in Exp. 2 were less pronounced than for Exp. 1 because soils in Exp. 1 had much higher clay content. Air permeability was greater in rape and FR treatments compared to rye and NC treatments within the high compaction treatment (Exp. 1 and 2) and for the medium compaction treatment (Exp.1 only). Air permeability following each of the three cover crops was greater than after NC treatment for the no compaction treatment in Exp. 1. In Exp. 2 where the soil sand fraction was greater, there was no effect on air permeability caused by the cover crops for the medium and no compaction treatments. Compaction had detrimental effects on both LLWR and air permeability; tap-rooted Brassica cover crops (especially rape) were able to increase air permeability but the magnitude of increased seemed to be less than the decrease by compaction.

## 1. Introduction

Though soil compaction was recognized during the early 19<sup>th</sup> century, it had become a worldwide problem only by the middle of 20<sup>th</sup> century because of the increasing and widespread use of machinery for field operations (Soane, 1994). This problem has been intensified in the past 40 years as a result of intensive cropping, increased use of heavy farm equipment, short crop rotations, and inappropriate soil management practices (Servadio *et al.*, 2001; Hamza and Anderson, 2005; Servadio *et al.*, 2005).

Soil compaction 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 caused by compaction occurs within the soil macro porosity. The rearrangement of soil aggregates induced by compaction also increases the tortuosity of pore conductivity. Therefore, compaction restricts plant root growth either by increasing penetration resistance or by decreasing supply of oxygen. Soil penetration resistance and aeration are dynamic parameters that are affected by bulk density, water content and soil texture. Reviewed by Unger and Kaspar (1994) and first shown by Shierlaw and Alston (1984), soil strength increased exponentially with bulk density, and the rate of soil strength increase becomes faster as water potential decreases. Soil aeration, which is related to the total and macro porosity, decreases as soil bulk density and water content increase for any given soil texture (Asady, 1989; Czyż, 2004). The interactions of soil water content and bulk

density on soil strength and aeration make it difficult to characterize soil compaction by individually consideration.

The least limiting water range (LLWR) approach may provide a better characterization of the effect of compaction on soil physical quality. This characteristic (LLWR) is 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 small” (da Silva et al., 1994). It integrates the effects of aeration, soil strength and water potential into one index on the basis of soil water content. The upper limit is arbitrarily chosen based on the water content at 10% air-filled pore space and field capacity (whichever is smaller), while the lower limit is arbitrarily chosen based on the water content at wilting point and penetration resistance of 2 MPa (whichever is greater). Outside the water content range, plant growth is most limited either by poor aeration or high soil strength and/or low water potential. A wider range of 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 or mechanical impedance and the soils is more productive, compared to soil with a narrower range of LLWR (da Silva and Kay, 2004). The critical bulk density at which LLWR equals zero can then be found. The concept of LLWR also has been applied to nitrogen mineralization (Drury et al., 2003) and crop production (da Silva and Kay, 1996; Lapen *et al.*, 2004; Beutler *et al.*, 2005). Corn shoot growth rate was highly negatively correlated to the proportion of the total number of measurements in which the water content fell outside the LLWR (da Silva and

Kay, 1996). However, plant growth is a dynamic process. The limitations of LLWR are that the upper limit of penetration resistance and lower limit of air-filled porosity are usually arbitrarily selected. It is necessary to take into account physiological and morphological adaptation by plants to environmental stresses when choosing values for two limits to calculate LLWR.

In conservation tillage systems, changes of soil bulk density and penetration resistance may or may not occur, depending on root distribution, plant residues and time scale, but the modification of soil structure associated with biological activity (plant roots and earthworms) has been reported (Stirzaker *et al.*, 1996; Ball *et al.*, 2005). Thus, LLWR may or may not be able to reflect the changes of pore structure made by plant roots or earthworms which are very important for root penetration, air and water movement in compacted soils. Soil air permeability, a parameter that determines the pore geometric effects on gas and liquid transport processes, can provide a better indicator for characterizing the changes of soil structure associated with biological activity. The geometric factors include total porosity, pore size distribution, pore continuity, tortuosity and shape (Ball, 1981a, 1988; Roseberg and McCoy, 1992). Air permeability is found to be very sensitive to macroporosity and pore continuity (Tuli *et al.*, 2005; Cavalieri *et al.*, 2009; Dörner and Horn, 2009). In the model proposed by (Ball, 1981a),  $\log k_a = \log M + N \cdot \log \varepsilon_a$ ,  $k_a$  is the air permeability,  $\varepsilon_a$  is the air-filled porosity, and the two constants, M is related to macro porosity, while N reflects pore continuity. The model has been testified and used by researchers (Ball, 1988; Roseberg and McCoy, 1992; Munkholm *et al.*, 2005c; Dörner and Horn, 2009). Air permeability

has been found to be well positively correlated with saturated hydraulic conductivity (Loll *et al.*, 1999; Chief *et al.*, 2008), so it can be used to predict saturated hydraulic conductivity because air permeability is relatively easier to measure in situ (Iversen *et al.*, 2003).

In the Mid-Atlantic region, no-till cropping systems have been widely practiced over the past twenty years. No till was originally aimed at reducing soil erosion, but has been shown to also benefit both crop production and soil quality (Diaz-Zorita *et al.*, 2004; Grandy *et al.*, 2006). Incorporating no-till with the planting of fall/winter cover crops is encouraged in this region as an effective practice to catch residual post harvest nutrients and to keep them from entering area water bodies (Coale *et al.*, 2001; Dean and Weil, 2009b). However, compaction remains a constant problem no matter which cropping systems are chosen unless traffic patterns are either altered or eliminated completely (Ball, 1997). The humid climate of the region sometimes makes field operations during wet conditions unavoidable. Thus, soil compaction can be particularly challenging in this region. Brassica cover crops, newly introduced to Maryland, were found to alleviate the effects of soil compaction (Williams and Weil, 2004). Their tap roots grow both 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. The modification to the soil structure caused by the Brassica cover crop roots may then provide easier penetration of the compacted soil for the subsequent summer crop roots and provide a better soil environment for root growth by increasing air and water



conductivity. Our objectives were (1) to quantify the LLWR for soils following different compaction/cover crop treatments; and (2) to compare the soil air permeability response of the compacted soil to the cover crops.

## **2. Material and Methods**

### *2.1 Site and soil description*

Two experiments were conducted in adjacent fields (NF-2B and NF-2C) on the north farm of USDA Wallace Agricultural Research Center at Beltsville, MD, a site that is in the coastal plain ecoregion in Maryland (39°01'N, 76°55' W). Experiment 1 was established in field NF-2B in August 2006 and continued until September 2008. Experiment 2 used some of the same treatments as experiment 1, and was conducted in field NF-2C for one year (August 2007 to September 2008). The two sites were limed in April of 2005 at a rate of 1,020 kg ha<sup>-1</sup> (calcium carbonate equivalent, dolomitic limestone). Prior to our experiments, conventional tillage consisting of moldboard plow followed by disking was used in both fields. The near-term cropping history for the Experiment 1 field was potato (*S. tuberosum*) during summer 2005 followed by rye cover crop planted in fall 2005. Near-term cropping history for Experiment 2 field site was green bean (*phaseolus vulgaris*) during summer 2005 followed by rye cover crop planted in fall 2005, and Zucchini (*cucurbita pepo*) during summer 2006 followed with grain rye planted in fall 2006. The soil series for the Exp. 1 field varied from Elsinboro series (fine-loamy, mixed, semiactive, mesic Typic Hapludults) at the west end to Woodstown series (fine-loamy, mixed, active, mesic Aquic Hapludults) in the

east end with 0-5% slope in the east-west direction. The soil series at Exp. 2 (NF-2C) varied from Elsinboro (fine-loamy, mixed, semiactive, mesic Typic Hapludults) at the southwest side to Galestown (siliceous, mesic Psammentic Hapludults) at the southeast side of the field. For the Exp. 1 field, the A horizon soil texture ranged from sandy loam (12.5% clay) to loam (18.2% clay); In the Exp. 2 field, the A horizon soil texture ranged from very coarse loamy sand (5.1% clay) to loamy sand (7.0% clay). Table 3.1 lists the two distinct soil profiles in each experimental site. Due to the variation of soil properties, both sites were divided into four blocks so as to make each block as homogeneous as possible with regard to soil properties.

## *2.2 Experimental design and treatments*

A randomized complete block design was used for both fields. In Exp. 1, three compaction treatments (high, medium and no compaction) were imposed and four cover crops (forage radish, rape, rye and no cover) were planted giving a total of 12 treatment combinations (factorial structure of the treatments) in each block. The dimension of each plot was 3.0 m X 9.0 m. The blocks were separated by a 10.7 m wide alley for turning the tractor and equipment during creation of the compaction treatments and during crop planting. Due to the availability of a smaller field, Exp. 2 included the three compaction treatments but only three cover crops (forage radish, rye and no cover) for a total of nine treatment combinations in each block. The plot dimensions in Exp. 2 were 3.3 m X 12.2 m.

One 12.2 m wide alley separating Blocks 1 and 2 from blocks 3 and 4 allowed for tractor turn-around during compaction.

Prior to establishment of the compaction treatments in late July 2006 (Exp. 1) and late July 2007 (Exp. 2) respectively, each field was deep-ripped to an average depth of 45 cm, followed by moldboard plowing to an average depth of 32 cm and finally disked to approximately 8 cm depth. The two fields were irrigated (7.2 cm of water) to saturate the soils on August 16 and 18, 2006 for Exp. 1, and August 13 and 16, 2007 for Exp. 2. For Exp. 1, a John Deere 544C tractor (axle load 11.88 Mg with a rear tire contact area of 1,652 cm<sup>2</sup>) was used to establish the compaction treatments on August 18, 21, and 22, 2006. High compaction treatments consisted of two passes, the second of which was done with the loader bucket full of rocks to give an axle load of 12.91 Mg. Medium compaction was established by one pass with the tractor without rocks in the bucket and no compaction was no passes of the tractor. For Exp. 2, a single pass with the same John Deere 544C tractor was used to create the high compaction treatment, a single pass with a John Deere 7220 tractor (axle load 5.83 Mg with a rear tire contact area of 1,610 cm<sup>2</sup>) was used to create the medium compaction treatment, and no tractor traffic occurred for the no compaction treatment on August 17 and 19, 2007.

### *2.3 Crop /plot management*

After the compaction treatments were imposed, the soil in both experiments was disked to a depth of approximately 8 cm on August 25, 2006

(Exp. 1) and August 29, 2007 (Exp. 2). Four cover crops used at for Exp. 1 were: no cover crop (NC), FR, rape and rye. Three cover crops used for Exp. 2 were NC, FR and rye. Cover crops were seeded in late August, 2006 and 2007 at Exp. 1, and August 29, 2007 at Exp. 2 using a no-till drill. Cover crop species seeding rates were 14.57 kg ha<sup>-1</sup> for FR, 8.97 kg ha<sup>-1</sup> for rape (Exp. 1) and 134.5 kg ha<sup>-1</sup> for rye. On September 22, 2006, nitrogen fertilizer (urea ammonium nitrate) was applied at a rate of 28 kg ha<sup>-1</sup> because of the observed nitrogen deficiency (pale yellowish green color of old leaves and stunted appearance). To ensure vigorous growth in 2007, the cover crops in both experiments were planted with the use of a starter nitrogen fertilizer (34-0-0 granular ammonium nitrate) at a rate of 22.4 kg ha<sup>-1</sup> in 2007.

Forage radish was frost-killed in the winter when temperature falls below -7°C. Rye, rape and weeds on no cover plots were killed using gramoxone (1,1'-Dimethyl-4,4'-bipyridinium dichloride) at a rate of 4.68 L ha<sup>-1</sup> with surfactant of 0.73 L ha<sup>-1</sup> on April 11, 2007 (Exp. 1), and a combination of Glyphosate (N-phosphonomethyl glycine) (4.68 L ha<sup>-1</sup>) and 2,4-D (2,4-dichlorophenoxy acetic acid) (2.34 L ha<sup>-1</sup>) on April 16, 2008 (both Exp. 1 and 2). Corn (*zea mays*, cultivar 'Pioneer' 34B62) was no-till drilled in late April of 2007 and 2008 at a rate of 74,000 seeds ha<sup>-1</sup> into four rows per plot with 76 cm inter row space. A starter fertilizer (34-0-0 granular ammonium nitrate) at a rate of 22.4 kg N ha<sup>-1</sup> was applied at planting. In middle May of both years, glyphosate (4.68 L ha<sup>-1</sup>) and 2,4-D (2.34 L ha<sup>-1</sup>) were sprayed to control weeds and any rape that had not been killed by the earlier application. Urea (30-0-0) (urea ammonium nitrate) was

sidedressed at a rate of 112 kg/ha in mid-June of both years. Corn was harvested as silage on August 24 2007 (Exp. 1). Following silage harvest, the field was sprayed with Glyphosate (4.68 L ha<sup>-1</sup>) to kill weeds prior to planting the second-year cover crops.

#### *2.4 Soil compaction measurement*

Soil strength measurements and soil cores were taken immediately after application of compaction treatments in August 2006 (Exp. 1) and August 2007 (Exp. 2) and again in spring 2008 (both experiments). A recording cone penetrometer (Spectrum Technologies, Plainfield, IL) was used to measure soil strength. The penetrometer has a 10 mm diameter steel rod with a 25 mm long and 15 mm maximum diameter cone tip integrated with a strain gauge and data logger. At each location, the penetrometer was pushed by hand at a constant rate down to the depth of 45 cm. Mean penetration resistance was recorded in kPa for every 5 cm depth increment to 45 cm. Penetration resistance was measured at 10 randomly selected locations per plot. In field of Exp. 2, because of the high content of gravels (ranging from 24% to 68% by weight from 5 to 40 cm depth in the west end and decreasing gradually eastwards) in block III, a dynamic cone penetrometer that is designed for gravelly soils (Herrick and Jones, 2002) was used. Concurrent with measuring soil strength, 10 undisturbed soil cores were taken per plot (40 cm depth) using a soil probe with a diameter of 1.85 cm. In block III of Exp. 2, soil samples were taken using a handle corer with the inside diameter of 6.4 cm for the same reason described above. The cores were divided

into 5 cm increments, weighed, dried and re-weighed to determine soil bulk density and soil moisture content. These soil strength measurements and soil cores were taken immediately after application of compaction treatments in August 2006 (Exp. 1) and August 2008 (Exp. 2) and again in spring 2008 (both experiments).

### *2.5 Soil water content and water tension determination*

In order to examine the effects of compaction and cover crops on soil least limiting water range, the soil depth of 10 -15 cm was evaluated because it was where differentiation for the compaction zones occurred because soil surface was disked to 8 cm after compaction treatments were applied. Soils samples were taken from the experimental sites at the 10-15 cm depth, dried, ground and sieved through a 2 mm sieve. These soils were packed into steel rings (inner diameter of 76.2 mm and depth of 35.8 mm). The known weights of soil was packed into the rings to achieve the desired bulk densities corresponding to those measured in the fields at the same depth and corresponding to the high, medium and no compaction treatments. Three replicates were used for each bulk density of each soil texture.

Each packed soil sample was placed in a water-filled Petri dish to allow the sample to become saturated by capillary rise of water. The saturated soil samples were then transported to the tension table where they were allowed to equilibrate to the selected pressure head, the procedure described by Topp and Zebchuk (1979). The tension table worked well at lower water tensions (less than

8.5 kPa). To determine soil water content at greater water tensions, soil samples were then moved to the pressure plate apparatus using the method described by Dane (2002). After equilibrium occurred at each desired water tension, samples were weighed to determine volumetric water content and quickly returned to the tension table /pressure plates. The process was repeated at 0.002, 0.004, 0.006 and 0.008 MPa on the tension table, and at 0.02, 0.04, 0.06, 0.08, 0.1, 0.3, 0.5 and 1.5 MPa in the pressure chamber. The time for equilibrium ranged from 24 to 48 hours at water tension greater than 0.1 MPa and 2-4 weeks at high water tensions. After the measurements were completed, soil samples were removed from the rings and dried in the oven at 105°C for 36 hours to determine the dry weights.

#### *2.6 Soil air permeability measurement*

A field air permeameter (Dept. of Agronomy and Soils, Auburn Univ., Auburn AL) that is based on concepts described by Jalbert and Dane (2003) was used to measure air permeability. To make the field measurements, at each sampling location in a field plot, a 16 cm long PVC cylinder with an inside diameter of 10.16 cm was pushed steadily into the soil. A cylindrical PVC chamber sealed at one end was then fitted over the inserted cylinder. The measurement was taken first with the PVC cylinder inserted to 3 cm depth. The chamber cover was then removed and the PVC cylinder was pushed further to the 6 cm depth for another measurement. This procedure was repeated at every 3 cm increment until the PVC cylinder reached the 12 cm depth. Tygon tubes connected the two ends from the sealed chamber to the air permeameter. A 9-volt

rechargeable battery-powered pump forced a constant low flow of air out from one end of the permeameter to the PVC cylinder inserted in the soil, while at the same time the change in air pressure above the soil was detected by the pressure transducer which sent a corresponding voltage signal to a voltmeter integrated with a computer chip to convert the voltage signal to a back-pressure reading in units of cm H<sub>2</sub>O at the other end. The air flow meter measured the rate of air flow at any point in time. For each depth, air temperature, back pressure, and air flow rate were recorded. After air permeability was measured at all 4 depths (3, 6, 9 and 12 cm), the volumetric soil moisture content was measured at 1.5, 4.5, 7.5 and 10.5 cm using horizontally-inserted capacitance soil moisture probe (EC-5, Decagon, Inc. Measurements were taken at 3 locations per plot. The locations were randomly selected in the pre-existed cover crop rows. Air permeability was measured in early to middle June 2008 in Exp 1 and 2.

### *2.7 Statistical analysis*

PROC NLIN procedure of SAS (SAS v. 9.1, SAS Institute, Cary, NC), as described by (Leao et al., 2005) was performed to estimate the fitting variables a, b, c d, e and f in equations (1) and (3). The assumption of  $k_a$  as a log normal distribution was tested first. The distributions of log transformed data were greatly improved though distributions of several sets of data at a few depths were not significant at  $\alpha = 10\%$ . The subsequent air permeability analysis was then based on the log transformed data. Air-filled porosity was included as a covariate when analyzing the air permeability. Depth was included as a repeated measure and



AR(1) (First-Order Autoregressive) was found to be the best fit covariance-structure because of the smallest AIC, AICC and BIC values compared with values of using other variance structures. Including depth as a repeated measure did not show any improvement when analyzing air permeability data of Exp.2, so the analysis was performed for each depth in order to fit the data better. When an F-test showed the effect of air filled porosity was not significant at  $\alpha < 5\%$  level, term of air-filled porosity was removed from further analysis. Mean comparisons of air permeability were done using PDIFF options of the LSMEANS statement to compare the difference among treatments and depths.

### 3. Theories

#### 3.1 Least limiting water range (LLWR)

The LLWR is a type of pedotransfer function which integrates the effects of soil bulk density, penetration resistance, water content and water potential into an index to estimate optimal soil water content for a given soil type. The functional relationship of penetration resistance (PR), water content ( $\theta$ ) and bulk density ( $D_b$ ) were fitted for each compaction treatment using the model employed by Silva et al. (1994).

$$PR = a \theta^b D_b^c \quad (1)$$

Or in the linearized form:

$$\ln PR = \ln a + b \ln \theta + c \ln D_b \quad (2)$$

The functional relationship between soil water content ( $\theta$ ) and water potential ( $\psi$ ) (known as soil water release curve), incorporated with the effect of soil bulk density ( $D_b$ ) were fitted using the model employed by Leao et al (2006).

$$\theta = \exp(d + e D_b) \psi^f \quad (1)$$

Or in the linearized form:

$$\ln \theta = d + e D_b + f \ln \psi \quad (2)$$

In the above equations, a, b, c, d, e and f are the model-fitting parameters.

Critical values of PR,  $\psi$  and air-filled porosity were obtained from literature. The field capacity and wilting point were established as  $\theta_s$  at -0.01 and -1.5 MPa; air-filled porosity  $\leq 10\%$  was assumed to be the critical value limiting plant growth (Brady and Weil, 2008). Because rye roots in our study decreased as a function of soil strength in both experiments, the regression lines leveled and met at PR of 2.5 MPa. It is also reported that root growth is usually reduced by 50% at PR between 2.0 and 3.0 MPa, and generally stops when PR is greater than 3.0 MPa (Bengough and Mullins, 1990). We chose a PR value of 2.5 MPa for limiting root penetration. The particle density ( $D_p$ ) of 2.65 g/cm<sup>3</sup> was assumed. Water content at which air-filled porosity was calculated as:

$$\theta_{AFP} = [(1 - D_b/D_p) - 0.1] \quad (5)$$

The calculation of LLWR depends on the values of functions  $\theta_{PR}$ ,  $\theta_{FC}$ ,  $\theta_{WP}$  and  $\theta_{AFP}$ . The selection of  $\theta$  values to calculate LLWR used the same method employed by Wu *et al.* (2003).

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

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

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

### 3.2 Soil air permeability

Soil air permeability ( $k_a$ ) is a parameter that describes pore geometry in terms of its effects on transport processes. The geometric factors include total porosity ( $\varepsilon_a$ ), pore size distribution (radius of pores), pore continuity (inverse to tortuosity (T)) and shape. Pore space and continuity in the soil govern the content and movement of gas and water. Air movement can be assumed to be laminar flow and Darcy's law is also applicable (Ball, 1981a). By combining Darcy's law and Poiseuille's law, air permeability was given by Ball (1981a) as:

$$k_a = n\pi r^4 / 8T\pi r_s^2 \quad (6)$$

where n is the number of channels that conduct air, r is the radius of channel,  $r_s$  is the radius of soil column, T is pore tortuosity, equals ratio of the length of channel (l) to the length of soil column. The porosity of the channels ( $\varepsilon_a$ ) is given as:

$$\varepsilon_a = nl\pi r^2 / L\pi r_s^2 = nT\pi r^2 / \pi r_s^2 \quad (7)$$

$$k_a = (r^2 / 8T^2) \varepsilon_a \quad (8)$$

This equation shows that air permeability will increase as air-filled porosity increases and/or pore size becomes larger but decrease as tortuosity increases.

The assumption that Darcy's law could be applicable to the air movement in the soil were proposed by Liang et al.(1995) and verified by Jalbert and Dane (2003). Thus, the equation to calculate the air permeability was based on Darcy's

law while taking the geometry of the cylinder into account employed by Jalbert and Dane (2003).

$$k_a = (\mu/DG) * (Q/\Delta P) \quad (9)$$

In the equation,  $k_a$  is the air permeability measured in the soil column ( $\mu\text{m}^2$ );  $\mu$  is the air dynamic viscosity, dependent on the air temperature;  $D$  is the diameter of the PVC cylinder;  $G$  is the geometric factor depending on the diameter of PVC cylinder and depth inserted;  $Q$  and  $\Delta P$  is the flow rate of the air pumped and pressure difference between the air inside the cylinder above the soil and the free atmosphere.

Air dynamic viscosity:  $\mu = (1717 + 4.8 T) \times 10^{-8}$  Pa s,  $T$ - air temperature ( $^{\circ}\text{C}$ ); Geometric factor:  $G = [(\pi/4 + D/H) * \ln (1+D/H)] / (1 + D/H)$ ,  $D$ -diameter of the PVC cylinder,  $H$  depth of PVC inserted. The calculation of  $G$  proposed by Jalbert and Dane (2003) was later verified by Chief *et al.*(2006).

Because we did not measure soil bulk density when measuring the air permeability, soil bulk densities at 0-3, 0-6, 0-9 and 0-12 cm depths were calculated from the bulk density of each of the 5 cm increments. Bulk densities at 0-5, 5-10, 10-15 cm were  $D_{b1}$ ,  $D_{b2}$  and  $D_{b3}$ . By using depth as a weighted parameter, soil bulk density at depth  $H$  was calculated as:

$$D_{bH} = D_{b1}, \text{ when } H = 3 \text{ cm};$$

$$D_{bH} = D_{b1} * (5/6) + D_{b2} * (1/6), \text{ when } H = 6 \text{ cm};$$

$$D_{bH} = D_{b1} * (5/9) + D_{b2} * (4/9), \text{ when } H = 9 \text{ cm}; \text{ and}$$

$$D_{bH} = D_{b1} * (5/12) + D_{b2} * (5/12) + D_{b3} * (2/12) \text{ when } H = 12 \text{ cm}.$$

The total porosity was then calculated as  $f_H = 1 - (D_{bH}/D_p)$ ; the air-filled porosity was calculated as  $\varepsilon_{aH} = f - \theta$ . Where  $D_p$  was the particle density (2.65 g/cm<sup>3</sup>) and  $\theta$  the measured volumetric water content.

## **4. Results and Discussion**

### *4.1 Soil bulk density and penetration resistance following compaction and cover crop treatments*

Figure 3.1 presents soil bulk density values for the three compaction treatments in the two experiments. Because the effect of cover crops on bulk density was not significant, changes of bulk density for two measuring dates did were also insignificant, only data for spring 2008 is shown. In Exp.1, bulk density for medium and high compaction treatments was greater, compared to no compaction, at 10, 15, 20, 35 and 40 cm depths. There was only one depth (15 cm) where bulk density for high compaction was greater than medium compaction. In Exp. 2, bulk density differed among the three compaction treatments from 5 to 25 cm depth; bulk density of high compaction remained greater compared to medium and no compaction at 30 cm. No differences for bulk density were found among the three compaction treatments below 30 cm in Exp. 2.

Figure 3.2 presents soil penetration resistance for the three compaction treatments in Exp. 1 and 2. The cover crop treatment effect on penetration resistance was not significant. Because soil penetration resistance varies with soil water content, no attempt was made to compare penetration resistance on different dates. In Exp. 1, penetration resistance differed among each of the three

compaction treatments from 5 to 25 cm depths; penetration resistance for the high compaction treatment was greater compared to the medium and no compaction treatments at 35 cm; and penetration resistance for the no compaction treatment was less compared to the medium and high compaction treatments at 45 cm depth. In Exp. 2, penetration resistance for the high compaction treatment was greater compared to the medium and no compaction treatments at 15-25 cm depths; and penetration resistance for the medium compaction treatment was greater compared to no compaction at the 20-30 cm depths.

#### *4.2 Coefficients from the least-squares fit of the soil water release and penetration resistance curves*

Coefficients from the least-squares fit of the soil penetration resistance curve for each experiment were

$$\text{Exp. 1: } \ln \text{PR} = 0.0566 - 0.543 \ln \theta + 5.49 \ln D_b, R^2 = 0.65;$$

$$\text{Exp. 2 block II \& IV: } \ln \text{PR} = 0.001 - 2.520 \ln \theta + 6.982 \ln D_b, R^2 = 0.52;$$

$$\text{Exp. 2 block I \& III: } \ln \text{PR} = 0.035 - 1.027 \ln \theta + 4.754 \ln D_b, R^2 = 0.66.$$

Soil penetration resistance varied negatively with water content but positively with bulk density. As soil water content increases, the cohesion force and the angle of internal friction is reduced, hence PR decreases (Camp, 1969; Bengough, 1997). As soil bulk density increases, the decrease of macro porosity and compaction of the soil matrix results in an increase of frictional force which results in an increase of soil penetration resistance (Vepraskas, 1984; Tarawally *et al.*, 2004; Servadio *et al.*, 2005).

Coefficients from the least-squares fit of the soil water release curve for each experiment were

$$\text{Exp. 1: } \ln\theta = -0.480 - 0.961 D_b - 0.167 \ln\psi, R^2 = 0.94;$$

$$\text{Exp. 2 block II \& IV: } \ln\theta = -1.334 - 0.726 D_b - 0.229 \ln\psi, R^2 = 0.86;$$

$$\text{Exp. 2 block I \& III: } \ln\theta = -1.281 - 0.624 D_b - 0.205 \ln\psi, R^2 = 0.91.$$

Soil water content varied negatively with soil bulk density and water tension, which is consistent with previous research (Leao et al., 2006).

Compaction usually alters the pore size distribution of the bulk soil with a decline of macro porosity and an increase of micro porosity, and is reflected by an increase in soil bulk density. These changes affect soil water status two ways: by decreasing total water holding capacity and by increasing soil water retention at lower potential (Tarawally et al., 2004).

#### *4. 3 Least limiting water range*

Figure 3.3 presents the variation of soil water content with bulk density at critical levels of field capacity moisture (-0.01 MPa), wilting point moisture (-1.5 MPa), air-filled porosity (10%) and soil resistance (2.5 MPa) at the 10-15 cm depth for the two experiments. For the three soils present in the two experimental sites, the LLWR became less as compaction level changed from no compaction, to medium compaction and finally to high compaction, indicating that the different compaction treatments created a different soil physical environment for plant growth (da Silva, 1996). The critical bulk density at which LLWR equaled zero was almost identical for the three soils. It was  $1.74 \text{ g cm}^{-3}$  at Exp.1,  $1.75 \text{ g}$

$\text{cm}^{-3}$  in block II & IV of Exp. 2, and  $1.76 \text{ g cm}^{-3}$  in block I & III of Exp. 2. In Exp. 1, soil water content at field capacity and 10% air-filled porosity intersected at bulk density of  $1.69 \text{ g cm}^{-3}$ , suggesting the upper limit of LLWR was controlled by aeration status as bulk density increased. Soil water content at wilting point and penetration resistance of 2.5 MPa intersected at bulk density of  $1.47 \text{ g cm}^{-3}$ , indicating mechanical impedance was the limiting factor as bulk density increased.

Table 3.2 presents the least limiting water ranges for three compaction levels in the two experiments and for three cover crops in Exp.2, block II & IV. There was no interaction effect of compaction and cover crop on LLWR for all experiments. In Exp. 1, LLWR in the no compaction treatment was the greatest, while LLWR was greater in medium compaction than in high compaction. Compared to no compaction in Exp. 1, LLWR in high and medium compaction was reduced by 81.8% and 58.8%, respectively. In block I & III of Exp. 2, neither compaction nor cover crop had effect on LLWR. In block II & IV of Exp. 2, least limiting water range was greater in no/medium compaction than in high compaction which was reduced by 45.6% compared to that in no compaction; LLWR was greater in FR treatment than in rye/NC treatment.

In Exp. 2 block I & III where soil was dominated by sand and/or gravel, soil water content at field capacity was always lower than that at 10% air-filled porosity (Fig. 3.3 b), reflecting soil aeration was not a limiting factor almost year around in the field. Soil water content at wilting point was always less than that at penetration resistance of 2.5 MPa, showing penetration resistance was a dominate limiting factor as bulk density increased. In Block II and IV of Exp. 2, soil was



less sandy than in block I and III and less clayey than in Exp. 1. Soil water content at field capacity for these two blocks (Figure 3.3 c) was lower than that at 10% air-filled porosity when bulk density was less than  $1.72 \text{ g cm}^{-3}$ . A few soil bulk densities greater than this value were found only at the high compaction treatment, indicating aeration may be a limiting factor for a highly compacted soil of this type. However, soil water content at the critical penetration resistance (2.5 MPa) was greater than that at wilting point for all three compaction levels, suggesting penetration resistance should be the main factor limiting plant growth when soil moisture was less than the lower limit.

In block II & IV of Exp. 2, forage radish treatment increased the LLWR. For a soil with the same texture, the LLWR is controlled by soil water contents either at the 10% air-filled porosity or at the critical penetration resistance or both. We expected that root channels created by FR increased the upper limit by improving soil aeration and decreased the lower limit by providing lower resistance paths, giving a greater LLWR. It was reported that LLWR was more sensitive in no-till than in conventional-tillage, because the effect of soil structure (bio-pores) on penetration resistance was greater in no-till (Tormena *et al.*, 1999). Though we did not detect any difference of soil penetration resistance for three cover crops on the whole experimental site base, the localized decrease of penetration resistance by FR cover crop would still be expected due to its greater ability to penetrate compacted soils. This is supported by the findings that limiting soil strengths for the growth of root oat (*Avena sativa* L.) were 3.6 MPa and 4.9 MPa, respectively, in conventional-tillage and no-till systems while the presence of bio-pore was not

detected by penetrometers (Ehlers *et al.*, 1983). Forage radish was also able to increase soil air permeability, especially at lower depths in highly compacted soils (Figure 3.6 a and 3.7 a). We could ascribe that the increase in air permeability would contribute to the increase of aeration at high compaction condition, and thus would contribute to the increase of LLWR.

The LLWR for the three soils in the two experimental sites is shown in Figure 3.4. Because the organic matter content was around 1 % in both experimental sites, the effect of organic matter content on LLWR was considered negligible. The clay content was different for the three soils: Exp. 1 (ranging from 12.5 to 18.2%), block II and IV of Exp. 2 (ranging from 7.0 -11.0%) and block I and III of Exp. 2 (ranging from 5-7%). The LLWR of soil in Exp. 1 was less at the lower bulk density and was greater at medium range bulk density, compared to the LLWR of soils in Exp. 2 (less clay content) at the same bulk densities, an outcome that is not in agreement with previous research (da Silva and Kay, 1997). This was because the soils in Exp.2 had very high percent coarse fragment/sand which resulted in greater penetration resistance even at moderate soil bulk density.

Because the heavier machine was used to compact soils in Exp. 1 and the relatively greater clay content was present at this experimental site, the change of LLWR reflected sensitivity of soils to both the axle load of machinery and difference of soil texture responding to compaction. The sensitivity of LLWR to management and soil internal properties leads it to be a potential index of soil physical quality (da Silva and Kay, 1997; Tormena *et al.*, 1999; Zou *et al.*, 2000). The application of LLWR has been used for estimating nitrogen mineralization.

Drury *et al.* (2003) reported when soil water content was near or above the upper limit of the LLWR, denitrification occurred. Literature relating LLWR to plant growth has shown that shoot dry matter of plants grown inside the LLWR was greater compared to plants grown outside the LLWR (da Silva, 1996; Siegel-Issem *et al.*, 2005).

#### 4.4 Soil air permeability

According to equation (8), air permeability would increase with increases of air-filled porosity and pore size, but decrease with tortuosity. Air permeability ( $k_a$ ) has, thus, been used in previous attempts to characterize soil pore geometry. Besides air permeability itself, indices of efficiency of pore organization were given as  $k_a/\epsilon_a$  and  $k_a/\epsilon_a^2$  by Ball (1981a), where  $\epsilon_a$  is air-filled porosity. When air filled pore space is made up of pores with the same size distribution and continuity,  $k_a/\epsilon_a$  would be the same; if the pore continuity is the same,  $k_a/\epsilon_a^2$  should be equal. If  $k_a/\epsilon_a^2$  is equal while  $k_a/\epsilon_a$  is not, the difference of  $k_a/\epsilon_a$  is due to the difference of pore size, soil having larger pore size should have greater  $k_a$  value. Soils may have the same  $k_a/\epsilon_a$  or  $k_a/\epsilon_a^2$  values but different  $k_a$ s because some of air-filled pores may be dead pores which did not conduct air (Fedotov, 1990; Dörner and Horn, 2009). When neither  $k_a/\epsilon_a^2$  nor  $k_a/\epsilon_a$  is equal, soil having greater  $k_a$  value should have better pore organization (greater pore continuity and/or larger pore size) (Ball, 1981b; Groenevelt *et al.*, 1984). This concept has received wide application for measuring the efficiency of pore organization by comparing  $k_a$  and  $k_a/\epsilon_a^2$  (Blackwell *et al.*, 1990b; Schjønning and Rasmussen,

2000; Munkholm *et al.*, 2005a). However, the application of these concepts has been restricted to laboratory measurements because the  $k_a$  has to be measured either under equal air filled porosity or under the same water potential.

Using air permeability to characterize soil structure has so far been performed by measuring the air permeability of intact soil cores under given soil water potentials in the laboratory. Though it was reported that in situ, on site and laboratory measurements of air permeability were well correlated (Iversen *et al.*, 2001), it was sometimes very difficult to use the above indices to interpret in situ measurements because the soil water status for the field condition was unknown, or the narrow range of air-filled porosity failed to detect its effect on air permeability. This was the outcome for measuring air permeability for this study. We found the effect of air-filled porosity on air permeability was only significant for measurements at 0-12 cm depth in no compaction treatment in block I, II and IV of Exp. 2, but not significant for all treatment combinations in Exp. 1 and cover crops and high and medium compaction treatment combinations in Exp. 2.

In both experiments, the interaction between compaction and cover crop treatments was not significant. Term of air-filled porosity was then removed from the analysis because of its insignificance. Because of the great percentage of coarse fragments in block III of Exp. 2, data from Block III was not included in the analysis and thus does not report here. Data reported hereafter was based on the comparisons of compaction and cover crop effects on  $\log(k_a)$ .

#### 4.4.1 Effect of compaction on air permeability

The effect of soil compaction on the air permeability, in the form of log ( $k_a$ ), in Exp. 1 and 2 are shown in Figure 3.5. In Exp. 1, Soil air permeability was greater for the no compaction treatment compared with the medium and high compaction treatments for all the depths. The effect of compaction on the air permeability in Exp. 2 was less pronounced than in Exp.1. In Exp. 2 (block I, II and IV), air permeability under no compaction was only greater than that under high compaction at 0-12 cm depth.

In both experiments, air permeability was greatly reduced by compaction. This was more evident in Exp. 1 because the soil clay content was higher and a heavier axle load tractor was used to establish the compaction treatments. Soil air permeability for the no compaction treatment was significantly greater across all measured depths compared with medium (one pass) and high (two passes) compaction treatments. There was no significant difference for air permeability between medium and high compaction treatments. This decrease of air permeability by wheel trafficking is in agreement with Blackwell's findings that air permeability was reduced greatly by a single trafficking pass; and that further passes of trafficking also decreased air permeability, but in a much smaller magnitude (Blackwell *et al.*, 1990a). Liang *et al.* (1994) reported that air permeability was more sensitive than bulk density in reflecting changes of soil compaction and moisture. Even though the soil was disked to 8 cm after compaction in both experimental sites, the data showed clearly that compaction

caused a reduction of air permeability, and indicated that damage to soil structure caused by compaction was not easily reversible by surface tillage.

The differences in soil air permeability in Exp. 2 for the three compaction treatments were smaller than observed in Exp. 1. The only significant difference of air permeability in Exp. 2 was between high compaction and no compaction at 12 cm. This was partially because the greater fraction of sand which were more resistant to compaction. The tractor axle load for the medium compaction in Exp. 2 was only half that in Exp. 1, while the tractor for high compaction in Exp. 2 was the same one used for the medium compaction in Exp. 1. The lighter machinery used to establish the compaction in Exp. 2 caused less damage to soil structure than in Exp. 1.

#### *4.4.2 Effects of cover crops on air permeability*

The effects of cover crops on air permeability for the three compaction treatments in Exp. 1 are shown in Figure 3.6. Under high compaction, soil air permeability in the rape treatment was greater than that in NC and rye treatments at the 3 cm depth, was greater than that in FR treatment at 6 cm and greater than that in NC treatment 9 cm depth; soil air permeability in FR treatment was greater compared to that in NC treatment at the 12 cm depth. The effect of cover crops on air permeability for the medium compaction treatment was similar to what occurred in the high compaction treatment. For the no compaction treatment, the air permeability for the rape treatment was consistently greater than what was observed for the NC treatment, air permeability in FR and rye treatments was

greater than in NC treatment at 9 cm, air permeability for rye treatment was greater than for NC treatment at 12 cm. The variation for air permeability at the four depths for each cover crop treatment was less compared with the air permeability observed under high and medium compaction treatments.

The effects of cover crops on air permeability in block I, II and IV for Exp. 2 are presented in Figure 3.7. For the high compaction treatment, air permeability in FR treatment was greater compared to the rye or NC treatments at 6, 9 and 12 cm depths. There were no significant cover crop effects on the air permeability for the no compaction and medium compaction treatments.

The modification of soil structure caused by cover crop roots was reflected by the differences observed for air permeability. Under high compaction, the greater air permeability in rape (Exp. 1) and FR (Exp.2) treatments than in rye or NC treatment was due to either larger pore size and/or better pore continuity after rape /FR cover crops. In Exp. 1 under medium compaction, the distribution of air permeability after four cover crop treatments was similar as under high compaction at each depth interval, though the difference was less pronounced. In Exp. 1 under no compaction, there was a trend that air permeability was greater in Rape, FR and rye treatments than in NC control for all depth intervals, and the air permeability in three cover crop treatments did not differ from each other. Because the difference in root diameter for the three cover crops was obvious, especially at shallow depth, we could assume that the modification of pore size by cover crop roots was negligible under no compaction treatment. The difference of air permeability could be mainly due to the pore continuity which enhanced by

the presence of root channels. The modification of soil structure by different species was reported by Groenvelt *et al.* (1984) who observed that air permeability was greater after the growth of forages (alfalfa) than after growth of corn.

In Exp. 2, the difference of air permeability by cover crop treatments was observed only under high compaction. Because the tractor used for medium compaction had only half of the axle load as that used for high compaction, and because of the high proportion of sand, there was less to no significant difference in soil bulk density between medium and no compaction treatments. Unlike clayey soils, the air permeability in sandy and granular soils are highly correlated with the volume of macropore space (Ball, 1981c). The overall contribution of cover crop roots to air permeability under no and medium compaction was also insignificant.

## **5. Conclusion**

The degree of compaction caused by tractors and field equipment was affected by the soil texture and the axle load for the tractors and equipment that pass over a field. As the soil clay content increased and as equipment became heavier, there was a greater reduction observed for both LLWR and air permeability. The reduction LLWR observed in the compaction treatments was caused by poor aeration in the upper limit and by greater mechanical impedance at the lower limit where soil had more clay content; while in sandy soils, the reduction of LLWR caused by compaction was often due to the increased



mechanical impedance in the lower limit. Least limiting water range was greater in FR treatment than in rye or NC treatment in one of the three soils probably because FR root channels lowered soil strength and increased soil aeration. Brassica cover crop roots were more capable of improving soil air permeability in the compacted situations, probably due to their greater ability to penetrate the compacted soils. Cover crop roots increased air permeability of the non-compacted soil that had higher clay contents but had no effect on the sandy soils. The improvement of air permeability by FR and rape cover crops may provide a better soil environment and easier access for the subsequent crop roots.

Table 3.1 Soil physical properties of the two experimental sites.

Site	Location	Horizon	Depth (cm)	Clay (%)	Soil Texture	Coarse Fragment
Exp. 1	West End (block 1)	Ap	20	12.5	sandy loam	
		AE	30	12.6	sandy loam	
		Bt1	40	18.0	sandy loam	
		Bt2	60	18.3	loam	
		Bt3	80	20.9	loam	
		Bt4	100	19.9	sandy loam	
		BC	120+	17.0	sandy loam	
	East End (block 4)	Ap	20	18.2	loam	
		AE	40	16.6	loam	
		Bt1	57	24.2	loam	
		CB	75	12.1	sandy loam	
		C	85+	10.0	sandy loam	
	Exp. 2	South east (block 4)	Ap	20	7.0	loamy sand
AE			40	7.0	loamy sand	
E			50	7.0	loamy sand	
BE			60	10.5	Sandy loam	
Bt			80	20.1	loam	
BC1			90	10.2	Sandy loam	
BC2			100+	10	Sandy loam	5-10%
South west (block 3)		Ap	20	5.1	Coarse loamy sand	
		AC	40	3.8	Very coarse sand	50 % cob
		C1	75	4.4	Very coarse sand	50 % cob
	C2	80+	4.4	coarse sand	>50% cob	

Table 3.2 Effects of compaction and cover crop treatments on least limiting water range ( $\text{cm}^3 \text{cm}^{-3}$ )

Exp.	Block	Compaction**			Cover Crop*		
		no	medium	high	FR	rye	NC
1		0.219a	0.090b	0.040c			
2	I&III	0.108a	0.119a	0.043a			
	II&IV	0.103a	0.107a	0.047b	0.109a	0.075ab	0.072b

\* Means with the same letter(s) did not differ from each other at  $\alpha < 0.05$  (LSD);

\*\* Means with the same letter(s) in the same row did not differ from each other at  $\alpha < 0.01$  (LSD).

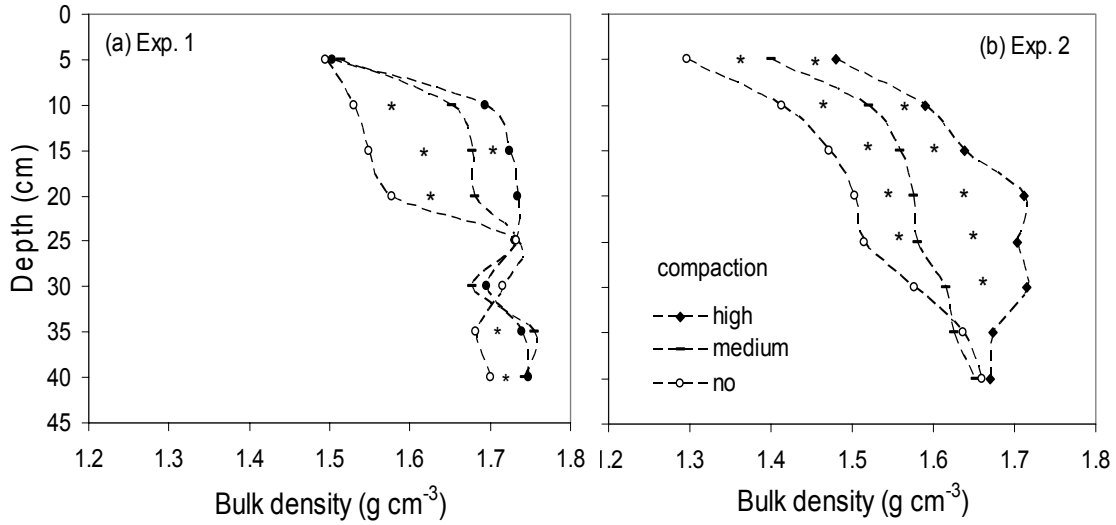


Figure 3.1 Variation of soil bulk density along the depth for three compaction treatments in the two experiments, in spring 2008.

\* Significant difference at  $\alpha < 0.05$  (LSD) between means at the same depth.

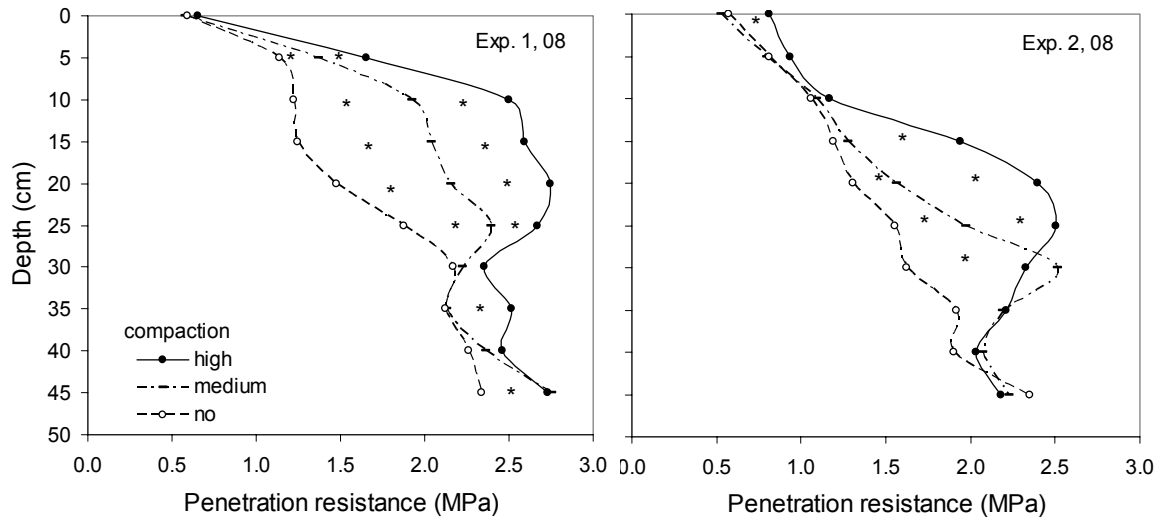


Figure 3.2 Variation of soil penetration resistance with the depth for three compaction treatments in the two experiments, in spring 2008.

\* Significant difference at  $\alpha < 0.05$  (LSD) between means at the same depth.

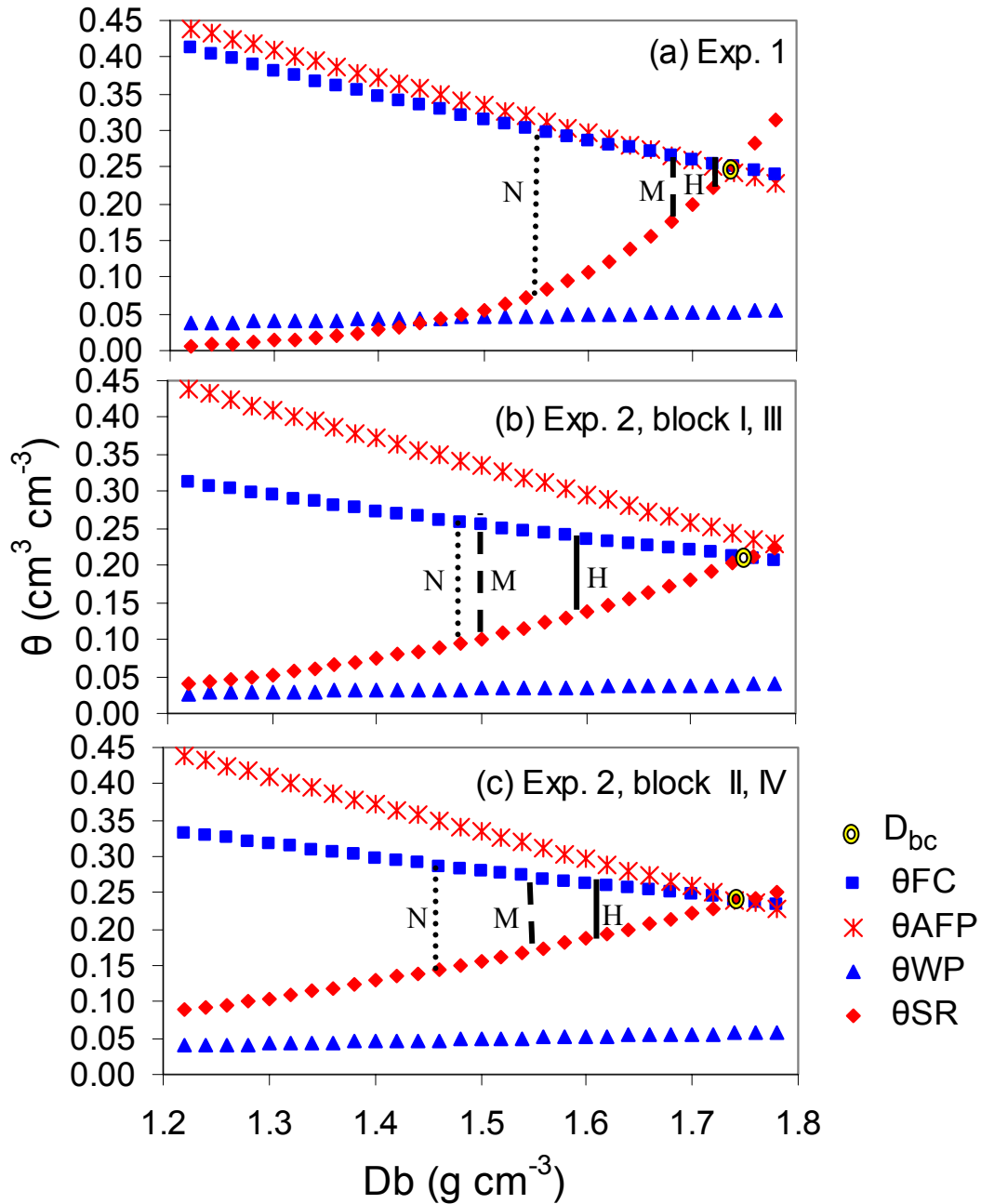


Figure 3.3 Soil volumetric water content ( $\theta$ ) variation with bulk density at critical levels of field capacity ( $\theta_{FC}$ ) (-0.01 MPa), wilting point ( $\theta_{WP}$ ) (-1.5 MPa), air-filled porosity ( $\theta_{AFP}$ ) (10%) and soil resistance ( $\theta_{SR}$ ) (2.5 MPa) at 10-15 cm in (a) Exp. 1, (b) Exp. 2 block I & III and (c) Exp. 2 block II & IV. Vertical lines indicate mean bulk densities of N=no compaction, M=medium compaction and H=high compaction.  $D_{bc}$  was the critical bulk density at which LLWR equaled zero.  $D_{bc}$  for (a), (b) and (c) were 1.74, 1.76 and 1.75  $\text{g cm}^{-3}$ , respectively.

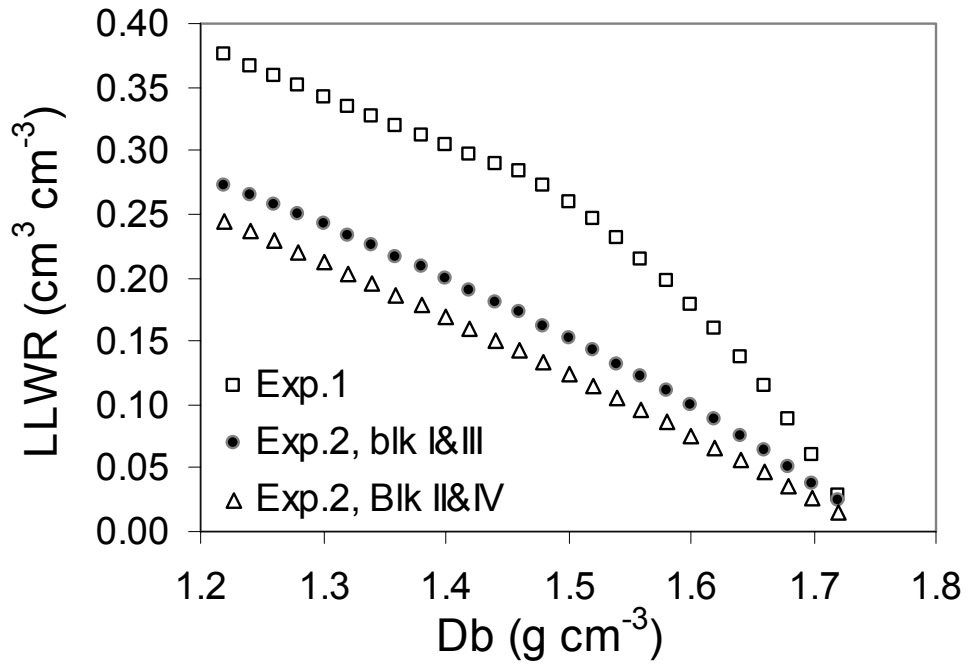


Figure 3.4 Least limiting water range (LLWR) variation with soil bulk density (Db) for three soils in the two experiments.

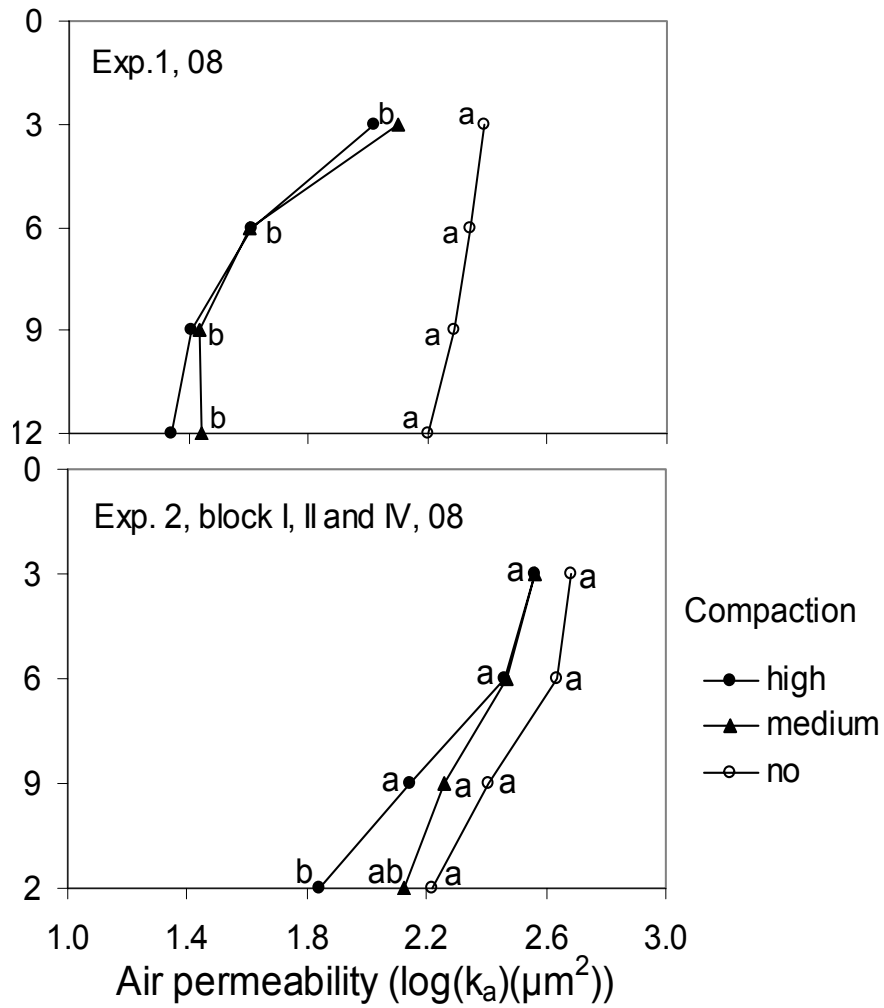


Figure 3.5 Soil air permeability ( $\log(k_a)$ ) variation with depth under three compaction treatments in Exp. 1 (upper), Exp. 2 block III (middle) and Exp. 2 block I, II and IV Means at the same depth with different letters significantly differ from each other at  $\alpha < 0.05$  level.

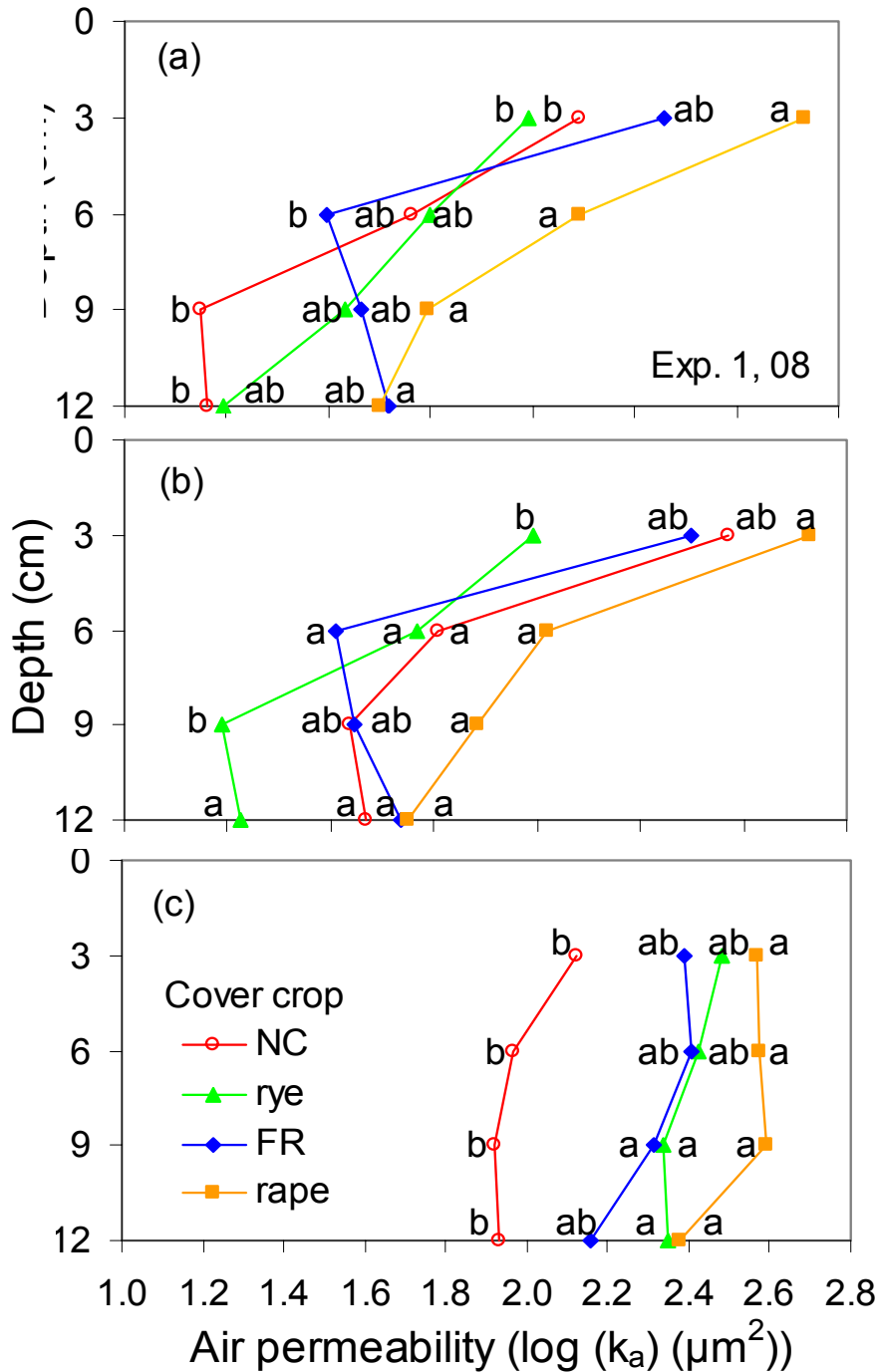


Figure 3.6 Soil air permeability ( $\log(k_a)$ ) variation with depth after four cover crop treatments under (a) high (b) medium and (c) no compaction in Exp. 1, 2008. Means at the same depth with different letters significantly differ from each other at  $\alpha < 0.05$  level (LSD)



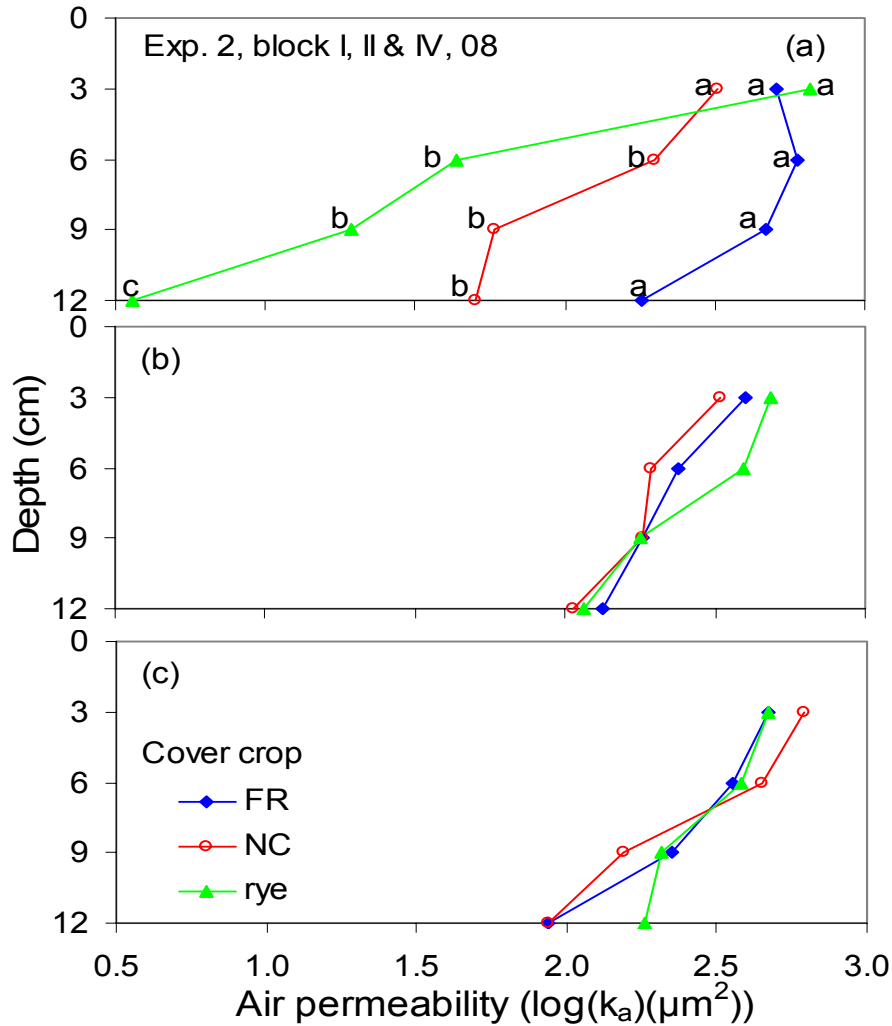


Figure 3.7 Soil air permeability ( $\log(k_a)$ ) variation with depth after three cover crops under (a) high (b) medium and (c) no compaction treatments in Exp. 2, block I, II & IV.

Means at the same depth with different letters significantly differ from each other at  $\alpha < 0.05$  level (LSD) (high compaction only).

## Chapter 4: Penetration of Winter Cover Crop Roots through Compacted Soils

### **Abstract**

Large diameter roots may be able to penetrate compacted soils better than small diameter roots because as they grow, the larger roots may exert greater forces to push soil particles aside. We evaluated root penetration of compacted soil by three winter cover crops: FR (forage radish: *Raphanus sativus* var. *longipinnatus*, cultivar ‘Daikon’), rape (rapeseed: *Brassica napus*, cultivar ‘Essex’), which have taproot systems, and rye (cereal rye: *Secale cereale* L., cultivar ‘Wheeler’), which has a fibrous root system. Three compaction levels (high, medium and no compaction) were created by wheel trafficking. Soil at 0-8 cm depth was loosened by disking for all compaction treatments to facilitate cover crop seeding. Bulk density and penetration resistance differed among the three compaction levels, mainly at 15-35 cm depth. Root number of each cover crop at every 5 cm increment was counted by core-break method. Roots of FR were least affected by compaction while rye root growth was most inhibited by compaction, especially where soil clay content was high and no pre-existing root channels were available. More FR and rape roots than rye roots penetrated into and through the compacted soil layer. At 15-50 cm depth under high compaction, FR had more than twice as many roots as rye and rape had about twice as many roots as rye in experiment 1. In experiment 2, 1.5 times as many roots of FR as of rye reached the 15-50 cm depth. In the no-compaction treatment, there was little difference in root vertical penetration among the three cover crops. The cover crops, especially rye, had more roots in the 15-50 cm depth in the second year compared to the first year after compaction, possibly because of re-use of root channels made during the first year. Rye roots were related to decreasing soil strength by a logarithm function, while the relationship with soil strength for rape roots was linear. There was no relationship between FR roots and soil strength. In both experiments, root

dry matter for rape and rye was positively correlated with the root counts. The correlation between FR root dry matter and root counts was negative at 5-20 cm and positive below 20 cm depth. We conclude that the soil penetration capabilities of the three cover crops were in the order of FR > rape > rye.

## **1. Introduction**

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

Partly to reduce soil erosion and water pollution associated with conventional tillage, the use of conservation tillage systems (e.g. reduced-till and no-till) have been gaining acceptance in the USA since the 1970s. More recently, leaching of post-harvest residual soil nitrogen has been shown to be a major source of water contamination. In the Middle Atlantic region the use of winter cover crops has been encouraged as a cost-effective means to remove residual soil

nitrogen and reduce the potential for nitrogen leaching to Chesapeake Bay (Ritter *et al.*, 1998; Coale *et al.*, 2001). Rye (*Secale cereale L.*) is a commonly used and widely studied cover crop in Maryland (Staver and Brinsfield, 1998).

However, even with the use of cereal cover crops, problems of soil compaction still remain. Using “plant roots as a tillage tool” (Elkins, 1985) may be a solution. The term “bio-drilling” (Cresswell and Kirkegaard, 1995) refers to the bio-pores created by the extension of deep tap roots into the soil and that remain after the crop has died that can be used by the roots of succeeding crops as low resistance pathways. This “bio-drilling” may work more efficiently in the no-till farm system because the root channels are kept intact (Stirzaker and White, 1995; Williams and Weil, 2004). Because roots of different species differ in the capacity to penetrate compacted soils (Bengough and Mullins, 1990; Clark *et al.*, 2003), it is believed that tap-rooted species that have greater root diameters than fibrous-rooted species may have a greater ability to penetrate the compacted soils than fibrous-rooted species (Misra *et al.*, 1986; Materechera *et al.*, 1991). Studies by Ishaq *et al.* (2001) suggested that incorporating species with a deep tap root system in the rotation was desirable to minimize the risks of soil compaction.

Two tap-rooted species in the Brassica family, forage radish (*Raphanus sativus L.*, cultivar ‘Daichon’) (FR) and rapeseed (*Brassica napus*, cultivar ‘essex’) (rape), have recently been introduced in the Middle Atlantic region. Their potential for capturing residual nitrogen as been determined to be as great as or greater than rye (Dean and Weil, 2009a). The goal of this study was to determine if these two tap-rooted species could alleviate soil compaction better than rye on

coastal plain soils under no-till management in the middle Atlantic region. The main objective of this study was to compare the effects of compaction on vertical penetration of the two Brassica cover crops (FR and rape) and rye roots, and find out which cover crop(s) is (are) more capable as a “tillage tool”.

## **2. Materials and Methods**

### *2.1 Sites and soil description*

Two experiments were located in adjacent fields (NF-2B and NF-2C) on the north farm of USDA Wallace Agricultural Research Center at Beltsville, MD, a site that is in the coastal plain ecoregion in Maryland (39°01'N, 76°55' W). Experiment 1 was established in field NF-2B in August 2006 and continued until September 2008. Experiment 2 used some of the same treatments as experiment 1, and was conducted in field NF-2C for one year (August 2007 to September 2008). The two sites were limed in April of 2005 at a rate of 1,020 kg ha<sup>-1</sup> (calcium carbonate equivalent, dolomitic limestone). Prior to our experiments, conventional tillage consisting of moldboard plow followed by disking was used in both fields. The near-term cropping history for the Experiment 1 field was potato (*S. tuberosum*) during summer 2005 followed by rye cover crop planted in fall 2005. Near-term cropping history for Experiment 2 field site was green bean (*phaseolus vulgaris*) during summer 2005 followed by rye cover crop planted in fall 2005, and Zucchini (*cucurbita pepo*) during summer 2006 followed with grain rye planted in fall 2006. The soil series for the Exp. 1 field varied from Elsinboro series (fine-loamy, mixed, semiactive, mesic Typic Hapludults) at the west end to

Woodstown series (fine-loamy, mixed, active, mesic Aquic Hapludults) in the east end with 0-5% slope in the east-west direction. The soil series at Exp. 2 (NF-2C) varied from Elsinboro (fine-loamy, mixed, semiactive, mesic Typic Hapludults) at the southwest side to Galestown series (gravelly, siliceous, mesic Psammentic Hapludults) at the southeast side of the field. For the Exp. 1 field, the A horizon soil texture ranged from sandy loam (12.5% clay) to loam (18.2% clay); In the Exp. 2 field, the A horizon soil texture ranged from very coarse loamy sand (5.1% clay) to loamy sand (7.0% clay). Table 4.1 lists the two distinct soil profiles in each experimental site. Due to the variation of soil properties, both sites were divided into four blocks so as to make each block as homogeneous as possible with regard to soil properties.

## *2.2 Experimental design and treatments*

A randomized complete block design was used for both fields. In Exp. 1, three compaction treatments (high, medium and no compaction) were imposed and four cover crops (forage radish, rape, rye and no cover) were planted giving a total of 12 treatment combinations (factorial structure of the treatments) in each block. The dimension of each plot was 3.0 m X 9.0 m. The blocks were separated by a 10.7 m wide alley for turning the tractor and equipment during creation of the compaction treatments and during crop planting. Due to the availability of a smaller field, Exp. 2 included the three compaction treatments but only three cover crops (forage radish, rye and no cover) for a total of nine treatment combinations in each block. The plot dimensions in Exp. 2 were 3.3 m X 12.2 m.

One 12.2 m wide alley separating Blocks 1 and 2 from blocks 3 and 4 allowed for tractor turn-around during compaction.

Prior to establishment of the compaction treatments in late July 2006 (Exp. 1) and late July 2007 (Exp. 2) respectively, each field was deep-ripped to an average depth of 45 cm, followed by moldboard plowing to an average depth of 32 cm and finally disked to approximately 8 cm depth. The two fields were irrigated (7.2 cm of water) to saturate the soils on August 16 and 18, 2006 for Exp. 1, and August 13 and 16, 2007 for Exp. 2. For Exp. 1, a John Deere 544C tractor (axle load 11.88 Mg with a rear tire contact area of 1,652 cm<sup>2</sup>) was used to establish the compaction treatments on August 18, 21, and 22, 2006. High compaction treatments consisted of two passes, the second of which was done with the loader bucket full of rocks to give an axle load of 12.91 Mg. Medium compaction was established by one pass with the tractor without rocks in the bucket and no compaction was no passes of the tractor. For Exp. 2, a single pass with the same John Deere 544C tractor was used to create the high compaction treatment, a single pass with a John Deere 7220 tractor (axle load 5.83 Mg with a rear tire contact area of 1,610 cm<sup>2</sup>) was used to create the medium compaction treatment, and no tractor traffic occurred for the no compaction treatment on August 17 and 19, 2007.

### *2.3 Crop /plot management*

After the compaction treatments were imposed, the soil in both experiments was disked to a depth of approximately 8 cm on August 25, 2006

(Exp. 1) and August 29, 2007 (Exp. 2). Four cover crops used at for Exp. 1 were: no cover crop (NC), FR, rape and rye. Three cover crops used for Exp. 2 were NC, FR and rye. Cover crops were seeded in late August, 2006 and 2007 at Exp. 1, and August 29, 2007 at Exp. 2 using a no-till drill. Cover crop species seeding rates were 14.57 kg ha<sup>-1</sup> for FR, 8.97 kg ha<sup>-1</sup> for rape (Exp. 1) and 134.5 kg ha<sup>-1</sup> for rye. On September 22, 2006, nitrogen fertilizer (urea ammonium nitrate) was applied at a rate of 28 kg ha<sup>-1</sup> because of the observed nitrogen deficiency. To ensure vigorous growth in 2007, the cover crops in both experiments were planted with the use of a starter nitrogen fertilizer (urea ammonium nitrate) at a rate of 22.4 kg ha<sup>-1</sup> in 2007.

Forage radish was frost-killed in the winter when temperature falls below -7°C. Rye, rape and weeds on no cover plots were killed using gramoxone (1,1'-Dimethyl-4,4'-bipyridinium dichloride) at a rate of 4.68 L ha<sup>-1</sup> with surfactant of 0.73 L ha<sup>-1</sup> on April 11, 2007 (Exp. 1), and a combination of Glyphosate (N-phosphonomethyl glycine) (4.68 L ha<sup>-1</sup>) and 2,4-D (2,4-dichlorophenoxy acetic acid) (2.34 L ha<sup>-1</sup>) on April 16, 2008 (both Exp. 1 and 2). Corn (*zea mays*, cultivar 'Pioneer' 34B62) was no-till drilled in late April of 2007 and 2008 at a rate of 74,000 seeds ha<sup>-1</sup> into four rows per plot with 76 cm inter row space. A starter fertilizer (34-0-0 granular ammonium nitrate) at a rate of 22.4 kg N ha<sup>-1</sup> was applied at planting. In middle May of both years, glyphosate (4.68 L ha<sup>-1</sup>) and 2,4-D (2.34 L ha<sup>-1</sup>) were sprayed to control weeds and any rape that had not been killed by the earlier application. Urea (30-0-0) (urea ammonium nitrate) was sidedressed at a rate of 112 kg/ha in mid-June of both years. Corn was harvested



as silage on August 24 2007 (Exp. 1). Following silage harvest, the field was sprayed with Glyphosate (4.68 L ha<sup>-1</sup>) to kill weeds prior to planting the second-year cover crops.

#### *2.4 Soil compaction measurement*

Soil strength measurements and soil cores were taken immediately after application of compaction treatments in August 2006 (Exp. 1) and August 2007 (Exp. 2) and again in spring 2008 (both experiments). A recording cone penetrometer (Spectrum Technologies, Plainfield, IL) was used to measure soil strength. The penetrometer has a 10 mm diameter steel rod with a 25 mm long and 15 mm maximum diameter cone tip integrated with a strain gauge and data logger. At each location, the penetrometer was pushed by hand at a constant rate down to the depth of 45 cm. Mean penetration resistance was recorded in kPa for every 5 cm depth increment to 45 cm. Penetration resistance was measured at 10 randomly selected locations per plot. In field of Exp. 2, because of the high content of gravels (ranging from 24% to 68% by weight from 5 to 40 cm depth in the west end and decreasing gradually eastwards) in block III, a dynamic cone penetrometer that is designed for gravelly soils (Herrick and Jones, 2002) was used. Concurrent with measuring soil strength, 10 undisturbed soil cores were taken per plot (40 cm depth) using a soil probe with a diameter of 1.85 cm. In block III of Exp. 2, soil samples were taken using a handle corer with the inside diameter of 6.4 cm for the same reason described above. The cores were divided into 5 cm increments, weighed, dried and re-weighed to determine soil bulk

density and soil moisture content. These soil strength measurements and soil cores were taken immediately after application of compaction treatments in August 2006 (Exp. 1) and August 2008 (Exp. 2) and again in spring 2008 (both experiments).

### *2.5 Cover crop shoot, root biomass and root penetration sampling*

In mid-November 2006, a golf cutter with an inner diameter of 10.44 cm and inserted to a depth of 16 cm was used to collect samples for cover crop root assessments. Each sample was divided into two segments: 0-8 cm (loose layer for all three compaction treatments) and 8-16 cm (loose layer for no compaction treatment, and dense layers for medium and high compaction treatments). Before taking the soil cores, the aboveground biomass (shoots for rape, rye and weeds in the no cover treatment; and shoots and a portion of the aboveground roots of FR) in the sampling area (the area of the golf cutter, 85.6 cm<sup>2</sup>) was collected. Aboveground and belowground samples were washed and dried prior to recording the dry matter yield. This step was done to compare the ratio of the aboveground dry matter biomass to belowground dry matter biomass.

Vertical root penetration under the different compaction treatments was examined using the core break method (Noordwijk, 2000). Soil cores were collected to a depth of 50 to 60 cm (maximum depth based on machine capability in these soils) using a tractor-mounted direct-drive hydraulic soil coring machine (Giddings, Inc., Windsor, CO) with a sampling tube of 6.4 cm inner diameter. In each plot, three cores were collected from an area occupied by a plant or plants

following removal of plant shoots by cutting them at the soil surface. The cylindrical soil cores collected were laid in horizontal holding troughs made of PVC plastic. Each core was broken by hand every 5 cm along its length. The number of roots protruding from both break faces was recorded. Because roots broke some distance (1 to 15 mm) from the break plane and therefore a given root could show on only one of the break surfaces, the root counts from both surfaces were added together and reported as the sum for the two break surfaces. Core break root counting was done in early December 2007 and late November 2008 to examine the vertical distribution of cover crop roots. For one of the three cores in each plot, the soil from each segment was collected, frozen, and stored at -12°C. These soil samples were later thawed and analyzed for root dry matter. Samples were manually washed with water using a sieve of 0.8 mm diameter opening (US standard sieve series no. 20). All roots in a core segment were collected with tweezers and dried at 65°C to determine root dry matter.

## *2.6 Statistical analysis*

Analysis of variance was performed using PROC MIXED (SAS v. 9.1, SAS Institute, Cary, NC). As described previously, both experiment 1 and 2 were used a randomized complete block design with a factorial arrangement of compaction and cover crop treatments. Treatment effects were considered significant when the F value was less than 0.05. All the mean comparisons were done at the same depth to avoid any confounding factors caused by the variation of soil properties at different depths. For each variable in the study, mean

comparison was done using the PDIFF option of the LSMEANS statement only when F test was significant ( $< 0.05$ ). Proc Model (SAS v. 9.1, SAS Institute, Cary, NC) was used to explore relationships between root dry matter and root number, and between root number and soil strength. The best-fit model for each paired data was chosen based on the maximum R square. Analysis was performed on data of each experiment-year separately and data of pooled experiment-years.

### **3. Results**

There were no significant changes in penetration resistance for each compaction treatment at the two measuring times (right after compaction was applied and in spring, 2008), except at 0-10 cm depths where the soil was disked after compaction. Please refer to figure 2.2 in chapter 2 for soil penetration resistances for the two experiments in spring 2008. In Exp. 1, greater differences in penetration resistance among the three compaction levels were found at 10-25 cm depth, though differences at 5, 35 and 45 cm also existed. In Exp. 2, the differences in penetration resistance among the three compaction levels were only observed at the 15-30 cm depth.

Table 4.2 presents the aboveground, belowground (0-16 cm) dry matter and their ratios for the different cover crop treatments at the three compaction levels from Exp. 1, in November 2006. Compaction had no effect on the aboveground dry matter of FR, rye or weeds, but high compaction decreased the aboveground dry matter of rape significantly compared with no compaction treatment. Compaction did not affect the belowground dry matter of rye or weeds,

while high and medium compaction decreased both FR and rape belowground dry matter. Rape and rye had higher ratios of aboveground to belowground dry matter under no compaction. Interaction effect of compaction and cover crop on the ratio of root dry matter at 0-8 cm to 8-16 cm was not significant, and cover crop showed no effect on the ratio either. Compaction was the only effect on the ratio of root dry matter at 0-8 cm to 8-16 cm that is shown in Figure 3.1. The greatest ratio was found under high compaction.

Table 4.3 presents root dry matter at 0-20 and 20-50 cm depth intervals obtained by core break method. Forage radish root dry matter at 0-20 cm depth was greater in no compaction than in high compaction in Exp. 1, 2006 and Exp. 2, 2007, but not Exp. 1, 2007; at 20-50 cm, FR root dry matter was less in high/medium compaction than in no compaction in Exp. 2, 2007. Rape root dry matter at both 0-20 cm and 20-50 cm were greater in no compaction than in high compaction only in Exp. 1, 2006, not 2007. Rye root dry matter at 0-20 cm did not differ among compaction treatments in all three Exp. – year; at 20-50 cm, rye root dry matter was greater in no compaction than in high compaction only in Exp. 1, 2006.

Table 4.4 presents the root numbers by depth of the three cover crops under high and no compaction in each experiment-year. The only difference observed for FR roots under the two compaction treatments was found at 5 and 10 cm. Rape had more roots under no compaction than under high compaction in 2006 at 15, 20, 25, 40, 45 and 50 cm, but only at 10 and 45 cm in 2007. In Exp. 1, rye had more roots under no compaction at all depths except 5 cm in 2006; more

rye roots were still observed at 20, 30, 35 and 40 cm under no compaction than under high compaction in 2007. In Exp. 2, rye roots under no compaction were only significantly greater at 10 and 35 cm than those under high compaction.

Figures 4.2 and 4.3 present the roots numbers of different cover crops under each compaction treatment that were planted right after compaction was applied in both experiments. In most cases, rye had more roots than rape or FR at 5 and 10 cm depth, regardless of compaction level. Under medium and high compaction treatments, FR was found to have more roots than rape or rye in and below the compacted layer (below 15 cm depth), while rye had the fewest roots below 15 cm. Under no compaction, the root numbers of the three cover crops did not differ at deeper depths; while at 0-10 cm depth, rye and rape had more roots than FR.

Figure 4.4 presents root numbers of second-year cover crops planted in Exp. 1 in November 2007. This assessment is following one year of cover crop-corn rotation after compaction was applied. FR continued to have more roots than rye at deeper depths under both medium and high compaction; the difference between rape and FR was seen only at a few depths. Under no compaction, differences among cover crop species were fewer and of smaller magnitude compared with differences observed under medium or high compaction, with fewer roots of rye than roots of FR or rape in only a few subsoil depth increments.

In Experiment 1 which had cover crops planted in fall of both 2006 and 2007, cover crop root numbers were generally higher in the 2007. The ratio of root difference (ratio = [roots in 2007 – roots in 2006] / roots in 2006) between 2007 and 2006 to roots in 2006 in Exp.1 is presented in Table 4.5. The purpose of

this table is to find out if there were any residue effect of soil compaction and/or effect of soil structure modification by the first-year cover crop-corn roots on root penetration of second-year cover crops. A negative ratio meant root penetration decreased in the second year, while a positive ratio meant an increase of root penetration in the second year. If a ratio was significantly different from zero at  $p < 0.05$  level (LSD), it indicated that the increase/decrease of roots in the second year was significant. There were only three negative ratios, two of which were insignificant. The ratio of rye roots under high compaction treatment was often found to be positive and significant from zero.

Correlations between root numbers and soil penetration resistance are presented in Figure 4.5. Rye root numbers were reduced as soil penetration resistance increased by logarithm functions for both experiments. Rape roots were negatively associated with increasing soil strength by a linear function in experiment 1. There was no significant correlation between FR roots and soil strength for both experiments.

Correlations between root numbers and root dry matter are presented in Table 4.6. Because root dry matter near the soil surface (above 15 or 20 cm for Brassica cover crops and above 5 cm for rye cover crop) was usually greater by a magnitude of 100 times or more than root dry matter at deep depths (below 15 or 20 cm for Brassica cover crops and below 5 cm for rye), two depth regions for each cover crop species were evaluated (20 cm for FR, 15 cm for rape and 5 cm for rye) in order to fit the data better. Below 5 cm depth, rye roots were positively related with root dry matter by natural logarithm functions at all three Exp. –years.

Rape roots and root dry matter were positively related by natural logarithm functions at all depths and for all Exp. –years. FR roots and root dry matter at 0-20 cm depth were found to be negatively correlated by either natural logarithm functions (Exp. 1, 2006, but insignificant and Exp. 2, 2007) or linear functions (Exp. 1, 2007 and pool of three Exp. years). Below 20 cm, FR roots were positively related to root dry matter by natural logarithm functions for all three Exp. years, but this correlation was only significant when pooling all three experiment-years.

#### **4. Discussion**

##### *4.1 Effects of compaction on aboveground and belowground (0-16 cm depth) dry matter of three cover crops*

There was a trend that the aboveground dry matter for all cover crops decreased as compaction varied from no to high, but this reduction was only significant for rape (Table 4.2). Compaction had no effect on root dry matter of winter weeds (NC treatment) and rye. Forage radish and rape belowground dry matters were decreased by compaction. The ratio of aboveground to belowground dry matter was greater for rape and rye under no compaction. These results are in agreement with the findings by Hussain et al. (1999) and Kahnt *et al.* (1986) that compaction decreased shoot growth more than root growth.



#### *4.2 Root behavior at the interface of the loose and compacted soil layers in Exp. 1*

Because the surface 8 cm of soil was loosened by disking after the compaction treatments were applied, differences were found in root behavior at the interface of the loose and compacted soil layers in plots under medium/high compaction. Comparing roots grown under no compaction with roots under high/medium compaction, it was obvious that mechanical impedance increased root growth of all cover crops in the loose soil layer adjacent to and above the dense soil layer. In Figure 4.1, the ratio of root dry matter in the loose layer to that at the dense layer under high compaction was about 6 times greater compared to no compaction. The phenomena and mechanics of root response to increased soil strength have been widely studied (Bengough et al., 2006). Stimulation of root growth and lateral proliferation of roots in a loose soil layer found above a high soil strength zone have been previously reported (Atwell, 1988; Misra and Gibbons, 1996).

We found that at 5 -10 cm, the trend was for the cover crops to generally have more roots under high compaction than no compaction (Table 4.4). It is widely reported that physiological responses of roots to high soil strength were an inhibition of axial growth of primary roots, but an increase of radial expansion of the root behind the apex and the abundance of lateral roots and root hair (Atwell, 1988; Garcia et al., 1988; Misra and Gibbons, 1996). Our results on root dry matter at 0-8 and 8-16 cm depth obtained by the golf cutter assessments and root number counts at 5-10 cm depth using the core break method illustrated that root response to soil compaction was similar regardless of species: root dry matter and

root number increased in the loose soil layer above a compacted zone, and that root growth was inhibited in the compacted zones.

#### *4.3 Effect of compaction on root dry matter distribution at shallow and deep soil depths*

Root dry matters obtained from deep soil cores were divided into 0-20 and 20-50 cm depths because flesh roots of FR and primary roots of rape were observed to locate mainly above 20 cm and consisted of more than 99% of total root dry matter. The insignificance of compaction effect on root dry matter of all three cover crops (except that FR had the greatest root dry matter in high compaction) in Exp. 1, 2007 at both depth intervals were probably due to effect of cover crop-corn rotation in the previous year (Table 4.3). Root dry matters of FR and rape at shallow depth (0-20 cm) were reduced by soil compaction in Exp. 1, 2006 and in Exp. 2, 2007, the year when compaction treatments were applied. Compaction did not affect rye root dry matter at the shallow depth, the same as was found at 0-16 cm. Because the increase of rye root dry matter in the loose layer (0-8 cm) compensated the reduction of its root dry matter in the compacted layer, which was not the case for FR or rape due their different root systems. These results were similar as described previously. In the deep soil depth (20-50 cm), root dry matter of FR was decreased by compaction in Exp. 2, 2007, compaction reduced root dry matters of both rape and rye in Exp. 1, 2006. The reduction of root dry matter by compaction are in agreement with the findings by Gilker, *et al.* (2002) and Panayiotopoulos, *et al.* (1994). Though the difference of

compaction treatments were observed at above 30 cm (see Figure 3.1 and 3.2 in chapter 3), root dry matters of FR in Exp. 2, 2007, of rape and rye in Exp. 1, 2006 at 30-50 cm were still reduced by compaction treatments (data does not show here). This may not be in agreement with the finding by Rosolem *et al.*(1998) who reported that a growth recovery of cotton (*Gossypium hirsutum*) roots when they grew out of the compacted layer into the bottom loose layer. Though root dry matter at both shallow and deep depths differed for different cover crops, we could not offer any further explanation on this because of species difference.

#### *4.4 Root penetration in the deep soil profile under different compaction levels*

Though roots for all cover crops behaved similarly in surface layers upon compaction, there were great differences in root behavior for the three cover crops at deeper soil depths. By examining the roots of each cover crop (Table 4.4) below the 15 cm depth, it can be seen that there were fewer roots under high compaction compared with no compaction for the three cover crops tested. This means that root numbers were decreased when confronted by a compacted zone. However, the change in numbers of FR roots under high and no compaction was the smallest compared with the other two cover crops and none of the differences for FR numbers at the deeper depths were significant in all three experiment-years. Contrary to the response for FR roots, the differences observed for rye roots under high and no compaction were the greatest in Exp. 1, 06 and was significant at all depths below 10 cm. The differences observed in rye root responses under high and no compaction were less pronounced in Exp. 1, 07 and Exp. 2, 07 , but still

significant at several deep depths. The differences of rape roots under high and no compaction below 15 cm depth were greater than that of FR roots, but less than that of rye roots. The average number of roots at 15-50 cm depth under no compaction compared with high compaction were 1.1, 1.0 and 1.0 times for FR, 2.0 and 1.2 times for rape, 3.3, 1.8 and 1.1 times for rye at Exp.1, 06, Exp.1, 07 and Exp. 2, 07 respectively.

The data suggested that FR root penetration was rarely decreased by compaction. Rape and rye roots were both reduced by compaction, but the reduction was greater for rye than for rape, and also more pronounced in the first year (Exp. 1, 06) than in the second year (Exp.1, 07). These results are in agreement with the findings conducted by Materechera et al. (1993) that tap-rooted species (with greater relative root diameter) had greater root density than fibrous-rooted species (with smaller relative root diameter) in compacted soils. This difference in Exp. 1, 07 and Exp. 2, 07 might be due to the difference in soil texture and magnitude of compaction in the two fields. Because soils at Exp. 2 (NF-2C) had higher sand content than at Exp. 1, it would be expected that soils at Exp. 2 had greater pore size compared to soils at Exp. 1, so provided easier access to rye roots under high compaction. It may also be that greater clay content at Exp. 1 led to greater frictional resistance experienced by the rye roots (Iijima et al., 2004).

#### 4.5 Effect of cover crop species on root penetration

In Figures 4.2 (a, b, c) and 4.3 (a, b, c), it can be seen that significant differences in root numbers occurred between FR and rye, rape and rye more frequently below the 20 cm depth when the soil was compacted. At Exp.1 at the 15-50 cm depth, the mean number of roots for FR was 2.65 (06) and 2.21 (07) times, 1.86 (06) and 1.76 (07) times, 0.81 (06) and 1.20 (07) times greater than the mean number of roots for rye under high, medium and no compaction, respectively; and the mean number of roots for rape was 1.95 (06) and 2.07 (07) times, 1.36 (06) and 1.60 (07) times, 1.14 (06) and 1.38 (07) times greater than the mean number of roots for rye under high, medium and no compaction respectively. At Exp. 2, 07, mean number of FR roots were 1.47, 1.10 and 1.21 times greater than the mean for rye root numbers under high, medium and no compaction, respectively. Forage radish and rape each had more than twice the number of roots as rye in and below the highly compacted soil layers. This outcome for FR and rape roots verified our hypotheses that the two Brassica cover crops would penetrate compacted soils better than rye roots. This is in agreement with Abdalla et al.'s (1969) and Materechera et al's (1991) findings that species that have thicker roots penetrated compacted soils better than species with thinner roots.

Misra *et al.* (1986) found that the maximum axial root growth pressure increased by a power function with an increase in root diameter. The mechanics of root growth in compacted soil has been suggested to be related to maximum root growth pressure (Greacen and Oh, 1972). Dexter (1987) proposed the root

growth model,  $R/R_{\max} = 1 - \psi_0/\psi_w - \sigma/\sigma_{\max}$ , where  $R_{\max}$  is maximum growth rate,  $\psi_0/\psi_w$  represents the effect of soil water potential ( $\psi_w$  - soil water potential at wilting point), and  $\sigma/\sigma_{\max}$  represents the effect of soil mechanical resistance ( $\sigma_{\max}$  - maximum growth pressure). Under wet conditions where the effect of soil water potential is near zero, only mechanical impedance would be the limiting factor if an anaerobic condition is not present. If soil strength  $\sigma$  is the same, plants having greater  $\sigma_{\max}$  would have greater relative growth rate. However, further studies by Clark and Barraclough (1999) discovered that roots with greater diameters (dicotyledons) did not always generate greater  $\sigma_{\max}$  than plant species with roots of smaller diameters (monocotyledons). Others who have done studies on root physical properties have suggested that roots with greater diameters were stronger (Bischetti et al., 2005) and more resistant to buckling (Whiteley et al., 1982). The suggestions by the latter two authors may, to some extent, explain the findings in our study that the species with thicker roots had greater ability to penetrate the compacted soils.

#### *4.6 Improvement of root penetration following cover crop-corn rotation*

Though the root response to soil compaction for the three cover crops in Exp. 1 followed the same pattern both years, more roots were present for each species the second year. The ratios of root number difference shown in Table 4.5 indicated that only FR at 5 cm under high compaction, rape at 5 cm under medium compaction and rye at 45 cm under no compaction had negative ratios; the rest were positive values, which indicated that more roots were present in

2007 compared to 2006, regardless of compaction treatment level. This second year increase in root number was most pronounced for rye roots under high compaction. We did not find any significant changes of soil bulk density or penetration resistance between the first year and second year, especially for soils with high and medium compaction treatments. The increase in root penetration in the second year was due to the pre-existing root channels left by cover crops and corn in the first year which provided an easier access to the compacted soils for the second-year cover crop roots, especially rye roots which were greatly inhibited in the first year. Evidences that previously created root channels are used by succeeding crops have been previously reported (Stirzaker and White, 1995; Rasse and Smucker, 1998; Williams and Weil, 2004).

#### *4.7 Relationships between soil strength and root penetration, root number and dry matter*

An earlier study on root growth in a compacted soil reported that a negative correlation between root elongation and soil strength existed (Taylor, 1969). Similar negative curvilinear relationships between root elongation rate (or relative root length or root dry mass production) and penetration rate were reported by Goss (1977) for barley, by Merrill *et al.* (2002) for wheat and by Panayiotopoulos *et al.* (1994) for maize. For an individual root, the elongation rate decreases linearly as soil strength increases (Taylor *et al.*, 1966; Tardieu, 1994). In our study, rye roots were negatively related to soil penetration resistance by a natural logarithm function; and rape roots were negatively related to soil strength

a linear function (pooled data of Exp. 1, 06 and 07). There was no relationship between FR roots and penetration resistance (Figure 3.5). The reason for this lack of relationship between FR roots and soil strength might be due to the inherent physiological properties of the FR fleshy root system. Studies by Thaler and Pagès (1999) found that when fast growing tap roots encountered homogeneous compaction conditions, the growth of secondary roots was unaffected while the growth of tertiary roots was enhanced. In other words, only the growth of the large tap roots (main axes) was arrested by the mechanical impedance that caused them to become shorter. Carrot roots responded to compaction by having an increase in number of fibrous roots and by an increased total root length, surface area and volume of fibrous roots in natural soil profiles to 50 cm depth (Pietola and Smucker, 1998).

Rape root number and root dry matter was positively correlated by natural logarithm functions at two depth regions (Table 4.6). Rye roots were positively related to the root dry matter by natural logarithm functions or linear function (pool of all three experiment-years' data). FR root numbers were negatively related to the root dry matter above the 20 cm depth, and their positive correlation below the 20 cm depth was only significant when pooling all three Exp. years' data. The overall correlation between root number and root dry matter for FR was the weakest among the three cover crops. If the fleshy tap roots had been separated from the branch roots when studying their responses to soil compaction, we might have observed better relationships between root number and soil strength, and root number and dry matter. However, this was not done and no



other study on the ability of fleshy roots like that of FR to penetrate compacted soils has been reported.

## **5. Conclusion**

Though the mechanism explaining why tap-rooted species have greater ability to penetrate compacted soils compared to the fibrous-rooted species awaits to be answered, our results clearly showed that for the three cover crops in the study, roots of FR were least affected by compaction while rye root growth was most inhibited by compaction, especially where soil clay content was high and no pre-existing root channels were available. The ranking for specie's ability for root penetration in compacted soils was FR >rape >rye. Forage radish and rape, therefore, should have an advantage over rye if used as a biological tillage tool. We, therefore, suggest that integrating FR or rape as cover crops may alleviate the effects of soil compaction, especially in no-till farming systems.

Table 4.1 Soil physical properties of the two experimental sites

site	location	horizon	depth (cm)	Clay (%)	Soil texture	Coarse fragment	
Exp. 1 (NF-2B)	West End (block 1)	Ap	20	12.5	Sandy loam		
		AE	30	12.6	Sandy loam		
		Bt1	40	18.0	Sandy loam		
		Bt2	60	18.3	Loam		
		Bt3	80	20.9	Loam		
		Bt4	100	19.9	Sandy loam		
		BC	120+	17.0	Sandy loam		
	East End (block 4)	Ap	20	18.2	Loam		
		AE	40	16.6	Loam		
		Bt1	57	24.2	Loam		
		CB	75	12.1	Sandy loam		
		C	85+	10.0	Sandy loam		
	Exp. 2 (NF-2C)	South east (block 4)	Ap	20	7.0	Loamy sand	
			AE	40	7.0	Loamy sand	
E			50	7.0	Loamy sand		
BE			60	10.5	Sandy loam		
Bt			80	20.1	Loam		
BC1			90	10.2	Sandy loam		
BC2			100+	10	Sandy loam	5-10%	
South west (block 3)		Ap	20	5.1	Coarse loamy sand		
		AC	40	3.8	Very coarse sand	50 % cob	
		C1	75	4.4	Very coarse sand	50 % cob	
	C2	80+	4.4	Coarse sand	>50% cob		

Table 4.2 Winter cover crop aboveground, belowground dry matter (g), and the ratio of above- to below- ground dry matter in the 85.6 cm<sup>2</sup> sampling area and to 16 cm depth (Exp. 1), December, 2006.

Cover crop	Compaction	Aboveground (g) *	Belowground (g) *	Ratio **
FR	High	18.7a	8.7ab	2.3ab
	Medium	23.4a	6.9a	3.4bc
	no	24.7a	11.9b	2.0ab
rape	High	16.4a	4.9a	3.2bc
	Medium	18.1ab	8.2a	2.3ab
	no	44.2b	9.8b	4.7c
rye	High	18.9a	11.4a	1.6ab
	Medium	18.6a	10.0a	1.9ab
	no	27.8a	8.9a	3.1bc
NC (weeds)	High	5.3a	5.2a	1.1a
	Medium	7.8a	4.6a	1.8ab
	no	7.9a	5.5a	1.5ab

\* Different letters indicate significant difference within the same cover crop under different compaction treatments at  $\alpha < 0.05$  (LSD). \*\* Different letters indicate significant difference among all cover crops at  $\alpha < 0.05$  (Tukey-Kramer adjustment).

Table 4.3 Winter cover crop root dry matter ( $\text{mg cm}^{-3}$ ) in three compaction treatments at 0-20, 20-50 cm intervals obtained by core break method at Exp. 1 and Exp. 2

Exp.	Time	Depth (cm)	FR			Rape			Rye		
			High	Medium	No	High	Medium	No	High	Medium	No
1	2006	0-20	5.82b	3.80bc	7.11a	3.87bc	2.83bc	9.79a	1.63c	1.95c	1.16c
		20-50	0.06a	0.03ab	0.05a	0.02b	0.03ab	0.06a	0.01b	0.04ab	0.06a
	2007	0-20	12.61a	7.21b	9.37ab	3.69bc	7.98b	5.16bc	1.54c	1.60c	1.27c
		20-50	0.06	0.25	0.07	0.06	0.06	0.13	0.04	0.09	0.21
2	2007	0-20	8.69c	15.69b	22.75a				1.38d	1.26d	1.77d
		20-50	0.11b	0.22b	0.36a				0.21b	0.17b	0.20b

\* Means with a same letter in the same row did not differ from each other at  $\alpha < 10\%$ .

Table 4.4 Cover crop root number (1000 m<sup>-2</sup>) under high and no compaction treatments in the three Exp. -years

Depth (cm)	FR						rape				rye					
	Exp.1, 06		Exp. 1, 07		Exp. 2, 07		Exp.1, 06		Exp.1, 07		Exp.1, 06		Exp. 1, 07		Exp. 2, 07	
	high	no	high	No	high	no	high	no	high	no	high	no	high	no	high	no
5	14.8a*	3.4b	4.4	3.7	3.5	3.0	13.2	10.2	13.8	11.9	20.9a	12.5b	22.1	14.7	14.4	14.4
10	9.1a	3.5b	9.0a	5.0b	4.5	3.6	5.9	8.1	6.4a	10.2b	3.5a	9.1b	10.4	9.8	9.5a	6.6b
15	4.6	4.4	9.5	7.3	8.7	4.2	4.6a	7.0b	6.8	9.3	1.3a	6.9b	5.9	8.3	6.8	5.3
20	2.9	4.0	8.9	8.8	7.8	5.5	3.2a	7.7b	6.6	9.2	2.2a	6.8b	3.2a	6.8b	6.1	4.9
25	4.3	4.5	6.0	7.7	5.9	5.2	3.6a	6.0b	7.7	9.2	1.6a	6.0b	3.0	5.4	4.5	4.1
30	3.8	4.4	5.5	7.0	6.5	5.7	3.2	5.2	7.7	8.3	1.6a	4.9b	2.5a	5.1b	4.3	6.2
35	4.0	4.1	5.9	6.2	5.5	6.1	2.8	4.3	6.7	5.4	1.3a	3.9b	2.4a	5.0b	3.1a	6.6b
40	4.4	4.0	5.9	5.3	5.3	6.2	1.9a	5.1b	6.0	6.1	1.1a	4.0b	2.7a	5.2b	3.4	4.9
45	3.8	3.5	6.8	5.5	4.8	6.8	2.3a	5.8b	4.2a	7.3b	1.3a	4.1b	2.7	4.6	2.6	3.6
50	3.3	3.8	5.9	5.4	4.7	6.7	1.3a	4.9b	5.4	6.3	1.4a	3.6b	2.3	3.9	2.7	2.8
<i>Avg (15-50)</i>	<i>3.9</i>	<i>4.1</i>	<i>6.8</i>	<i>6.7</i>	<i>6.1</i>	<i>5.8</i>	<i>2.9</i>	<i>5.8</i>	<i>6.4</i>	<i>7.6</i>	<i>1.5</i>	<i>5.0</i>	<i>3.1</i>	<i>5.5</i>	<i>4.2</i>	<i>4.8</i>

\* Different letters indicated significant difference at a <0.05 (LSD) within the same Exp.-year for the same cover crop at each depth. No significant difference existed for values without letters. No comparison was attempted for the average roots at depth 15-50 cm.

Table 4.5 Ratio of root difference between 2007 and 2006 to roots in 2006 in Exp. 1 under no-till system

Depth (cm)	high			medium			No		
	FR	rape	rye	FR	rape	rye	FR	rape	Rye
5	-0.68*	0.18	0.09	0.05	-0.21	0.40	0.19	0.19	0.23
10	0.46	0.11	2.14*	1.03	0.55	0.24	0.40	0.28	0.15
15	1.20	0.92	6.83*	0.20*	0.99	1.01	1.37	0.40	0.31
20	2.79*	1.57	1.86*	0.15	0.91	0.80	1.73*	0.22	0.02
25	0.51	1.01	11.75*	0.66	0.61	0.73	1.29	0.64	0.02
30	0.72	1.39	3.13*	0.67	0.60	1.37	0.61	0.75	0.09
35	0.55	1.40	4.89*	0.39	0.80	0.35	0.48	0.28	0.33
40	0.48	2.29	4.94*	1.03	0.67	0.31	0.34	0.18	0.34
45	0.84	0.79	3.32	1.13	1.16	1.60*	0.81	0.52	-0.41
50	1.58	3.11	8.86*	2.20	2.85	2.40	0.44	0.32	0.09

\* Ratio was significant from zero at a <0.05 (LSD).

Table 4.6 Correlations between root number and root dry matter for the three experiment-years

Cover crop	Exp.-year	(0-15) cm Depth			(15-50) cm Depth		
		r	p	n	r	p	n
FR	Exp.1, 06	-0.17*	0.3590	32	0.21*	0.0605	81
	Exp.1, 07	-0.40	0.0094	36	0.26*	0.0167	82
	Exp.2, 07	-0.53*	0.0012	34	0.17*	0.1356	77
	Overall	-0.40	<.0001	102	0.20*	0.0021	240
Rape	Exp.1, 06	0.60*	0.0002	35	0.58*	<.0001	75
	Exp.1, 07	0.45*	0.0058	36	0.51*	<.0001	79
	Overall	0.53*	<.0001	71	0.59*	<.0001	153
Rye**	Exp.1, 06	0.14	0.6709	12	0.73*	<.0001	106
	Exp.1, 07	0.09	0.7739	12	0.79*	<.0001	104
	Exp.2, 07	0.43*	0.1662	12	0.54*	<.0001	108
	Overall	0.15*	0.3723	36	0.71	<.0001	322

r-correlation coefficient, p-P value, n-sample used.

\* Nonlinear relationship between roots and dry matter as roots = ln (dry matter).

\*\* Rye roots were divided into groups of (0-5) cm and (5-50) cm depth.

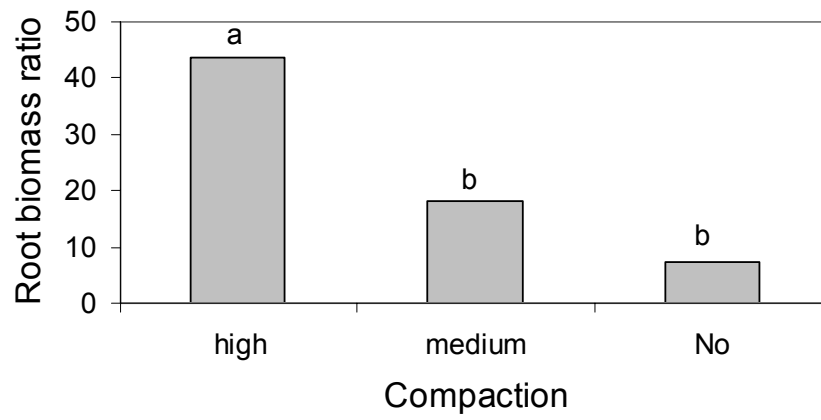


Figure 4.1 Ratio of root dry matter at 0-8 cm depth (loose layer) to that at 8-16 cm depth (dense layer under medium and high compaction), Exp. 1, Nov., 2006. Different letters indicate significant difference at  $\alpha < 0.01$  (LSD).

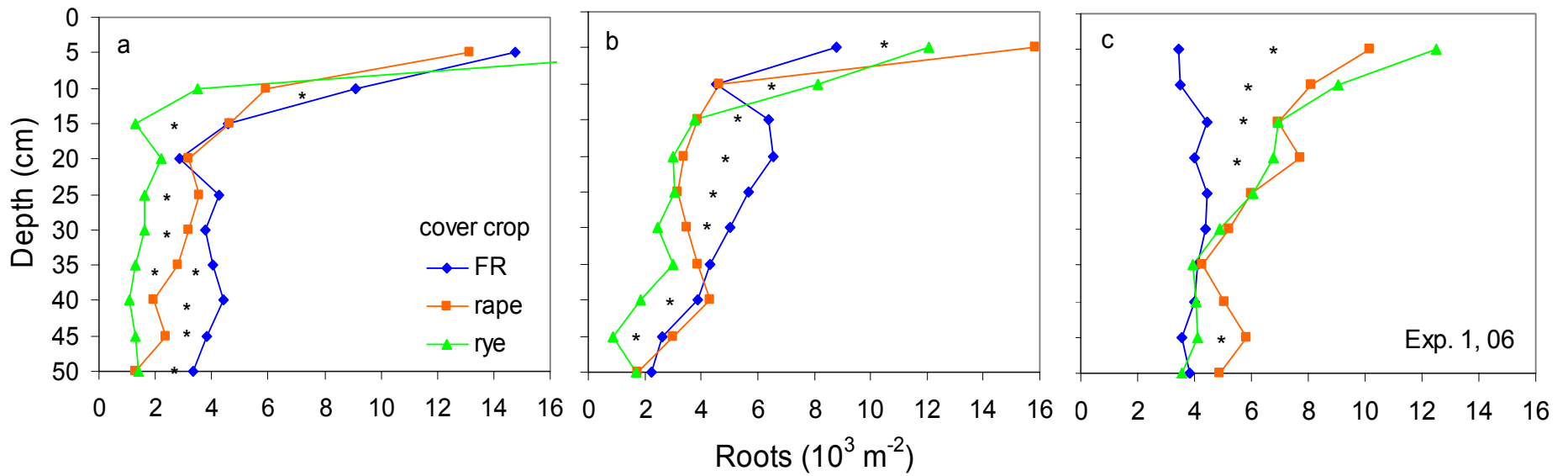


Figure 4.2 Root penetrations of cover crops under (a) high (b) medium and (c) no compaction in Exp. 1, in Dec., 2006. (First-year cover crops were planted right after compaction treatment was applied.)

\* indicates significant difference of means at the same depth at  $\alpha < 0.05$  (LSD).



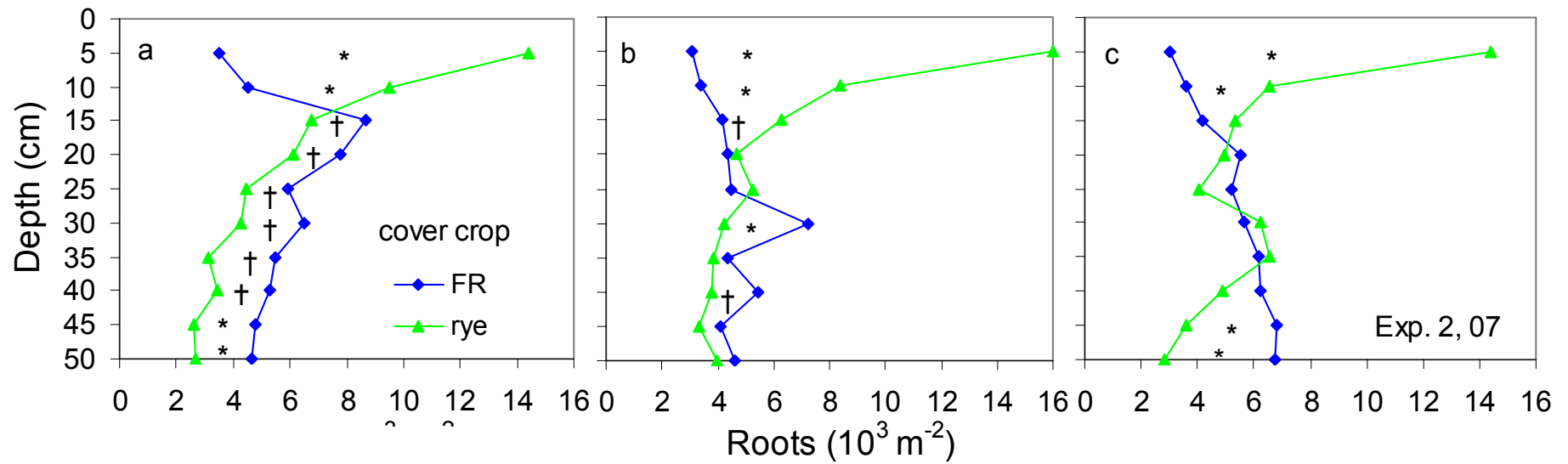


Figure 4.3 Root penetrations of cover crops under (a) high (b) medium and (c) no compaction in Exp. 2, in Nov., 2007. (First-year cover crops were planted right after compaction treatment was applied.)

\* indicates significant difference of means at the same depth at  $\alpha < 0.05$ , † significant at  $\alpha < 0.10$  (LSD).

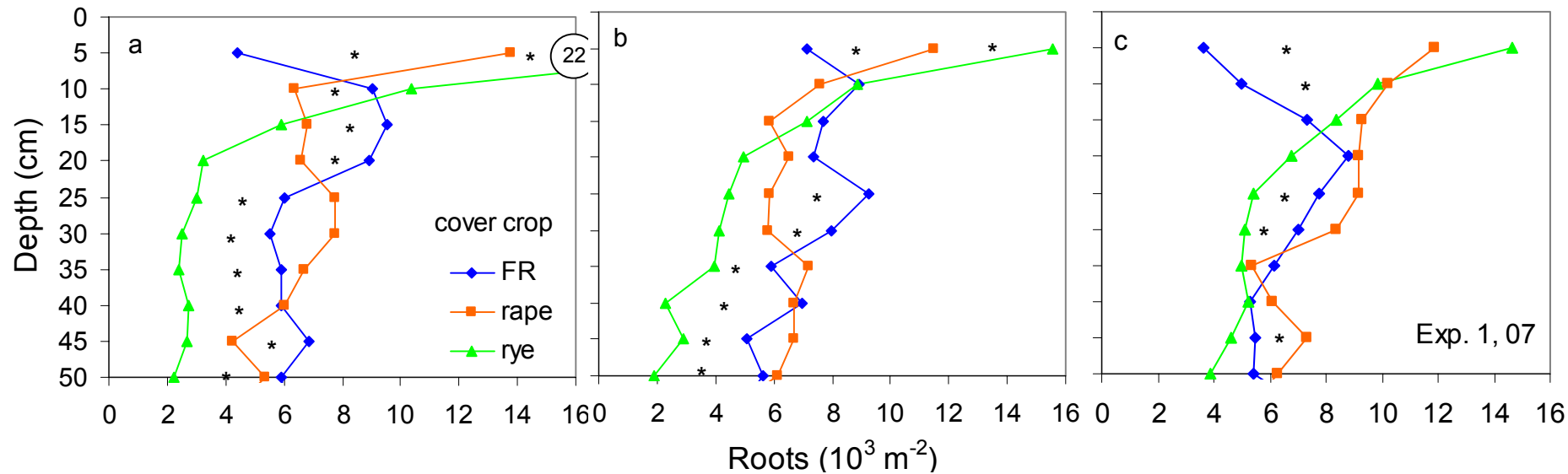


Figure 4.4 Root penetrations of cover crops under (a) high (b) medium and (c) no compaction in Exp. 1, in Nov., 2007. (Second-year cover crops were planted after one year cover crop – corn rotation; compaction was applied only once before the first-year cover crops were planted.)

\* indicates significant difference of means at the same depth at  $\alpha < 0.05$  (LSD)

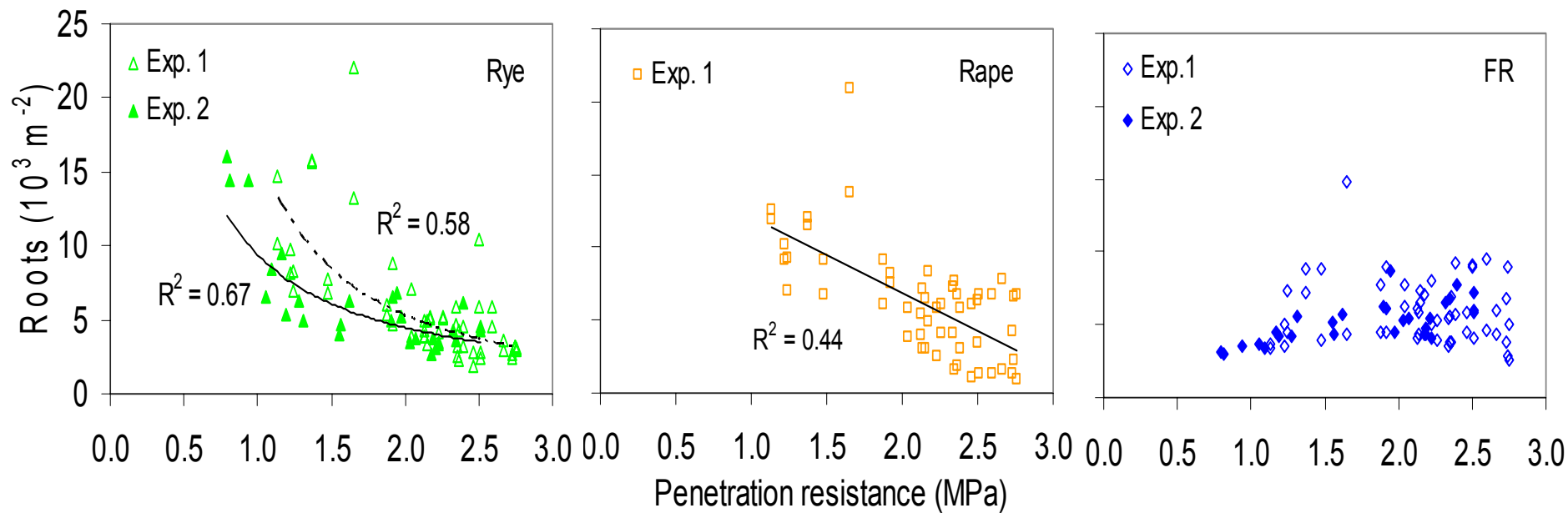


Figure 4.5 Correlation between cover crop (rye, rape and FR) roots ( $10^3 \text{ m}^{-2}$ ) and soil strength (MPa) in the two experiments (two years' data in Exp. 1) ( $p < 0.0001$  for both rye and rape).

## Chapter 5: Root Penetration, Subsoil Water Uptake and Yield of Maize as Affected by Soil Compaction and Preceding Cover Crops

### **Abstract**

Channels produced by cover crop roots in fall and winter when soils are relatively moist can facilitate the penetration of compacted soils by roots of subsequent crops in summer when the soil is relatively dry and hard. Tap-rooted cover crops may be able to penetrate compacted soils and provide such channels better than fibrous-rooted cover crops. We studied the effects of four cover crops on maize (*Zea mays*, cultivar ‘Pioneer’ 34B62) root penetration, subsoil water uptake and yield under compacted soils. The fall planted cover crops were FR (forage radish: *Raphanus sativus* var. *longipinnatus*, cultivar ‘Daikon’), rape (rapeseed: *Brassica napus*, cultivar ‘Essex’) rye (cereal rye: *Secale cereale* L., cultivar ‘Wheeler’) and NC (no cover crop). In two field experiments we found that maize in highly compacted soils achieved more deep-roots after FR and rape than after rye or NC. There was little to no cover crop effect on maize deep rooting when the soil was not compacted. Hourly monitoring of subsoil water content during maize growing season showed that maize following FR or rape took up subsoil water earlier and more rapidly during the whole growing season regardless of soil compaction treatment. The greater water uptake from the subsoil suggests the presence of more maize roots in that layer. In year 1 on highly compacted soil, maize following NC or rye took up less subsoil water than maize following FR or rape. In year 2 this trend was similar but not significant, possibly

because of the presence of pre-existing root channels from the year 1 crops. In year 1 but not year 2, total number of maize roots was positively correlated with total number of cover crop (FR and rye) roots at the 20-50 cm depth under high compaction. The number of maize roots was also correlated with the minimum soil water content reached in late July at 50 cm depth. These correlations support our hypotheses that FR and rape cover crops enhanced maize root penetration and subsoil water uptake in highly compacted soils. The effect of compaction on maize yield was significant only in year 1 of experiment 2. Maize following FR, rape and rye trended toward greater yields than maize following NC. Drought stress experienced during the study may have been insufficient to effectively determine whether greater subsoil rooting by maize following FR and rape could result in greater yields than for maize following rye.

## **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 middle to late in the 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 such deep tillage may be short-living (Hall et al., 1994) and costly in terms of energy, capital and time. Increasing concerns about environmental impacts of tillage have led to

interest in reduced- or no-tillage farming systems and incorporation of cover crops into crop rotations to reduce soil erosion, water pollution and greenhouse gas emissions. No-till management can effectively control soil erosion and surface sealing (Tebrugge and During, 1999; Williams *et al.*, 2009) and can also improve soil quality and health by increasing soil organic matter content (Weil and Magdoff, 2004). Use of deep ripping tillage to alleviate compaction disrupts the surface mulch that develops after years of no-till management, increasing the soil's susceptibility to erosion and sealing.

The need to maintain sustainable crop production and a healthy environment re-establish the important role of crop rotation (Ball *et al.*, 2005) though it has been practiced for thousands of years. The possibility of using “plant roots as tillage tools” was investigated by Elkins (1985) . However, there have been few studies on the effects of pre-existing bio-pores (root channels and earthworm holes) on plant root growth (Wang *et al.*, 1986). In the few studies published (Materechera *et al.*, 1992; Merrill *et al.*, 2002), there is a generally agreement that roots with greater diameter (often tap-rooted dicots) are more capable of penetrating strong soils than roots with smaller diameter (usually fibrous-rooted monocots), although the mechanisms for this difference are not clearly understood (Clark *et al.*, 2003). The ability to penetrate strong soils varies among species and among cultivars within species (Materechera *et al.*, 1991; Merrill *et al.*, 2002).

It is therefore important to study a range of species and/or cultivars to evaluate their potential use as “tillage tools”. For example, Rasse and Smucker

(1998) found that maize after alfalfa achieved a higher percentage of roots in the subsoil than maize after maize, a finding which is in agreement with Materechera et al. (1991)'s conclusion. However, Cresswell and Kirkegaard (1995) found that a previous canola crop did not improve wheat rooting depth, though it did increase the wheat grain yield. Cresswell and Kirkegaard suggested that perennials might be more capable of providing root channels in compacted soils than annuals. It has been suggested (Cresswell and Kirkegaard, 1995) that it is possible for an annual species to be effective at "Biodrilling" the soil to the benefits of following crops by providing deep root channels. The observation of soybean [*Glycine max* (L.) Merr.] roots growing through compacted plowpan soil using channels made by decomposing canola cover crop roots confirmed this (Williams and Weil, 2004). In Middle-Atlantic region of USA erratic precipitation and high evapotranspiration during the summer crop growing season typically results in plant water stress that result in yield reduction where irrigation is not available. This is more so where compacted soil prevents crops from growing deep root systems, but instead promotes extensive shallow roots. Water stored in the subsoil horizons is usually enough to meet crop requirements and avoid drought stress if this stored subsoil water is made available to plant roots.

The incorporation of Brassica cover crops into the maize-soybean rotation systems in the Middle-Atlantic region may provide multiple benefits (Weil and Kremen, 2007). Dean and Weil (2009b) reported that Brassica cover crops were more effective than by rye in reducing the leaching loss of nitrogen. Maize following a Brassica cover crop (forage radish) achieved the same improvement

in yield as it did following a legume cover crop; Jones (2008) suggested that the increase of maize yield may be due to the benefit of “biodrilling” provided by forage radish. However, quantitative studies on the ability of Brassica cover crops to alleviate soil compaction for summer crops and to enhance subsoil water uptake are needed. Our objectives were (1) to compare the effects of four cover crop treatments, [forage radish (FR), rapeseed (rape), rye and no cover (NC)] on the vertical penetration of maize roots into soils at three levels of traffic compaction; (2) to determine maize water uptake at 15 (interface of loosened and compacted layers) and 50 cm (below compacted layer) depths as affected by cover crops; and (3) to compare the effects of cover crops and levels of soil compaction on maize yield.

## **2. Materials and Methods**

### *2.1 Site and soil description*

Two experiments were located in adjacent fields (NF-2B and NF-2C) on the north farm of the USDA Wallace Agricultural Research Center at Beltsville, MD, a site that is in the coastal plain ecoregion in Maryland (39°01'N, 76°55' W). The annual precipitation (1971-2000 average) is 1125 mm and the average precipitation from May to mid-August during maize growing season is 355 mm. The precipitation deviations from the above value during May – mid-August were -202 mm in 2007 and +135 mm in 2008 (Figure 5.1).

Experiment 1 was established in field NF-2B in August 2006 and continued until September 2008. Experiment 2 used some of the same treatments



as experiment 1, and was conducted in field NF-2C for one year (August 2007 to September 2008). The two sites were limed in April of 2005 at a rate of 1,020 kg ha<sup>-1</sup> (calcium carbonate equivalent, dolomitic limestone). Prior to our experiments, conventional tillage consisting of moldboard plow followed by disking was used in both fields. The near-term cropping history for the Experiment 1 field was potato (*S. tuberosum*) during summer 2005 followed by rye cover crop planted in fall 2005. Near-term cropping history for Experiment 2 field site was green bean (*phaseolus vulgaris*) during summer 2005 followed by rye cover crop planted in fall 2005, and Zucchini (*cucurbita pepo*) during summer 2006 followed with grain rye planted in fall 2006. The soil series for the Exp. 1 field varied from Elsinboro series (fine-loamy, mixed, semiactive, mesic Typic Hapludults) at the west end to Woodstown series (fine-loamy, mixed, active, mesic Aquic Hapludults) in the east end with 0-5% slope in the east-west direction. The soil series at Exp. 2 (NF-2C) varied from Elsinboro series at the southwest side to Galestown series, gravelly variant (siliceous, mesic Psammentic Hapludults) at the southeast side of the field. For the Exp. 1 field, the A horizon soil texture ranged from sandy loam (12.5% clay) to loam (18.2% clay); In the Exp. 2 field, the A horizon soil texture ranged from very coarse loamy sand (5.1% clay) to loamy sand (7.0% clay). Due to the variation of soil properties, both sites were divided into four blocks so as to make each block as homogeneous as possible with regard to soil properties.

## *2.2 Experimental design and treatments*

A randomized complete block design was used for both fields. In Exp. 1, three levels of compaction (high, medium and no compaction) and four levels of cover crops (forage radish, rape, rye and no cover) were combined in a factorial arrangement to provide a total of 12 treatments in each block. The dimensions of each plot were 3.0 m X 9.0 m. The blocks were separated by a 10.7 m wide alley for turning the tractor and equipment during creation of the compaction treatments and during crop planting. Due to the smaller field size available, Exp. 2 included all three compaction levels but only three cover crop levels (forage radish, rye and no cover) for a total of nine treatment combinations in each block. Table 5.1 lists treatment combinations for both experiments. The plot dimensions in Exp. 2 were 3.3 m X 12.2 m. One 12.2 m wide alley separating Blocks I and II from blocks III and IV to allow for maneuvering farm machinery.

Prior to establishment of the compaction treatments in late July 2006 (Exp. 1) and late July 2007 (Exp. 2) respectively, each field was deep-ripped to an average depth of 45 cm, followed by moldboard plowing to an average depth of 32 cm and finally disked to approximately 8 cm depth. The two fields were irrigated (7.2 cm of water) to saturate the soils on August 16 and 18, 2006 for Exp. 1, and August 13 and 16, 2007 for Exp. 2. For Exp. 1, a John Deere 544C tractor (axle load 11.88 Mg with solid rubber tires and a rear tire contact area of 1,652 cm<sup>2</sup>) was used to establish the compaction treatments on August 18, 21, and 22, 2006. High compaction treatments consisted of two passes on the entire plot surface area (each pass required four trips offset horizontally so that each set of

tire tracks was adjacent to the previous set). 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 with the tractor without rocks in the bucket and no compaction had no pass by the tractor. For Exp. 2, a single pass with the same John Deere 544C tractor was used to create the high compaction treatment, a single pass with a John Deere 7220 tractor (axle load 5.83 Mg with pneumatic tires and a rear tire contact area of 1,610 cm<sup>2</sup>) was used to create the medium compaction treatment, and no tractor traffic occurred for the no compaction treatment on August 17 and 19, 2007.

### *2.3 Crop/plot management*

After the compaction treatments were imposed, the soil in both experiments was disked to a depth of approximately 8 cm on August 25, 2006 (Exp. 1) and August 29, 2007 (Exp. 2). Cover crops were seeded in late August, 2006 and 2007 at Exp. 1, and August 29, 2007 at Exp. 2 using a no-till drill. Cover crop species seeding rates were 14 kg ha<sup>-1</sup> for FR, 9 kg ha<sup>-1</sup> for rape (Exp. 1) and 134 kg ha<sup>-1</sup> for rye. On September 22, 2006, nitrogen fertilizer (urea ammonium nitrate) was applied at a rate of 28 kg ha<sup>-1</sup> because of the observed nitrogen deficiency. To ensure vigorous growth, in 2007 the cover crops in both experiments were planted with the use of a starter nitrogen fertilizer (urea ammonium nitrate) at a rate of 22.4 kg ha<sup>-1</sup>.

Forage radish was frost-killed in the winter when temperature fell below -7°C. Rye, rape and weeds on no cover plots were killed on April 16, 2008 (both

Exp. 1 and 2) using gramoxone (1,1'-Dimethyl-4,4'-bipyridinium dichloride) at a rate of 4.68 L ha<sup>-1</sup> with surfactant of 0.73 L ha<sup>-1</sup> on April 11, 2007 (Exp. 1), and a combination of Glyphosate (N-phosphonomethyl glycine) (4.68 L ha<sup>-1</sup>) and 2,4-D (2,4-dichlorophenoxy acetic acid) (2.34 L ha<sup>-1</sup>). In late April 2007 and 2008 four 76 cm wide rows of maize (*Zea mays*, cultivar 'Pioneer' 34B62) were no-till planted in each plot (74,000 seeds ha<sup>-1</sup>). A starter fertilizer (34-0-0 granular ammonium nitrate) at a rate of 22.4 kg N ha<sup>-1</sup> was applied at planting. In middle May of both years, glyphosate (4.68 L ha<sup>-1</sup>) and 2, 4-D (2.34 L ha<sup>-1</sup>) were sprayed to control weeds and kill any rape that had not been killed by the earlier application. Urea ammonium nitrate (30-0-0) was side dressed at a rate of 112 kg/ha in mid-June of both years.

Maize silage was harvested by hand in mid August 2007 and 2008. Maize plants in 3 m-length of the two central rows per plot were cut 1 cm above the soil surface. The fresh weight and total plant counts in the harvest area (6 m x 0.76 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. Following silage harvest on August 24 2007 (Exp. 1), the field was sprayed with Glyphosate (4.68 L ha<sup>-1</sup>) to kill weeds prior to planting the second-year cover crops.

In July 2007 in Exp. 1 the soil was too dry and hard to allow planned deep soil core sampling. Therefore 23 mm and 51 mm of irrigation water were applied on July 2, and July 23-25, respectively, to moisten the soil sufficiently for these measurements to be made. In 2008, both Exp. 1 and Exp. 2 received a total of

102 mm of irrigation water to make possible deep soil coring, but the irrigation was delayed until July 30 to August 7 so that the treatment effects on soil water use could be monitored during all of July, a critical period for maize water uptake.

#### *2.4 Soil compaction measurement*

Soil strength measurements and soil cores were taken immediately after application of compaction treatments in August 2006 (Exp. 1) and August 2007 (Exp. 2) and again in spring 2008 (both experiments). A recording cone penetrometer (Spectrum Technologies, Plainfield, IL) was used to measure soil strength. The penetrometer has a 10 mm diameter steel rod with a 25 mm long and 15 mm maximum diameter cone tip integrated with a strain gauge and data logger. At each location, the penetrometer was pushed by hand at a constant rate down to the depth of 45 cm. Mean penetration resistance was recorded in kPa for every 5 cm depth increment to 45 cm. Penetration resistance was measured at 10 randomly selected locations per plot. In Exp. 2, because of the high content of gravels in block III (ranging from 24% to 68% by weight at 5 to 40 cm depth), a drop-hammer type dynamic cone penetrometer designed for stony soils (Herrick and Jones, 2002) was used. Concurrent with measuring soil strength, 10 undisturbed soil cores (diameter of 1.85 cm) per plot were taken to 40 cm depth. Because of the just described high gravel content of the soil, in block III of Exp. 2, soil samples were taken to 40 cm using a drop-hammer corer with inside diameter of 6.4 cm. The cores were divided into 5 cm increments, weighed, dried and re-weighed to determine soil bulk density and soil moisture content. These soil

strength measurements and soil cores were taken immediately after application of compaction treatments in August 2006 (Exp. 1) and August 2008 (Exp. 2) and again in spring 2008 (both experiments).

### *2.5 Root penetration measurements*

Vertical penetration of maize roots was measured using the core break method which counts only non-brittle living roots (Noordwijk, 2000). Soil cores were collected to a depth of 50 to 60 cm (maximum depth based on machine capability in these soils) using a tractor-mounted direct-drive hydraulic soil coring machine (Giddings, Inc., Windsor, CO) with a sampling tube of 6.4 cm inner diameter. In each plot, three cores were collected in the two central non-wheel track inter-rows (where no wheel trafficking was received after compaction treatments were applied) 5 cm away from representative maize plants. The cylindrical soil cores collected were laid in horizontal holding troughs made of PVC plastic. 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 to 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 as the sum for the two break surfaces. Core break root counting was done in late July and early August 2008 to examine the vertical distribution of maize roots.

## *2.6 Soil moisture measurement and calibration*

From late June to middle August in both 2007 and 2008, granular matrix electrical resistance sensors (Watermark™, Irrrometer Co., Riverside, CA) were placed at 15, 50 cm depth between the two central maize rows in plots of FR, rye and no cover crop under high and no compaction treatments to measure the soil moisture status. The sensor was glued to the end of a PVC pipe of the same diameter and the wire leads directed inside the pipe. A slide hammer driven probe was used to make pilot holes to a depth of 15 or 50 cm. A previously water-saturated sensor was pushed to the bottom of the hole which was bit smaller in diameter than the sensor so that there was good contact between the sensor and the soil. Bentonite clay was used to seal the surface around the protruding pipe so that no surface water could percolate downwards along the tubes. The electrical resistance readings were adjusted for soil temperature and converted by dataloggers (Watermark monitor 3.1, Irrrometer, Inc., Riverside, CA) to hourly readings of soil water tension in units of kPa.

To calibrate the sensors with respect to soil water contents, soils from 15 and 50 cm depth of each experimental site were dried, ground and packed in 15.5 cm diameter, 18 cm deep containers to the same bulk densities as measured in the field (i.e. mean bulk densities for high and no compaction for 15 cm depth). Two Watermark sensors were buried inside each calibration container. Starting with saturated soil, the soil was allowed to slowly dry and water tension and container weight were recorded twice daily. The calibration continued until the sensor reading reached its upper limit (239 kPa). Best fit equations relating soil water

tension and content were developed by non-linear least squares regression. The resulting calibration equations were used to convert field water tension measurements to volumetric soil water contents.

### *2.7 Statistical analysis*

Analysis of variance was performed using PROC MIXED (SAS v. 9.1, SAS Institute, Cary, NC). As described previously, both experiment 1 and 2 were randomized complete block designs with a factorial arrangement of compaction and cover crop treatments. Treatment effects were considered significant when F value was less than 0.05. Mean daily soil moisture content was analyzed using time as a repeated measurement to fit the best variance structure by comparing AIC (Akaike information criterion), BIC (Bayesian information criterion) and AICC (finite-population corrected AIC) values. (The smaller the values are, the better the model is.) All mean comparisons were done at the same soil depth to avoid any confounding factors caused by the variation of soil properties at different depths. For each variable in the study, mean comparison was done using PDIFF option of the LSMEANS statement when the F test was significant (<0.05). Correlation analysis was performed to explore relationships between maize root counts and soil bulk density, between maize root counts and cover crop root counts (Chen, 2009), and between maize root counts and soil water content reached in late July. Proc Model (SAS v. 9.1, SAS Institute, Cary, NC) was used to find the best-fit nonlinear regression equations for soil moisture calibrations based on the maximum R square.



### **3. Results**

#### *3.1 Soil bulk density and penetration resistance following compaction and cover crop treatments*

Figure 5.2 presents soil bulk density under three compaction treatments in two experiments. Because the effect of cover crop on bulk density was not significant and because there was little difference in bulk density between the two measuring times, only data from spring 2008 is shown. In Exp.1, bulk density under medium and high compaction was greater than that under no compaction at 10, 15, 20, 35 and 40 cm depths. Bulk density of high compaction was only greater than that under medium compaction at 15 cm. In Exp. 2, bulk density for high and medium compaction treatments differed from that for no compaction treatment at all depths between 5 to 25 cm. Bulk density of high compaction was greater than that of medium and no compaction at 30 cm. No treatment effect on bulk density was found below 30 cm.

No significant cover crop effect on penetration resistance was observed. Figure 5.3 presents soil penetration resistance for the three compaction treatments in Exp. 1 and 2. Because soil penetration resistance varies with water content (Bengough, 1997), no attempt was made to compare penetration resistance at two different times. In Exp. 1, penetration resistance differed among each of the compaction treatments from 5 to 25 cm; penetration resistance under high compaction was greater than that under medium and no compaction at 35 cm; penetration resistance of no compaction was less than that of medium and high compaction at 45 cm. In Exp. 2, penetration resistance under high compaction

was greater than that under medium and no compaction at 15-25 cm, penetration resistance under medium compaction was greater than that under no compaction at 20-30 cm depth.

### *3.2 Hourly changes in soil water during maize growing season*

Figure 5.4 and 5.5 present the soil volumetric water content at 15 cm depth, in Exp. 1 and Exp. 2 respectively for the period from June 25 to July 30, 2008 when no irrigation water was applied. At 15 cm depth in Exp. 1, soil in the HNC and NNC had the highest and lowest water contents, respectively, while soils in the HFR, NFR, Hrye and Nrye treatments had intermediate ranges of water contents between the high and low boundaries. In Exp. 2 at 15 cm depth, soils in NFR treatment had the lowest water content; soils in Hrye, HNC and Nrye treatments had the highest water contents.

Figure 5.6 and 5.7 present the soil volumetric water content at 50 cm depth, in Exp. 1 and in Exp. 2, respectively, during summer 2008. There was a significant ( $\alpha < 0.01$ ) interaction of cover crop x compaction x time in both experiments. In Exp. 1 (Figure 5.6), soil in the HNC treatment had the greatest water content during most of the period, except from June 29 to July 10 when soil in the Hrye treatment had greater water contents than HNC. Soils in the Nrape treatment had the lowest water content during the whole period. Soil water contents in HFR treatment soils were close to those in the NNC treatment soils, and soil water contents in both HFR and NNC differed from that in the Nrape treatment after July 7. Soil in Hrape treatment had relatively high soil water

contents in late June, and then water content decreased rapidly after July 3 and reached the same low levels on July 24 as were present in the HFR treatment. HRye treatment soil had similar water contents on most days as those of HNC, but the soil water contents were slightly lower in late July. Soils in Nrye and NFR treatments were in between the high and low water content boundaries. In Exp. 2 at 50 cm, soil water contents in all treatments were gradually declining during maize growing season. In late June at 50 cm depth, there were generally two moisture regimes (Figure 5.7 a. b): soils in HFR, NFR and NNC treatments had slightly less water content; soils in Hrye and Nrye treatments had greater water content. From then on till the end of July, water content in soils of HFR and NFR treatments were slowly and steadily decreasing; water content in soils of Nrye treatment decreased rapidly from July 10, and reached the same water content level as soils in FR treatment on July 25. Water content in soils of NNC treatment was decreasing but at a slower pace compared to soils of NFR and Nrye treatments. There was only a slight decrease in soil water content in plots of HNC and Hrye treatments, and the soil water content in these plots was always the highest during the whole growing season.

### *3.3 Vertical penetration of maize roots*

Figure 5.8 presents the maize root penetration in Exp. 1. Under high compaction (Figure 5.8 a), maize in Hrape treatment had the most roots and differed in the number of roots in HFR, Hrye and HNC treatments from 20 -40 cm depth. Maize in HFR treatment had more deep-roots than in HNC or Hrye only at

45 cm depth. Under medium compaction (Figure 5.8 b), maize had the fewest roots in MNC and had more roots in MFR than in MNC at 15, 30 and 35 cm depth. Under the no compaction (Figure 5.8 c), the various cover crop treatments had similar maize root counts at each depth.

Figure 5.9 shows maize root counts following the different cover crops for Exp. 2. Under high compaction (Figure 5.9 a), maize in HFR treatment had the most roots at the deeper depths while no difference in number of maize roots was observed in Hrye and HNC treatments. Under medium compaction (Figure 5.9 b), maize root counts in MFR were significantly greater than those in MNC or Mrye treatments only at 35 and 40 cm depths. Under no compaction (Figure 5.9 c), maize in Nrye treatment had the most roots from 10-40 cm; while maize in NFR and Nrye treatments had more roots compared to NNC treatment from 35-60 cm depths.

#### *3.4 Relationships between maize root counts and soil bulk density, maize and cover crop root counts, maize root counts and soil water content at 50 cm depth*

Figure 5.10 presents the linear regression of maize root counts against soil bulk densities for both experiments. In both experiments, maize roots decreased linearly with an increase of bulk density.

Relationships between root counts at 20-50 cm depth for maize in early August 2008 in Exp. 2 and cover crops root counts at that depth in November, 2007 are presented in Figure 5.11. Forage radish roots were significantly correlated with maize roots for all compaction levels (Figure 5.11 a). Roots of rye

cover crop and maize were not correlated across compaction levels. Pooled roots of FR and rye cover crops were well correlated with maize roots only under high compaction (Figure 5.11 b), but not so under medium or no compaction treatments. No significant correlation between November 2007 cover crop root counts and August 2008 maize root counts was found in Exp.1.

Figure 5.12 presents the regressions between soil volumetric water contents at 50 cm depth reached on July 24 and root counts (average of 45-55 cm depth) observed in late July, 2008 across four blocks for each experiment. Soil water content declined linearly as root counts increased for both experiments.

### *3.5 Maize plant stands and yield*

Table 5.2 shows the effects of compaction and cover crops on maize plant stands and silage yield. There was no interaction of compaction and cover crop treatments. In Exp. 1, 2007, maize had more plants following FR and rape than following NC or rye. Maize yield was the highest after FR and the lowest after NC, while maize yields after rape and rye were intermediate. There was no compaction effect on maize yields in Exp. 1 either both 2007 and 2008. In Exp. 1, 2008, maize had better stand density following FR and rape, and lowest plant density following rye cover crop; maize had higher stand density under medium compaction than under no compaction; and maize silage yield was lower after NC than after any other cover crop treatments. In Exp. 2, 2008, there was no difference in maize stand density among all treatments; maize yields were lower

after NC than after FR or rye cover crops, and lower under high compaction than under medium or no compaction.

#### **4. Discussion**

##### *4.1 Changes in soil water content at 15 cm depth from 25 June – 31 July.*

In addition to plant uptake and transpiration, soil water content at 15 cm is affected by differences in rates of evaporation, drainage and infiltration rates during precipitation events. The killed rye cover crop left a thick surface mulch that persisted during the summer. Very little FR residue remained by summer, resulting in the FR soil being mostly bare but punctuated by large holes left by the FR roots. The soil in the no cover crop plots had intermediate amounts of residues left by winter weeds killed before maize planting (see Figure 5.13).

During most of July the surface horizon (15 cm) was driest in the FR treatments for the high compaction soil in Exp. 1 (Figure 5.4) and regardless of soil compaction level in Exp.2 (Figure 5.5), probably because almost no FR residue was left by this time and because the large (1 to 5 cm diameter) holes left by FR roots encouraged rapid soil drying by both drainage and evaporation.

In both Exp.1 and Exp.2, the soil in the high compaction plots tended to be wetter than in the no compaction plots, regardless of cover crop treatment (Figures 5.4 and 5.5). However, in Exp. 1, soil compaction had by far the greatest effect on soil water content in the NC plots. The soil at the 15 cm depth in the Exp. 1 NC plots was consistently the driest among the cover crop treatments in the no compaction plots, but consistently the wettest in the high compaction plots

(Figure 5.4). In contrast, compaction level had little effect on soil water in the rye treatment plots in Exp. 1. In Exp. 2, by contrast, compaction had much less effect on soil water content for the NC plots (Figure 5.5).

In Exp. 1, the soil water content increased more in response to rain events and declined more rapidly thereafter in the rye treatment plots than in the other cover crop treatments. However, in Exp. 2, soil water rose and fell nearly in parallel by all cover crop treatments, with the exception of less response by HFR to the rain events on 24 and 27 July.

Soil water content at the 15 cm depth following NFR and NNC treatments was less than that observed following HNC treatment throughout the season. In Exp. 2, soil moisture in HFR treatment was greater than that in NFR treatment (Figure 5.5 a and b). Starting from early July in Exp. 1 and late July in Exp. 2, soil water content in the Hrye/Nrye treatments decreased faster and was significantly lower than the soil water content was in the HNC treatment (Figure 5.4 a and 5.5 a), suggesting that in the rye treatment more maize roots had penetrated to the compacted zone by that time. We ascribe the abrupt decline of soil moisture in early July in the Hrye and Nrye treatments Exp. 1 and 2 to progressive maize root growth and resulting increases in water uptake. The higher water content in plots of HNC treatment suggested that there were fewer roots in the compacted layer to take up water. That soil moisture content in both experiments followed a similar pattern (wet in plots of HNC treatment, dry in plots of FR treatments, and rapid change from wet to dry in plots of rye treatments) suggests similar cover crop effects on maize root growth in the compaction treatments.

One of the most striking effects of the compaction treatment was that it accentuated the diurnal fluctuation of soil water content. On a daily basis, soil water content decreased in response to drying during the daytime when evapotranspiration is active and increased at night when evapotranspiration nearly ceases. The nightly increases in soil water most likely resulted from capillary adjustments bringing water up from wetter layers and root exudation of water from the relatively high water potential in the roots in the absence of evaporative demand toward the lower water potential in the dry soil. In Exp. 1 (Figure 5.4) this diurnal pattern was very consistent and pronounced in the high compaction soil, but virtually absent in the no compaction soil. We speculate that the diurnal changes may be more pronounced where compaction has compressed most of the inter-aggregate macropores into micropores that enhance the potential for capillary adjustment. This reasoning is supported by the fact that the diurnal soil water content fluctuations were consistently evident in both high and no compaction treatments at the 50 cm depth (Figures 5.6 and 5.7), where the bulk density is greater and micropores more predominant, regardless of compaction treatments.

#### *4.2 Changes in soil water content at 50 cm depth from 25 June – 31 July.*

At 50 cm depth, the effect of evaporation, precipitation and drainage on soil water content should be smaller in magnitude and less variable with time. At this depth, the decreases in soil water content were mainly due to root uptake of water. Rasse and Smucker (1998) reported that maize roots reached the Bt



(subsoil) horizon in their study within 40 days after planting. In 2008, maize was planted in our study on April 14, and soil moisture recording started on June 25 for both experiments. Though there was a cool, wet period after maize was planted in 2008, we expected that there would be maize roots at the 50 cm depth by late June (70 days after planting) where compacted soil did not inhibit their downward growth. Because for Exp. 1 the last tillage operation and the imposition of the compaction treatments occurred in summer 2006, the summer 2007 maize crop most likely resulted in the presence of more intact root channels by the time of soil water monitoring (summer 2008), in plots of Exp. 1 than in Exp. 2, even where no cover crops were grown. This fact, along with the generally coarser textured soil, helps explain some of the differences in water regime and rooting behavior between the two experiments.

Increases in soil water content at the 50 cm depth in response to rain events (especially those on 28 June and 29 July) were obvious only for rye and rape cover crop treatments (Hrye, Nrye, Hrpe, Nrpe) which had heavy surface mulch of spring-killed cover crop residues. The rapid increase in subsoil water content following the rainfall events for these treatments was probably due to greater infiltration rate for the soils with heavy residue mulch. This explanation is supported by air permeability measurements (data not shown here) that revealed greater air permeability in Hrpe than in HNC, Nrye or HFR (Chen, 2009). The surface mulch effect on water increases at 50 cm was more pronounced in Exp. 1 (Figure 5.6) than in Exp 2 (Figure 5.7), most likely because in the latter few undisturbed root channels from the previous year's crop would have been present

to promote preferential flow of water to the subsoil layers. In both experiments, the plots with little surface residue (HFR, NFR, HNC, NNC) showed little or no soil water increase at 50cm in response to rain events. These results highlight the importance of a mulch-protected open, surface structure in allowing recharge of subsoil water.

With no compaction in Exp. 1, maize roots in the Nrye rapidly penetrated to 50 cm and took up water resulting in a progressive drying trend during July such that by 20 July the water content of Nrye soil was essentially the same as that for NFR and NNC (Figure 5.6 b). Under high compaction in Exp. 2, soil water content in Hrye and HNC remained much higher suggesting that fewer maize roots had been able to penetrate to 50 cm in those treatments than in HFR (Figure 5.7 a). The lowest level of water use, and hence maize root penetration, appeared to occur in HNC of Exp. 1.

In both experiments the Brassica cover crop treatments (NFR, HFR, Nrape and/or Hrape) had lower soil water contents at 50cm early in the monitoring period than did Nrye, Hrye, NNC or HNC, suggesting that more maize roots had penetrated to and were using water from the 50 cm deep soil by late June. The difference in soil water content at 50 cm persisted through July, indicating a continued greater maize rooting at that depth in the Brassica cover crop treatments. This interpretation of the soil water data is supported by the fact that the difference between the Brassica and non-Brassica treatments was much more pronounced in the high compaction than in the no compaction plots.

In both experiments, soil moisture regimes were similar in HFR and NNC treatments, suggesting that as many maize roots were able to penetrate to 50 cm after FR in the highly compacted soil as penetrated in the no compaction soil without a cover crop.

Williams and Weil (2004) reported very limited evidence (only a single day of soil water data) that a Brassica cover crop could enhance soil water uptake below a compacted plowpan by a subsequent summer crop (soybean in their case). Our two experiments provide very clear evidence of persistent effects of FR and rape in enhancing maize water uptake below compacted layers. Our result also suggest that rye may have enhanced water uptake below the compacted layer, but only to a limited extent and only if there were root channels available from the previous year (as in Exp. 1).

#### *4.3 Maize root counts as affected by cover crops and compaction.*

Under high and medium compaction, fewer maize roots penetrated to the deep soil layers in the NC treatment plots than in plots that had had cover crops (Figure 5.8 and 5.9). Compared to the root counts in HNC treatment plots, mean maize root counts at 20-60 cm depth were 1.8, 3.2 and 1.7 times greater in the HFR, Hrape and Hrye treatments, respectively, in Exp.1, and 2.3 and 1.2 times greater in the HFR and Hrye treatments in Exp. 2, respectively. It is, therefore, clear that cover crops increased maize root penetration. Furthermore, the data suggest that the enhanced maize root penetration was due to cover crop root channels, rather than mulch or organic matter influences as the enhancement was

greater for FR than for rye. Subsoil maize root counts in rye treatment plots were not significantly greater than those in NC treatment plots under high or medium compaction (except at 50 cm under high compaction in Exp.1). Maize in the Hrrape treatment plots in Exp.1 and in HFR treatment plots in Exp. 2 achieved the most roots in the compacted layers. In Exp. 1, maize in HFR treatment had more deep roots than in Hrye, though the difference was significant at only at few depths. Maize in Hrrape had more roots than that in HFR in Exp. 1 at most depths. The data do not conclusively determine which Brassica cover crop, FR or rape, had greater ability to provide root channels for maize in compacted soils. However, it can be concluded that in our study, the ability to increase maize root penetration in compacted soils was in the order of NC < rye < Brassica crops (FR and rape).

Under no compaction, in Exp.1 the variation of maize root penetration was generally very small among cover crop treatments because there was no compacted layer to inhibit maize root growth (Figure 5.8 c). Still, in Exp. 2 maize had more roots in plots of Nrye treatment at 10-60 depth and in plots of NFR treatment at 35-60 cm depth than were observed in plots of NNC treatment (Figure 5.9 c). Soil strength increases as soil becomes drier (Bengough, 1997). Because rye provided a heavy surface mulch that conserved soil moisture (see high moisture contents at 15 cm in Figure 5.6), soil strength in the rye treatment in July would likely have been lower than in other cover crop treatments. Also the rye cover crop could have provided some root channels through the compacted soil. In HFR compared to Hrye, even though FR left little to no residue mulch and

therefore allowed the surface soil horizons to dry out (Figure 5.6) and gain in soil strength, there were probably more root channels in the deeper soil layers which provided maize roots easier access to the subsoil moisture in HFR.

In the NC and rye treatment plots in both experiments, increasing the soil compaction level markedly decreased the numbers of maize roots penetrating to the deeper soil layers (Figure 5.8 and 5.9). However, in the FR and rape treatments, there was no effect of soil compaction level on the number of maize roots penetrating to the deeper soil layers, suggesting that these cover crop treatments had effectively ameliorated the imposed levels of soil compaction.

#### *4.4 Relationships among maize roots, soil bulk density and cover crop roots*

As already mentioned, soil strength is a dynamic parameter that varies with soil moisture. Soil moisture was not only affected by compaction, but greatly modified by cover crops. The existence of root channels from cover crops might also modify soil strength locally within a treatment plot. In order to examine the effect of compaction on maize root penetration in this study, bulk density was a more suitable parameter. Several studies have reported that maize root length in compacted layers decreased linearly (Shierlaw and Alston, 1984) or exponentially (Osuna-Ceja et al., 2006) as soil bulk density increased. Overall, maize roots in our study were also negatively related to bulk density by a linear function (Figure 5.10). This relationship was significant despite variability in maize root growth caused by the cover crop effects.

We also examined the relationships between total cover crop roots present in late fall (see Chapter 4) and total maize roots present the following summer in the 20-50 cm layer (i.e., in and below the compacted zone). Across all three compaction treatments, maize root counts were not significantly related to root counts for any of the cover crops in Exp. 1, nor were maize root counts related to the rye cover crop root counts under both no and medium compaction in Exp. 2. However, an important outcome in Exp. 2 was that maize root counts were found to be significantly related to the previous FR root counts (Figure 5.11 a). There was also a close relationship between cover crop roots (both FR and rye) and maize roots when soil was highly compacted (Figure 5.11 b). The absence of a significant relationship between cover crop roots and maize roots in Exp. 1 in 2008 might be affected by preexisting root channels made by the cover crops or the maize during the 2006-2007 study years. In Exp. 2, the surface soil in rye cover crop treatment plots usually had relatively higher water contents than in FR cover crop treatment plots. When soil water content was high (plots of rye treatment), soil strength in plots under medium and no compaction treatments would not be great enough to inhibit maize root penetration. This could explain the lack of significant relationships between cover crop roots (both FR and rye) and maize roots under no or medium compaction, and between rye roots and maize roots in Exp. 2. Our results are similar to the outcome found by Rasse and Smucker (1998) who observed that the extent of the alfalfa root system in one year was positively related to the extent of the maize root system in the following year. The significant positive relationships between FR roots and maize roots

across compaction levels and between cover crop roots and maize roots under high compaction in Exp. 2 support our hypothesis that FR cover crop roots enhance maize root vertical penetration into compacted soils.

We also found a significant relationship between maize root counts and the minimum soil water content at 50 cm depth reached in late July (Figure 5.12). This relationship suggests that as more roots explored the deep profile, more subsoil water was taken up by the plants. This observation is in agreement with other positive relationships reported between root parameters and soil water uptake. For example, Hamblin and Tennant (1987) reported that water loss during the growing season was better correlated to maximum rooting depth rather than root length density, a conclusion shared by the Parker et al. (1989). Lipiec et al. (1993) also found that higher total water uptake from undisturbed horizons was related to denser root systems.

#### *4.5 Maize plant population densities and yields*

The total amount and daily distribution of precipitation during the maize growing season had a great effect on maize plant establishment and yield (Table 5.2). In 2007, the total precipitation from May to mid-August was only 43% of that in the normal year, while the monthly precipitation in May, June and July was 11%, 103% and 30%, respectively of that in the normal year (Figure 5.1). By contrast, in 2008 the total precipitation from May to mid-August was 138% of the normal year precipitation, and the monthly precipitation in May, June and July was 212%, 148% and 89%, respectively of that in the normal year. In 2007, Exp.

1 received 23 mm and 55 mm of irrigation water in early and late July for the purposes described in the materials and methods. This irrigation alleviated some of the late season drought stress in 2007.

In 2007, compaction treatments had no effect on maize plant density or yield, but cover crop treatments did (Table 5.2). Maize following FR treatment had the most plants and highest yield; maize following rye cover crop had relatively fewer plants but yield was similar as following FR cover crop. This could be due to different mechanisms for the rye and FR effects. The FR treatment left little surface residue to interfere with no-till planting, but favored deep maize root growth to use subsoil water. On the other hand, rye left thick residue mulch that interfered with closure of the no-till seed furrow openings (resulting in lower stand density) but conserved water by reducing evaporation loss. The higher water contents in the surface soil compensated for the lower plant stands. It should be noted that the lower maize plant stand density in rye plots may have affected root counts in 2008 since all root cores were taken 5 cm from representative maize plants. Individual maize plants were larger where stand densities were lower in the rye treatment plots, so the observed root counts may have overestimated the counts averaged for the entire plot area.

In 2007, although maize achieved more plants following rape than following NC treatment, there was no significant difference in yields between these treatments. The cool and wet weather after maize planting in May 2008 caused greater variation of maize stands in Exp. 1 than in Exp. 2, because of the higher clay content and variation in profile drainage of the soils in the former. In



Exp. 1, 2008 with very wet conditions at maize planting time, the lower maize stands after rye could be due to the poor drainage or the poor soil-seed contact because of the thick mulch. The lower maize stands under no compaction compared to medium or high compaction was surprising and we can offer no explanation. In spite of the difference in plant stands, maize yield following rye cover crop was not different from that following rape or FR treatments, and maize yield following NC treatment was the lower than that following cover crops as a group. This could be due to the compensating effects of easier access to subsoil water (i.e. following FR or rape cover crops) or more surface soil water available (i.e. following rye or rape cover crops which left a thick mulch).

In Exp. 2, the cool wet weather early in the 2008 growing season had little effect on stands because the soil was sandy and well drained. In Exp. 2, maize yield was greater under no compaction than high compaction, greater after rye and FR than after NC. The reasons for the improvement of maize yield by cover crops were similar to those in Exp. 1. The marked maize yield reduction under high soil compaction was probably related to the reduction of deep roots and resulting reduced water accessible during the maize growing season.

## **5. Conclusion**

The accessibility of subsoil water to plants during dry portions of the summers in the mid-Atlantic region is crucial for crop production. Our data suggests that root channels left by cover crops could be advantageous for summer crop root penetration, particularly under high soil compaction. Our results clearly

show that, when grown following FR and rape cover crops, maize achieved a similar number of deep-roots under high soil compaction as it did under no compaction. Alleviation of soil compaction effects by these cover crops was further supported by changes in subsoil water content during July that suggested that the maize plants were able to take up more soil water below the compacted zone. The greater number of roots in the subsoil was probably one reason for the greater maize yields observed after cover crops compared with winter fallow (no cover). The cover crop effect on maize yield was more pronounced in 2007, which was a much drier growing season than 2008. Though rye roots may have provided some root channels for maize to grow under high soil compaction, the number of channels was apparently much smaller than provided by FR or rape cover crops. When grown after a rye cover crop, maize grew better, had more deep roots and took up more subsoil water under no compaction than under high or medium compaction. The thick surface mulch of rye residue reduced maize plant stands on the finer textured soil in a wet spring. This stand effect may be compensated for by the beneficial effect of the mulch on water conservation, depending on the available rainfall in the growing season and/or the access to the subsoil water. Maize following a rye cover crop grew best in the non-compacted, well-drained soil where the crop was able to achieve normal plant stands and to rapidly take up water from the surface soil and subsoil layers. Although this study did not include such a mixture, it seems logical that cover crop benefits might be maximized by using a mixed cover crop of rye and FR (or rape) planted in alternate rows. The rows of FR/rape could be located in the summer crop planting

rows to provide “biological subsoil tillage” effects and to allow better summer crop stands. The rows of rye cover crop might provide a thick mulch in the summer crop interrows to improve conservation of surface soil water for plant uptake. We recommend continued research into improved cover crop systems to alleviate soil compaction.

Table 5.1 Description of treatment combinations

Treatment combination	compaction	Cover crop
HFR	High	Forage radish
HNC	High	No cover crop
Hrape	High	Rapeseed
Hrye	High	Rye
MFR	Medium	Forage radish
MNC	Medium	No cover crop
Mrape	Medium	Rapeseed
Mrye	Medium	Rye
NFR	No	Forage radish
NNC	No	No cover crop
Nrape	No	Rapeseed
Nrye	No	Rye

Table 5.2 Corn plant stand density and silage yield as affected by cover crop and compaction treatments in each experiment–year.

Exp. #	Year	Cover crop treatment				Compaction level		
		FR	NC	Rape	Rye	High	Medium	No
Corn stand density, 10 <sup>3</sup> plants ha <sup>-1</sup>								
1	2007	69.2a*	61.0c	67.1ab	62.4bc	62.8A	66.0A	65.9A
1	2008	66.2a	60.5ab	67.4a	52.6b	62.2AB	66.0A	56.9B
2	2008	70.1a	71.0a	N/A	66.9a	71.2A	67.4A	69.4A
Corn silage yield, ton ha <sup>-1</sup>								
1	2007	10.3a	7.8c	8.3bc	9.3ab	8.8A	8.9A	9.1A
1	2008	10.6ab	9.5b	11.1a	11.8a	10.7A	11.2A	10.3A
2	2008	10.0a	8.3b	N/A	11.4a	8.7B	10.0AB	11.0A

Legend symbols: FR = forage radish cover crop treatment; rape = rapeseed cover crop treatment; rye = rye cover crop treatment; NC = no cover crop treatment.

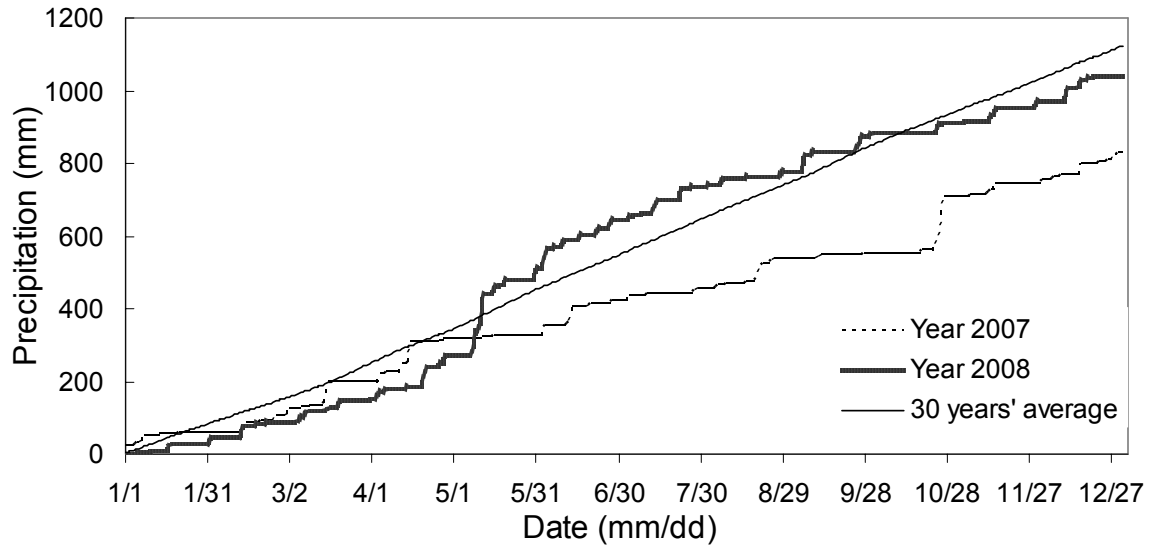


Figure 5.1 Cumulative precipitations of 30 years' average, in experimental year 2007 and 2008.

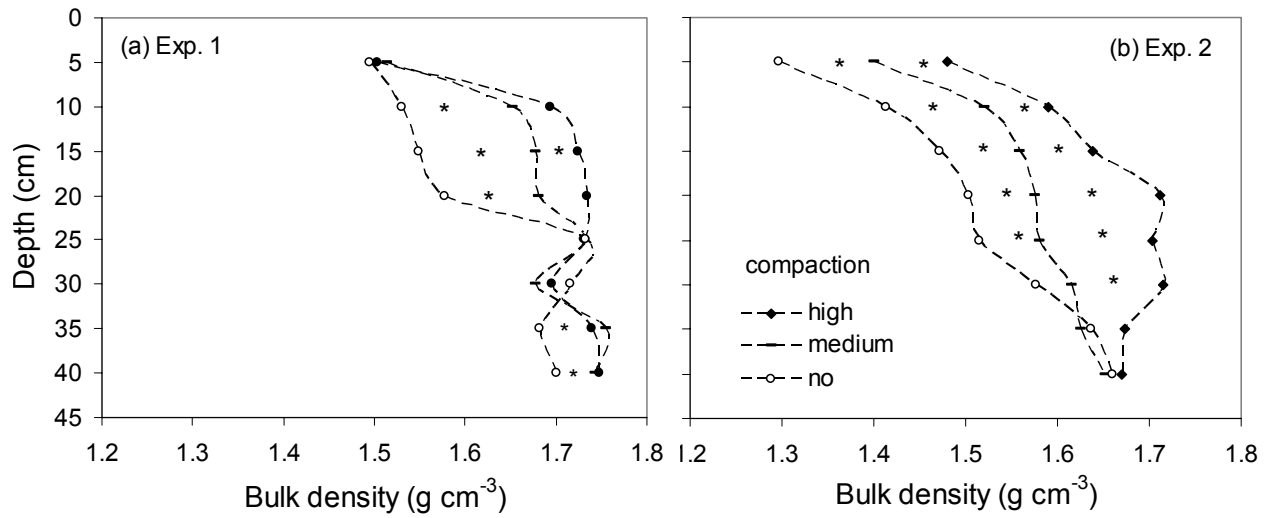


Figure 5.2 Variation of soil bulk density as a function of depth for three compaction treatments in the two experiments, in spring 2008.

\* Significant difference at  $\alpha < 0.05$  (LSD) between means at the same depth.

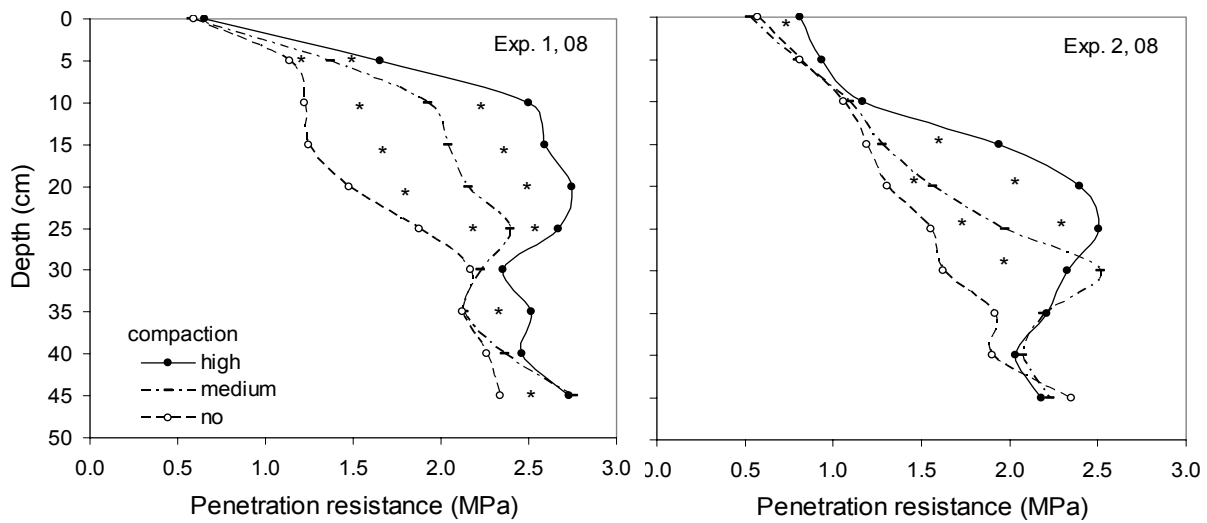


Figure 5.3 Variation of soil penetration resistance as a function of depth for three compaction treatments in the two experiments, in spring 2008.

\* Significant difference at  $\alpha < 0.05$  (LSD) between means at the same depth.

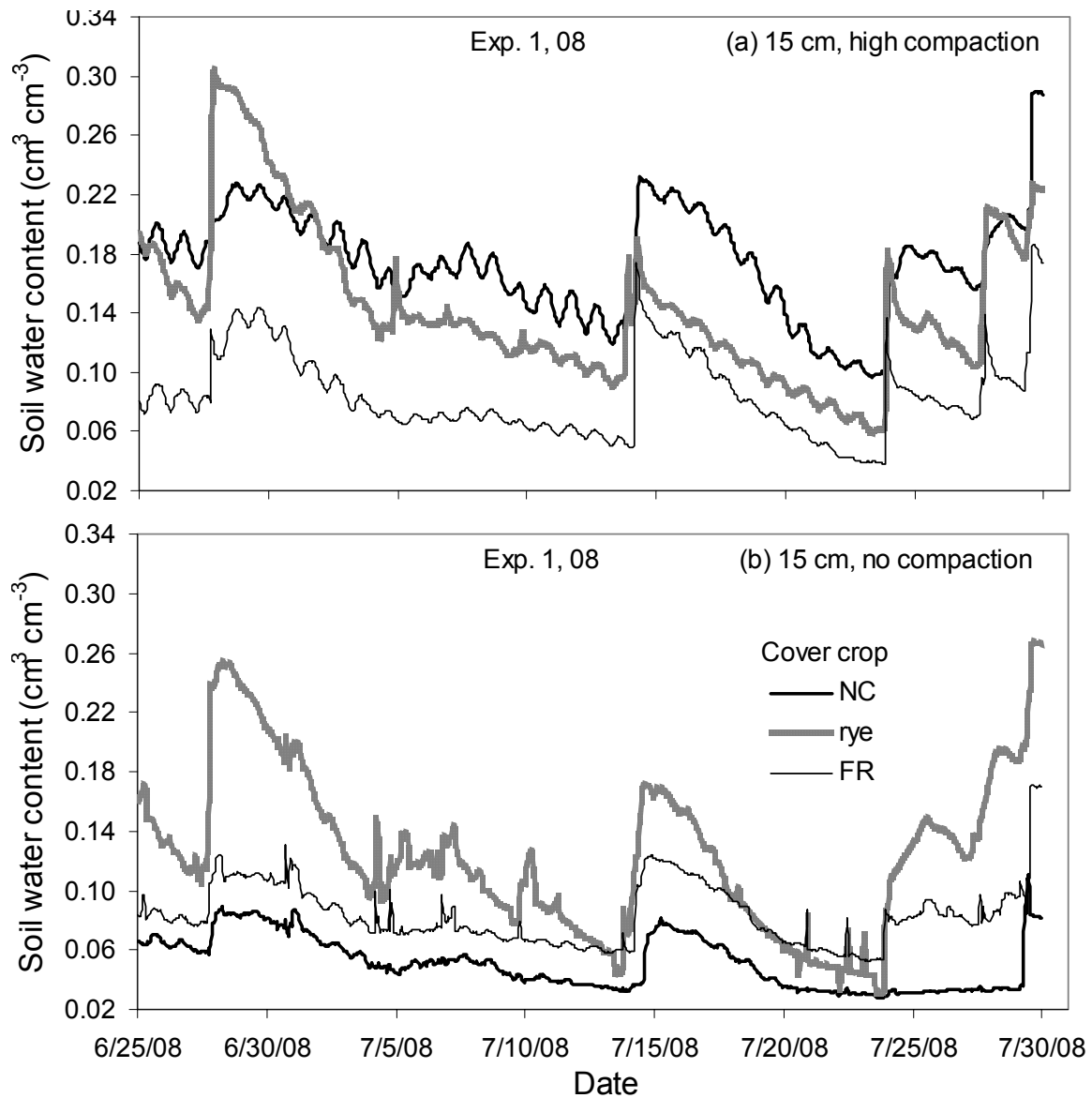


Figure 5.4 Volumetric soil water content at 15 cm depth during corn growing season, Exp.1, 2008. Each line of data shown represents the mean of data from four sensors. Legend symbols: H = high compaction; N = no compaction; FR = forage radish cover crop treatment; rape = rapeseed cover crop treatment; rye = rye cover crop treatment; NC = no cover crop treatment.

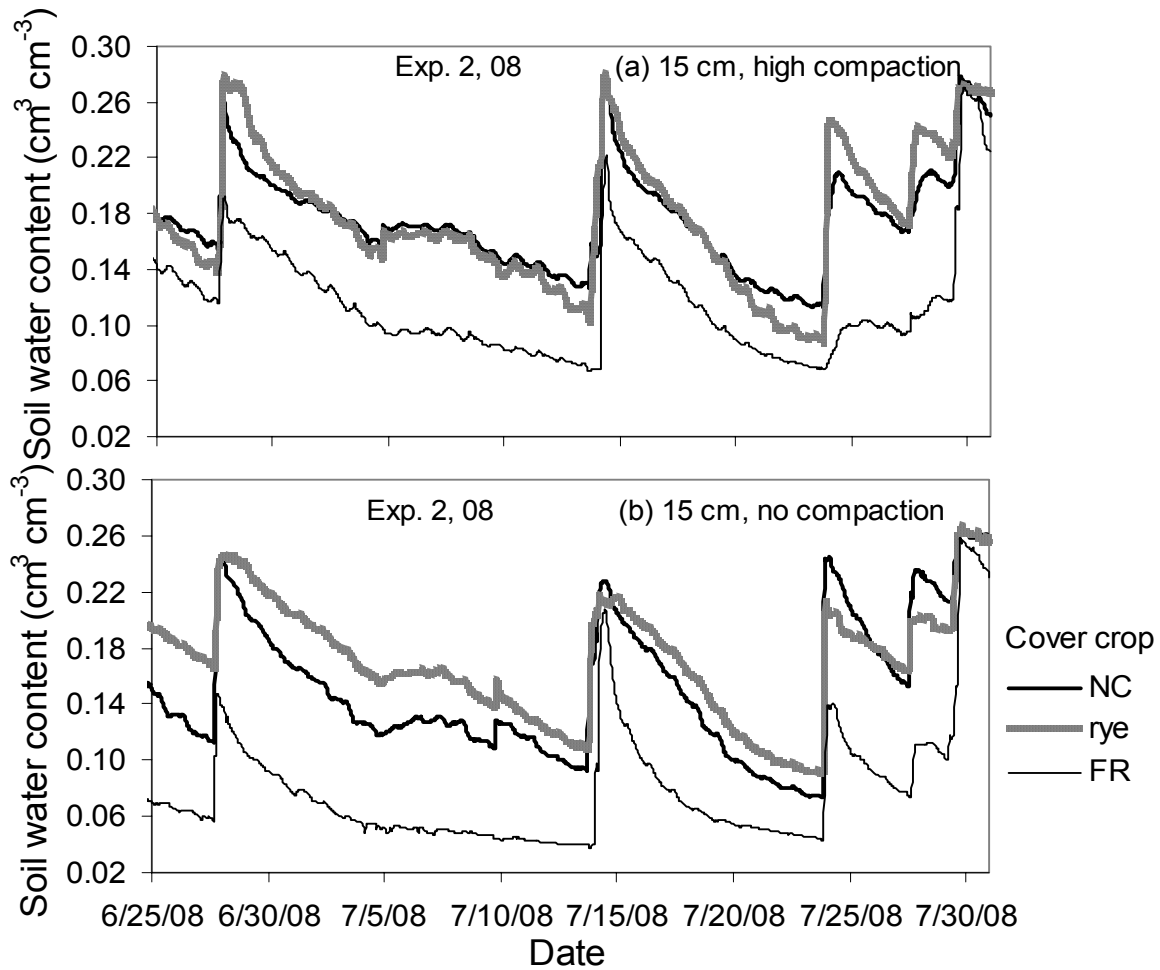


Figure 5.5 Volumetric soil water content at 15 cm depth during corn growing season, Exp.2, 2008. Each line of data shown represents the mean of data from four sensors. Legend symbols: H = high compaction; N = no compaction; FR = forage radish cover crop treatment; rye = rye cover crop treatment; NC = no cover crop treatment.



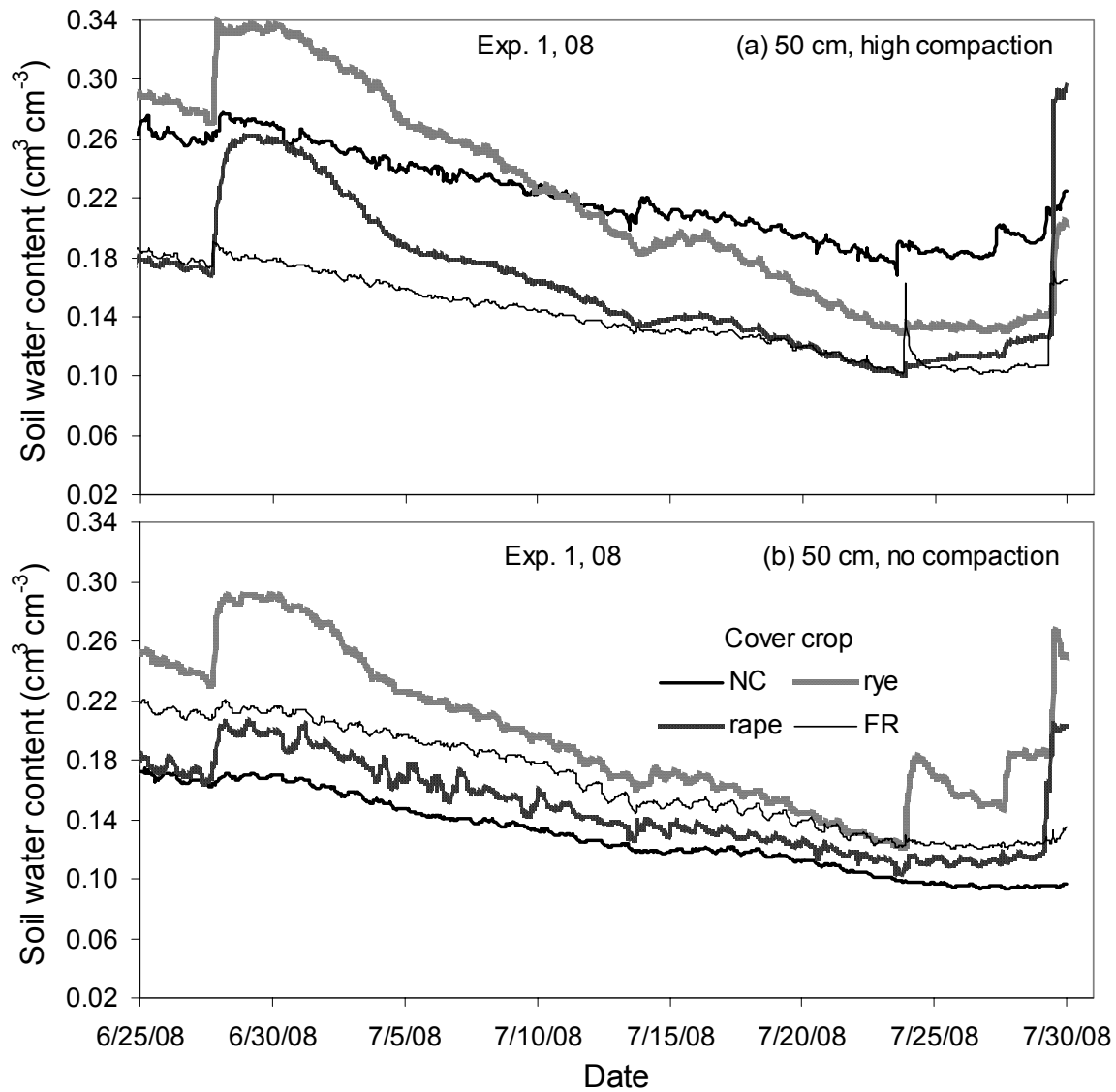


Figure 5.6 Volumetric soil water content at 50 cm depth during corn growing season, Exp.1, 2008. Each line of data shown represents the mean of data from four sensors. Legend symbols: H = high compaction; N = no compaction; FR = forage radish cover crop treatment; rape = rapeseed cover crop treatment; rye = rye cover crop treatment; NC = no cover crop treatment.

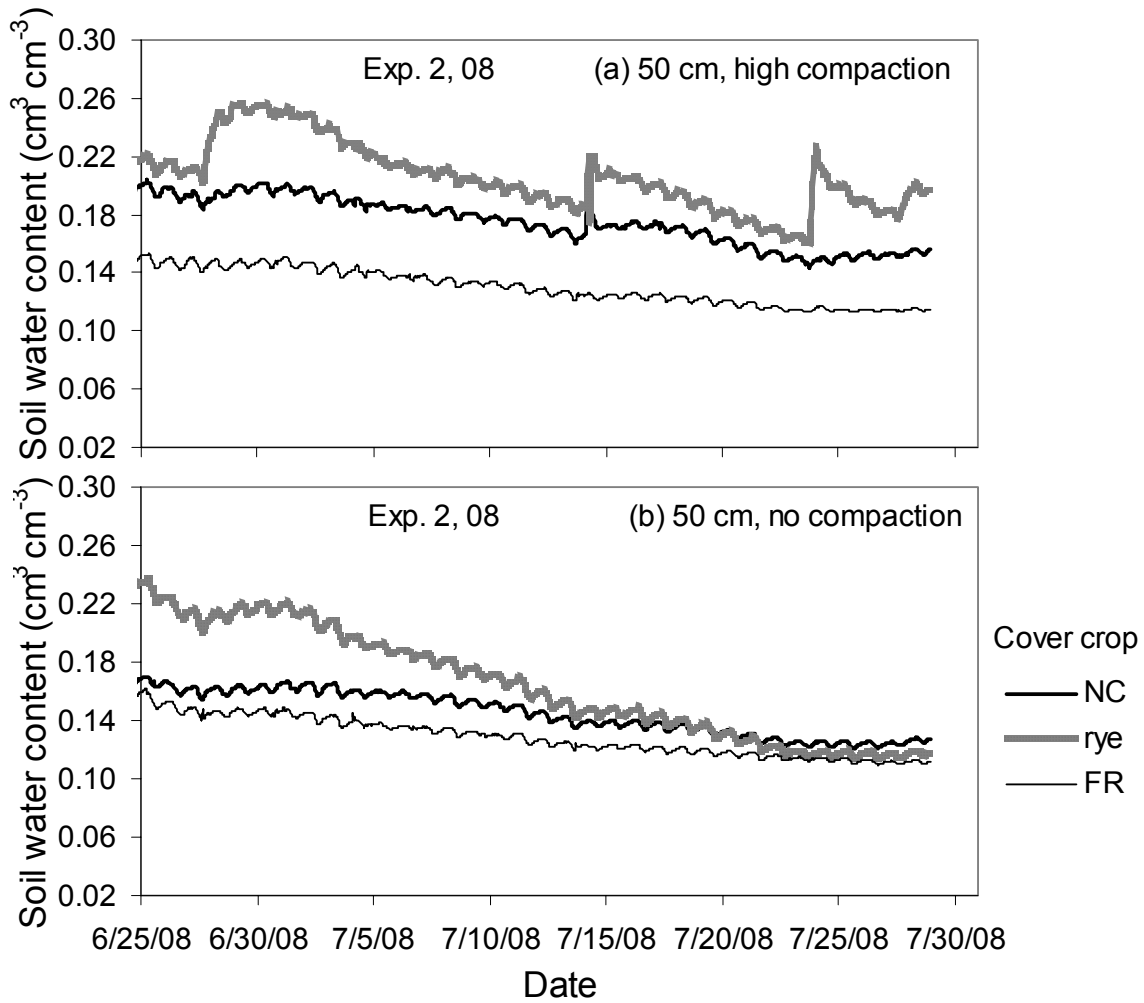


Figure 5.7 Volumetric soil water content at 50 cm depth during corn growing season, Exp.2, 2008. Each line of data shown represents the mean of data from four sensors. Legend symbols: H = high compaction; N = no compaction; FR = forage radish cover crop treatment; rye = rye cover crop treatment; NC = no cover crop treatment.

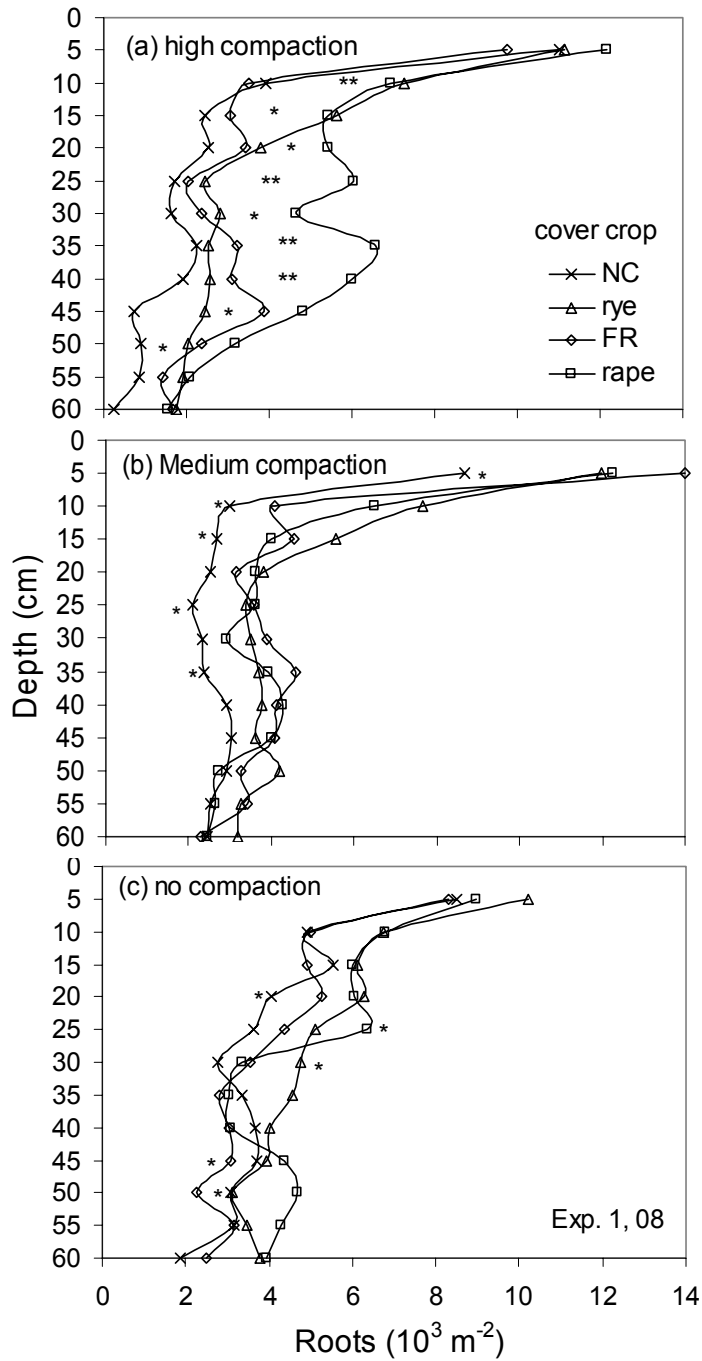


Figure 5.8 Corn roots vertical penetration followed different winter cover crops under (a) high (b) medium and (c) no compaction, Exp. 1, 08. \* Significant difference at  $\alpha < 0.05$ , \*\* significant difference at  $\alpha < 0.01$  (LSD)

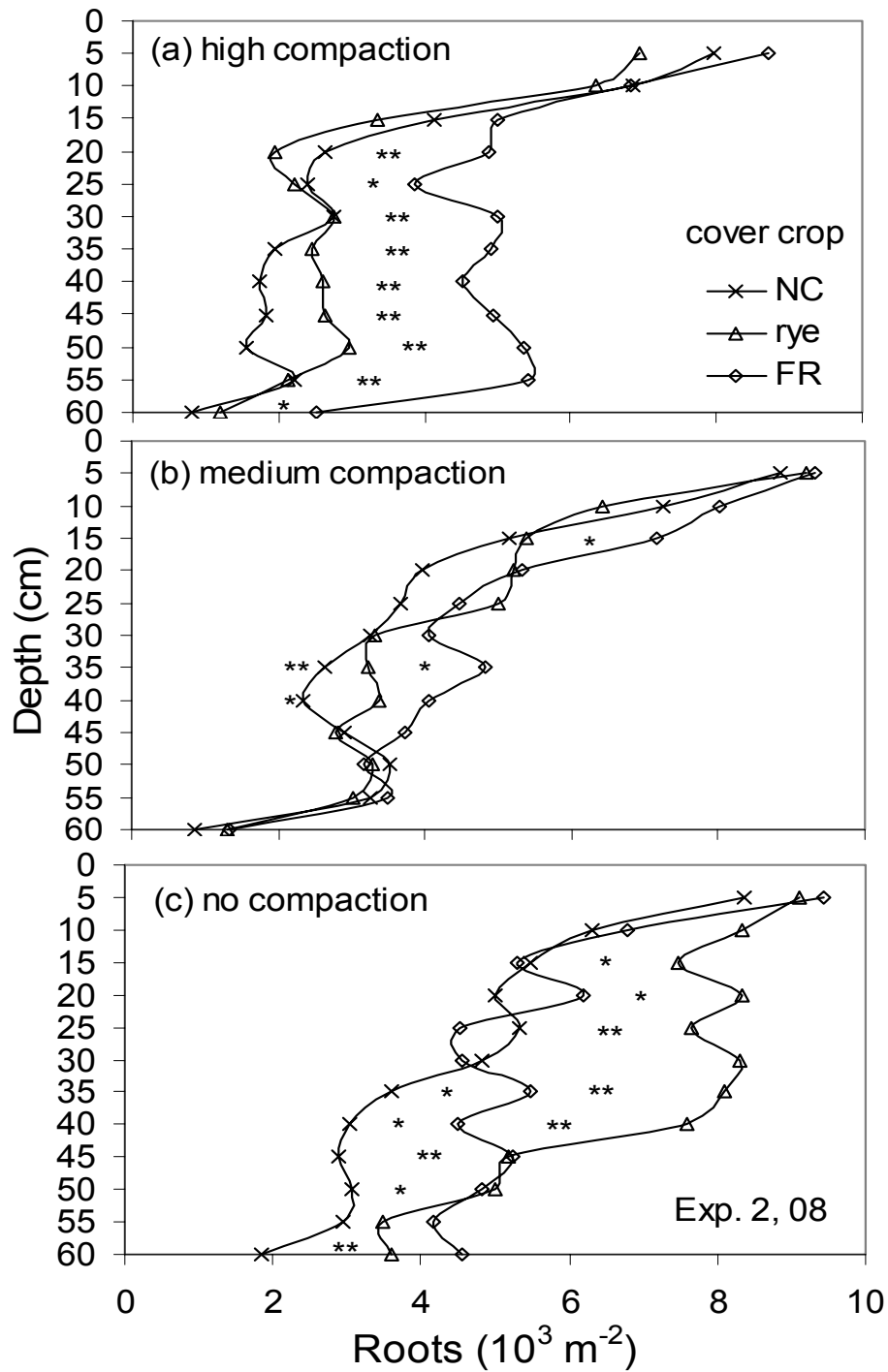


Figure 5.9 Corn roots vertical penetration followed different winter cover crops under (a) high (b) medium and (c) no compaction, Exp. 2, 08. \* Significant difference at  $\alpha < 0.05$ , \*\* significant difference at  $\alpha < 0.01$  (LSD).

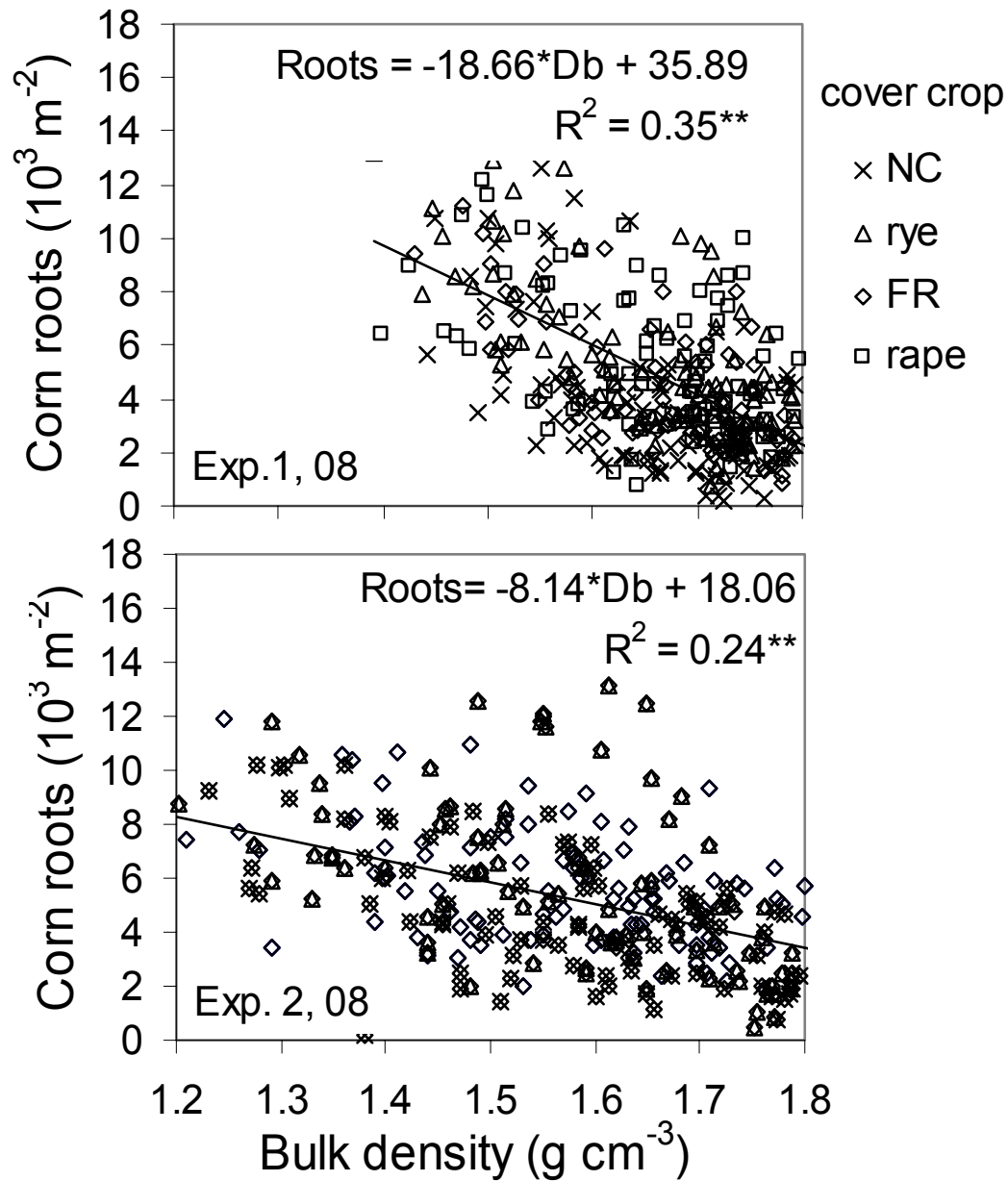


Figure 5.10 Relationship between corn roots and soil bulk density at 5-40 cm deep in the soil profile of Exp. 1 (right side) and Exp. 2 (left side).

\*\* indicates significance at  $\alpha < 0.0001$ . FR, NC, rye and rape are forage radish, no cover, rye and rape cover crop treatments.

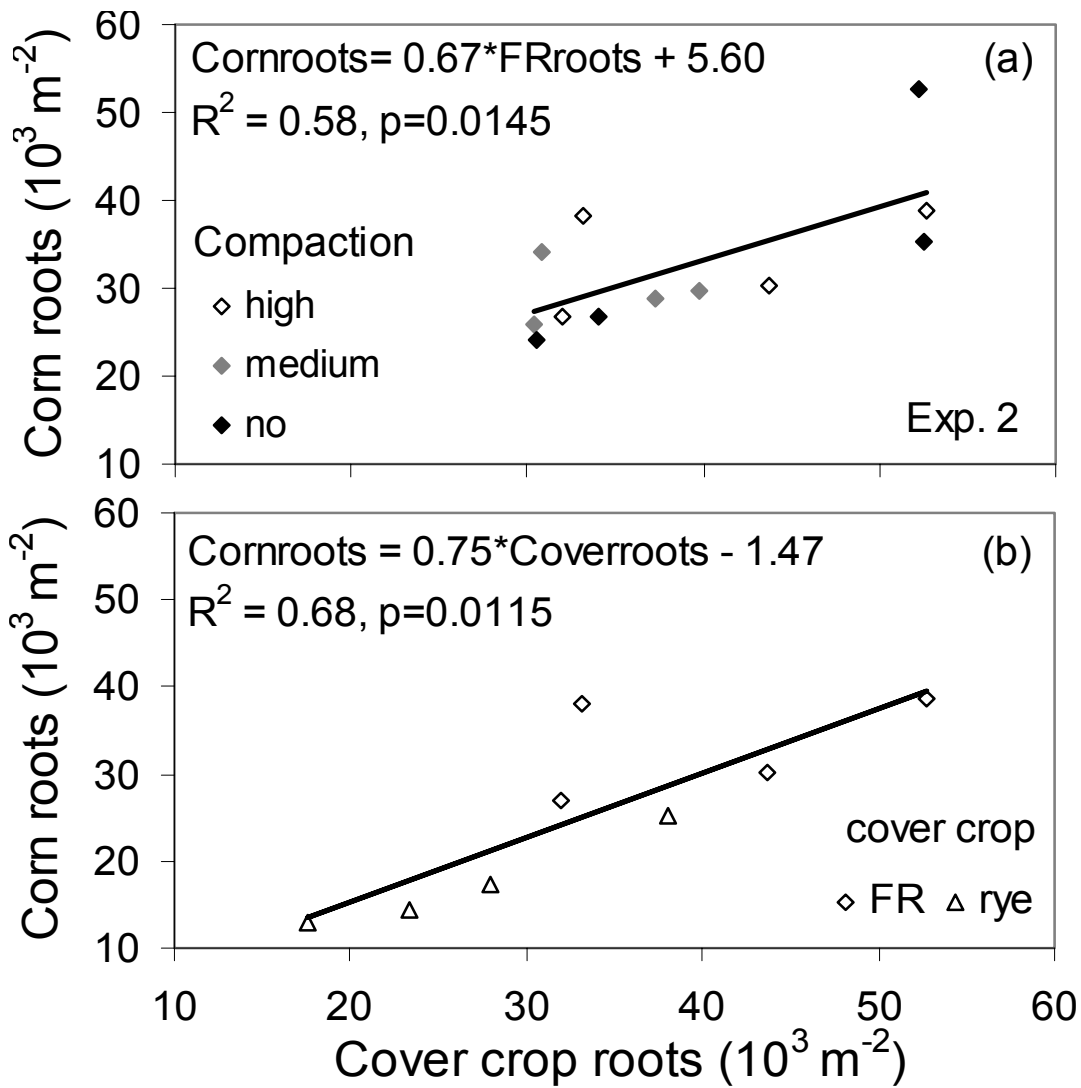


Figure 5.11 Total corn roots (early August, 2008) as a function of (a) total FR roots for all compaction levels (later November, and (b) total cover crop roots for both FR and rye under high compaction 2007) in and below the compacted layer (20-50 cm depth), Exp. 2.

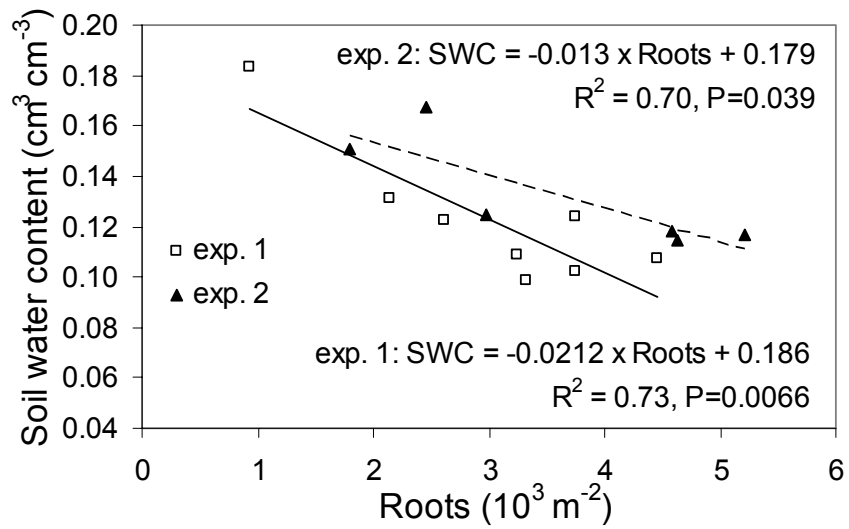


Figure 5.12 Relationships of volumetric water contents at 50 cm depth on July 24 and root counts (average of 45, 50 and 55 cm depths) observed in late July across four blocks in each experiment.



Fig. 13 Appearance of surface residues from NC (left), FR (middle) and rye (right) cover crop treatments at time of maize planting.

## Chapter 6: Corn and Soybean Root Penetration of a Compacted Plow Pan as Affected by Previous Cover Crops

### **Abstract**

Plant residues and the development and distribution of root systems in crop rotation systems can profoundly affect the soil's chemical, physical and biological environments. The use of tap-rooted species in crop rotation systems may alter the soil structure by providing root channels in compacted zones for the subsequent crops to utilize and thus increase subsoil water uptake. A two-year field experiment was conducted in Maryland to investigate the effect of winter cover crops to improve summer crop root penetration of and water uptake from subsoil compacted by a legacy plow pan. Three fall/winter cover crop treatments: forage radish (*Raphanus sativus* var. *longipinnatus*, cultivar 'Daikon') (FR), rye (*Secale cereale* L.) and no cover crop (NC), were planted in August 2004 on a no-till corn /soybean rotation. Corn (*Zea mays*, 'Pioneer 34B62') (summer 2005) or soybean (*Glycine max*, Syngenta's NK brand 'S39Q4') (summer 2006) roots were counted to a depth of 60 cm by the core break method and soil water tension was monitored hourly above (at 15cm) and below (at 50 cm) the plow pan. More corn roots followed FR in 2005 in the deeper soil layers than followed rye or NC. In the FR treatment, soil dried faster between summer rainfall events than in either rye or NC treatments, indicating that corn following FR consumed more subsoil water than corn in the other treatments. Soybean growth in 2006 was influenced by the residual effect of cover crops from fall 2004 (no cover crop was established



in fall 2005). Although the effects of the cover crop treatments on root penetration through the plow pan was not as pronounced as it was for corn in 2005, in general, the soybeans in 2006 grew more deep roots and took up subsoil water more rapidly in the FR treatment plots than in the other treatments. Minirhizotron observations provided useful insights into root growth at different stages, but with the limited replication did not detect any quantitatively significant treatment effects. However, there was a close correlation between FR root counts and soybean root counts that were obtained from minirhizotron images, confirming the enhanced soybean root penetration of the plow pan in the FR treatment. We conclude that compared to rye or NC, the FR treatment provided more root channels through the plow pan, resulting in increased deep rooting and subsoil water uptake by subsequent corn and soybean crops.

## **1. Introduction**

The importance of crop rotation, which is the sequential production of different plant species on the same land, has been recognized for thousands of years. The use of nitrogen fixing legume species in crop rotation systems, termed as “green manure” in Asia, is an important factor in sustainable soil fertility management (Karlen and Sharpley, 1994). Moreover, crop rotation systems may profoundly affect the soil physical environment, especially with respect to the development and distribution of root channels. The use of tap-rooted species in a crop rotation system may provide root channels that roots of subsequent crops can use to penetrate the compacted soils, a process termed “biodrilling” by Cresswell

and Kirkegaard (1995). Such biodrilling may improve the efficiency of nutrient and water uptake in the rotation.

Cover crops are short duration crops grown for purposes other than harvest. They are increasingly used to address concerns about such agriculture impacts on the environment as soil erosion and post harvest nitrate leaching. Use of cover crops for environmental quality purposes is especially important in the Middle Atlantic Region because nutrient and sediment losses from farmland have been identified as major causes of impaired water quality in the Chesapeake Bay ((Staver and Brinsfield, 2001; McCarty *et al.*, 2008)).

The inclusion of tap-rooted cover crops in crop rotations may ameliorate soil compaction at less monetary and environmental cost than the deep ripping tillage traditionally used to alleviate soil compaction problems. Because there is great variation in root penetration capability among plant species and cultivars (Materechera *et al.*, 1991), it is important to choose plants that can effectively penetrate dense soil layers as well as efficiently capture residual soil nitrogen. Brassica cover crops, which have only recently been introduced to the Middle Atlantic region, have been shown to provide root channels that can be used by subsequent soybean roots to grow through dense plow pan layers and increase soybean yield (Williams and Weil, 2004). Brassica cover crops, possibly because of more rapid and deep rooting, were found to capture more N in fall compared to a commonly used cover crop in the mid-Atlantic region, winter rye (Dean and Weil, 2009b). However, little quantitative information is available on the distributions of cover crop roots or soybean/corn roots after different cover crops,

and on the effect of these root distributions on a succeeding crop's subsoil water use. Our objectives in this study were to (1) determine vertical root distribution of corn and soybean as affected by the Brassica cover crop, forage radish (FR), rye and no cover crop (NC); (2) investigate the relationship between roots of winter cover crops and roots of summer crops; and (3) to determine how subsoil water use by summer crops is influenced by the preceding cover crop.

## **2. Materials and Methods**

### *2.1 Site and soil description*

A field experiment was conducted at the University of Maryland Central Maryland Research and Education Center, Beltsville Facility [CMREC] which is located at 39.02°N, 76.53°W, and experiences a moist continental climate (mean annual precipitation, 1112 mm; mean annual temperature, 12.8°C). The precipitation for the corn (2005) and soybean (2006) growing seasons during the experiment is presented in Figure 6.1. The soil was last plowed on 31 March 1999 and then put into a no-till corn (*Zea mays* L.)/winter wheat (*Triticum aestivum* L.)/double crop soybean (*Glycine max* (L.) Merr.) rotation until this experiment started in August 2004.

The soil was a complex of two highly permeable sandy soils: Cedartown series (Siliceous, mesic Psammentic Hapludults) and Evesboro series (Mesic, coated Lamellic Quartzipsamments).

## *2.2 Soil strength and bulk density measurement*

Soil strength was measured in a grid pattern across the field in 2003 and an old plow pan was found at depth of 25-35 cm (Figure 6.2 b). A cone penetrometer with a 25 mm long and 15 mm maximum diameter cone tip (Spectrum Technologies, Plainfield, IL) was used to measure soil strength. At each location, the penetrometer was pushed in at a constant rate to the depth of 45 cm. Mean penetration resistance was recorded in kPa for every 5 cm depth increment to 45 cm. The highest soil strength was measured at the northeastern quadrant, which was the lowest elevation and the place where equipment traffic usually entered the field (Figure 6.3).

Soil bulk density (Figure 6.2 a) was measured in each treatment plot in 2004 using a drop hammer driven sampler (inside diameter 6.3 cm) to collect undisturbed cores in 5 cm increments to a depth of 50 cm. The bulk density data showed evidence of a plow pan at about 25 to 35 cm depth.

## *2.3 Experiment design and crop management*

The field was divided into four blocks according to soil variation, with two blocks dominated by Cedartown loamy sand and the other two by Evesboro loamy sand. The experiment used a randomized complete block design with three cover crop treatments and four replicate blocks. Each treatment plot was 3.7 m wide and 9.1 m long. The three cover crop treatments were FR, rye and NC. During this experiment the crop rotation was: fall cover crop / corn / full-season soybean.

On 25 August 2004, FR and rye were no-till drilled at 13 and 126 kg seed ha<sup>-1</sup>, respectively in 15-cm wide rows. The FR was freeze-killed between December 2004 and January 2005, while rye and weeds in NC plots were killed when all plots were sprayed with glyphosate (2.3 L ha<sup>-1</sup> AI; N-(phosphonomethyl)-glycine) on 27 April 2005. On 05 May 2005, lime was surface applied according to soil test recommendations at a rate of 1120 kg ha<sup>-1</sup>. Corn (*Zea mays*, 'Pioneer 34B62') was planted at a rate of 65,000 seeds ha<sup>-1</sup> with 76-cm row spacing on 10 May 2005. On 04 June, roundup was sprayed at a rate of 3.5 L ha<sup>-1</sup> to control weeds. On 15 June, nitrogen fertilizer (30-0-0) (urea ammonia nitrate) was sidedressed at a rate of 109 kg ha<sup>-1</sup>. Corn silage was harvested on 15 August by cutting two central rows of 3 m long corn plants per plot 1 cm above the soil surface. After counting the number of plants and recording their fresh weight, six plants were randomly selected to record the fresh weight, and then brought back to the lab to get the dry weight.

On 26 August 2005, an attempt was made to sow the FR and rye cover crops by broadcasting the seeds (at the same rates as used in 2004) into the standing corn canopy using a hand cranked spinner-spreader. However, because of very dry conditions after seeding, the cover crop seeds either failed to germinate or died after germination, and less than 5% ground cover was achieved in each plot. Therefore for the purposes of defining the cover crop treatment effects on the following soybean crop, only the 2004 cover crop was considered. However, a small area (0.5 x 1.0 m) above the minirhizoton tube (see below) in

each plot was irrigated by hand in order to ensure good cover crop growth for root distribution observations.

On 03 May 2006, gramoxone extra and 2,4-D ester were sprayed on all plots at a rate of 2.34 L ha<sup>-1</sup> and 1.17 L ha<sup>-1</sup> respectively with 0.58 L ha<sup>-1</sup> of adjuvant. Glyphosate resistant soybean, Syngenta's NK brand 'S39Q4' was drilled at a rate of 384,385 seeds ha<sup>-1</sup> with four rows of soybeans per plot on 19 May, except the area above each minirhizotron tube where soybean seeds were hand-planted to avoid damage to the tubes which projected 5 cm above ground. On 08 June, glyphosate was sprayed at a rate of 3.51 L ha<sup>-1</sup> for additional control of weeds. From middle to late July, soybean around the minirhizotron tubes was manually irrigated in order to maintain sufficient plant growth for root observations. The soybean crop was machine harvested on 20 October 2006 using a combine that recorded the grain weight for each plot.

#### *2.4 Cover crop biomass sampling*

Cover crop biomass was sampled using a 0.5 X 0.5 m quadrat at each end of each plot (two quadrats per plot) on November 4, 2005, before FR was killed by frost. The fleshy root of each FR plant was carefully pulled out of the ground with the shoot. The FR shoots and roots were cut apart and the samples were rinsed in the field and again in the lab to eliminate soil particles. Samples were dried at 65°C for about 7 to 10 days before recording their dry matter.

### *2.5 Soil moisture monitoring and Laboratory calibration of moisture sensors*

From late June to mid-August in both 2005 and 2006, granular matrix electrical resistance sensors (Watermark™, Irrrometer Co., Riverside, CA) were placed at 15 and 50 cm depths between the two center crop rows in each plot to measure the soil moisture tension. Each cylindrical Watermark sensor (2.5 cm diameter x 7.5 cm length) was glued to a 2.5 cm diameter PVC pipe and the lead wires placed inside the pipe. A slide hammer driven probe was used to make holes of the same diameter to a depth of 15 or 50 cm. The saturated Watermark sensor was pushed down to the end of the hole which was smaller than the sensor so that the sensor and soil kept well contacted. Bentonite clay was used to seal the surface so that no surface water could percolate downwards along the tubes. The electrical resistance reading was converted automatically to a calibrated water tension reading in centibars (or kPa) and recorded hourly by the data logger. Because of limited equipment in 2005, these Watermark sensors were only placed in two of the four blocks.

Soil samples from the two soil series were collected at 15 and 50 cm depth, dried and sieved through a 2 mm sieve. The sieved soil was then packed into 15 cm diameter unlaced terra cotta ceramic flower pots at the same bulk density as measured in the field. The terra cotta pots were used so that the soil could dry by evaporation in all directions, not just from the top. There were two replicates per soil sample in addition to an extra control pot used to measure the moisture contents of the pot itself and the Watermark sensor. The sensors were saturated overnight and then one sensor was buried in the center of each pot. Calibration

started at saturation water content, and the samples were allowed to air dry slowly over a period of weeks. The watermark reading and the total weight of each pot was recorded twice daily. Each time when taking readings, the soil in the controlled pot was emptied to record the moist weights of the pot and watermark sensor. Calibration was completed when the watermark reached its highest reading (199 kPa). The total weight of the moist soil was calculated by subtracting the moist weight of the pot and the watermark sensor using the same moisture proportion of the control pot for soil from the same soil series and depth. The soil water contents and paired Watermark cbar readings for each soil sample were then used to develop the best fit non-linear regression equations to convert water tension readings into soil water content values<sup>1</sup>.

#### *2.6 Root observation via minirhizotron camera*

From late May to early June 2005, one minirhizotron tube (1.83 m long with inside diameter of 50.8 mm) was installed near the south end of each plot. Holes of the exact same diameter as the tube outside diameter were bored into the soil at 45 degree angle with a special drop-hammer designed to compress the soil core rather than the hole wall. The tubes were then inserted into the holes such that a tight fit was achieved. The tubes were placed directly under the crop rows in Block A, B and C, and between two center rows in block D, the 15 cm of each tube that projected above ground was covered with a black plastic cover to keep out water and light when not in use. Periodically, the minirhizotron camera (Model BTC-2, Bartz Technology, Santa Barbara, CA) was inserted into the tube, and

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<sup>1</sup> See Appendix B for calibration equations.



images (13.5 x 18.0 mm) were taken and saved to a computer drive at 13.5 mm intervals starting at the soil surface progressing downwards. The camera position was precisely controlled by the camera handle apparatus so that the same soil zone could be imaged repeatedly. Images were taken to the bottom of each tube, or to a vertical depth around 95 to 100 cm. In 2005, corn root images were taken on June 24, July 7, 18, 29, and August 11. Cover crop root images were taken on October 3, and November 4, 2005. In 2006, soybean root images were taken on June 29, July 6, 14, 21, 30 and August 12. Root numbers of corn, cover crops and soybean were counted in each image taken from the plow pan soil depth (20 to 50 cm). Root numbers for every 5 cm depth increment were summed and expressed as root counts per m<sup>2</sup> based on the actual area covered in the summed images.

### *2.7 Root enumeration by core-break method*

A 30 cm long drop-hammer driven corer with a cutting diameter of 6.3 cm was used to take undisturbed soil cores to a depth of 60 cm. A mechanical vehicle bumper jack was used to smoothly retrieve the corer without losing any soil. In each plot, three cores were taken about 5 cm away from the crop plants in the two central rows, two cores within rows and one between rows. After the first soil core was taken at 0-30 cm, the corer was put back into the same hole to take a second core at 30-60 cm depth. The cylindrical soil core was broken into precise 5 cm increments and the number of roots sticking out of both soil surfaces was recorded. Roots broke some distance from the plane of observation, so each root showed only on one side of the break. Therefore, the roots on both sides were

summed as the same root could not be counted on both sides of the break. Core-break enumeration was performed from late July to early August for corn (2005) and for soybean (2006).

### *2.8 Statistical analysis*

Analysis of variance was performed using PROC MIXED (SAS v. 9.1, SAS Institute, Cary, NC) with block treated as a random effect. Daily soil moisture content of 2005 and 2006 was analyzed using time as a repeated measurement to fit the best variance structure by comparing AIC, BIC and AICC values. For variables in the study, mean comparison was done using PDIFF option of the LSMEANS statement when F-test was significant at  $\alpha < 0.05$  level. All comparisons were performed within the same depth to avoid confounding by the variation of soil properties among different depths. Correlation analysis was done to explore relationships between cover crop roots and subsequent soybean roots based on the minirhizotron images.

## **3. Results and Discussion**

### *3.1 Cover crop dry matter*

Cover crops in fall 2004 had achieved 100% ground cover. Because cover crop seeds were broadcast in the standing corn canopy and there was no precipitation in the month after planting cover crops in the fall of 2005, cover crop seeds failed to germinate, and less than 5% cover was achieved in each plot. Only cover crops around minirhizotron tubes achieved good groundcover because

of irrigation. Figure 6.4 shows the dry matter of three cover crop shoots and FR roots in fall 2004. Forage radish had the greatest total dry matter. Besides, forage radish root dry matter was greater than its shoot dry matter, and the shoot dry matter of rye and weeds. Forage radish has previously been shown to take up more N than rye because of its greater biomass production (Dean and Weil, 2009b). We did not have data on root numbers to correlate with the dry matter yield reported here, but in other studies, we did find that root numbers across the soil profile depths measured was positively correlated (significant) with the dry matter yield (unpublished data). Both Jose *et al.* (2001) and Box and Ramseur (1993) previously had reported significant, positive correlations between root counts and root dry matter.

### *3.2 Minirhizotron observations of root penetration by treatment effects*

There were some reasons that we did not include root data in the upper 20/25 cm. The first reason was that it has been often reported that the minirhizotron method to quantify roots in the upper soil profile is questionable and that better results have been achieved when data from the upper soil profile is excluded (Levan *et al.*, 1987; Parker *et al.*, 1991). The second reason was that we wanted to focus on root penetration in the compacted plow pan. We also found that corn roots from one of the tubes under the NC treatment were constant as 10 times or more as roots from any other tubes in all three sampling times. Because tubes were installed in June when corn was in V4-V5 stage, the disturbance of soil at that time could have caused root preferential growth along the tubes.

However, we did not find soybean root preferential growth along this tube in the second year. The same phenomena were reported by Joslin (1999) who observed that the disturbance effect during minirhizotron installation was more pronounced in the first year.

Figure 6.5 presents root numbers at 25 - 30 cm, 30 - 35 cm and 35 - 40 cm depths from three periodical minirhizotron observations for corn in 2005 and soybean in 2006. For both crops, there was the similar and consistent trend that root numbers increased during the growing season. However, only the increase of corn roots at 25 - 30 cm depth between June 24 and July 29 was significant at  $\alpha < 0.05$  level. For soybean roots, the significant changes were found between July 7 and 30. Soybean roots at 25 - 30 cm decreased slightly but the decrease was not significant; soybean roots at 30 - 35 cm increased significantly at  $\alpha < 0.05$ , and at 35 - 40 cm at  $\alpha < 0.10$ . Corn roots responded to compaction quite similarly for all cover crop treatments, and there were slightly more corn roots following FR than were observed following the rye or NC treatments on June 24 in the compaction zone. Soybean roots responded to compaction similarly for all cover crop treatments on the two earlier days, but on the last sampling date, the trend was for soybean after FR to have fewer roots above and more roots below the plow pan, which was the opposite of what was observed for the rye and NC treatments. It was interesting that at the 25-40 cm depth, soybean had more roots than corn, possibly because of its tap-root system. However, we could not find any significant treatment effect based on the minirhizotron observations because of the high amount of variability and low number of replicates.

Figure 6.6 presents root number from minirhizotron observations on the two dates when destructive soil core samples were taken to examine root penetration. Though corn and soybean had more roots in and below the plow pan after FR and at some depths after rye, there was no significant difference for the same reason as described above.

Attempt was also made to look at rooting depth of the two summer crops and cover crops in fall 2005. However, we again could not find any treatment effect either because of the late sampling dates or the great variation of samples.

Figure 6.7 (a) shows rye and FR roots in fall 2005 from minirhizotron observations. Both species presented the same trend upon soil compaction, while FR had more roots than rye. Again we could not make a conclusion because the difference was insignificant among all depths. The correlation between cover crop roots and subsequent soybean roots on day July 30, 06 is presented in Figure 6.7 (b). Forage radish roots were positively correlated with soybean roots, and rye roots had a very weak positive correlation with soybean roots. This evidence could, to some extent, verify our hypothesis that FR was more capable of providing root channels for subsequent summer crops in the compacted soil layer than rye.

The installation of tubes in the standing corn plants disturbed root and soil which resulted preferential root growth along one of tubes and the data could not be used. Lower number of replicates made it impossible to detect any treatment difference. What was more learned, however, was that it is very difficult to install tubes where the plow pan had a high clay content or iron stones were present. For

these reasons, field installation damaged several tubes even though extra care was taken to install them. We recommend using other methods rather than minirhizotron observations for studying the effect of soil compaction on annual crops.

### *3.3 Root penetration observed by core break method and treatment effect*

Figure 6.8 presents data of root vertical penetration based upon data from the core break method. In 2005, corn after FR had more roots compared to corn after the NC treatment from 5-55 cm, and more roots than after rye at 10-20 cm and 35-55 cm depth. Corn after rye treatment had more roots than corn after NC only at the upper 5 cm depth. Numbers of corn roots declined at a fast rate above 30 cm for all the cover crop treatments, and reached the lowest numbers around 35-40 cm depth following the NC and rye treatments. Corn root numbers below 30 cm remained more constant after FR than after rye and NC, which suggested corn root penetration through the compacted plow pan was enhanced after the FR cover crop, similar to the response for soybean roots observed by Williams and Weil (2004).

In 2006, the effect of cover crop on the distribution of soybean roots was in the order of FR > rye > NC, though soybean had significantly more roots in plots after FR than in plots after NC or rye only at 30 and 60 cm depths, and the difference of soybean roots in plots after rye and in plots after NC was not significant. Unlike corn, soybean is tap-rooted species, so it may be able to more easily develop more deep-roots that penetrate the plow pan than corn

(Materechera et al., 1991). Because of the no-till system, root channels left by cover crops could be kept intact and utilized by future soybean roots. Because of the low groundcover (less than 5%) of cover crops in fall 2005 due to the dry weather condition after cover crops were planted, the effect of cover crops on soybean roots in plots except the areas around minirhizotron tubes was attributed to the residue effect of cover crops in fall 2004. Manual irrigation had kept good groundcover of cover crops around minirhizotron tubes. Our minirhizotron data showed that soybean roots at 20-50 cm depth were highly correlated with FR roots but only weakly correlated with rye roots at the same depth in fall 2005 (Figure 6.7). This confirmed that soybean root distribution observed by core break was not random, but affected by cover crops grown one and half years ago.

Comparing the root number at the same depth for minirhizotron observation and core break methods, it was found that root number from minirhizotron observation was about 10 times greater than the root number from core break, and there was no correlation between the data from the two methods. This is attributed to the fact that when examining roots in the image, all roots presented were counted, this included all branch and lateral roots. However, for core break, only roots sticking out on the break faces were counted, which included only the vertical roots. In addition, soil cores were taken on the furthest point in each plot away from the minirhizotron tubes, which meant the sample was usually 7-8 m far away from the minirhizotron tubes. It was not surprising that there was no correlation between data from these two methods even though the sampling time was close. Samson and Sinclair (1994) reported that the

relationship between the results from the two methods varied with sampling time even when excluding data from top 30 cm depth and made it very difficult to generate any conclusion. Some studies comparing the minirhizotron image technique with the core sampling method have found good correlations (Ephrath *et al.*, 1999; Jose *et al.*, 2001) when the sampling distance between the two methods were close. There are advantages and disadvantages of each method. As (Ruijter *et al.*, 1996) concluded in their study, soil coring was the best method for studying spatial distribution, while both soil coring and minirhizotron methods can be used to study biotic and abiotic factors on root systems. In our study, because we took three cores but had only one tube per plot, it was hard to conclude which method was better. However, for the root vertical penetration of corn and soybean after different cover crop treatments, the core break method gave better results. This, to some extent, is in agreement with Ruijter *et al.*'s (1996) conclusion.

### *3.4 Precipitation, soil water content and root growth*

Precipitation distribution during corn growing season in 2005 was evenly distributed across the season (Figure 6.3). Figure 6.9 presents soil moisture content at 15 and 50 cm depth during the corn growing season. Between every two rainfall events, soil moisture at 15 cm in plots following FR decreased the fastest. From middle July to early August, soil water content at 15 cm in plots after rye declined faster than in plots after NC, but still slower than in plots after FR. The pattern of soil water variation reflected the fact that corn had more roots



after FR and rye than after NC even at the upper 15 cm depth, so they took up more water. Because rye residue conserved more soil water, soil in plots after rye cover crop dried out more slowly.

The rainfall events also affected soil moisture at 50 cm because of the low clay content and good drainage. From middle July to early August when corn water demand was the greatest, soil water content at 50 cm depth in plots after FR was less than in plots after NC and rye, while in plots after NC was less than in plots after rye, except the few days during each rainfall event. The core break results clearly showed that corn achieved more deep-roots after FR than after the other two cover crops, which resulted in more subsoil water taken up by corn. There was no difference in corn root numbers after the NC and rye treatments at the 45-55 cm depth, though the trend was for slightly more roots after rye. The possible reason that soil moisture at 50 cm was greater after rye than found after NC could be the thick residue mulch of rye that reduced subsoil water loss by capillary rise.

Precipitation during soybean growing season in 2006 was less than and had more uneven distribution than during the corn growing season in 2005 (Figure 6.1). In response to the two heavy rainfall events from late June to early July, soil had high water content at both 15 and 50 cm depth. That subsoil water content (50 cm) in plots after NC was less than in plots after FR or rye during this period could be due to better conservation of water for FR and rye. From middle June till soybean maturity in middle August, there was very little precipitation that could fulfill plant water demand. Figure 6.10 shows a rapid decrease of both

surface and subsoil water contents from early July till late July, and in early August soil water content at both 15 and 50 cm was depleted. During middle to late July, soil water content at 50 cm declined more rapidly in plots after FR treatment than in plots after NC or rye treatment; soil water content at 15 cm in plots after FR and rye treatments decreased faster than in plots after NC treatment. Recalling the effect of cover crop treatments on soybean root distribution (Figure 6.8 b), it could tell that FR cover crop in fall 2004 still improved soybean root penetration of the plowpan in 2006 and hence enhanced subsoil water uptake by soybean. Both FR and rye positively affected soybean water uptake from the surface soil layer. Because soybean is tap-rooted, we assumed its roots could penetrate deeper than 50 cm to get water from deeper soil profile after soil water above 50 cm was depleted. This was confirmed when examining the rooting depth from the minirhizotron images where we observed roots at the far end of most the tubes (around 100 cm depth).

Figure 6.11 (a) shows correlation between corn roots from core break and soil water content on the day root sampling started. Corn roots and soil water content were negatively correlated, which indicated that more soil water was taken up where more roots were found. This finding is consistent with Lipiec *et al.*'s (1993) results that the higher total water uptake from undisturbed horizons was related to the denser root systems. Our results in another experiment also showed the same negative relationship between corn roots and subsoil water content (unpublished data). Figure 6.11 (b) presents the correlation between soybean roots from core break and soil water content on the day root sampling started. However, there was

no correlation. Because the sampling dates were in late July to early August when soil water at 50 cm depth in most plots were depleted (Figure 6.10), water that supplied live roots and plants must be taken up from deeper layer as illustrated in Bengough's (1997) model. Therefore, there might be a better correlation between rooting depth and soil water uptake, as was found in Stone *et al.*'s (2001) research. Unfortunately, we did not have such data to verify this relationship.

#### **4. Conclusion**

The study on the effect of cover crop rotation on corn and soybean root penetration in a legacy plow pan at 30-40 cm depth on a loamy sand soil determined that the Brassica cover crop, FR, improved corn root penetration through and below the compacted layer better than rye and NC, and consequently, enhanced subsoil water use. Corn silage yield in 2004 did not show a significant treatment response. The effect of the cover crops planted in fall 2004 was still evident on soybean root penetration in summer 2006, although the effect was not as pronounced as on corn root growth and water uptake in summer 2005. The minirhizotron observation data showed that in and below the plow pan, soybean root counts were highly significantly correlated with the fall 2005 FR root counts. The relationship between 2006 soybean root counts and fall 2005 rye root counts was only significant at 5% level. Taken together, the two years of data strongly supports our hypotheses that 1) a fall planted cover crop can enhance the following summer crop's root penetration of a compacted plowpan and 2) forage radish was a more effective cover crop for this action than was cereal rye.

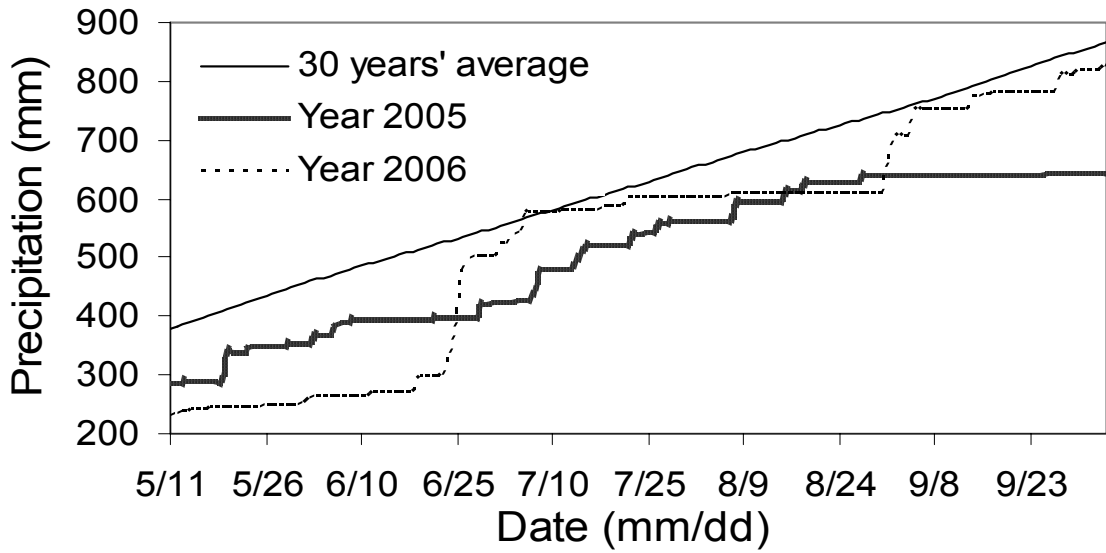


Figure 6.1 Cumulative precipitation during corn (2005) and soybean (2006) growing season

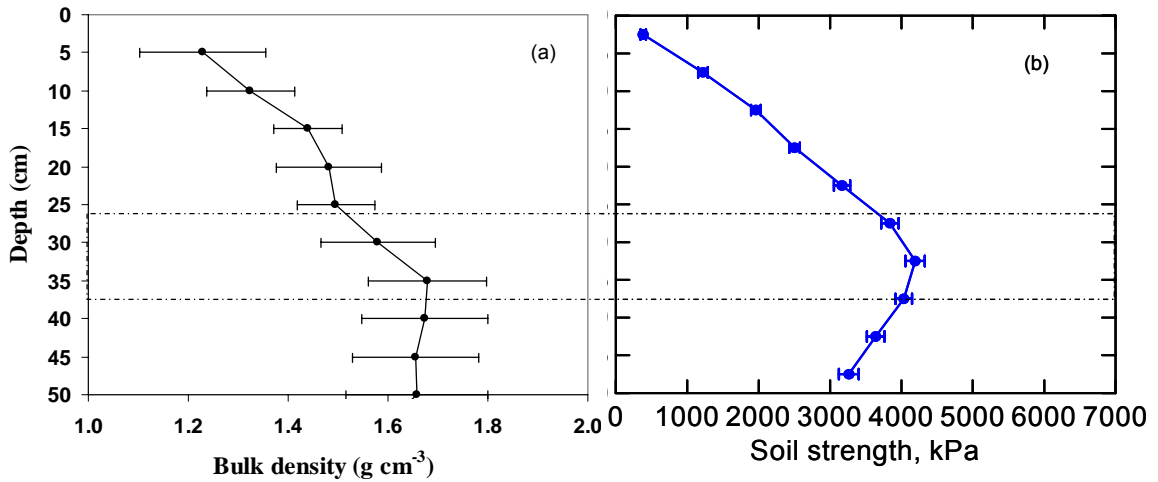


Figure 6.2 Vertical profile of soil bulk density (a) and soil strength (b) at CMREC experimental site with compacted legacy plowpan indicated by zone between dashed lines.

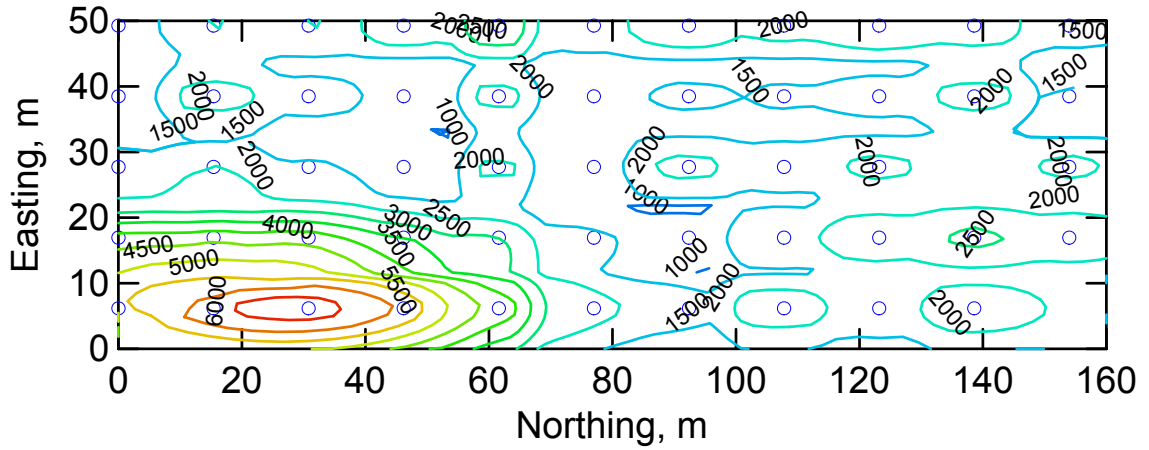


Figure 6.3 Spatial variation in soil strength (kPa) at 35 cm depth at the CMREC experiment site.

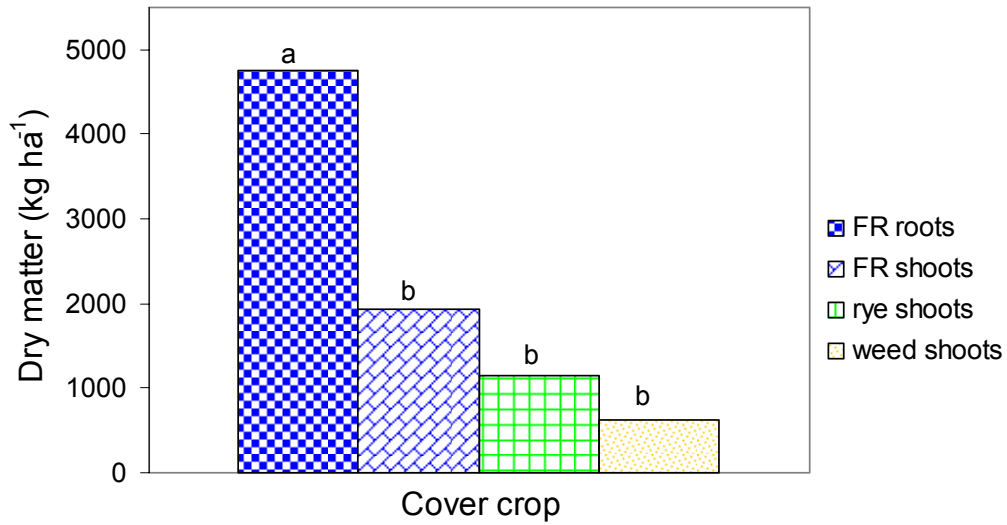


Figure 6.4 Dry matter of cover crop shoots and roots (FR only) on November 4, 2004.

Different letters indicate significant difference of means at  $\alpha < 0.05$  (LSD).

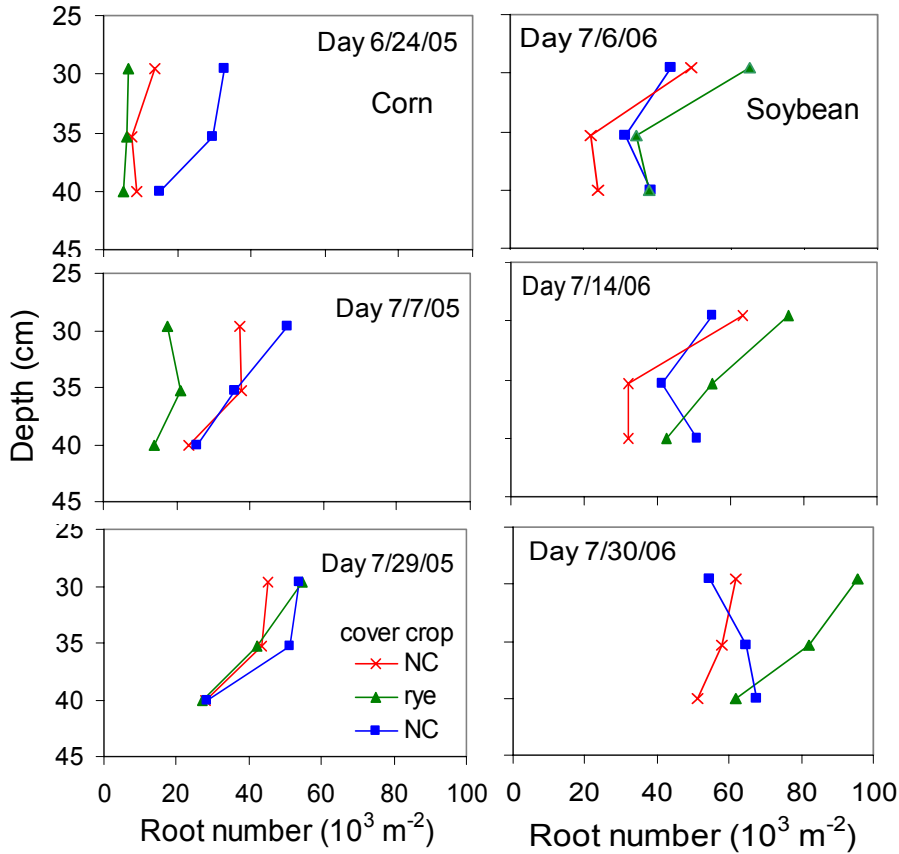


Figure 6.5 Minirhizotron observations of corn (2005) and soybean (2006) roots penetration through the plowpan following different cover crop treatments

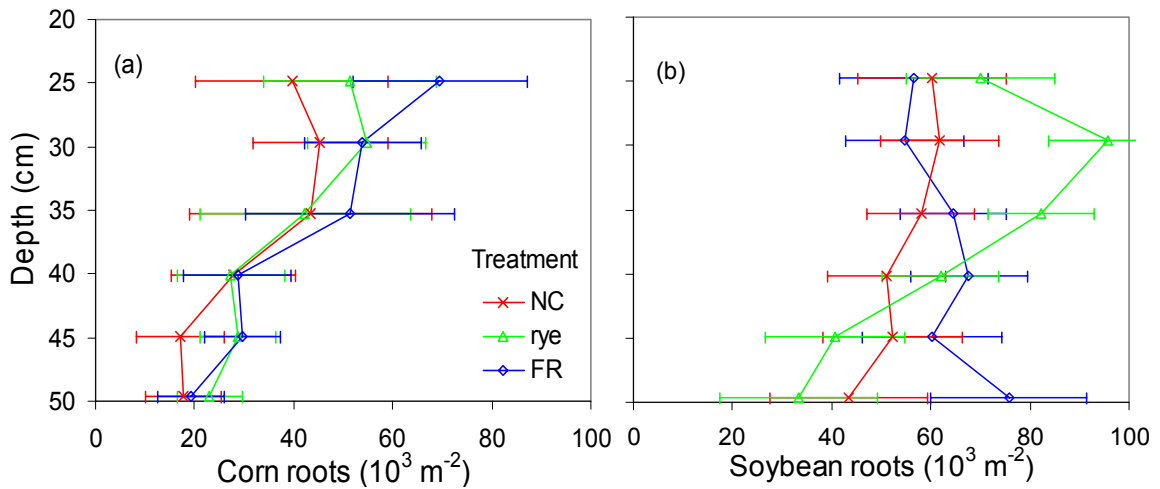


Figure 6.6 Minirhizotron observations of summer crop root penetration through and below the plowpan after different cover crop treatments (a) corn on July 29, 05 (b) soybean on July 30, 06.

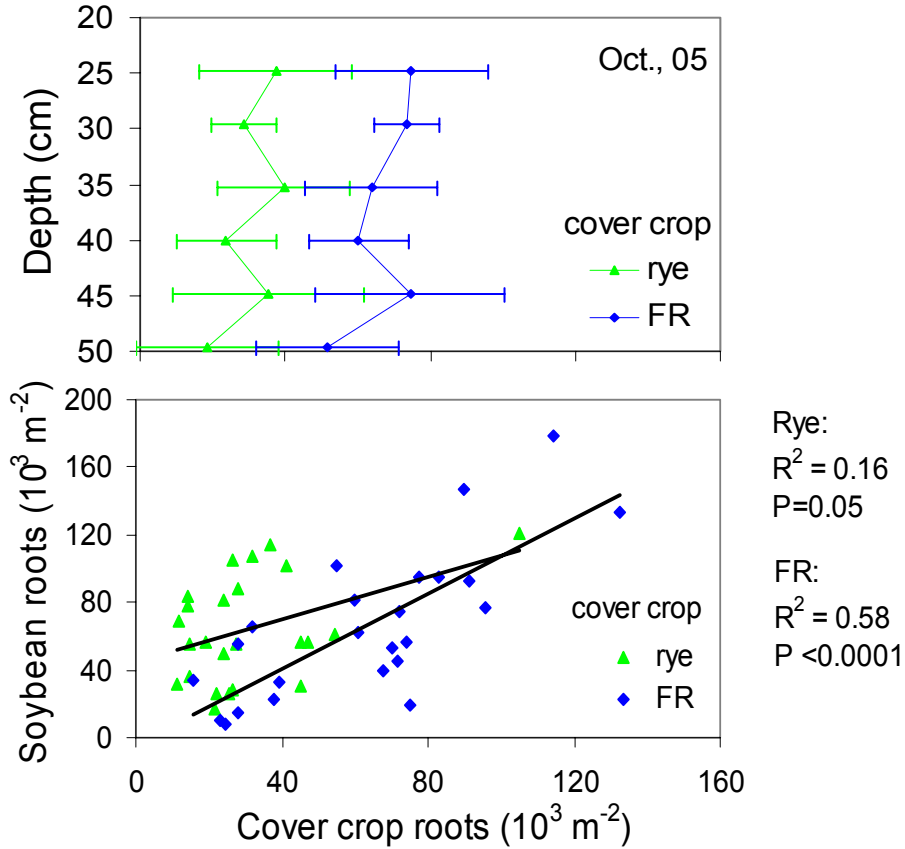


Figure 6.7 Minirhizotron observation of (a) cover crop roots in fall 2005 and (b) correlations between cover crop roots and subsequent soybean roots in summer 2006 (down).

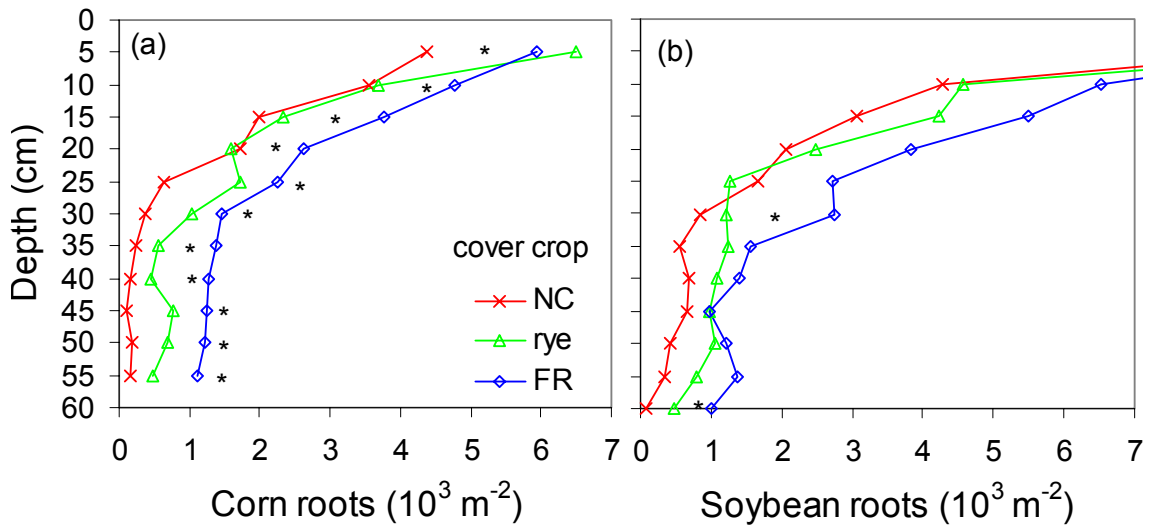


Figure 6.8 Summer crop root counts showing root penetration through the plowpan for (a) corn in 2005 (b) soybean in 2006 as affected by fall 2004 cover crop treatment. Roots were enumerated by core break method. \* Indicates that adjacent means are significantly different at  $\alpha < 0.05$  (LSD).

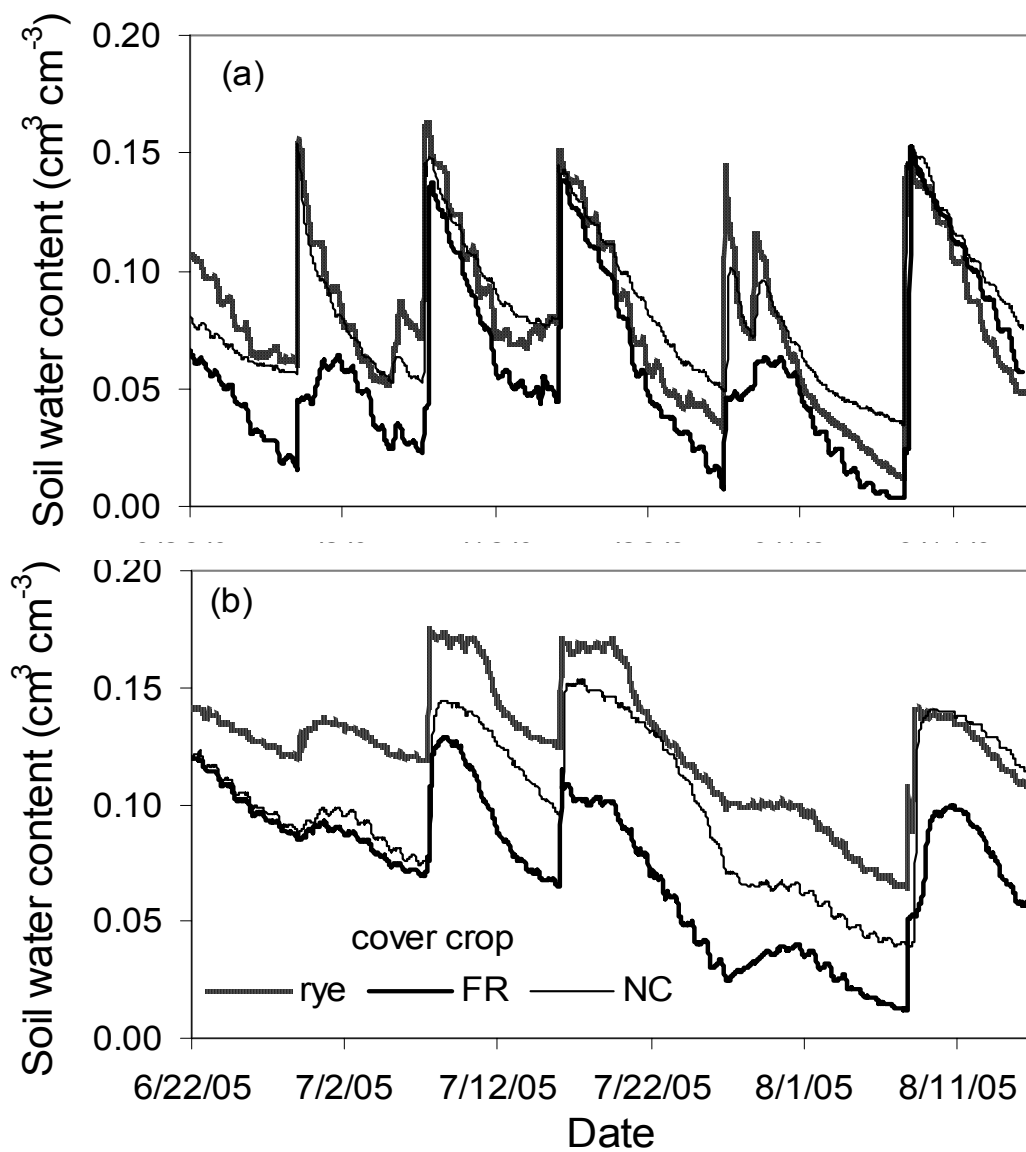


Figure 6.9. Variation of soil water content with time at (a) 15 cm and (b) 50 cm depth during corn growing season, 2005 after different cover crop treatments.



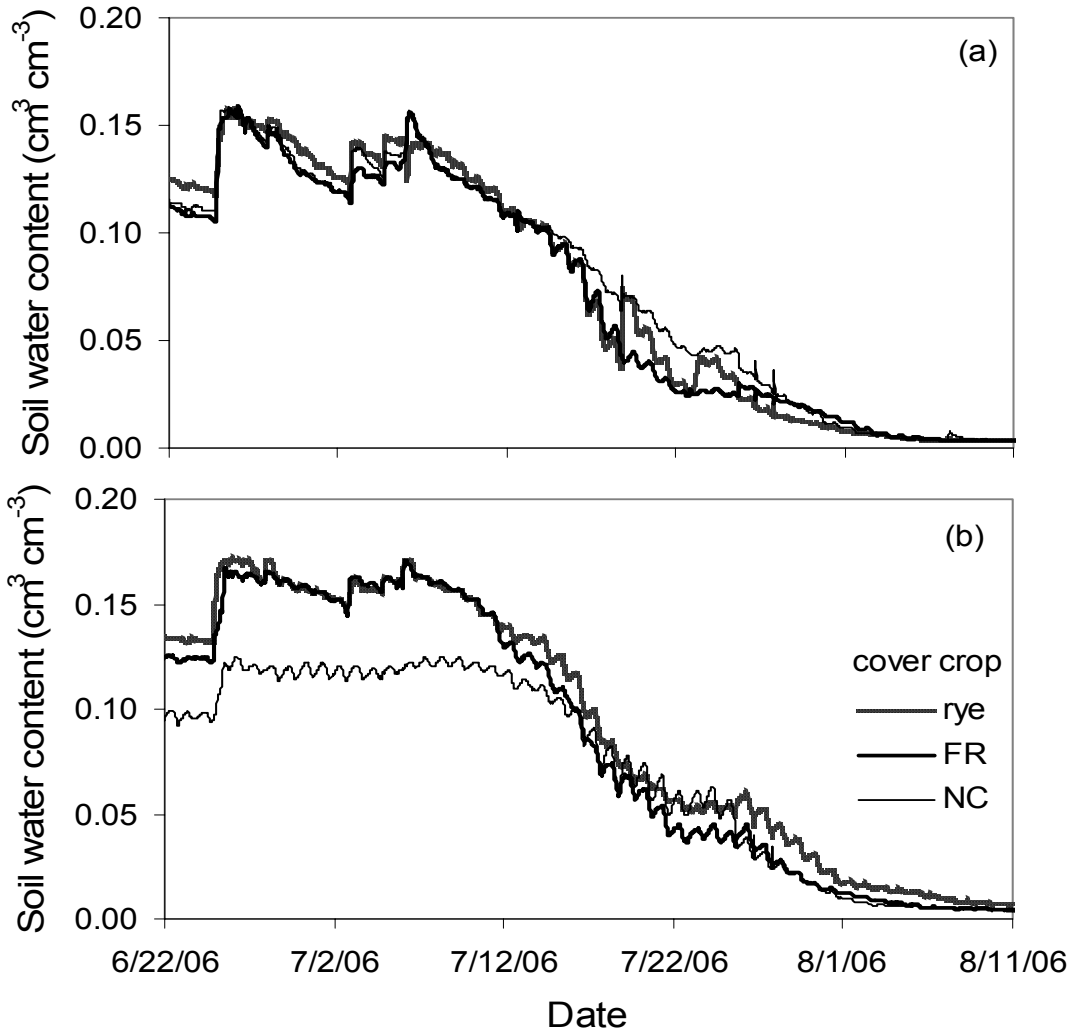


Figure 6.10 Variation of soil water content with time at (a) 15 cm and (b) 50 cm depth during soybean growing season, 2006 after different cover crop treatments.

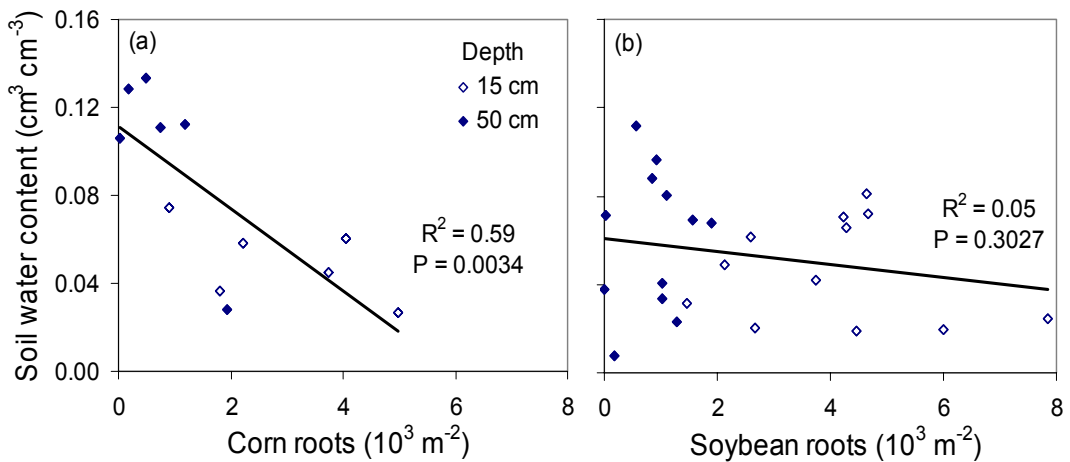


Figure 6.11 Correlations between soil water content at 15/50 cm depth on July 24 and (a) corn, (b) soybean roots averaged from 10-20 cm and 45-55 cm (Roots were enumerated by core break method).

## Chapter 7: Conclusion

### **1. “Ability of Biodrilling” for Three Cover Crops**

Cover crops are usually planted in Middle-Atlantic region in late fall when the soil is relatively moist and therefore soil strength was relatively low. Though the mechanism explaining why tap-rooted species have greater ability to penetrate compacted soils compared to the fibrous-rooted species awaits to be answered, our results clearly showed that for the three cover crops in the study, roots of FR were least affected by compaction while rye root growth was most inhibited by compaction, especially where soil clay content was high and no pre-existing root channels were available. Under high compaction, FR had 2 to 4 times as many roots as rye in Exp. 1 and 1.5 times as many roots as rye in Exp. 2. Under no-compaction treatment, there was little difference in root vertical penetration among the three cover crops. The ranking for specie’s ability of “biodrilling” in compacted soils was FR >rape >rye. Forage radish and rape, therefore, should have an advantage over rye if used as a biological tillage tool. We, therefore, suggest that integrating FR or rape as cover crops may alleviate the effects of soil compaction, especially in no-till farming systems.

### **2. Effects of Compaction and Cover Crops on Least Limiting Water Range and Air Permeability**

The degree of compaction caused by tractors and field equipment is affected by the soil texture and the axle load for the tractors and equipment that

pass over a field. As the soil clay content increased and as equipment became heavier, there was a greater reduction observed for both least limiting water range (LLWR) and air permeability. LLWR was highly affected by compaction. The narrower LLWR observed in the compaction treatments was caused by poor aeration in the upper limit and by greater mechanical impedance at the lower limit where soil had more clay content; while in sandy soils, the narrowness of LLWR caused by compaction was often due to the increased mechanical impedance in the lower limit. Least limiting water range was increased by forage radish in one of three soils in the experiments, probably because forage radish roots lowered local soil strength and increased soil aeration. Brassica cover crop roots were more capable of improving soil air permeability in the compacted situations, probably due to their greater ability to penetrate the compacted soils. Cover crop roots increased air permeability of the non-compacted soil that had higher clay content but had no effect on the sandy soils. The improvement of air permeability by FR and rape cover crops may provide a better soil environment and easier access for the subsequent crop roots.

### **3. Alleviation of Soil Compaction Effects by Cover Crops**

Effects of soil compaction on growth of summer crops usually include a reduction of deep-roots and less accessibility to subsoil water. From our study on surface horizon compaction, corn in FR and rape treatments under high compaction achieved more deep-roots than in rye or NC treatments, while under no compaction there was less to no difference of corn deep-roots. Though rye

roots might provide channels for corn to grow under high soil compaction, the number of channels was much less than that provided by FR or rape cover crops. In subsoil compaction experiment, corn/soybean had more roots in and below the plow pan in FR than in rye or NC treatment. Data also showed that FR and rape enhanced corn/soybean to take up more subsoil water during the growing course regardless of compaction treatments, while corn in NC or rye treatment under high compaction took up least amount of subsoil water. Significant correlations were found between corn and cover crop (FR and rye) roots at 20-50 cm under high compaction, and between FR and soybean roots at 20-50 cm depth where plow pan existed. The significant correlation between corn roots and minimum soil water content at 50 cm reached in late July from the three experiments verified that corn root penetration and subsoil water uptake in the compacted soils was enhanced by cover crops, especially FR and rape. The thick surface mulch of rye residue reduced corn plant stands on the finer textured soil in a wet spring. This stand effect may be compensated for by the beneficial effect of the mulch on water conservation, depending on the available rainfall in the growing season and/or the access to the subsoil water. Corn following a rye cover crop grew best in the non-compacted, well-drained soil where the crop was able to achieve normal plant stands and to rapidly take up surface and subsoil water.

Corn yield was greater in both Brassica (FR and rape) and rye cover crop treatments compared with winter fallow (no cover). The greater number of corn roots in the subsoil in Brassica cover crop treatments was probably one reason for

the greater corn yields. The conservation of surface soil water by rye residue was probably another mechanism for the greater corn yield.

#### **4. Recommendations**

The conservation of surface soil water and accessibility of subsoil water to plants during dry portions of the summers in the mid-Atlantic region are crucial for crop production. Although this study did not include such a mixture, it seems logical that cover crop benefits might be maximized by using a mixed cover crop of rye and FR (or rape) planted in alternate rows. The rows of FR/rape could be located in the summer crop planting rows to provide “biological subsoil tillage” effects and to allow better summer crop stands. The rows of rye cover crop would provide a thick mulch in the summer crop interrows to improve conservation of surface soil water for plant uptake. We also recommend continuous research into improved cover crop systems to alleviate soil compaction

## Appendix A

Calibration of water tension (from watermark water tensions) to soil moisture content (w) by weight

### 1. NF-2B: at 15 cm depth

water tensions $\leq 91$ cb: $w \text{ (g/g)} = 0.1889 - 0.0017 * \text{water tension}$ , RR=0.90, water tensions $> 91$ cb: $w \text{ (g/g)} = -0.0235 * \text{LN}(\text{water tension}) + 0.14$ , RR=0.49
--

### 2. NF-2B at 50 cm depth

water tensions $\leq 24$ cb: $w \text{ (g/g)} = 0.2186 - 0.0036 * \text{water tension}$ , RR=0.71, water tensions $> 24$ cb: $w \text{ (g/g)} = 1.0932 * (\text{water tension})^{-0.6597}$ , R2=0.91
---

### 3. NF-2C at 15 cm depth

Blk (I+III), No compaction (Db=1.52): water tension $\leq 7$ cb, $w = -0.0059 * \text{water tension} + 0.1832$ , $R^2 = 0.14$ , water tension $> 7$ cb, $w = -1.56E-08 * \text{water tension}^3 + 0.00001 * \text{water tension}^2 - 0.00207 * \text{water tension} + 0.1568$ , $R^2 = 0.99$
--

Blk (I+III), high compaction (Db=1.64): water tension $\leq 8$ cb, $w = -0.0053 * \text{water tension} + 0.1773$ , $R^2 = 0.254$ ; water tension $> 8$ cb, $w = -2.11E-08 * \text{water tension}^3 + 0.000012 * \text{water tension}^2 - 0.00217 * \text{water tension} + 0.151$ , $R^2 = 0.986$
--

Blk (II+IV), No compaction (Db=1.52): $W = -2.28E-08 * \text{water tension}^3 + 0.000013 * \text{water tension}^2 - 0.00245 * \text{water tension} + 0.1857$ , $R^2 = 0.9939$
--

Blk (II+IV), high compaction (Db=1.64): $W = -1.96E-08 * \text{water tension}^3 + 0.000011 * \text{water tension}^2 - 0.00222 * \text{water tension} + 0.1766$ , $R^2 = 0.99$
--

### 4. NF-2C at 50 cm depth

Block I: water tensions $\leq 10$ cb, $\log(w) = -0.60210 - 0.53423 * \log(\text{water tension})$ , $R^2 = 0.40$ water tensions $> 10$ cb, $\log(w) = -0.31332 - 0.52001 * \log(\text{water tension})$ , $R^2 = 0.96$
---

Block II water tensions $\leq 10$ cb, $\log(w) = -0.58163 - 0.14991 * \log(\text{water tension})$ , $R^2 = 0.64$ water tensions $> 10$ cb, $\log(w) = -0.11486 - 0.53618 * \log(\text{water tension})$ , $R^2 = 0.96$
---

Block III water tensions $\leq 10$ cb, $\text{Log}(w) = -0.92547 - 0.05419 * \log(\text{water tension})$ , $R^2 = 0.46$ water tensions $> 10$ cb, $\text{Log}(w) = -0.27199 - 0.59318 * \log(\text{water tension})$ , $R^2 = 0.95$
--

Block IV water tensions $\leq 10$ cb, $\log(w) = -0.64949 - 0.10877 * \log(\text{water tension})$ , $R^2 = 0.73$ water tensions $> 10$ cb, $\log(w) = -0.63811 * \log(\text{water tension})$ , $R^2 = 1.0$
--

## Appendix B:

Soil moisture calibration equations for soils at experiment site of chapter 6 (Hayden Farm):

At 15 cm depth:

$$\text{Soil water (g/g)} = 0.112 * e^{-0.0199 * \text{watermark reading}}$$

$$R^2 = 0.81$$

At 50 cm depth:

$$\text{Soil water (g/g)} = 0.1113 * e^{-0.0192 * \text{watermark reading}}$$

$$R^2 = 0.89$$

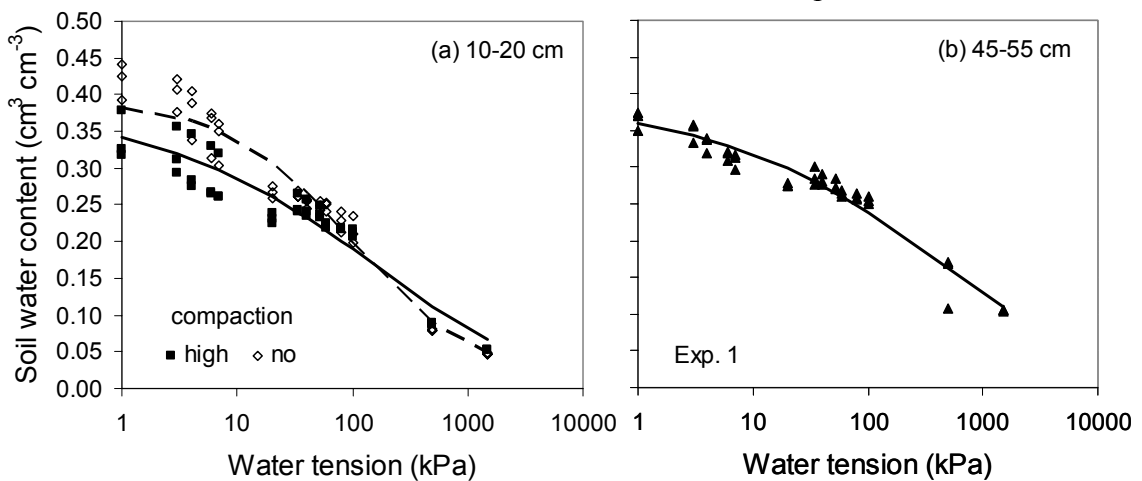
## Appendix C

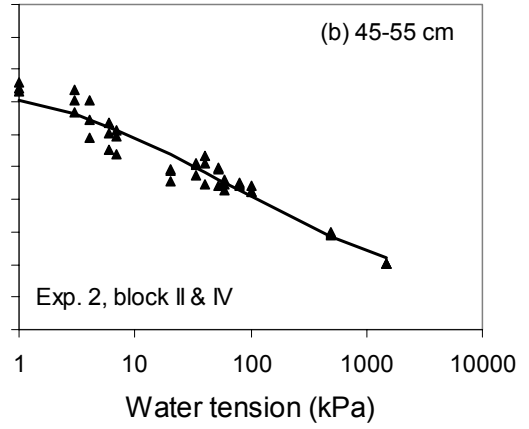
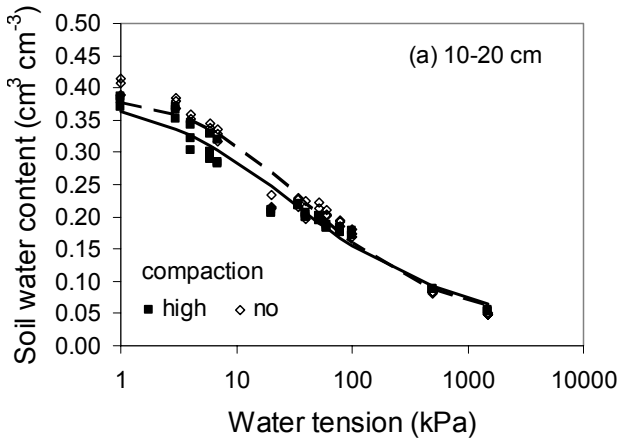
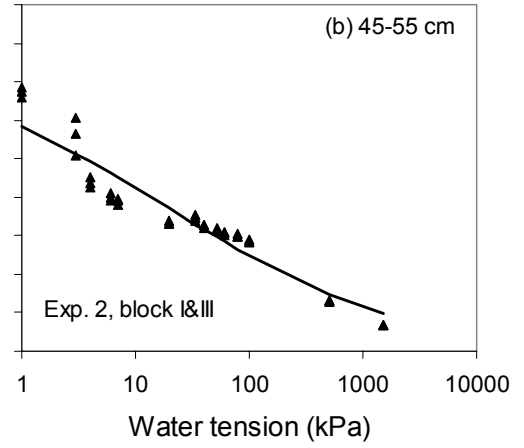
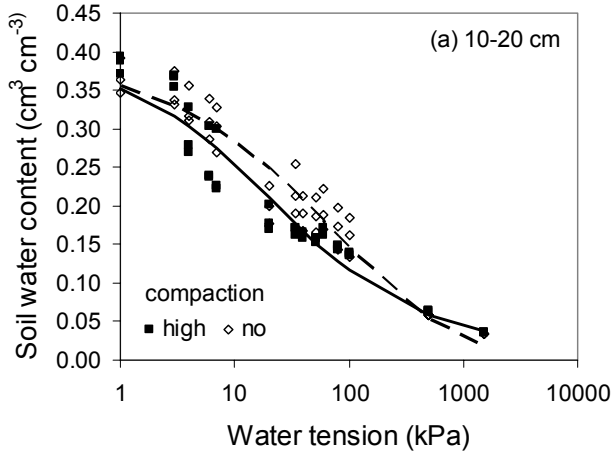
Soil water release curves for soils at 10-20 cm depth (high and no compaction treatments) and 45-55 cm depth (no effect of compaction treatment) were based on the relationship of soil water content and matric suction proposed by Fredlund and Xing (1994).

Variation of volumetric soil water content ( $\Theta_v$  ( $\text{cm}^3 \text{cm}^{-3}$ )) as a function of matric water suction,  $\psi$  (kPa):

$$\Theta_v = \theta_s * \left( \frac{1}{\ln[e + (\psi/\alpha)^n]} \right)^m$$

$\theta_s$  – soil water content at saturation,  $e$  – natural a,  $m$ ,  $n$  – fitted parameters







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