

THE EFFECTS OF WINTER COVER CROPS AND SOIL COMPACTION TREATMENTS  
ON SOIL PROPERTIES AND SOYBEAN PRODUCTION IN ILLINOIS

BY

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THESIS

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## ABSTRACT

Winter cover crops (WCC) are suggested as a tool to alleviate compaction while improving soil properties. However, WCC have also been reported to have detrimental effects on the following crop. Our goals in this study were twofold: i) to evaluate the short-term ability of radish and companion cover crops to alleviate induced soil compaction and improve soil physical and chemical properties and ii) to assess soybean growth, development and yield following compaction and cover crop treatments under conventional corn-soybean systems in two different environments and on poorly drained soils typical of Illinois. The experimental design was a 6 x 4 factorial arrangement of the WCC and compaction treatments in a CRD with two reps. WCC included radish (*Raphanus sativus* L. var. *longipinnatus*) “R”, alone and mixed with rye (*Secale cereale* L.) “RR”, triticale ( $\times$  *Triticosecale* cv *Presto*) “RTR”, buckwheat (*Fagopyrum esculentum* L. Moench) “RB”, or hairy vetch (*Vicia villosa* Roth) “RHV”, and a control with no cover crop “NCOV”. Compaction treatments included a control with no compaction (Nc), and three levels of compaction achieved with either a small tractor (ST), a large tractor (LT) or a hauling truck (TK). After the WCC growing season, soil physical properties improved compared for all treatments including the NCOV. The studied soils in this experiment showed high resilience to imposed compaction treatments probably related to inherently high levels of soil organic carbon and of natural weathering processes. Soybean growth parameters, yield components and grain yield showed no significant differences due to compaction treatments, WCC or their interactions. Results from this study show that one growing season is not enough time to evidence changes in the soil related to the incorporation of cover crops in the rotation, and that following adequate management practices WCC should not affect soybean growth and yield parameters.

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# CHAPTER 1. WINTER COVER CROPS AND SOIL COMPACTION ALLEVIATION

## EFFECTS IN ILLINOIS

### ABSTRACT

The increase in farm machinery weight in the recent decades has increased the likelihood of soil compaction compromising soil productivity and environmental quality. Winter cover crops (WCC) are suggested as a tool to alleviate compaction while improving soil properties. Our goal was to evaluate the short-term contributions of radish and companion cover to a) alleviate induced soil compaction and b) improve soil physical and chemical properties in conventional corn-soybean systems in two different environments and on poorly drained soils typical of Illinois. The experimental design was a 6 x 4 factorial arrangement of the WCC and compaction treatments in a CRD with two reps. WCC included radish (*Raphanus sativus* L. var. *longipinnatus*) “R”, alone and mixed with rye (*Secale cereale* L.) “RR”, triticale ( $\times$  *Triticosecale* cv *Presto*) “RTR”, buckwheat (*Fagopyrum esculentum* L. Moench) “RB”, or hairy vetch (*Vicia villosa* Roth) “RHV”, and a control with no cover crop “NCOV”. Compaction treatments included a control with no compaction (Nc), and three levels of compaction achieved with either a small tractor (ST), a large tractor (LT) or a hauling truck (TK). After the WCC growing season, bulk density and penetration resistance decreased compared to the values determined after compaction for all treatments including the NCOV. The studied soils in this experiment showed high resilience to imposed compaction treatments probably related to inherently high levels of soil organic carbon and of natural weathering processes. Water aggregate stability and soil chemical properties showed no significant differences after one WCC growing season in both environments. Results from this study show that one growing season is not enough time to evidence changes in the soil related to the incorporation of cover crops in the rotation.

## INTRODUCTION

Since the beginnings of agriculture farmers have relied heavily on tillage practices for crop production. Soil degradation induced by misuse of land and intensification of tillage practices has been a trade-off of agriculture productivity, affecting agricultural sustainability and environmental quality (Tilman et al., 2001). Soil compaction has been identified as one of the leading causes of soil degradation threatening future productivity of American farmland (Voorhees, 1987). It has been estimated that different degrees of soil compaction affect more than 68 million hectares worldwide (Oldeman et al., 1991), yet more recent estimates indicate there are more than 83 million hectares severely degraded by subsoil compaction (Wiebe, 2003).

Changes in soil physical properties induced by compaction alters soil nutrient and water dynamics, reducing crop growth and yield and lowering the efficiency of cultivation inputs while increasing the susceptibility of soils to wind and water erosion, affecting short-term fluxes of greenhouse gases, and the pollution of surface and ground waters. Thus, soil compaction contributes substantially to the United States costs associated with soil erosion (around \$37 billion per year, Pimentel, 2006), agricultural greenhouse gas emissions (estimated as 6.2% of total US emissions, EPA, 2010), water pollution (\$4.3 billion annually, Dodds et al., 2009), and increased energy use (15% of agricultural production costs, SARE, 2010) (Hamza and Anderson, 2005; Beare et al., 2009). These issues call for remedial measures to increase and maintain current productivity while preserving agriculture's non-renewable resource, the soil.

Cropping systems and tillage practices changed dramatically in the United States in the last fifty years. In 1950, the average farm in the United states was 90 hectares (Dimitri, 2005), more than 90 % of farm tractors had power levels of less than 26 kW and few wheel type tractors exceeded 37 kW (Ngunjiri, 1994). By 2007, the average farm size in the US was 169 hectares

and the largest tractors produced more than 300 kW (USDA farm facts). According to the NASS Illinois Field office (2010) farm size in Illinois increased from 78 hectares in 1960 to 143 hectares in 2009. This trend towards bigger farms is explained by a reduction in farm number, almost by half in this same period. As farm size increased, farmers continued in the search for bigger labor-saving farm equipment; disc rippers, soil finishers, planters and harvesters in order to do field activities in a timely manner. Increased size and weight of farm machinery in the last fifty years has increased the likelihood of soil compaction (Soane and Van Ouwerkerk, 1998).

Larger farm equipment resulted in the need for larger and more powerful tractors to pull them. Large tractors with large power levels allow farmers to conduct field operations in wetter conditions than smaller tractors allowed in the past, increasing the likelihood of soil compaction. Most of the soil compaction in modern agriculture is caused and fostered by wheel traffic of heavy machinery use on wet soils, which is exacerbated with monocultures or with the use of a limited number of species in crop rotations (Van Owerkerk and Soane, 1994; Hamza and Anderson, 2005; Servadio et al., 2005; Hoorman, 2009). Intensification of tillage practices and crop rotations in the Midwest have increased the concerns of soil compaction. Extensive tillage on heavy soils in the Midwest causes compaction (Horn et al., 1995; Brevik et al., 2002) and it is estimated that farmers in the region lose over \$100 million each year due to soil compaction (Mann, 2008).

Soil compaction directly alters soil structure decreasing pore size distribution and aeration, increasing bulk density and root penetration resistance, and lowering the resistance of soil aggregates to water (Horn, 2004). Soil structure refers to the arrangement of sand, silt and clay particles into aggregates which affects water and air movement through soil, influencing its ability to sustain life. The result of compaction is the densification and distortion of the soil and



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 physical properties affected by compaction include bulk density, soil strength and aggregate stability or the ability of soil aggregates to resist disintegration by tillage, water or wind. Soil bulk density values vary with soil texture and soil organic matter, and it refers to the capacity of a soil to store and transport water and air. Soil strength, also referred to as penetration resistance, is a measure of force required to push a cone-tipped probe through a soil and it relates to root ability to overcome mechanical resistances of soil aggregates.

Penetration resistance varies with soil texture, organic matter content, bulk density and water content; showing a positive correlation to soil bulk density and a general negative relationship with soil organic matter and water content. Variations in penetration resistance correlate well with variations in the overall resistance to root penetration (Unger and Kaspar, 1994). Soil compaction can be divided into two types: surface compaction and subsoil compaction. Surface or topsoil compaction is associated with traffic and ground pressure during field operations, especially during periods of high soil moisture. In the Midwest region soils are typically wet at seed bed preparation and planting in the spring and during fall harvest. The weakened aggregates and thus, soil structure resulting of topsoil compaction are susceptible to water and wind erosion leading to soil crusting and run-off after rain events. Topsoil compaction affects crop emergence and water infiltration yet it can be disrupted by natural forces and biological activities and tillage (Larson and Allmaras, 1971; Voorhees, 1983). On the other hand subsoil compaction can be caused by field activities such as tillage (plow pans), excessive axle loads (usually below the tilling depth) and by processes of soil formation such as fragipans and claypans. Heavy farm machinery can create subsoil compaction (Hakansson and Reeder, 1994) which is very difficult

to remediate and may exist permanently. In the last hundred years, tillage practices have decreased soil organic levels by 60% worldwide (International Panel on Climate Change, 1996; Lal, 2004). Farmers used to restore and maintain soil physical and chemical fertility through crop rotations, but as farm size increased in the last decades the number of commodities produced per farm decreased (NASS Illinois Field office 2010). Cropping systems shifted from diverse rotations involving cash grains crops like corn, soybeans, winter wheat, oats with pastures and livestock to short rotations of corn and soybeans or corn monocultures, thus increasing tillage intensity and the risk for soil degradation (Voorhees and Lindstrom 1994).

Crop rotations benefits include increased soil organic matter levels (Bullock, 1992; Bremer et al., 2008) improved soil structure (Raimbault and Vyn, 1991), and reduced grain yield variability (Varvel, 2000). Yet, current subsidy policies and economic trends favor corn monoculture or the biculture of corn and soybeans over more diverse cropping systems (Karlen et al., 2006; Liebman et al., 2008). Karlen et al (2006) after analyzing rotations profitability and soil ratings from three long-term studies in Iowa and one in Wisconsin reported that extended rotations had a positive effect on soil quality indicators. The lowest soil quality rating values and 20-yr average profit were associated with continuous corn, while extended rotations that included at least 3 year of forage crops had the highest soil quality rating values. Similarly, Liebman et al (2008) reported on how various rotation systems compared in terms of soil quality ratings and profitability. They compared over a 4-year period of time a conventionally managed 2-year rotation system corn-soybean with a 3-year corn-soybean-small grain + red clover (*Trifolium pratense* L.) rotation, and a 4-year corn-soybean-small grain +alfalfa (*Medicago sativa* L.) rotation. Without subsidy payments, net returns were highest for the 4-year system,

intermediate for the 2-yr systems and lowest for the 3-yr system. With subsidies, differences among systems in net returns were smaller, as subsidies favored the 2-yr system.

Diversified farming systems in the Midwest used to include small grains with alfalfa and clovers (Liebman, 2008). Longer rotations including perennials protected soils from compaction reducing the need of tillage for several years after seeding, and reducing traffic across the field; usually associated with hay harvesting when the soil is dry and less susceptible to compaction. Compared with a crop rotation with annual plowing to 30 cm soil depth, perennial forage crops increased soil C content, N content, had higher densities of medium and coarse biopores at a depth of 35 cm and larger water-stable soil macroaggregates (Kautz, 2010). Long term rotations with perennial crops have also been found to maintain or increase soil organic carbon levels (Wilts et al., 2004; Russell et al., 2006; Varvel, 2006). Soil organic matter plays a key role in the ability of a soil to resist compaction by increasing binding forces between particles and within aggregates, increasing elasticity (Soane, 1990). Organic residues on the soil have the ability to be compressed and return to their original form after traffic has passed, protecting soil from compaction. Although surface residues are important to protect soils from traffic and water and wind erosion, residues within the soil profile may be even more important. Effects of soil organic matter levels and the development of compaction have been widely studied and there is evidence that soils with low organic matter contents are more susceptible to compaction (Soane, 1990; Diaz Zorita, 2000).

While going back to longer rotations could prove to be a challenge to modern farm management practices or economically unviable, including winter cover crops (WCC) in a cropping system could prevent soil degradation resultant of tillage and rotation intensification. Cover crops are defined as crops planted between periods of cash crop production to reduce loss

of nutrients, decrease runoff from agricultural fields and provide ground cover to reduce soil erosion (Reeves, 1994; Dabney et al., 2001; Phatak et al., 2002). Cover crops may be utilized in farming systems as companion crops to cash crops or grown during fallow periods between cash crops in field rotations. Including cover crops in cropping systems provides numerous benefits such as carbon sequestration, increased residue cover, integrated pest management, and enhance nutrient cycling (Marshall et al., 2002; Taboada-Castro et al., 2006; Balkcom et al., 2007) that might result in greater crop yield or enhanced yield stability (Snapp et al., 2005). Winter cover crops can enhance soil structure by maintaining or increasing soil carbon and nitrogen, reducing bulk density and penetration resistance, and improving water aggregate stability of the topsoil (Kuo et al., 1997; Latif et al., 1992; Calegari, 1995; Meisinger and Delgado 2002; Sainju et al., 2002; Williams et al., 2002; Villamil et al., 2006; 2008). Changes in soil physical properties subsequently impact several soil chemical and biological properties ultimately affecting crop growth, development and yield.

Plant roots have been proposed as “tillage tools” to ameliorate effects of soil compaction (Elkins, 1985). The growth and decomposition of roots leaves voids and root channels, biopores, that could be later used as low resistance pathways for subsequent crop roots, ma processes dubbed “biodrilling” (Creswell and Kirkegaard, 1995). Winter cover crops with vigorous root systems can also alleviate compacted subsoils (Dexter, 1991), providing a more uniform rupture of compacted layers than the common mechanical methods offering both economic and environmental benefits over subsoiling (Camargo and Alleoni, 1997). Roots are also an active source of organic exudates which are effective stabilizing agents in soil aggregation (Reid and Goss, 1981). Different plant species and cultivars within the same species may differ in their ability to penetrate compacted soils (Rosolem et al., 2002; Cairns et al., 2004). Root length

density in compacted soils is positively correlated to root diameter. Thus roots with larger relative root diameters, usually tap rooted dicots, have a greater ability to penetrate through compacted soil layers than roots with smaller diameters, usually fibrous-rooted monocots (Materechera et al., 1991;1992; Merrill et al., 2002). Deep-rooted cover crops penetrate compacted soil layers (Chen and Weil, 2010), ameliorating soil compaction (Clark, 2007; Williams and Weil, 2004), and increasing nutrient use efficiency by capturing nutrients from deeper soil layers (Kristensen and Thorup-Kristensen, 2004; Thorup-Kristensen, 2006; Dean and Weil, 2009).

Although the potential of perennial grass and legume forages to improve soil physical properties and ameliorate soil compaction has been extensively researched and supported for various crops (Elkins et al., 1985; Rasse and Smucker, 1998; Katsvairo et al., 2007) the potential effects of annual crops is still under research. Da Silva and Rosolem (2002) found that annual cover crops of black oat (*Avena strigosa* Schreb.), pigeon pea (*Cajanus cajan* L.), and pearl millet (*Pennisetum glaucum* L.) were the most effective in disrupting compacted layers favoring the subsequent growth of soybean roots through the compacted layers. Similarly, Williams and Weil (2004) reported that soybean roots were able to grow through a compacted plowpan soil using channels made by decomposing canola cover crop roots.

The predominant cover crop selections in the Midwest region are winter annuals, particularly winter cereals, followed closely by hairy vetch (Singer, 2008). Cereal rye, wheat (*Triticum aestivum* L.), triticale, and annual rye grass (*Lolium multiflorum* L.) are used as catch crops for their high nitrogen scavenging potential, biomass production, winter hardiness, and ease to kill with herbicide (Odhiambo and Bomke, 2001). Other relatively new cover crops in this region include Brassica species, such as radishes, and summer annuals, such as buckwheat.

These last options might be more appealing to producers because they do not overwinter, thus removing the concern of appropriate killing times to prevent negative effects on the establishment and yield of the following cash crop. In the Midwest region, planting dates and harvest schedules of crop production systems often create restricted periods to maximize the advantages of traditional cover crop use.

Previous research in Illinois has shown the potential of hairy vetch and rye and their mixture to improve soil structure in no-till corn soybean systems compared to bare fallow (Villamil et al., 2006; 2008). Rotations including vetch or a mixture of rye and vetch significantly increased the soil organic matter in the top 30cm of the soil profile with resulting reductions in bulk density and penetration resistance and a significant increase in water aggregate stability, total porosity and related water retention properties. Yet information is currently lacking for other cover crop options and tillage systems.

I hypothesize that winter cover crops will alleviate induced soil compaction and improve soil properties as compared with winter fallowing in conventional corn soybean systems. I also expect that winter cover crops with different root systems will differ in either the magnitude or the direction of the observed response. Radish cover crops are expected to have greater effects on loosening deep soil compacted layers due to stronger and larger root diameters while grass cover crops effects will be reflected primarily on the topsoil due to a reduced ability to penetrate induced compacted layers. I anticipate that the mixtures of radishes and grasses will have a greater effect on soil compaction alleviation due to combined effect of different root systems. The main objectives of this research were therefore to evaluate the short-term differential effects and contributions of radish and companion cover crops to a) alleviate soil compaction and b)

improve soil physical and chemical properties in conventional corn-soybean systems established in poorly drained soils typical of Illinois.

I expect that the results of this research will provide useful and currently lacking information on the effects of compaction in Illinois poorly drained soils, and the potential alleviation effects of selected cover crops informing their inclusion in corn-soybean systems.

## **MATERIALS AND METHODS**

### **Experimental sites and treatments**

The study was carried out at Urbana, Illinois, in 2010 and 2011 at the Crop Sciences Research and Education Center (South Farms) of the University of Illinois. A different field coming out of wheat production (*T. aestivum* L.) was used each year. Both fields were on Drummer silty clay loam (fine silty, mixed, superactive, mesic Typic Endoaquoll) with less than 2% slope. Drummer series consist of dark colored, very deep, poorly drained soils developed in 100- to 150-cm of loess or other silty material under prairie vegetation. Permeability is moderate and surface runoff is negligible to low (Soil Survey Staff, 2012). The two selected fields had several years of corn-soybean rotation followed by one year with winter wheat prior to our experiments. We decided to start our experiments after winter wheat in order to induce the compaction treatments and plant the WCC in a timely manner. Before establishing our experiment, conventional tillage consisting of a deep ripper followed by disking was used to control weeds and to prepare the seed bed. Compaction levels and cover crop treatments were arranged in a 4 x 6 factorial in a completely randomized design (CRD) with two replications.

Four levels for compaction (high “Truck” (TK), medium “Large tractor” (LT), low “Small tractor” (ST) and No compaction (Nc) were achieved by 5 passes of the different vehicles with the soil at field capacity. The plot dimensions were 6.09 m x 15.24 m. Fields were separated by 9.14 m wide alleys for tractor and equipment turning during creation of the compaction treatments and cover crops planting.

The compaction treatments were established using a John Deere 7210 Tractor (Deere & Company, Moline, IL) with an total weight of 4.5 Mg with pneumatic tires and a rear tire contact area of 3225 cm<sup>2</sup>) for the ST, a John Deere 8225 Tractor (Deere & Company, Moline, IL) (total weight 9.5 Mg with solid rubber tires and a rear tire contact area of 7197 cm<sup>2</sup>) for the LT, and a Top Kick Fuel injection GMC Truck (GMC, Detroit, MI) (total weight 9 Mg rear tire contact 1067 cm<sup>2</sup>) for the TK treatments. No tractor traffic occurred for the Nc treatments. All treatments consisted of five passes of each farm implement after a rain event with soils at field capacity simulating the annual number of field activities (i.e. spraying, planting, harvesting and hauling grain). For the second year we used three levels of compaction (TK, LT, and Nc) since we found the compaction levels achieved with the large tractor and the small tractor to be similar. Previous research reported that topsoil compaction is related to ground pressure and subsoil compaction to total axle load independently of ground pressure (Botta et al., 1999; Hakansson and Reeder, 1994). The ground contact pressure is what causes soil compaction (Hamza and Anderson, 2005). Ground contact pressure is the axle load divided by the surface area of contact between the load and soil. This is measured in kPa, which is a unit of pressure. Following the calculation of ground pressure, we decided to drop the ST treatment for the second year of the due to similar load-pressure as the LT (ST=135 kPa, LT=129kPa, TK= 833kPa).



Each year and a week after imposing the compaction treatments, the field was disked to a depth of approximately 8 cm to establish a suitable seedbed for the cover crop treatments. The six cover crops levels consisted of: radish (*Raphanus sativus* L. var. *longipinnatus*) “R”, sown alone or along with rye (*Secale cereale* L.) “RR”, triticale ( $\times$  *Triticosecale* cv *Presto*) “RTR”, buckwheat (*Fagopyrum esculentum* L. Moench) “RB”, or hairy vetch (*Vicia villosa* Roth) “RHV” and a control with no cover crop, “NCOV”.

Planting date for WCC was September 27<sup>th</sup> 2010 and September 7<sup>th</sup> 2011. Seeding rate was 10 kg ha<sup>-1</sup> for radish sown alone, 28 kg ha<sup>-1</sup> for rye in combination with radish, 38 kg ha<sup>-1</sup> for triticale in combination with radish, 30 kg ha<sup>-1</sup> for hairy vetch in combination with radish and 45 kg ha<sup>-1</sup> for buckwheat in combination with radish. The seeding rate for radish in combination with other WCC was 5 kg ha<sup>-1</sup>. Hairy vetch was inoculated every year with *Rhizobium leguminosarum* var. *viciae*. WCC were chemically suppressed with glyphosate (N-(phosphonomethyl) glycine) at 1.2 kg a.i. ha<sup>-1</sup> in the spring, approximately two weeks before planting the main crop based on guidelines developed by Ruffo (2001) and Crandall (2003). Soybean was planted on June 3<sup>rd</sup> on 2011 and on May 15<sup>th</sup> 2012 respectively.

### **Soil sampling and analysis**

After a preliminary penetration resistance characterization of both fields, complete soil sampling was conducted during fall and spring seasons, each time after establishment of the compaction treatments and before planting the main soybean crop. On September 7 2010 and August 15 2011, and May 15 2011 and May 5 2012, two soil subsamples per plot up to 50-cm in depth were taken with a Giddings® sampler (29.5-mm diam., Giddings machine Co., Fort Collins, CO) for bulk density (BD) and soil chemical analysis. The cores were then cut to obtain 0-10, 10-20, 20-30, 30-40, and 40-50-cm subsamples, and stored in plastic bags. After weighing

the subsamples and measuring water content gravimetrically, BD values were obtained using the core method (Blake and Hartge, 1986). The results were averaged for each plot and depth considered.

The same samples were air-dried, and passed through a 2-mm sieve to perform the following tests: pH (potentiometry; 1:1 soil: water), total carbon and total nitrogen (TC and TN by combustion with CHNSO Analyzer; Costech Analytical Technologies Inc. Valencia, CA), NO<sub>3</sub>-N (flow injection analysis with Lachat automated analyzer, Lachat Instruments, Loveland, CO) and available P (Bray-1). On the same date of soil sampling, profile soil penetration resistance measurements (PR, kPa) were recorded with a Field Scout<sup>TM</sup> SC 900 Soil Compaction Meter (Spectrum Technologies, Plainfield, IL) with a cone basal area of 1.28 cm<sup>2</sup> and a cone angle of 30°. Three subsamples were recorded at each plot and the results averaged at the selected depths of 0-10, 10-20, 20-30, 30-40, and 40-50-cm in order to get one measurement per plot per depth. Gravimetric water content was later used as a covariate in the statistical analysis of BD and PR. Two 5 g subsamples of the 0-10 and 10-20 cm depths were used to determine water aggregate stability (WAS, g g<sup>-1</sup>) with an Eijkelkamp® wet sieving apparatus (Eijkelkamp, Giesbeek The Netherlands) on the 1-to 2- mm aggregate size fractions following the standard procedure developed by Kemper and Rosenau (1986). On 21 April 2011 and 28 April 2012 one sample from the center of each plot was taken with a shovel down to a depth of 20 cm for determination of particle size distribution and proctor test (ASTM, 1982) for the calculation of relative compaction (RC) From each sample, two 50 g subsamples of air dried soil were passed through a 2-mm sieve to analyze for particle size distribution via the hydrometer method (Gee and Bauder, 1986). Percentages by weight of clay (<0.002-mm), silt (0.002-0.05-mm) and sand (0.05-2-mm) separates were obtained by the hydrometer method. Additional characterization of

the sand size (very coarse 2-1mm; coarse 1-0.5-mm; medium 0.5-0.25-mm; fine 0.25-0.10; and very fine 0.1-0.05-mm sand) and silt size (coarse silt <0.05-mm) fractions was carried out with a set of 5 ultrasonic sieves corresponding openings of 1-, 0.5-, 0.25-, 0.1-, and 0.05-mm (ATM Sonic Sifter, ATM Corporation, Milwaukee, WI.). Relative compaction (RC) results from the quotient between bulk density determined with the core method, and soil maximum bulk density determined by means of Proctor tests following the standard ASTM procedure (American Society for Testing and Materials, 1982). Briefly, the proctor test involves sequentially compacting a soil sample at different water contents to be able to plot a curve of the bulk density obtained at each moisture content and then determine the maximum bulk density attainable for that soil. To that end, about 1.5 kg of 2 mm sieved soil was split into three separate portions. The first portion was added to a stainless steel cylinder (volume 944 cm<sup>3</sup>) and compacted by 25 blows of a 2.5 kg drop hammer from a height of 40 cm. Once the first portion was compacted two successive portions were added to the cylinder and compacted in the same way. The compaction test was performed at a minimum of five and occasionally six soil water contents to obtain a relationship between BD and soil water content (gravimetric method). Maximum bulk density was estimated as the intersection point of the ascending and descending lines between soil water content and BD in the proctor curves.

### **Experimental design and statistical analysis**

As previously detailed, each year we used a different field to set up a factorial combination of 4 (3 in 2011) compaction levels and 6 levels of cover crop treatments arranged in a CRD with two replications. The field-year combination will be hereby referred as the random factor environment (E) whereas the fixed factors of compaction and cover crop will be referred as COMP and CC, respectively.

The linear model used for the statistical analysis of the dependent variables was

$$y_{ijkl} = \mu + E_i + \alpha_j + \beta_k + E_i\alpha_j + E_i\beta_k + \alpha_j\beta_k + E_i\alpha_j\beta_k + \text{Error}$$

$y_{ijkl}$  = observation for the  $i^{\text{th}}$  level of E for the  $j^{\text{th}}$  level of COMP and the  $k^{\text{th}}$  level of CC.

$\mu$  = grand mean.

$E_i$  = random effect due to the  $i^{\text{th}}$  level of factor E.  $df=i-1 = 2-1=1$

$\alpha_j$  = fixed effect of the  $j^{\text{th}}$  COMP.  $df=j-1 = 4-1=3$

$E_i\alpha_j$  = random effect due to  $i^{\text{th}}$  level of factor E and the  $j^{\text{th}}$  COMP.  $df=(i-1)(j-1) = 3$

$\beta_k$  = fixed effect due to the  $k^{\text{th}}$  level of factor CC  $df=k-1=6-1=5$

$\alpha_j\beta_k$  = fixed effect due to the  $j^{\text{th}}$  level of factor COMP and the  $k^{\text{th}}$  CC.  $df=(i-1)(j-1)(k-1) = 15$

$E_i\beta_k$  = random effect due to  $i^{\text{th}}$  level of factor E the  $k^{\text{th}}$  CC.  $df=(i-1)(k-1) = 5$

$E_i\alpha_j\beta_k$  = random effect due to  $i^{\text{th}}$  level of factor E the  $k^{\text{th}}$  COMP and the  $k^{\text{th}}$  CC.  $df=(i-1)(j-1)(k-1) = 15$

Error = residual effect assumed identically and independently distributed (i.i.d.)  $N(0, \sigma^2)$ .

These models were analyzed using the MIXED procedure of SAS 9.3 (SAS Institute Inc, 2012). For dependent variables that were measured at specific and subsequent depths, a fixed factor D (depth) was added to the model. Dependent variables that were measured at several depths on the same experimental units were analyzed using a repeated measures approach (Littell et al., 2002). The model used for the variance-covariance matrix of the residuals was unstructured (UN) with random effects for subject (S) and it was selected based on the lowest Akaike's Information Criterion and the Schwarz's Bayesian Criterion (Littell et al., 2000).

When covariance parameter estimates appeared to be negative or zero, we used the -2Log Likelihood test to compare successive reduced forms of the original models (Littell et al., 2002). To compare differences among treatments and depths the PDIFF options of the LSMEANS statement was used. Mean separation procedure was accomplished by using Fisher's Protected Least Significant Difference (LSD) with a probability of Type I error or alpha level ( $\alpha$ ) set at 0.1.

The matching SAS coding was as follows,

```
proc mixed data=thesis;
class E S CC COMP D;
model variable = CC|COMP|D;
random E E*CC E*COMP E*D E*CC*COMP E*COMP*D E*CC*D
repeated D/type = UN subject = S; run;
```

Where E, environment; S, subject; CC, cover crop; COMP, compaction; and D, depth.

The variable nitrates ( $\text{NO}_3\text{-N}$ ), water aggregate stability (WAS), and available P required transformations due to lack of normality of residuals and heterogeneity of variances. Possible transformations were explored by using the BOXCOX macro in SAS (Friendly, 1991). When two or more transformations were possible, the one most commonly used in the literature was chosen. Thus the transformation used for nitrates was logarithm ( $\log_{10}$ ) the transformation used for WAS was  $\lambda=2$ , and the transformation for available P was natural  $\log_n$ .

## **RESULTS AND DISCUSSION**

### **Establishment of compaction treatments and preliminary characterization of experimental plots**

#### *Soil Texture and Particle Size Distribution.*

Our experiment was conducted on Drummer soils yet the series concept involves a broad range of properties such as the arrangement of soil horizons, thickness and soil type. Results from the particle size analysis show that the textural class of the soils used in this experiment is silty clay loam (Figure 1.1). The lack of significant differences among particle size separates of the soils studied in this experiment is of critical importance for assessing changes in soil properties since the texture of a given soil and its mineral composition determine the nature and behavior of the soil (Hillel, 1998). Moreover different textures give rise to different pore sizes in the soil (Dexter, 2004), and therefore could behave differently to the imposed compaction treatments. The compared soils are highly homogenous in particle size distribution as data in Table 1.1 and Table 1.2 show which is preferred given the range of variability for each textural class (Fig 1.1). When using small treatment plots and limited number of replications, small variations in clay or sand content or even in the amount of coarse or fine sand fractions may lead to wrong conclusion since many of the soil properties (PR, BD, WAS, etc.) are very sensitive to differences in particle size distribution (Amezket, 1999).

#### *Soil physical properties*

Compaction treatments were achieved after a rainfall in a recently tilled, loose soil, in order to achieve the maximum level of compaction possible. The treatments consisted in five passes of each implement small tractor (ST), large tractor (LT) and hauling truck (TK), through each plot. The number of passes selected reflects typical farm trafficking and cultivation

operations for a given season in IL: seed bed preparation, planting, spraying and harvesting. Traffic intensity (number of passes) plays an important role in soil compaction because number of passes increases soil deformation (Bakker and Davis, 1995). It is estimated that under conventional tillage systems vehicular traffic exceeds 100% of the ground area during one crop cycle (Soane et al., 1982). After the induced compaction, differences between treatments were evident: as expected TK achieved a greater level of compaction and sealing of the topsoil due to its axle load and smaller contact area. Differences between the compaction achieved with the LT and ST were less evident. Although the axle load of the LT was almost double the axle load of the ST, the fact that it had dual tires lowered the overall pressure exerted on the soil. Several soil physical parameters were examined to quantify the effects of the different compaction treatments.

As expected bulk density (BD) values showed significant differences for the interaction of compaction level and depth ( $p < 0.0001$ ), and main effects compaction level ( $p < 0.0036$ ) and depth ( $p < 0.0064$ ). BD values showed that compaction was confined to the topsoil. The TK treatment achieved the greater BD values in the top 20cm. After the 20cm depth differences in BD values started decreasing. There were no significant differences in BD values after the 30cm depth (Table 1.3). A similar trend was observed for penetration resistance (PR) values. After compaction PR showed significant differences for the interaction of compaction level and depth ( $p < 0.0001$ ), and main effects compaction level ( $p < 0.0116$ ) and depth ( $p < 0.0325$ ). TK achieved the highest PR values in the top 30cm. After the 30cm depth there were no significant differences in PR (Table 1.4). Though the highest values were observed in the Nc treatment, water aggregate stability (WAS) values showed no significant differences after the compaction treatments for the interactions or the main effects (Table 1.5). Relative compaction (RC) was

obtained by dividing the actual soil bulk density derived from the soil cores by the maximum soil bulk density (MBD) determined from the Proctor test, and expressing the result on a percentage basis. MBD values for the studied soils ranged from 1.5 to 1.6 Mg m<sup>-3</sup> and agree with the range reported as growth limiting BD (GLBD) for root growth for silty clay loam soils. Relative compaction can be a useful index to assess soil compaction on agricultural soils. RC values of 77-84% are associated with optimal crop production regardless of soil texture and organic matter content, optimal crop production is reduced when RC is greater than 90% (Carter, 1990). RC values after compaction showed significant differences for the interaction of compaction level and depth ( $p < 0.0053$ ), and for the main effect compaction level ( $p < 0.0606$ ). RC values after the induced compaction responded similarly as BD and PR, TK had the highest RC values for the top 20 cm (Table 1.6).

### *Chemical Properties*

In contrast to the evident changes in soil physical properties after the compaction treatments, changes in soil chemical properties were less evident. Changes in soil chemical properties due to soil compaction have been related to alterations of microbial processes (Lee et al, 1996). Changes in mineralization of soil organic carbon and nitrogen rates can be expected under high bulk densities starting at 1.6 Mg ha<sup>-1</sup> (De Neve and Hofman, 2000). Nitrogen losses due to denitrification related to soil compaction have also been reported (Bakken, 1987). After compaction treatments no statistical differences in total nitrogen (TN) values were determined for the interactions, or the main effects (Table 1.7). Similarly no statistical differences in total carbon (TC) values were determined for the interactions, or the main effects. As expected significant differences were determined in depth ( $p < 0.0001$ ), (Table 1.8). Although after compaction treatments statistical differences in soil nitrate (NO<sub>3</sub>-N), pH and available P were



determined the magnitude of these differences had no agronomic importance. Soil nitrate values showed a significant differences for the interaction of compaction level and depth ( $P < 0.0008$ ) and the main effect depth ( $p < 0.0001$ ). Differences across compaction levels did not show a clear trend across treatments. Soil nitrate levels decreased with depth (Table 1.9). Likewise, soil pH values showed differences for the compaction level and depth interaction ( $P < 0.0008$ ) and for the main effect depth ( $p < 0.0001$ ). Values of pH were slightly higher in the compacted treatments in comparison to the control in the top 20 cm. After the 20 cm depth there were no differences in soil pH. Soil pH increased with depth (Table 1.10). In addition, soil available P showed a significant interaction effect between compaction level and depth ( $p < 0.0640$ ) and for the main effect depth ( $p < 0.0806$ ). Average Bray P1 test levels in this experiment decreased with depth (Table 1.11).

### **Cover crop establishment and biomass production**

Cover crops (WCC) were established successfully on both years of this study. Buckwheat was the most susceptible to cold temperatures and was killed by the first frosts on both years. The cover crops that successfully overwintered were rye, triticale and hairy vetch. Radish was intermediate in cold hardiness but did not overwinter. The differences in the length of the WCC growing season help explain differences in biomass production and in turn may explain differences between the studied variables. WCC biomass production was measured before soil sampling at the end of the cover crop growing season and before planting the soybean crop and serves as a measure of success of the different cover crops (Table 1.12). For the cover crops that did not over winter biomass at sampling was negligible. There were no significant differences on cover crop biomass due to compaction levels or interactions between cover crop and compaction level (data not shown).

### *Changes in Soil Physical Properties after Winter Cover crops*

Optimal bulk-density values refer to maximum root growth or crop yield, and GLBD values refer to conditions where root growth is stopped or reduced to some 20% of the maximum (Kaufmann, 2010). The optimal BD for root growth in fine textured soils is in the order of 0.8 to 1.2 Mg m<sup>-3</sup> (Reynolds et al., 2002) and the GLBD for the soils in this study (silty clay loam, averages of 13% sand, 57% silt, and 29% clay) is between 1.50 and 1.55 Mg m<sup>-3</sup> (USDA-NRCS, 1996). After the WCC growing season, no significant differences were determined for BD for the interactions between cover crops and compaction levels or the main effects except depth ( $p < 0.0027$ ) for both environments (Table 1.13). As expected lower bulk densities were found at the surface 10cm and increased in depth. This difference in bulk density in depth is due to greater additions of organic residues and greater activity of micro and macro fauna and roots in the topsoil. BD values were near the optimal bulk density for all the treatments including the NCOV, and all BD values also decreased in comparison to the values reported right after the compaction treatments were imposed. We expected to find greater differences in BD in the top layers of the soil profile after WCC but the lack of significant differences can be explained at least partly, by the seed bed preparation tillage needed to establish the WCC. It is also important to point out that prior to our experiment the fields were on winter wheat and immediately after harvest the stubble was incorporated with tillage, mixing organic residues in the top 20 cm of soil. Addition of organic matter to the topsoil through incorporation of plant residues has been widely studied and it is known to improve bulk density and soil porosity (Soane, 1990; Zhang, 1994; Hamza and Anderson, 2005). Lastly, Drummer soils are characterized by having a high content of highly expandable smectitic clays in the topsoil (Soil Survey Staff, 2012) that experience important shrink-swell cycles with changes in water content. We believe that the shrink swell and wet dry

cycles in the topsoil of the studied plots, along with the inherently high levels of soil organic matter plus the residues added via the previous wheat crop, played a significant role in the high resilience showed by these soils to applied compaction.

PR values after the cover crop growing season were significantly different for the interaction of cover crop and depth ( $p < 0.0001$ ) and compaction level and depth ( $p < 0.0064$ ). The main effects cover crop ( $p < 0.0028$ ) and depth ( $p < 0.0001$ ) were also significant. As with bulk density, penetration resistance increases with depth (McFarland et al., 1990). PR values decreased for all the treatments (Table 1.14) in comparison to values after the compaction treatments were imposed and the values recorded were lower than those suggested as restricting root growth; 1000 to  $>4000$  kPa (Hamblin, 1985). For the top 10 cm the WCC treatments that produced the largest amounts of biomass: RR, RHV, and RTR had the lowest PR values but yet again, the NCOV treatment showed similar values. The compaction alleviating effect of natural forces has been reviewed by Dexter (1991) and specifically reported by Voorhees (1983) for a silty clay loam soil in Minnesota where natural weathering reduced cone index by 20–50% after 5 years of wheel induced traffic. Although PR values were below the ranges suggested as limiting root growth, the cover crops that overwintered had consistently higher PR below the 20 cm depth. Similar increases in PR after cover crops were observed by Drury et al. (1999) and Villamil et al. (2006). It has been suggested that intensification of wet-dry cycles can lead to closer contact between particles (Singer et al., 1992), therefore increasing PR values.

Mean values of RC (Table 1.15) after the WCC growing season fell within optimal ranges for crop production yet they displayed a significant difference for the interaction between WCC treatments and compaction levels ( $p < 0.018$ ). For the TK compaction treatment the lowest RC values were achieved by RB, RTR and R. For the LT treatment RHV, RR and RTR showed

the lowest RC values. The lowest RC values for the ST treatment were achieved by RR and RHV. Under Nc, cover crop treatments of R, RTR and RHV had the lowest RC values. Overall across compaction levels, the mixtures including both grasses and legumes had very similar RC values to the R sown alone.

Above ground and below ground biomass production by the WCC was expected to increase WAS values of the surface soil by protecting aggregate breakdown from rainfall. After one WCC growing season there were no significant differences among the treatments for WAS (Table 1.16). The lack of differences could be explained by the high levels of soil carbon across the treatments,  $29.9 \text{ g kg}^{-1}$  for the topsoil. Tisdall (1982) suggested there is a content of organic carbon above which there is no further increase in water stable aggregation.

#### *Changes in Soil Chemical Properties*

In both environments, after one WCC growing season there were no significant differences for total nitrogen (TN) between the treatments and interaction effects were non-significant as well (Table 1.17). The surface layer of most cultivated soils contains between  $0.6 \text{ g kg}^{-1}$  and  $5 \text{ g kg}^{-1}$  of TN (Bremner and Mulvaney, 1982) and the TN values obtained in this study ranged between 2.3 for the topsoil and 0.7 to the lower depths. This lack of response can be explained mainly because TN pools in cultivated soils remain relatively constant over periods of time (Sainju et al., 2003). Similarly, there were no significant differences for total carbon (TC) between the treatments, and interaction effects were non-significant as well. Although there were no significant differences, a small positive trend for TC was identified for the WCC that produced the highest biomass (Table 1.18). The only significant difference observed was that resulting of the commonly reported nutrient stratification in depth ( $p < 0.001$ ). Although there is an important addition of organic residues through the WCC used in this study, changes in soil

TC are more commonly reported in long-term experiments. After 6 years of a corn (*Zea mays* L.) rotation including several leguminous and non-leguminous cover crops in Washington, cereal rye and annual ryegrass (*Lolium multiflorum* Lam.) were observed to increase soil TC levels (Kuo, 1997). However in southern Illinois on a moderately eroded Typic Fragiudalfs no differences in soil TC were determined after 8 years of a corn-soybean rotation with or without cover crops (Olson, 2010). The Drummer soil has a naturally high level of total C and total N and relatively small increases of C and N associated with WCC would likely go undetected except in a stable long-term study. Similar results were reported by Ebehlar (1984) and Villamil (2006).

After one WCC growing season in both environments, there were no significant differences for soil nitrates ( $\text{NO}_3\text{-N}$ ) between the treatments; interaction effects were non-significant as well (Table 1.19). As no nitrogen source was used in this experiment, existing levels of soil nitrates are attributed to mineralization of the organic matter, residual nitrates from the nitrogen fertilization of the previous wheat crop, and to whereas differences in the scavenging abilities of the WCC. We did not expect to find differences related to residual nitrogen effects after wheat because in Illinois wheat is fertilized in late winter or early spring of the previous year (Illinois Agronomy Handbook, 2009). In the present study, results of soil pH ranged between 5.4 and 5.8 for the top 10 cm with values increased in depth (Table 1.20). The lower pH was found at the surface soil which might be associated with residual effects of nitrogen fertilization of the previous winter wheat crop. Significant differences were observed for the three way interaction between cover crop, compaction level and depth ( $p < 0.0008$ ) and cover crop and depth ( $p < 0.0539$ ) and for the main effect depth ( $p < 0.044$ ). Although reductions on available soil P with the use of WCC have been reported for legumes and grasses (McVay et al., 1989; Eckert, 1991; Villamil et al., 2006) no significant differences were determined in this

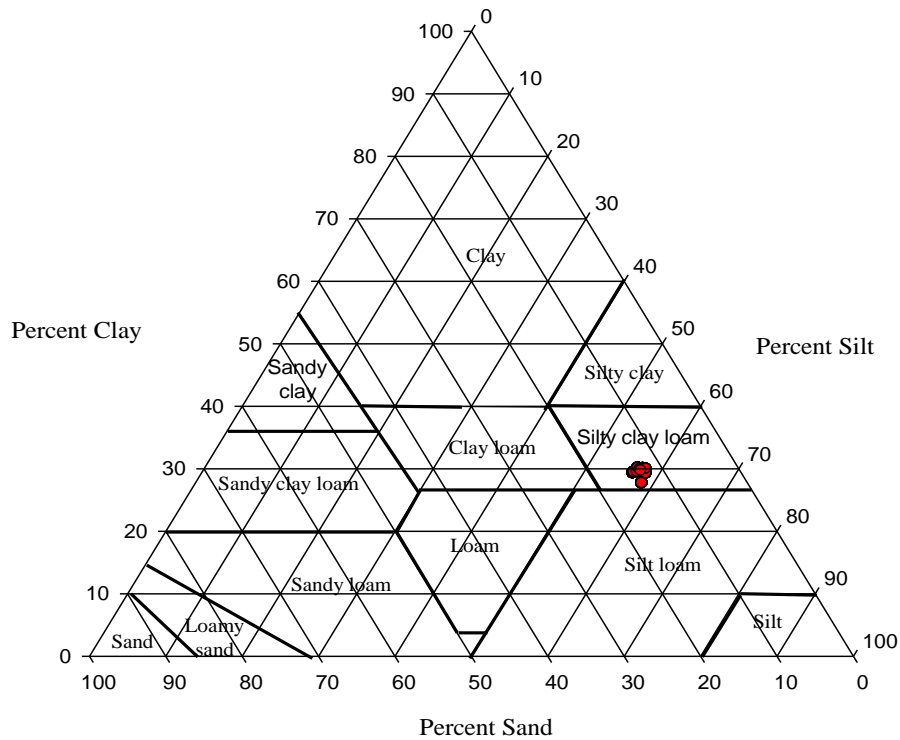
study. Soil available P values after WCC showed no significant differences for the interaction or the main effects of compaction and cover crop treatments, yet as expected, P values decreased with increasing depths ( $P < 0.0470$ ). Available P levels found in the topsoil are considered in the high supply range for corn and soybean production in IL according to the Illinois Agronomy Handbook (Nafziger, 2004) (Table 1.21).

## CONCLUSION

This work provides needed and currently lacking information regarding the potential alleviation effect of WCC on imposed soil compaction treatments and their contribution to soil general fertility. It is the first study in Illinois and in the Midwest region that shows the effect of selected WCC mixtures including Brassicas sp. on short term soil physical and chemical properties. Despite research on cover crops, reporting positive effects on soil properties, adoption rates within the corn-soybean rotation in the Corn Belt, at least as measured by observation of fields after harvest in the fall, remains low. Recent interest in cover crops has been gauged by press articles, promotional efforts, and brochures from companies who sell cover crop seed or provide services such as aerial seeding. In many of these efforts, cover crop benefits are exaggerated –and disadvantages minimized- to the point of being regarded as a ‘silver-bullets’ fast acting solutions to agricultural problems. Though the use of cover crops might be desirable in many situations, increased adoption on these terms may prove counterproductive. Changes in in soil properties and cropping systems do not occur overnight. As soil compaction, the effects of cover crops on soil properties are build-up processes that take time to become evident or

measurable. Results from this study show that one growing season is not enough time to evidence changes in the soil related to the incorporation of cover crops in the rotation. Although WCC did not differ from the control in improving soil physical properties in both environments, management practices that maintain or increase soil carbon through additions of organic residues will help soil resilience to compaction. Further research is needed on the use of WCC as soil compaction management tool in stabilized corn-soybean-WCC rotations especially in fields with persistent compaction problems.

## TABLES AND FIGURES



**Figure 1.1** Textural triangle showing the percentages by weight of clay (<0.002-mm), silt (0.002-0.05-mm), and sand (0.05-2mm) separates of the studied soils in the conventional USDA soil textural classes.



**Table 1.1** Mean values of particle size separates for cover crops and compaction treatments.

	Particle size separate (g kg <sup>-1</sup> )		
	Sand	Silt	Clay
Cover crop			
NCOV	14.0	56.7	24.2
R	11.8	57.9	25.4
RB	12.2	58.4	24.3
RHV	13.3	56.9	24.6
RR	13.2	57.2	24.6
RTR	12.1	57.7	25.3
SE†	2.00	0.67	1.02
Compaction			
Nc	13.0	57.2	25.3
ST	12.1	58.5	24.3
LT	13.1	56.8	25.5
TK	13.0	57.4	23.8
SE†	1.90	0.49	1.09

NCOV, no cover; R, radish; RB, radish+buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

†SE, standard error of mean.

**Table 1.2** Additional characterization of the sand and silt size separates.

Cover crop	Sand size fraction					Silt fraction	
	¶VCoS	CoS	MS g kg <sup>-1</sup>	FS	VFS	CoSi g kg <sup>-1</sup>	FSi
NCOV	1.0	1.5	3.8	3.7	1.0	16.6	40.1
R	0.6	1.2	3.1	3.1	0.9	16.7	41.3
RB	0.8	1.3	3.2	3.1	0.9	17.1	41.3
RHV	0.9	1.5	3.6	3.4	0.9	16.6	40.3
RR	0.8	1.4	3.5	3.5	1.0	17.3	39.8
RTR	0.8	1.4	3.3	3.1	0.9	16.6	41.2
SE†	0.3	0.5	1.5	1.9	0.5	0.5	0.6
Compaction							
Nc	0.8	1.4	3.5	3.4	1.0	16.2	40.9
ST	0.8	1.3	3.2	3.0	0.8	17.3	41.3
LT	0.8	1.4	3.5	3.5	1.0	16.9	39.9
TK	0.9	1.4	3.6	3.4	1.0	16.9	40.5
SE†	0.3	0.5	1.5	1.9	0.5	0.6	0.7

¶Vcos, very coarse sand; CoS, coarse sand; MS, medium sand; FS, fine sand; VFS, very fine sand; CoSi, coarse silt, and FSi, fine silt.

NCOV, no cover; R, radish; RB, radish+buckwheat; RHV, radish+hairy vetch; RR, radish+rye; RTR, radish+triticale.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

†SE, standard error of mean.

Depth (cm)	Compaction								†SED
	Nc		ST		LT		TK		
	Mg m <sup>-3</sup>								
5	1.13	cC	1.23	bAB	1.22	bB	1.27	bA	0.02
15	1.38	bB	1.39	aAB	1.37	aB	1.42	aA	0.01
25	1.44	abA	1.40	aB	1.43	aAB	1.44	aA	0.01
35	1.43	abA	1.45	aA	1.43	aA	1.42	aA	0.01
45	1.45	Aa	1.42	aA	1.44	aA	1.44	aA	0.01

†SED, standard error of the differences.

Between compaction levels and for each row, means followed by the same uppercase letter at a given depth are not significantly different at  $p=0.1$ .

**Table 1.4** Mean values of PR as affected by compaction and depth.

Compaction										
Nc			ST		LT		TK			
Depth (cm)		KPa								†SED
5	307	cD	838	cC	1056	bB	1319	cA	81	
15	1246	bC	1461	abB	1567	aB	1886	aA	91	
25	1279	bB	1430	abB	1393	aB	1635	bA	77	
35	1338	abA	1364	bA	1366	aA	1434	bcA	60	
45	1514	aA	1589	aA	1546	aA	1592	bA	65	

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

†SED, standard error of the differences.

Within compaction level and for each column, means followed by the same lowercase letter are not significantly different at  $p=0.1$ .

Between compaction levels and for each row, means followed by the same uppercase letter at a given depth are not significantly different at  $p=0.1$ .

**Table 1.5** Mean values of WAS as affected by compaction and depth.

	Compaction							
	Nc		ST		LT		TK	
Depth (cm)	WAS <sup>2</sup> (%)							
5	7396	(86)	6724	(82)	6889	(83)	6889	(83)
15	7225	(85)	7225	(85)	6724	(82)	6724	(82)
SE†	594		767		594		594	

†SE, standard error of the transformed mean values.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

**Table 1.6** Mean values of RC as affected by compaction and depth.

	Compaction								
	Nc		ST		LT		TK		
Depth (cm)	RC (%)								SED†
5	78.6	bC	85.6	baB	84.6	bB	87.4	bA	1.6
15	90.6	aB	92.6	aAB	90.9	aB	93.8	aA	1.6

†SED, standard error of the differences.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

Within compaction level and for each column, means followed by the same lowercase letter are not significantly different at  $p=0.1$ .

Between compaction levels and for each row, means followed by the same uppercase letter at a given depth are not significantly different at  $p=0.1$ .

**Table 1.7** Mean values of TN as affected by compaction and depth.

Depth (cm)	Compaction				†SE
	Nc	ST	LT	TK	
g kg <sup>-1</sup>					
5	2.3	2.2	2.2	2.3	0.1
15	2.2	2.0	2.2	2.2	0.1
25	1.7	1.6	1.6	1.6	0.1
35	0.9	0.9	0.9	0.9	0.1
45	0.7	0.7	0.7	0.7	0.1

†SE, standard error of the mean values.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

**Table 1.8** Mean values of TC as affected by compaction and depth.

Depth (cm)	Compaction				†SE
	Nc	ST	LT	TK	
g kg <sup>-1</sup>					
5	29.9	29.8	29.5	30.8	0.3
15	28.5	27.4	28.3	27.8	0.3
25	20.9	20.6	20.7	20.4	0.4
35	12.2	11.7	11.7	11.7	0.3
45	8.4	8.4	8.1	8.1	0.3

†SE, standard error of the mean values.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.



**Table 1.9** Mean values of available NO<sub>3</sub>-N as affected by compaction and depth.

Table 15. Mean values of available NO <sub>3</sub> -N as affected by compaction and depth.													
Depth (cm)	Compaction												
	Nc			ST			LT			TK			
	log <sub>10</sub> mg NO <sub>3</sub> -N kg soil <sup>-1</sup> (mg NO <sub>3</sub> -N kg soil <sup>-1</sup> )												
5	1.3	aAB	(21.6)	1.3	aB	(19.6)	1.3	aB	(19.4)	1.4	aA	(24.9)	0.1
15	1.3	aAB	(18.9)	1.3	aAB	(17.8)	1.3	aA	(19.7)	1.2	bB	(16.5)	0.1
25	0.9	bB	(9.5)	1.1	abB	(11.8)	1.1	bA	(12.3)	1.1	cA	(11.9)	0.1
35	0.8	bA	(6.4)	0.8	cA	(6.1)	0.8	cA	(6.3)	0.8	dA	(5.9)	0.1
45	0.6	Ca	(4.4)	0.7	dA	(5.1)	0.6	daB	(4.3)	0.6	eB	(4.1)	0.2

†SED, standard error of the transformed mean values.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

Within compaction level and for each column, means followed by the same lowercase letter are not significantly different at  $p=0.1$ .

Between compaction levels and for each row, means followed by the same uppercase letter at a given depth are not significantly different at  $p=0.1$ .

**Table 1.10** Mean values of pH as affected by compaction and depth.

Table 110. Mean values of pH as affected by compaction and depth.										
		Compaction								
		Nc		ST		LT		TK		
Depth (cm)		pH								SED†
5		5.3	dB	5.4	dAB	5.4	dA	5.4	cA	0.03
15		5.6	cB	5.8	cA	5.7	cAB	5.7	cAB	0.04
25		6.0	bA	5.9	bcA	5.9	cA	5.9	bcA	0.02
35		6.2	bA	6.2	bA	6.3	bA	6.2	bA	0.03
45		6.5	aBC	6.5	aBC	6.6	aB	6.7	aA	0.05
SE†		0.1								

†SED, standard error of the differences.

†SE, standard error of the mean values.

Within compaction level and for each column, means followed by the same lowercase letter are not significantly different at  $p=0.1$ .

Between compaction levels and for each row, means followed by the same uppercase letter at a given depth are not significantly different at  $p=0.1$ .

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

**Table 1.11** Mean values of available P as affected by compaction and depth.

Table 11.1 Mean values of available P as affected by compaction and depth.													
Depth (cm)	Compaction												
	Nc			ST			LT			TK			
	log mg P kg soil <sup>-1</sup> (mg P kg soil <sup>-1</sup> )												
5	3.5	aA	(32.7)	3.6	aA	(35.4)	3.5	aA	(32.9)	3.5	aA	(33.2)	0.1
15	3.0	abAB	(20.8)	2.9	aB	(17.3)	3.2	aA	(24.3)	3.0	aB	(19.6)	0.1
25	2.2	abAB	(9.1)	2.4	abB	(11.4)	2.3	abA	(10.0)	2.1	bB	(8.2)	0.1
35	1.9	bA	(6.7)	1.9	bA	(6.5)	1.8	bA	(6.0)	1.7	bA	(5.7)	0.1
45	1.5	aB	(4.5)	1.2	bA	(3.4)	1.4	bA	(4.0)	1.4	bA	(4.0)	0.2

†SED, standard error of the transformed mean values.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

Within compaction level and for each column, means followed by the same lowercase letter are not significantly different at  $p=0.1$ .

Between compaction levels and for each row, means followed by the same uppercase letter at a given depth are not significantly different at  $p=0.1$

**Table 1.12** Winter cover crop aboveground biomass before termination.

Growing season	WCC dry biomass			SED†
	RR	RTR	RHV	
	Mg ha <sup>-1</sup>			
2010-2011	8.66	8.15	2.29	0.38
2011-2012	6.05	5.96	4.03	0.35

†SED, standard error of the mean values.

RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

**Table 1.13** Mean values of BD after cover crop growing season for cover crop level and depth.

Depth (cm)	Cover crop					
	NCOV	R	RB	RHV	RR	RTR
	Mg m <sup>-3</sup>					
5	1.15	1.16	1.15	1.13	1.14	1.15
15	1.30	1.27	1.29	1.23	1.23	1.23
25	1.34	1.32	1.29	1.26	1.29	1.27
35	1.33	1.33	1.30	1.25	1.28	1.29
45	1.35	1.33	1.33	1.27	1.32	1.29
SE†	0.03					

†SE, standard error of the mean values.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

**Table 1.14** Mean values of PR after cover crop growing season for cover crop level and depth.

Depth (cm)	Cover crop												†SED
	NCOV		R		RB		RHV		RR		RTR		
	kPa												
5	447	dB	576	dA	655	cA	467	dB	370	eB	417	eB	81
15	917	cBC	906	cC	1027	baB	1385	cA	981	dB	1223	dA	106
25	1087	bB	1006	bB	1031	bB	1714	abA	1418	cA	1700	cA	150
35	1210	bC	1122	bC	1122	bC	1680	bB	1555	bB	1901	bA	132
45	1384	aC	1311	aC	1288	aC	1818	aB	1734	aB	2098	aA	120

†SED, standard error of the differences.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

Within cover level and for each column, means followed by the same lowercase letter are not significantly different at  $p=0.1$ .

Between cover levels and for each row, means followed by the same uppercase letter at a given depth are not significantly different at  $p=0.1$ .

**Table 1.15** Mean values of RC as affected by cover crop and compaction level.

	Compaction							
	Nc		ST		LT		TK	
Cover crop	RC (%)							
NCOV	79	aAB	76	bcB	83	aA	84	aA
R	76	bcB	83	aA	83	aA	81	abA
RB	80	aA	82	aA	80	aA	77	cB
RHV	78	abB	81	aA	80	abAB	83	aA
RR	80	aAB	79	abB	79	bB	84	aA
RTR	75	bcB	82	aA	79	abA	80	bA
†SED	3		3		3		3	

†SED, standard error of the differences.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

Within compaction level and for each column, means followed by the same lowercase letter are not significantly different at  $p=0.1$ .

Between cover crop levels and for each row, means followed by the same uppercase letter are not significantly different at  $p=0.1$ .

**Table 1.16** Mean values of WAS as affected by cover crop and depth.

	Cover crop											
	Nc		R		RB		RHV		RR		RTR	
Depth (cm)	WAS <sup>2</sup> (%)											
5	6838	(83)	6395	(80)	6423	(80)	6423	(82)	6537	(81)	6700	(82)
15	7157	(85)	7702	(88)	7038	(84)	7776	(88)	7870	(89)	7762	(88)
SE†	797											

<sup>†</sup>SE, standard error of the transformed mean values.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish +rye; RTR, radish +triticale.



**Table 1.17** Mean values of TN as affected by compaction and depth.

Depth (cm)	Cover crop						†SE
	NCOV	R	RB	RHV	RR	RTR	
	g kg <sup>-1</sup>						
5	2.2	2.3	2.4	2.3	2.2	2.3	0.1
15	2.0	2.0	2.1	2.1	2.1	2.1	0.1
25	1.6	1.7	1.6	1.6	1.7	1.7	0.1
35	0.9	0.9	0.9	0.9	0.9	0.9	0.1
45	0.7	0.7	0.7	0.7	0.7	0.7	0.1

†SE, standard error of the transformed mean values.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish +rye; RTR, radish +triticale.

**Table 1.18** Mean values of TC as affected by compaction and depth.

Depth (cm)	Cover crop						†SE
	NCOV	R	RB	RHV	RR	RTR	
	g kg <sup>-1</sup>						
5	29.0	28.9	30.8	30.2	29.9	30.3	1.1
15	26.6	26.5	28.2	28.7	28.1	28.2	1.3
25	20.1	21.0	20.4	20.3	21.2	21.5	1.5
35	11.1	11.8	10.7	11.6	11.7	11.9	1.0
45	8.5	7.9	7.4	7.8	8.8	7.9	0.9

†SE, standard error of the transformed mean values.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish +rye; RTR, radish +triticale

**Table 1.19** Mean values of NO<sub>3</sub>-N as affected by cover crop and depth.

Depth (cm)	Cover crop												†SE
	NCOV		R		RB		RHV		RR		RTR		
	log <sub>10</sub> mg NO <sub>3</sub> -N kg soil <sup>-1</sup> (mg NO <sub>3</sub> -N kg soil <sup>-1</sup> )												
5	0.84	(7.00)	0.72	(5.27)	0.68	(4.76)	0.55	(3.53)	0.50	(3.13)	0.32	(2.10)	0.32
15	0.74	(5.50)	0.59	(3.90)	0.60	(3.99)	0.33	(2.12)	0.29	(1.93)	0.16	(1.46)	0.32
25	0.53	(3.43)	0.43	(2.70)	0.49	(3.08)	-0.04	(0.91)	0.01	(1.03)	-0.13	(0.74)	0.32
35	0.40	(2.53)	0.23	(1.69)	0.28	(1.92)	-0.23	(0.59)	-0.29	(0.51)	-0.05	(0.90)	0.32
45	0.28	(1.90)	0.20	(1.59)	0.23	(1.70)	-0.26	(0.55)	-0.21	(0.62)	-0.31	(0.49)	0.32

†SE, standard error of the transformed mean values.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish +rye; RTR, radish +triticale.

**Table 1.20** Mean values of pH after cover crop growing season for cover crop level and depth.

	Cover crop												
	NCOV		R		RB		RHV		RR		RTR		
Depth (cm)	pH												†SED
5	5.5	bA	5.6	bA	5.5	bA	5.5	bA	5.5	bA	5.6	bA	0.1
15	5.7	bAB	5.7	bAB	5.7	bAB	5.8	bA	5.5	bB	5.7	bAB	0.1
25	5.8	bA	5.7	bA	5.7	bA	5.8	bA	5.9	bA	5.8	bA	0.1
35	6.2	abA	6.2	aA	6.2	aA	6.2	aA	6.1	abA	6.1	abA	0.1
45	6.3	aA	6.2	aA	6.3	aA	6.2	aA	6.3	aA	6.2	aA	0.1

†SED, standard error of the differences.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

Within cover level and for each column, means followed by the same lowercase letter are not significantly different at  $p=0.1$ .

Between cover levels and for each row, means followed by the same uppercase letter at a given depth are not significantly different at  $p=0.1$ .

**Table 1.21** Mean values of available P as affected by cover crops and depth.

	Cover crop										†SE		
	NCOV		R		RB		RHV		RR			RTR	
Depth (cm)	log mg P kg soil <sup>-1</sup> (mg P kg soil <sup>-1</sup> )												
5	3.1	(23.2)	3.2	(25.2)	3.4	(28.7)	3.2	(23.9)	3.3	(26.1)	3.2	(23.7)	0.3
15	3.0	(19.8)	3.0	(19.8)	3.1	(21.7)	2.9	(17.6)	3.0	(20.2)	2.9	(18.3)	0.3
25	2.4	(10.7)	2.5	(11.9)	2.7	(14.6)	2.5	(11.7)	2.5	(12.7)	2.6	(13.2)	0.3
35	2.0	(7.8)	2.1	(8.3)	2.0	(7.6)	2.1	(7.8)	2.0	(7.8)	2.1	(7.9)	0.3
45	2.0	(7.7)	2.0	(7.7)	2.0	(7.5)	2.0	(7.6)	2.1	(7.8)	2.0	(7.8)	0.3

†SE, standard error of the transformed mean values.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish +rye; RTR, radish +triticale.

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## CHAPTER 2. COVER CROPS AND SOIL COMPACTION EFFECTS ON SOYBEAN PRODUCTION IN ILLINOIS

### ABSTRACT

The inclusion of radish (*Raphanus sativus* L. var. *longipinnatus*) as a winter cover crop (WCC) has been suggested as a valuable soil compaction management tool for the corn-soybean (*Zea mays* L.) [*Glycine max* (L.) Merr.] rotation of the U.S. Midwest. However, little information is available on the effects of radishes and its combinations with other cover crops on the following soybean crop. Recent interest in cover crops has been gauged by articles, NRCS promotional efforts, and sales promotions from companies who sell cover crop seed and services such as aerial seeding. Still, it has to be acknowledged that cover crops have not been shown definitively to provide a positive return on investment, at least within farming systems most commonly used in this region. Increased knowledge of the effects of WCC on growth, development and yield of the following crop will inform the decision of WCC inclusion within corn-soybean rotations in the Midwest. The objective of this study was to evaluate soybean growth and development under different cover crop combinations and compaction induced treatments on a typical Illinois Drummer soil at Urbana, IL. The cover crops used were: radish (*Raphanus sativus* L. var. *longipinnatus*) “R”, sown alone and its combination with rye (*Secale cereale* L.) “RR”, triticale ( $\times$  *Triticosecale* cv *Presto*) “RTR”, buckwheat (*Fagopyrum esculentum* L. Moench) “RB”, hairy vetch (*Vicia villosa* Roth) “RHV” and a control with no cover crop “NCOV” after compaction induced treatments in Fall 2010 and Fall of 2011. The compaction treatments included a control with no compaction (Nc), and three levels of compaction achieved with either a small tractor (ST), a large tractor (LT) or a hauling truck (TK). Compaction levels and cover crops were arranged in a 4 x 6 factorial in a completely

randomized design (CRD) with two replications. In 2011 the ST treatment was dropped due to similar contact pressure and compaction achieved with the LT. The degrees of compaction achieved in this study had no significant effect on soybean growth, development and yield. WCC showed significant differences for soybean population: WCC that over wintered had 5-20% less plants than the WCC that did not overwinter and the control. WCC also showed significant differences for LAI and number of nodes, soybeans had 8% more nodes on the plots without over wintering WCC. Differences disappeared towards harvest. Overall yield components and grain yield showed no significant differences due to WCC or their interactions. With adequate management practices soybean growth parameters and yield should not be affected by WCC and may prove to be a useful tool for soil compaction management especially in fields with persistent compaction.

## **INTRODUCTION**

Farmers recognize soil compaction as a threat to crop productivity. Compaction reduces void space in the soil reducing water storage and availability for crops. Mechanical loosening using deep tillage, chiseling and subsoiling have been the most common practices to alleviate compacted layers for decades. However recent research has shown that these effects are temporary, usually lasting no longer than one growing season (Busscher et al., 2002; Horn et al., 2002; Araujo et al., 2004). Moreover the benefits of subsoiling can be offset by its high cost and the risk of re-compaction after trafficking the same area (Raper and Kirby, 2006). Alternatives to tillage practices include natural processes of wetting and drying, freezing and thawing cycles,

and biological processes related to root exploration, and activities of soil microbes and fauna (Dexter, 1988; Barzegar, 1995).

Soil compaction and its negative effects on crop production have been widely researched for various crops and soil types (Letey, 1985; Haakanson, 1988; Arvidsson, 1991). Changes in soil properties related to soil compaction affect root growth and development (Unger and Kasper 1994; Dexter, 2004) nutrient uptake (Arvidsson, 1999), and can dramatically alter plant morphology, reducing yields and decreasing soil productivity and farmers profits (Andrade et al., 1993; Radford et al., 2001; Passioura, 2002; Sadras et al., 2005). Restricted soybean root growth in compacted sandy loam and clay loam soils can exacerbate water stress and reduce yields (Buttery, 1998). Reductions in soybean yields of 9-19%, were observed in a three year experiment after 10 Mg and 20 Mg axle load compaction treatments in a poorly-drained heavy-textured soil in northwest Ohio (Flowers, 1998). Similarly, in southern Minnesota compaction imposed treatments including 4.5 Mg, 9 Mg and 18 Mg axle loads on a clay loam soil, affected soybean plant height and integrated leaf area index reducing yields by 15% and up to 27% (Johnson and Voorhees, 1990). Effects of compaction on crop production varies with soils, seasons and crops since soil compaction is the result of a complex interaction between machines, soil, crop, and weather (Soane and van Owerkerk, 1994). In particular, yield variability found in compaction studies is highly dependent on the season's rainfall and may not always affect the crop negatively. Johnson and Voorhees (1990) found general decreases in yield during a wet year and yield increases during a dry year in response to compaction and, in 5 out of 14 location-years an intermediate compaction level (9 Mg axle load) out yielded the control treatments with no compaction. Likewise, in a 2 year experiment on a Wisconsin clay loam soil, Lindemann (1982) found significant differences in soybean yield after imposed compaction treatments

including different number of passes with a tractor weighing 3.5 Mg; yields were higher in the compacted treatments in a dry season and lower in the compacted treatments in a wet season. Yield reductions following rainfall patterns have also been reported in maize; by up to 50% in a wet season and 25% in a drier-than-normal season after imposed compaction treatments in poorly drained silt loam soils in Indiana (Gaultney et al., 1982). Attempts to measure and understand the degree of soil compaction have been hindered due to the difficulty of isolating the effects of compaction from the season effect and other factors present in the soil (Voorhees et al., 1987; Morgan et al., 1993).

Soil organic matter plays a key role in a soil's susceptibility to compaction since organic matter retains soil water and has the ability to rebound after being compacted (Thomas et al., 1996; Reeves, 1997; Dexter, 2004). Moreover, organic residues are lighter and less dense than silt, clay and sand particles therefore management practices that can increase additions of organic materials into the soil profile can lower soil bulk density (Zhang, 1994). Typically, soils with high organic matter values are more resilient to soil compaction, thus management practices that maintain or increase organic matter will help to prevent or avoid soil compaction (Soane, 1990). One of these practices is the incorporation of winter cover crops in rotation (Kuo, 1997). The inclusion of WCC in modern cropping systems has been suggested to improve soil structure (Shepherd, 2002; Lal, 2004) and help alleviate soil compaction (Clark, 2007; Williams and Weil, 2004; Chen and Weil, 2010). Due to the short growing season after harvest of the main crop in the fall, the prevalent cover crops in the Midwest region are winter annuals (Singer, 2008). Winter rye is the most common small grain winter cover crop in the central U.S. (Bollero 1994; Singer, 2008) while hairy vetch is considered to be the best legume option for the central and southern U.S (Smith et al., 1987). Separately or in mixtures, cereal rye and hairy vetch are the

most studied cover crops in the Midwest (Ruffo, 2004; Villamil 2006; Singer, 2008). Cereal rye has a high biomass production, ranging from 1 to 8 Mg ha<sup>-1</sup> (Baker, 2009), and has a high nitrogen scavenging potential, thus reducing nitrogen leaching from agricultural land (Shipley et al., 1992). Hairy vetch has good winter hardiness and is usually used in rotation with corn for its ability to fix large amounts of nitrogen 90-100 kg ha<sup>-1</sup> (Ebelhar, 1984). Farmers interested in cover crops in the Midwest have been recently interested in species of the Brassicaceae family, such as radish (*Raphanus sativus* L. var. *longipinnatus*) for their rapid growth in fall, potential nutrient cycling, compaction alleviation abilities and die off in winter.

Including winter cover crops (WCC) in a cropping system provides multiple benefits to the soil and to crops that can result in greater crop yield or enhanced yield stability (Snapp et al., 2005). Soil productivity with WCC can be increased through increased soil organic matter, weed and pest suppression, reduced nutrient loss and enhanced nutrient cycling (Sainju et al., 2002; Williams et al., 2000; Meisinger and Delgado 2002, Villamil et al., 2006; 2008). WCC are one of the most researched conservation practices, yet adoption levels are still low. Results after a mail survey including 3500 farmers in Illinois, Indiana, Iowa and Minnesota showed that 18% of farmers had used cover crops once and 11% had planted cover crops between 2001 and 2005 (Singer et al., 2007; Singer 2008). One of the reasons for this low adoption of cover crops is that under certain circumstances WCC have been reported to lower crop yields. Including cover crops in modern cropping systems requires adequate management practices to minimize any possible negative impacts (Snapp et al., 2005). Crop yield reductions are usually associated to water depletion by the WCC, and or delayed emergence and growth of the cash crop (Raimbault et al., 1991; Unger et al., 1998; Westgate 2005). Difficulties in establishing soybeans in high biomass overwintering cover crops such as rye have been reported by Williams et al. (2000) and Reddy et

al. (2003). Rye has been reported to decrease (Eckert, 1988; Williams et al., 2000; Davis, 2010) increase (Williams et al., 2000; Williams, 2004), or have no effect (Swanton, 1988, Reddy, 2003; Ruffo, 2004; Strock, 2004) on the yield of the following soybean crop. More recently, radish has been reported to have positive or neutral effects on soybean yield (Chen and Weil, 2010). Although there is an increased interest in the use of WCC in Illinois conflicting information pertaining to the effects on the following crop's yield is an important limitation for farmer adoption.

Previous studies in Illinois have focused on management strategies for rye, hairy vetch and the rye -vetch mixture in no-till systems (Crandall, 2005; Davis 2010), their effects on weed and pest suppression, residue decomposition, and crop yields (Wagger et al., 1998; Reddy et al., 2003; Ruffo and Bollero., 2003). Moreover, Villamil et al. (2006; 2008) have shown the potential of these cover crops to improve soil structure and increase soil organic matter and nutrient cycling in no-till systems. Yet conventional systems continue to dominate the agricultural landscape in IL and there is little information regarding the effects of cover crops, including brassicas on the following cash crop. Literature regarding cover crops and crop yield typically only report crop yield data without growth and development parameters. Although there are studies in the Illinois showing soybean growth and development under different cover crop systems (Ruffo, 2004; Davis, 2010) and the effects of cover crops on the growth and development of the following corn crop (Miguez et al., 2006) there are studies conducted under no-till management and there are no studies showing the combined effects of compaction and cover crops on the following soybean crop growth, development and yield in conventional systems. Evaluation of crop growth and development parameters such as light interception, leaf area index, crop growth rate and dry matter accumulation is a useful tool for comparing different



management systems (Pedersen, 2004). Evaluating crop growth and development parameters of soybeans under WCC may lead to improved management decisions that can help maximize benefits while minimizing negative effects associated with the use of WCC. The objective of this study was to examine the effects of compaction and WCC treatments on soybean development, growth and yield through the evaluation of development parameters: Leaf area index (LAI), dry matter accumulation (DM), crop growth rate (CGR), relative growth rate (RGR), and yield components in conventional systems in two different environments in IL.

I expect that the results of this study will provide currently lacking information regarding the effects of compaction induced treatments and of selected WCC on the subsequent soybean crop growth and yield to help inform the decision of the inclusion of WCC as a soil compaction management tool in corn-soybean systems.

## **MATERIALS AND METHODS**

### **Experimental sites and methods**

The study was carried out at Urbana, Illinois, in 2010 and 2011 at the Crop Sciences Research and Education Center (South Farms) of the University of Illinois. A different field coming out of wheat production (*T. aestivum* L.) was used each year. Both fields were on Drummer silty clay loam (fine silty, mixed, superactive, mesic Typic Endoaquoll) with less than 2% slope. Drummer series consists of dark colored, very deep, poorly drained soils developed in 100- to 150-cm of loess or other silty material under prairie vegetation. Permeability is moderate and surface runoff is negligible to low (Soil Survey Staff, 2012). The two selected fields had

been cultivated to an average depth of 20cm. Before establishing our experiment, conventional tillage consisting of a deep ripper followed by disking was used to control weeds and prepare the seed bed. Compaction levels and cover crop treatments were arranged in a 4 x 6 factorial in a completely randomized design (CRD) with two replications. Four levels for compaction (high “Truck” (TK), medium “Large tractor” (LT), low “Small tractor” (ST) and No compaction (Nc) were achieved by 5 passes of the different vehicles with the soil at field capacity. The plot dimensions were 6.09 m x 15.24 m. Fields were separated by 9.14 m wide alleys for tractor and equipment turning during creation of the compaction treatments and cover crops planting.

The compaction treatments were established using a John Deere 7210 Tractor (Deere &Company, Moline, IL) with a total weight of 4.5 Mg with pneumatic tires and a rear tire contact area of 3225 cm<sup>2</sup> for the ST, a John Deere 8225 Tractor (Deere &Company, Moline, IL) with a total weight 9.5 Mg with solid rubber tires and a rear tire contact area of 7197 cm<sup>2</sup> for the LT, and a Top Kick Fuel injection GMC Truck (GMC, Detroit, MI) with a total weight 9 Mg rear tire contact 1067 cm<sup>2</sup> for the TK treatments. No tractor traffic occurred for the Nc treatments. All treatments consisted of five passes of each farm implement after a rain event with soils at field capacity simulating the annual number of field activities (i.e. spraying, planting, harvesting and hauling grain). For the second year we used three levels of compaction (TK, LT, and Nc) since we found the compaction levels achieved with the large tractor and the small tractor to be similar. Previous research reported that topsoil compaction is related to ground pressure and subsoil compaction to total axle load independently of ground pressure (Botta et al., 1999; Hakansson and Reeder, 1994). The ground contact pressure is what causes soil compaction (Hamza and Anderson, 2005). Ground contact pressure is the axle load divided by the surface area of contact between the load and the soil. This is measured in kPa, which is a unit of

pressure. Following the calculation of ground pressure we decided to drop the ST treatment for the second year of the study due to similar load-pressure as the LT (ST=135 kPa, LT=129 kPa, TK=833 kPa). Each year and a week after imposing the compaction treatments, the field was disked to a depth of approximately 8 cm to establish a suitable seedbed for the cover crop treatments. The six cover crops levels consisted of: radish (*Raphanus sativus* var. *longipinnatus*) “R”, sown alone or along with rye (*Secale cereale* L.) “RR”, triticale (x *Triticosecale* cv *Presto*) “RTR”, buckwheat (*Fagopyrum esculentum* L. Moench) “RB”, or hairy vetch (*Vicia villosa* Roth) “RHV” and a control with no cover crop, “NCOV”.

Planting date for WCC was September 27<sup>th</sup> 2010 and September 7<sup>th</sup> 2011. Seeding rate was 10 kg ha<sup>-1</sup> for radish sown alone, 28 kg ha<sup>-1</sup> for rye in combination with radish, 38 kg ha<sup>-1</sup> for triticale in combination with radish, 30 kg ha<sup>-1</sup> for hairy vetch in combination with radish and 45 kg ha<sup>-1</sup> for buckwheat in combination with radish. The seeding rate for radish in combination with other WCC was 5 kg ha<sup>-1</sup>. Hairy vetch was inoculated every year with *Rhizobium leguminosarum* var. *viciae*. WCC were chemically suppressed with glyphosate (N-(phosphonomethyl) glycine) at 1.2 kg a.i. ha<sup>-1</sup> in the spring, approximately two weeks before planting the main crop based on guidelines developed by Ruffo (2001) and Crandall (2003). Glyphosate-resistant (RR) soybeans maturity group 3.4 were planted on June 3<sup>rd</sup> on 2011 and on May 15<sup>th</sup> 2012 respectively.

### **Soil sampling and analysis**

After a preliminary penetration resistance characterization of both fields, complete soil sampling was conducted during both fall and spring seasons, each time after establishment of the compaction treatments and before planting the main soybean crop. On September 7 2010 and August 15 2011, and May 15 2011 and May 5 2012, two soil subsamples per plot up to 50-cm in

depth were taken with a Giddings® sampler (29.5-mm diam., Giddings machine Co., Fort Collins, CO) for bulk density (BD) and soil chemical analysis. The cores were then cut to obtain 0-10, 10-20, 20-30, 30-40, and 40-50-cm subsamples, and stored in plastic bags. After weighing the subsamples and measuring water content gravimetrically, BD values were obtained using the core method (Blake and Hartge, 1986). The results were averaged for each plot and depth considered.

The same samples were air-dried, and passed through a 2-mm sieve to perform the following tests: pH (potentiometry; 1:1 soil: water), total carbon and total nitrogen (TC and TN by combustion with CHNSO Analyzer; Costech Analytical Technologies Inc. Valencia, CA), NO<sub>3</sub>-N (flow injection analysis with Lachat automated analyzer, Lachat Instruments, Loveland, CO) available P (Bray-1). On the same date of soil sampling, profile soil penetration resistance measurements (PR, kPa) were recorded with a Field Scout<sup>TM</sup> SC 900 Soil Compaction Meter (Spectrum Technologies, Plainfield, IL) with a cone basal area of 1.28 cm<sup>2</sup> and a cone angle of 30°. Three subsamples were recorded at each plot and the results averaged at the selected depths of 0-10, 10-20, 20-30, 30-40, and 40-50-cm in order to get one measurement per plot per depth. Gravimetric water content was later used as a covariate in the statistical analysis of BD and PR. Two 5 g subsamples of the 0-10 and 10-20 cm depths were used to determine water aggregate stability (WAS, g g<sup>-1</sup>) with an Eijkelkamp® wet sieving apparatus (Eijkelkamp, Giesbeek, The Netherlands) on the 1-to 2- mm aggregate size fractions following the standard procedure developed by Kemper and Rosenau (1986). On 21 April 2011 and 28 April 2012 one sample from the center of each plot was taken with a shovel down to a depth of 20 cm for determination of particle size distribution and proctor test (ASTM, 1982). From each sample, two 50 g subsamples of air dried soil were passed through a 2-mm sieve to analyze for particle size

distribution via the hydrometer method (Gee and Bauder, 1986). Percentages by weight of clay (<0.002-mm), silt (0.002-0.05-mm) and sand (0.05-2-mm) separates were obtained by the hydrometer method. Additional characterization of the sand size (very coarse 2-1mm; coarse 1-0.5-mm; medium 0.5-0.25-mm; fine 0.25-0.10; and very fine 0.1-0.05-mm sand) and silt size (coarse silt <0.05-mm) fractions was carried out with a set of 5 ultrasonic sieves corresponding openings of 1-, 0.5-, 0.25-, 0.1-, and 0.05-mm (ATM Sonic Sifter, ATM Corporation, Milwaukee, WI.). Relative compaction (RC) results from the quotient between soil bulk density determined with the core method, and the maximum bulk density determined by means of Proctor tests following the standard ASTM procedure (American Society for Testing and Materials, 1982).

### **Plant sampling**

Triticale and rye and hairy vetch were chemically terminated in the pre-anthesis (Feeks 10.5.1) and pre-bloom stages respectively, on 19 May 2011 and 26 April 2012 with glyphosate (1.2 kg a.i. ha<sup>-1</sup> of glyphosate [*N*-(phosphonomethyl) glycine]). Soybean was no-till planted using 76-cm row spacing on 3 June 2011 June, and 15 May 2012 at a seeding rate of 350,000 plants per hectare. Population was determined 21 days after planting. Soybean vegetative stages were measured starting 21 days after emergence (DAE) during the growing season as suggested by Ritchie et al (1996). Plants samples were hand-harvested and counted from 0.76 m<sup>2</sup> every 10 days to determine soybean growth parameters such as leaf area index (LAI), height (cm), number of nodes, dry matter accumulation (DM) crop growth rate (CGR) and relative growth rate (RGR) until soybean pod fill (R5 stage). There were six sampling dates (T) through-out the growing season (21, 31, 41, 51, 61, and 71 DAE). In 2011 LAI measurements was determined with a Licor Li-3100 Area meter. In 2012 LAI measurements were determined with a Licor Li-2200 Plant canopy analyzer (Licor, Lincoln, NE).

Prior to soybean harvest a dry matter sample was hand- harvested from 0.38 m<sup>2</sup> of each plot. Yield components: pod density, beans per pod and number of beans were determined from a sample of three plants randomly collected from the hand-harvested section. Soybean yield was determined with an Almaco combine (Nevada, IA) and adjusted to 130 g/kg moisture.

### **Experimental design and statistical analysis**

As previously detailed, each year a different field was used to set up a factorial combination of 4 (3 in 2012) compaction levels and 6 levels of cover crop treatments arranged in a CRD with two replications. The field-year combination will be hereby referred as the random factor ENVIRONMENT (E); whereas the fixed factors of compaction and cover crop will be referred as COMP and CC, respectively.

The linear model used for the statistical analysis of the dependent variables was

$$y_{ijkl} = \mu + E_i + \alpha_j + \beta_k + E_i\alpha_j + E_i\beta_k + E_i\alpha_j\beta_k + \text{Error}$$

$y_{ijkl}$  = observation for the  $i^{\text{th}}$  level of E for the  $j^{\text{th}}$  level of COMP and the  $k^{\text{th}}$  level of CC

$\mu$  = grand mean.

$E_i$  = random effect due to the  $i^{\text{th}}$  level of factor E.  $df=i-1 = 2-1=1$

$\alpha_j$  = fixed effect of the  $j^{\text{th}}$  COMP.  $df=j-1 = 4-1=3$

$E_i\alpha_j$  = random effect due to  $i^{\text{th}}$  level of factor E and the  $j^{\text{th}}$  COMP.  $df=(i-1)(j-1) = 3$

$\beta_k$  = fixed effect due to the  $k^{\text{th}}$  level of factor CC  $df=k-1=6-1=5$

$E_i\beta_k$  = random effect due to  $i^{\text{th}}$  level of factor E the  $k^{\text{th}}$  CC.  $df=(i-1)(k-1) = 5$

$\alpha_j\beta_k$  = fixed effect due to the  $j^{\text{th}}$  level of factor COMP and the  $k^{\text{th}}$  CC.  $df=(i-1)(j-1)(k-1) = 15$

$E_i \alpha_j \beta_k$  = random effect due to  $i^{\text{th}}$  level of factor E the  $j^{\text{th}}$  COMP and the  $k^{\text{th}}$  CC.  $df=(i-1)(j-1)(k-1)=15$

Error (1) = residual effect assumed identically and independently distributed (i.i.d.)  $N(0, \sigma_e^2)$ .

These models were analyzed using the MIXED procedure of SAS (SAS Institute Inc, 2012). For dependent variables that were measured at several times, a fixed factor T (time) was added to the model. Dependent variables that were measured at several times on the same experimental units were analyzed using a repeated measures approach (Littell et al., 2002). The lowest Akaike's Information Criterion and the Schwarz's Bayesian Criterion were used to select the variance-covariance model. AR1 was used for CGR, Toep was used for DM, RGR, and LAI, and UN was used for Number of nodes and Height. When covariance parameter estimates appeared to be negative or zero, we used the -2Log Likelihood test to compare successive reduced forms of the original models (Littell et al., 2002). To compare differences among treatments and times the PDIFF options of the LSMEANS statement was used. Mean separation procedure was accomplished by using Fisher's Protected Least Significant Difference (LSD) with a probability of Type I error or alpha level ( $\alpha$ ) set at 0.05.

The matching SAS coding was as follows,

```
proc mixed data=thesis;
class E S CC COMP T;
model variable = CC|COMP|T;
random E E*CC E*COMP E*T E*CC*COMP E*COMP*T E*CC*T
repeated T/type = UN subject = S; run;
```

Where E, environment; S, subject; CC, cover crop, COMP, compaction; and T, time.

The variables total dry matter (TDM), number of pods (Npod), beans per plant (Bnpl) and (RGR) required transformations due to lack of normality and heterogeneity of variances.

Possible transformations were explored using the BOXCOX macro in SAS (Friendly, 1991). The square transformation was used for TDM, while natural logarithm ( $\log_n$ ) was used Npod, Bnpl and RGR.

## **RESULTS AND DISCUSSION**

Growing conditions during 2011 and 2012 were very dissimilar and challenging for crop production (Figure 2). Soil moisture conditions at WCC planting was limiting for the 2011 growing season which was characterized by a dry Fall, and optimum for the 2012 growing season. The total amount of precipitation was different for the 2011 (693 mm) and 2012 (485 mm) cover crop growing seasons. Rainfall during the soybean growing season (May-September) was 384 mm for 2011 and 435 mm for 2012. While 2011 was characterized by a wet spring with ample soil moisture at soybean planting time, 2012 showed a warm and dry spring with just sufficient soil moisture at planting time. Although the total amount of precipitation was similar between years it was far below average (507 mm) in both growing seasons. An important difference was the precipitation received in June-July (146 mm in 2011 vs. 60 mm in 2012) being July especially important for soybean development and yield determination since pod set (R3-R4) occurred in late July in both years.

### *Winter cover crop biomass*

Significant differences in cover crop biomass production were observed between cover crops and environments (Table 2.1). Among cover crops, the main contributors to the differences in biomass production during spring time are winter hardiness and planting time. WCC plating was delayed almost a month from the desired date (August) due to an unusually dry fall in 2010.



These differences in biomass production show the widely reported importance of early fall planting for successful establishment and biomass production of WWC (Clark et al., 1997; Miguez and Bollero, 2006) especially important for radish, buckwheat and hairy vetch, because of their susceptibility to winterkill. Buckwheat was the most susceptible to low temperatures, and was killed by the first frosts on both years. Rye, triticale and hairy vetch overwintered well in both years. Radish was intermediate in winter hardiness but as expected did not overwinter in the two years of this study. As suggested by Crandall (2005) rye and triticale were killed 2 weeks prior to soybean planting to optimize rye biomass and yield of the subsequent crop. Rye and hairy vetch biomass obtained in this study showed similar ranges to previous studies in Illinois (Ruffo and Bollero 2003; Ruffo et al., 2004; Miguez and Bollero 2006; Davis, 2010).

#### *Soybean Population and Growth Parameters*

Soybean population was measured two weeks after emergence. Significant differences were determined for the main effect cover crop ( $p < 0.0204$ ), and there were no interactions between compaction level and cover crops (Table 2.2). Differences in population can be explained by the difficulty to plant into the stubble of the WCC that over wintered. Reduced soybean stands after rye cover crop caused by poor seed-soil contact may be associated with excessive cover crop growth as reported by Eckert, (1988) and Reddy, (2001).

Soybean vegetative growth characteristics starting 21 days after emergence (DAE) to R5 stage, seed filling period (Fehr and Caviness, 1977) were evaluated by changes in plant height and node number on the main stem. Differences in plant height between treatments may reflect unfavourable growth conditions (Reddy, 1998) and were evident along the growing season between cover crops treatments. Starting 21 days after emergence (DAE) soybean plants in the plots with highest WCC biomass showed the tallest plants in part to overcome the thick mulch

and reach full sunlight. These differences in plant height were reverted by R5 stage soybean plants under rye and triticale were 9.6 and 7.9 cm shorter than the plants in the no cover plots (Table 2.2). Plant height values showed significant differences for the interaction of cover crop and time ( $p < 0.028$ ) and the main effect time ( $p < 0.001$ ). There were no significant differences for the interactions between cover crop and compaction levels (Table 2.3). Differences in plant height between the WCC treatments can be explained by the differences in population and interplant competition in the plots with higher population in comparison with the plots with lower populations. These differences disappeared towards harvest but were maintained well into the R5 stage (seed filling period).

Node number and percentage of reproductive nodes (pod bearing nodes) is a proxy for number of pods (Pedersen and Lauer, 2004). The interaction of cover crop and time ( $p < 0.0001$ ), and the main effects cover crop ( $p < 0.0001$ ) and time ( $p < 0.0001$ ) showed significant values for number of nodes. There were no significant differences for the interactions between cover crop and compaction levels (Table 2.4). Differences in the number of nodes on the main stem first appeared 31 DAE (R1/R2), soybeans had 8% more nodes on the plots without over wintering WCC. As with plant height, differences in node number across the WCC treatments can be explained by the differences in population and the overproduction of nodes and branches in the plots with lower populations. Again, node number differences started decreasing towards harvest but were maintained well into the R5 stage.

Leaf area index (LAI), crop growth rate (CGR) and relative growth rate (RGR) were measured along the growing season to examine how the treatments affected these parameters and ultimately soybean yield. LAI is defined as the ratio of unit leaf area of the crop to unit ground area. Previous research on soybeans indicates that LAI values of 3.5 to 4.0 by R2 and R4

developmental stages (full flowering to full pod) are critical in order to maximize photosynthetic potential (Board and Harville, 1992; Westgate, 1999). Soybean leaf area index values showed significant differences for the main effects cover crop ( $p < 0.049$ ) and time ( $p < 0.0262$ ). There were no significant differences for the interactions between cover crop and compaction level or the main effects (Table 2.5). At R5 stage LAI showed reductions of 10-15% for the WCC that overwintered. Although restricted by drought events on both growing seasons LAI values were maximum at R5 stage ranging from 3.9 to 4.7.

CGR is defined as dry matter accumulation rate per day per unit land area. Canopy photosynthetic rate and CGR directly control total dry matter (TDM) production (Board, 2011). Final yield is a function of (TDM) produced and the percentage of dry matter transferred into harvestable portion indicated by harvest index (Loomis and Connor 1992). Relative growth rate (RGR) is defined as dry matter accumulation per day per unit plant material, and it serves as a measure of biomass production efficiency (Evans, 2003).

Dry matter accumulation (DM) showed significant values for the three way interaction between cover crop compaction and time ( $p > 0.0005$ ), the interaction between cover crop and time ( $p < 0.0051$ ) and the main effect time ( $p < 0.0012$ ) (Table 2.6). Although differences in DM were observed throughout the growing season, there were no differences TDM at harvest. Despite maximum LAI recorded at R5 stage, DM at this stage was below the  $500 \text{ g m}^{-2}$  value suggested as a threshold to maximize yield (Egli et al., 1987). Likely the drought conditions present during both growing seasons led to stomata closure reducing photosynthesis and thus CGR and TDM (Board, 2011). In addition, CGR season showed significant differences in the three way interaction between cover crop compaction and time ( $p > 0.0001$ ), and for cover crop and time ( $P < 0.0007$ ) throughout the growing season (Table 2.7). Overall CGR from R1-R5

showed no significant differences between cover crops or compaction levels. Relative growth rates (RGR) showed no significant differences for the interactions between cover crop and compaction levels or for the main effects (Table 2.8). The lack of significant differences in RGR agrees with the results from TDM and CGR indicating that growth patterns were similar across treatments.

### *Soybean Yield Components and Yield*

In soybean, as in most other grain crops, seed number per unit area is an important determinant of yield in many crop plants including soybean (Egli, 1998). Pods and seed number in soybean is largely determined by the environmental conditions between initial bloom R1 stage (Fehr and Caviness, 1977) and the beginning of seed filling R5 stage (Egli, 1998). This period is critical for soybean yield. Stresses during this period should be avoided to achieve optimum pod number and yield (Board and Tan, 1995). Jiang and Egli (1995) reported results showing a linear relationship between average CGR during R1 to R5 and seeds production, indicating that seeds per square meter is determined primarily by canopy photosynthesis during flowering and podset. In the present study, soybean yields were very dissimilar for both environments in agreement with differences in total precipitation and deviations from the 30 year average (Figure 2.1). In 2011 overall soybean yield was 4.250 Mg ha<sup>-1</sup>, and above the average for Champaign County for that year (3.7 Mg ha<sup>-1</sup>). In 2012 Soybean grand mean yield across treatments was 2.820 Mg ha<sup>-1</sup> below the average for Champaign County (3.1 Mg ha<sup>-1</sup>). No interactions between WCC and compaction treatments were observed for yield data. No significant yield differences were observed across WCC and induced compaction treatments. However, the lower yielding plots coincided with plots with high WCC biomass: RR and RTR yield was 0.24 Mg ha<sup>-1</sup> lower in comparison with the NCOV plots. These results agree with results reported by Crandall (2005)

and Wortman (2012) and the importance of appropriate cover crop residue management in maximizing potential agronomic benefits associated with cover crops. The NCOV plots in turn were out yielded by the R, RB and RHV plots by 0.24 Mg ha<sup>1</sup>. Yield trends between compaction treatments were smaller; Nc yielded 0.1Mg ha<sup>1</sup> more than TK (Table 2.2). The lack of significant effect of WCC on soybean yield agrees with results reported by Wagner-Riddle et al. (1994) Swanton et al. (1998), Reddy (2003) and Ruffo et al. (2004). No interactions were observed between WCC and compaction levels for soybean yield components. Additionally yield components: pod number, seeds per pod and seed number per plant were not significant for either cover crops or compaction treatments. Seed number per pod was very consistent across WCC and compaction treatments. Number of seeds per plants were higher for the rye WCC and was evident that plants were compensating yield for lower population with an increase production of seeds per plant. Soybean has the ability to regulate branch production in response to available space within a canopy (Carpenter and Board, 1997) and pod per reproductive node to produce similar seed and pod number as higher populations (Board, 2000).

## **CONCLUSION**

This study provides lacking information regarding the effects of compaction induced treatments and selected WCC on soybean production in poorly drained soils in Illinois. The two environments evaluated differed greatly between them and from the 30 year average in Central Illinois. The compaction levels achieved in this study disappeared during the winter season likely due to self-mulching capacity of the studied soils and thus we were unable to evaluate the effect

of compaction on the soybean crop yet future research is needed in this regard. Interestingly though the WCC generated differences in soybean population, these differences did not have a negative impact on the final soybean yield. Similarly differences in LAI, height and number of nodes measured during the growing seasons did not affect yield. Based on this study we concluded that following appropriate management practices, WCC should not affect negatively soybean growth parameters and yield. This is an important consideration for producers in the region who may be reluctant to incorporate WCC based on the perception of lower yields following WCC.

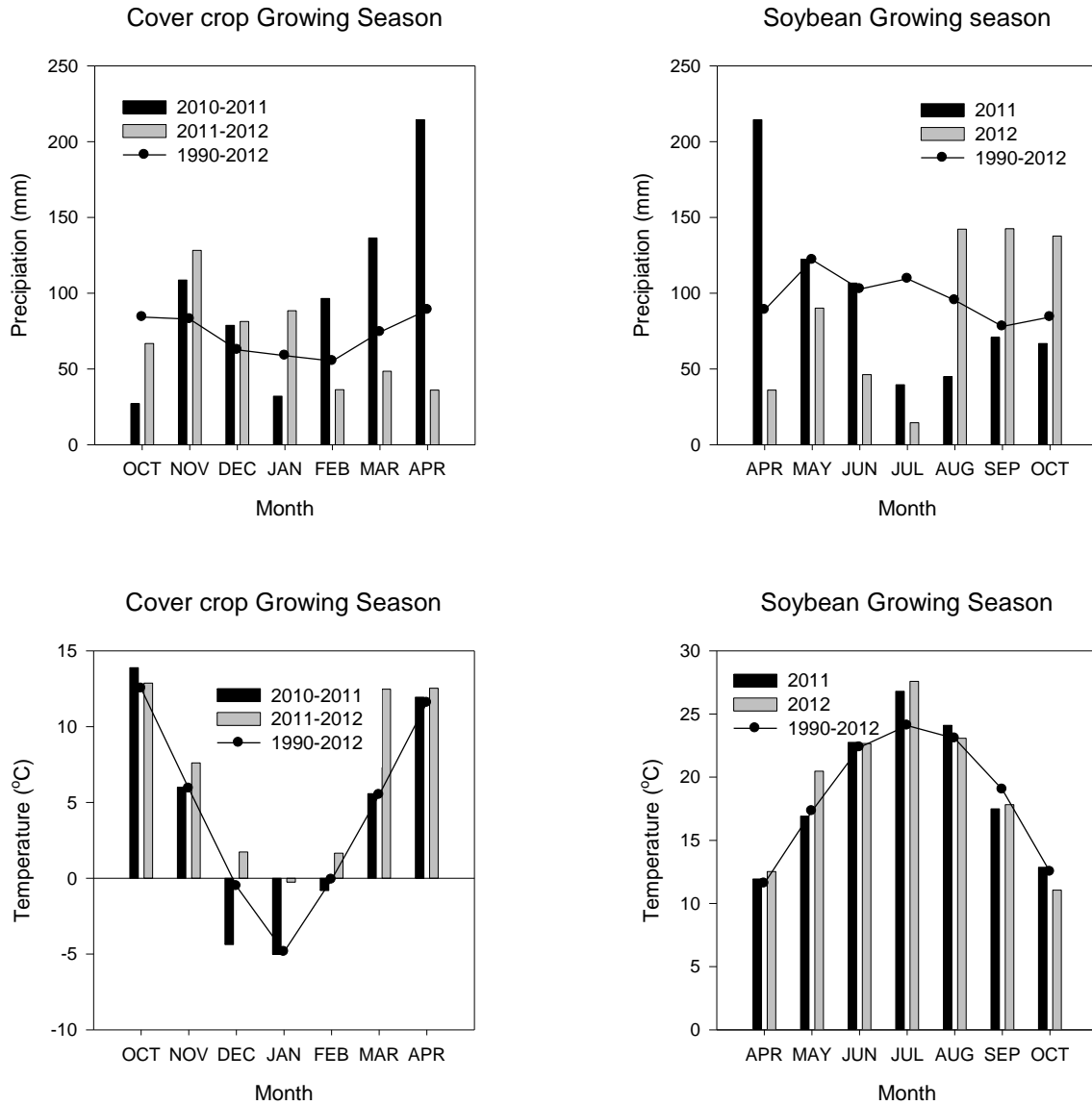
## TABLES AND FIGURES

**Table 2.1** Winter cover crop aboveground biomass before termination.

Growing season	WCC dry biomass			SED†
	RR	RTR	RHV	
	Mg ha <sup>-1</sup>			
2010-2011	8.66	8.15	2.29	0.38
2011-2012	6.05	5.96	4.03	0.35

†SED, standard error of the mean values.

RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.



**Figure 2.1** Precipitation and temperature for the cover crops (left panels) and soybean growing seasons (right panels) 2011 and 2012 compared with the average for 1990-2012.



**Table 2.2** Mean of main effects cover crop and compaction level for yield and yield components at harvest.

Treatment	Population	Height	Yield	Number of Nodes	Pod number	Seed number	Seed number	Harvest index	CGR R1-R5	
Cover crop	Plants ha <sup>-1</sup>	cm	kg ha <sup>-1</sup>	Nodes plant <sup>-1</sup>	ln pods pl <sup>-1</sup>	(pods pl <sup>-1</sup> )	Seeds pod <sup>-1</sup>	Seeds plant <sup>-1</sup>	%	g m <sup>-2</sup> day <sup>-1</sup>
NCOV	333755	90.6	3507	17.7	3.4	(32.4)	2.4	77.0	50.3	7.2
R	343809	94.2	3723	17.8	3.5	(33.0)	2.4	78.0	50.1	7.7
RB	339649	91.6	3701	17.6	3.5	(33.1)	2.4	78.0	53.3	7.7
RHV	317476	90.3	3759	17.5	3.6	(35.9)	2.4	84.1	47.7	8.2
RR	268104	84.0	3268	17.7	3.7	(42.1)	2.3	98.1	38.5	7.6
RTR	294530	85.2	3373	16.9	3.6	(35.6)	2.3	80.9	45.1	7.1
†SED	14886	7.4	252	0.5		0.1	0.1	9.9	7.7	1.1
Compaction										
Nc	316965	89.5	3513	17.6	3.5	(33.4)	2.4	79.1	45.5	7.4
ST	316993	89.2	3674	17.4	3.6	(37.2)	2.3	88.5	48.9	6.8
LT	319257	89.5	3564	17.5	3.5	(34.7)	2.3	80.5	47.9	8.6
TK	311667	89.1	3470	17.5	3.6	(36.1)	2.3	82.6	47.8	7.4
SED	17696	3.4	140	0.3		0.1	0.0	5.2	2.1	0.5

†SED, standard error of the differences.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

‡CC, Cover crop; CL, Compaction level.

**Table 2.3** Means of main effects cover crop and compaction level for height at different sampling times.

Treatment		Height (cm)									
DAE		21		31		41		51		61	71
Cover crops											
NCOV		13.1	b§	23.5	a	32.2	a	59.4	a	84.0	ab
R		12.8	b	22.4	a	33.7	a	61.1	a	84.4	ab
RB		10.6	b	23.1	a	33.7	a	60.6	a	89.0	a
RHV		12.2	b	23.7	a	33.8	a	59.3	a	85.6	ab
RR		14.8	ab	23.8	a	32.6	a	52.7	a	77.8	b
RTR		24.1	a	24.9	a	35.0	a	53.8	a	76.7	b
†SED		6.5		1.6		1.9		2.5		3.0	3.0
Compaction											
Nc		12.8		23.6		32.3		57.8		81.1	90.1
ST		13.3		23.8		35.3		60.0		84.0	88.9
LT		19.0		23.5		33.3		55.8		83.9	90.1
TK		13.3		23.5		33.2		57.6		82.8	89.5
SED		4.5		1.0		1.3		1.7		2.0	2.2

†SED, standard error of the differences.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

‡CC, Cover crop; CL, Compaction level.

§Within columns and for each factor, means followed by the same lowercase letter are not significantly different at  $p=0.05$

**Table 2.4** Means of main effects cover crop and compaction level for number of nodes at different sampling times.

Treatment		Number of nodes											
DAE		21		31		41		51		61		71	
Cover crops													
NCOV		3.0	a§	3.9	ab	7.4	a	11.6	ab	15.5	ab	17.8	ab
R		3.1	a	3.8	ab	7.7	a	11.6	ab	15.3	ab	17.9	a
RB		2.9	a	3.8	ab	7.6	a	11.7	a	15.9	a	17.6	ab
RHV		3.0	a	4.0	a	7.4	a	11.1	bc	15.5	ab	17.5	ab
RR		2.9	a	3.4	c	6.8	a	10.7	c	14.9	b	17.7	ab
RTR		2.9	a	3.7	bc	6.8	a	10.5	c	14.3	c	16.9	b
†SED		0.1		0.2		0.2		0.3		0.3		0.5	
Compaction													
Nc		2.9		3.7		7.3		11.1		15.1		17.6	
ST		3.0		3.7		7.3		11.3		15.7		17.5	
LT		2.9		3.8		7.3		11.1		15.1		17.5	
TK		2.9		3.9		7.3		11.3		15.1		17.5	
SED		0.1		0.1		0.1		0.1		0.1		0.1	

†SED, standard error of the differences.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

‡CC, Cover crop; CL, Compaction level.

§Within columns and for each factor, means followed by the same lowercase letter are not significantly different at  $p=0.05$

**Table 2.5** Mean of main effects cover crop and compaction level for LAI at different sampling times

Treatment	LAI					
DAE	21	31	41	51	61	71
Cover crops						
NCOV	0.3	1.8	2.6	3.2	3.4	4.7
R	0.4	2.0	2.7	3.3	3.5	4.6
RB	0.3	1.9	2.8	3.4	3.7	4.7
RHV	0.3	1.8	2.5	3.0	3.3	4.4
RR	0.3	1.6	2.4	2.9	3.1	4.2
RTR	0.3	1.6	2.3	2.8	2.8	4.0
†SED	0.2	0.2	0.2	0.2	0.2	0.2
Compaction						
Nc	0.3	1.8	2.6	3.1	3.3	4.3
ST	0.3	1.8	2.6	3.4	3.5	4.8
LT	0.3	1.8	2.5	3.0	3.2	4.3
TK	0.3	1.7	2.5	3.0	3.2	4.2
SED	0.1	0.1	0.1	0.1	0.1	0.1

†SED, standard error of the differences.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

‡CC, Cover crop; CL, Compaction level.

**Table 2.6** Means of main effects cover crop and compaction level for DM at different sampling times.

Treatment		DM																					
DAE		21		31		41		51		61		71											
Cover crops																							
NCOV		16.6	a§			80.7	a			108.5	a			260.0	a			313.4	a			344.6	a
R		17.9	a			71.6	a			107.8	a			268.0	a			307.4	a			343.0	ab
RB		15.7	a			68.5	a			112.8	a			254.1	ab			304.6	a			319.4	b
RHV		15.0	a			72.5	a			115.6	a			255.6	a			321.2	a			351.7	a
RR		12.3	a			64.0	a			99.2	a			272.8	a			282.1	ab			329.7	ab
RTR		13.0	a			67.7	a			99.5	a			240.9	b			266.2	b			343.4	ab
†SED		12.7				12.7				12.7				12.7				12.7				12.7	
Compaction																							
Nc		15.6				74.1				105.4				257.0				282.0				347.8	
ST		14.7				68.9				111.6				266.3				326.8				352.1	
LT		15.3				69.6				105.3				260.0				293.4				328.6	
TK		14.8				70.7				106.6				251.0				294.5				326.1	
SED		10.6				10.6				10.6				10.6				10.6				10.6	

†SED, standard error of the differences.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

‡CC, Cover crop; CL, Compaction level.

§Within columns and for each factor, means followed by the same lowercase letter are not significantly different at  $p=0.05$

**Table 2.7** Means of main effects cover crop and compaction level for CGR at different sampling times.

Treatment		CGR																
DAE		21		31		41		51		61		71						
Cover crops																		
NCOV		0.8	a§		5.5	a		2.6	a		17.1	ab		6.6	ab		6.2	b
R		0.9	a		5.0	a		3.4	a		17.9	ab		5.3	b		6.3	b
RB		0.7	a		4.7	a		4.1	a		16.4	b		6.7	ab		5.2	b
RHV		0.7	a		5.2	a		4.2	a		16.2	b		7.8	a		5.7	b
RR		0.6	a		4.7	a		2.8	a		19.4	a		2.7	c		8.7	a
RTR		0.6	a		4.9	a		2.8	a		16.2	b		4.1	c		11.1	a
†SED		1.3			1.3			1.3			1.3			1.3			1.3	
Compaction																		
Nc		7.4			5.1			3.2			15.4			5.4			10.6	
ST		7.5			4.6			4.3			16.0			8.8			6.9	
LT		7.3			4.4			3.7			16.1			6.3			8.3	
TK		6.2			4.7			3.7			15.1			7.0			7.6	
SED		1.1			1.4			1.4			1.4			1.4			1.4	

†SED, standard error of the differences.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

‡CC, Cover crop; CL, Compaction level.

§Within columns and for each factor, means followed by the same lowercase letter are not significantly different at  $p=0.05$

**Table 2.8** Mean of main effects cover crop and compaction level for RGR at different sampling times.

Treatment	RGR (g m <sup>-2</sup> plant day <sup>-1</sup> )					
DAE	21	31	41	51	61	71
Cover crops						
NCOV	0.02	0.02	0.02	0.02	0.02	0.01
R	0.02	0.02	0.02	0.02	0.01	0.01
RB	0.02	0.02	0.02	0.02	0.02	0.01
RHV	0.02	0.02	0.02	0.02	0.02	0.01
RR	0.02	0.02	0.02	0.02	0.01	0.01
RTR	0.02	0.02	0.02	0.02	0.01	0.02
†SED	0.001	0.001	0.001	0.001	0.001	0.001
Compaction						
Nc	0.02	0.02	0.02	0.02	0.01	0.02
ST	0.02	0.02	0.02	0.02	0.02	0.01
LT	0.02	0.02	0.02	0.02	0.02	0.01
TK	0.02	0.02	0.02	0.02	0.02	0.01
SED	0.001	0.001	0.001	0.001	0.001	0.001

†SED, standard error of the differences.

NCOV, no cover; R, radish; RB, radish +buckwheat; RHV, radish +hairy vetch; RR, radish+rye; RTR, radish+triticale.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

‡CC, Cover crop; CL, Compaction level.

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## APPENDIX

**Table A.1** Mean values of PR before compaction 2010.

Depth (cm)	Compaction				†SE
	Nc	ST	LT	TK	
	KPa				
5	135	168	167	160	20
15	771	802	755	768	53
25	1160	1221	1165	1170	47
35	1226	1314	1224	1240	37
45	1396	1396	1386	1427	41

†SE, standard error of the mean values.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.

**Table A.2** Mean values of PR before compaction 2011.

Depth (cm)	Compaction			SE†
	Nc	LT	TK	
		KPa		
5	284	244	303	53
15	1072	981	1116	119
25	1197	1147	1318	123
35	1371	1298	1263	53
45	1518	1453	1426	53

†SE, standard error of the mean values.

Nc, no compaction; ST, small tractor; LT, large tractor; TK, truck.