A STUDY ON THE EFFECT OF TYRE INFLATION PRESSURE ON SOIL PROPERTIES, GROWTH AND YIELD OF MAIZE AND SOYBEAN IN CENTRAL ILLINOIS

MD RAYHAN SHAHEB

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HARPER ADAMS UNIVERSITY

NEWPORT, SHROPSHIRE, TF10 8NB, UNITED KINGDOM

ABSTRACT

This study was conducted with the aim of determining the effects of Ultraflex tyres operating at low and standard tyre inflation pressure modes on soil properties, crop growth and yield in a maize (*Zea mays* L.) / soybean (*Glycine max* L.) rotation for three tillage systems (deep tillage, 450mm; shallow tillage, 100mm and no-till) in Champaign County, Illinois, USA, from 2016 to 2018. The experimental design was a split-plot, factorial randomized complete block, with five blocks. Tyre inflation pressure and tillage systems were the main treatment plots and the 8 crop rows/plot, and a central non-trafficked inter-row/zone were considered as sub-plots. Data on soil physical properties, crop growth and yield were recorded. A novel tool X-Ray Computed Tomography (CT) was used to determine the effects on soil porosity with high resolution (98 µm) of undisturbed soil (soil core, 300 mm length) collected from the maize field in 2017.

The results revealed that reducing tyre inflation pressure had shown significant benefits of managing soil conditions by maintaining soil porosity following tillage, together with lower penetrometer resistances. The penetrometer resistance in the upper soil layers was significantly higher in no-till than deep tillage and shallow tillage while in the lower soil layers the PR of soil was in the order of deep tillage > shallow tillage > no-till. The non-trafficked inter-row zone had significantly higher soil moisture content ($P = <0.001$) in maize plots in 2017 and 2018 and in the soybean field in 2017 ($P = <0.001$) and lower penetrometer resistance ($P = <0.001$) than the trafficked crop row in maize ($P = <0.001$) and soybean ($P = <0.001$) plots, respectively. In general, the heavily trafficked zone and crop row had significantly lower soil moisture content (%) and higher penetrometer resistance than the non-trafficked and reduced trafficked zones.

The results showed that the use of low tyre inflation pressure had a positive effect on increased crop growth; for examples, plant height in 2017 and 2018 ($P = 0.04$ and 0.004, respectively), plant establishment (%) and the number of plants ha^{-1} of maize ($P = 0.007$ and 0.005, respectively) and soybean ($P = <0.001$ and 0.001, respectively) in 2018 were greater than those of the standard tyre inflation pressure. The depth of tillage had a significant effect on the growth of maize and soybean. No-till had a significantly greater number of plants ha^{-1} in 2017 ($P = <0.001$) while deep tillage had a significantly greater plant and ear heights of maize in 2018 ($P = 0.004$ and 0.05, respectively). Where for soybean, no-till and deep tillage systems increased the plant establishment in 2017 ($P = 0.009$) while deep tillage had a significantly greater plant establishment in 2018 ($P = <0.001$), number of plants ha^{-1} in 2017 ($P = 0.01$) and plant height in

2017 and 2018 (P = 0.001 and 0.032). Less trafficked and non-trafficked crop rows resulted in significantly greater crop growth in comparison to the heavily trafficked crop rows.

The yield data revealed that reducing tyre inflation pressure increased the grain yield of maize by 4.31% in 2017 (15.02 Mg ha^{-1}) and 2.70% in 2018 (14.76 Mg ha^{-1}) compared to the standard tyre inflation pressure treatments (14.40 Mg ha^{-1} and 13.76 Mg ha^{-1}, respectively). While for soybean, reducing tyre inflation pressure had a 3.70% greater yield benefit (4.25 Mg ha^{-1}) in comparison to the standard tyre inflation pressure system (4.10 Mg ha^{-1}) in 2018 (P = 0.021). Deep tillage and shallow tillage systems resulted in significant yield advantages over no-till for soybean in 2017 (P = 0.001) and maize in 2018 (P = <0.001). The grain yield of maize in 2018 for both deep (15.11 Mg ha^{-1}) and shallow tillage systems (13.98 Mg ha^{-1}) was 18.69 % and 9.82 % greater than that of no-till (12.73 Mg ha^{-1}). The grain yield of soybean in 2017 for both deep (4.86 Mg ha^{-1}) and shallow tillage systems (4.73 Mg ha^{-1}) was 4.52 % and 1.72 % greater than no-till (4.65 Mg ha^{-1}). Compared to heavily trafficked crop rows the less and non-trafficked crop rows had a significantly greater hand harvest yield of maize in 2016 and 2018 (P = 0.03 and <0.001) and soybean in 2018 (P = <0.001).The X-ray CT data of soil showed that the low inflation pressure tyre system in HT location resulted in a significant increase in the CT measured macro-porosity (4.66%) (P = 0.004) compared to standard inflation pressure tyre with CT measured macro-porosity of 2.87%. Adding the CT measured macro-porosity to the field capacity porosity of silty clay loam soil (39%) results in a total porosity similar to that derived by classical soil physics.

The economic analysis of the maize/soybean farming system showed that the annual benefit of the use of low inflation pressure tyres after discounting the additional tyre costs was of approximately $7357 and $32969 over the standard inflation pressure tyres for 200 and 800 ha farms, respectively. The payback period of the use of Ultraflex tyre was less than two years, ranging from 0.31 years for the deep tillage system on the bigger farm to 1.27 years for the shallow tillage system on the smaller farm.

Hence, the study confirms the hypothesis that reducing tyre inflation pressure improves crop growth and yield by reducing soil compaction in a maize - soybean rotation in silty clay loam soil in Central Illinois of the United States.

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DECLARATION

I, Md Rayhan Shaheb, hereby declare that this research work with the title "**A Study on the Effect of Tyre Inflation Pressure on Soil Properties, Growth and Yield of Maize and Soybean in Central Illinois**" was my own, and solely composed by myself and that no help was provided from other sources as those allowed. Except where stated otherwise by reference or acknowledgement, the work presented is entirely my own.

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LIST OF SYMBOLS AND ABBREVIATIONS

θ	Soil Moisture Content (%)
W_1	Weight of Wet Soil (g)
W_2	Weight of Dry Soil (g)
ρ_s	Soil Particle Density (Mg m^{-3})
M_s	Mass of Oven-Dry Soil (g)
V_s	Volume of Solid Soil Without Air (g)
ρ_d	Soil Bulk Density (Mg m^{-3})
M_s	Mass of Oven-Dry Soil (g)
V_t	Volume of Soil (g)
N	North Field, One of Two Experimental Sites
S	South Field, One of Two Experimental Sites
φ	Total Pore Space/Porosity (%)
g	Gram
ABE	Agricultural and Biological Engineering
ASTM	American Society for Testing and Materials
BD	Bulk Density of Soil (Mg m^{-3})
BDp	Bulk Density Porosity/Total Porosity (%)
CI	Cone Index
CEC	Cation Exchange Capacity
Circularity	Measure of How Circular Pores are in the Scanned Image
CR	Crop Row
CTp	Computed Tomography Measured Macroporosity
DAP	Days After Planting
DT	Deep Tillage Involved Fall Deep Ripping at 450 mm
EC	Electrical Conductivity (mSm^{-1})
FOV	Field of View
HAU	Harper Adams University
HT	Heavily Trafficked Location, areas of vehicles wheel traffic
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference and Information Centre
ISWS	Illinois State Water Survey

LTP	Low Tyre Inflation Pressure, Meaning the Tyres Have a Low Air Pressure
Max.	Maximum
MC	Moisture Content (%)
Mg	Mega Grams
Min.	Minimum
MPa	Mega Pascal
NT	No-Till
Perimeter	Length of the Outside Boundary of a Pore
PS	Percent Pore Space
PR	Penetrometer Resistance
RCBD	Randomized Complete Block Design
ROI	Region of Interest
RTK	Real Time Kinematic Guidance
Solidity	Area of an Object Divided by Its Convex Area (Imaginary Convex Hull Around it)
SOM	Soil Organic Matter
SPECT	Single-Photon Emission Computerized Tomography
ST	Shallow Tillage Involved Spring Tillage (100 mm)
STP	Standard Tyre Inflation Pressure, Meaning the Tyres Have a High Air Pressure
TIFF	Tagged Image File Format
TPA	Total Pore Area
TS	Tillage System
UIUC/UofI	University of Illinois at Urbana Champaign/ University of Illinois; Both Names are Generally Used to Describe the University
USDA	United States Department of Agriculture
NASS	National Agricultural Statistics Service
NRCS	Natural Resources Conservation Services
UT	Un-Trafficked; These are the Middle of Plots that See No Traffic at All
X-ray CT	X-Ray Computed Tomography

GLOSSARY OF TERMINOLOGY

A

Agricultural mechanization: Agricultural mechanization is the process whereby equipment, machineries and implements are utilized to boost agricultural and food production.

Agricultural productivity: The efficiency with which inputs are transformed into outputs in the agricultural sector. It is driven by innovations in on farm tasks, changes in the organization and structure of the farm sector, research aimed at improvements in farm production, and/or random events like weather.

Agricultural sustainability: It considers the concept of the economic, environmental and social aspects of farming, while also promoting the resilience and persistence of productive farming landscapes (Garibaldi et al., 2017).

Agricultural systems: An agricultural system is an assemblage of components which are united by some form of interaction and interdependence and which operate within a prescribed boundary to achieve a specified agricultural objective on behalf of the beneficiaries of the system.

Agroecosystems: A system where communities of plants, microbes and animals inhabiting farmed land, pastures, grasslands or rangelands, interact with each other and their physical environment.

Air filled porosity: It is the voids in soil at any point of time, which is not filled with water. Air-filled porosity varies with soil moisture content and can be determined by subtracting the volumetric water content (cm^3 of water cm^{-3} of soil) from the total porosity of the soil.

B

Biodiversity: According to Ecological Society of America, it is defined as the range of variation found among microorganisms, plants, fungi, and animals. Also, the richness of species of living organisms.

Biological/ bio-drilling tillage tools: Roots of tap-rooted crops penetrate compacted soils, ameliorate the subsoil compaction, may help the succeeding crop roots referred the role of plant roots in soil as “biological tillage tools” (Chen and Weil, 2010) and bio-drilling tillage (Cresswell and Kirkegaard, 1995).

Bulk density: The bulk density of a soil sample, generally represented by ρ_b, is a physical property defined as the ratio of the total mass of solids to the total volume of the sample.

C

Carbon sequestration: Carbon sequestration is the process by which atmospheric carbon dioxide (CO_2), the most important greenhouse gas, is removed from the atmosphere and stored in the ocean, on the land surface, or in geological formations.

Climate smart agriculture: It is an approach that calls for integration of the need for adaptation and the possibility of mitigation in agricultural growth strategies to support food security.

Compaction: It is the reduction of the volume of a given mass of soil, i.e. decrease in void ratio and porosity and, conversely, increase in bulk density (Keller, 2004). The modification of the pore volume and pore structure of the soil in which the size and number of macropores are reduced and shape and continuity of pores are changed (Soane, Blackwell, Dickson, & Painter, 1980).

Compression: Decreases or densifies of soil volume through the expulsion of soil air (Koolen, 1994).

Computed tomography: It is an imaging procedure that uses special X-ray equipment to create detailed pictures, or scans, of areas inside an object. It is sometimes called computerized tomography or computerized axial tomography (CAT).

Cone index: The cone index of a soil is the degree of its strength which has been shown to be affected by its water content and bulk density.

Conservation agriculture: Conservation agriculture is a farming system that promotes maintenance of a permanent soil cover, minimum soil disturbance (i.e. no-till), and diversification of plant species.

Conservation tillage: Agricultural sustainability Institute, UC Davis, defines conservation tillage as an agricultural management approach that aims to minimize the frequency or intensity of tillage operations in an effort to promote certain economic and environmental benefits.

Controlled traffic farming: It is the term used for a field traffic system that confines agricultural machinery to permanent wheel or traffic lanes that are separate from distinct crop zones (Gasso et al., 2014).

Conventional field traffic: It is the extensive use of tractors, combines and other farm machinery “randomly” in the field for producing crops. Consequently, leads to compaction of soil, the most recognized problem in agriculture.

Conventional tillage: It consists of primary cultivation using a mouldboard plough that inverts the soil and secondary cultivation using tine, disc or rotary cultivator to prepare the field for planting (Hallett & Bengough, 2013; Morris et al., 2010).

Cover crops: Crops grown to provide soil cover during seasons when an annual grain crop is absent.

Crop productivity: Crop productivity is the quantitative measure of crop yield in given measured area of field.

Crop rotation: Practice of growing two or more annual crops in a given field in a planned pattern or sequence in successive crop years.

Cropping systems: The term cropping system refers to the crops, crop sequences and management techniques used on a particular agricultural field over a period of years. It includes all spatial and temporal aspects of managing an agricultural system.

D

Drawbar pull: Drawbar power is the power transferred through the drive wheels or tracks to move the tractor and implement. It is a function of velocity, and in general decreases as the speed of the vehicle increases (due both to increasing resistance and decreasing transmission gear ratios).

Denitrification: The loss or removal of nitrogen or nitrogen compounds specifically, reduction of nitrates or nitrites commonly by bacteria (as in soil) that usually results in the escape of nitrogen into the air.

Draught forces: The force required to pull a plough or other implement.

Dynamic loads: Dynamic loads are typically motor loads comprising either single-phase or three-phase motors driving mechanical loads applying fixed or varying torque on the motor.

E

Ecological sustainability: A capacity of ecosystems to maintain their essential functions and processes and retain their biodiversity in full measure over the long-term.

Edaphology: Edaphology is one of the two main divisions of soil science that encompasses the study of the effect of soil on living organisms, mainly plants.

Electrical conductivity of soil: Electrical conductivity is the ability of a material to conduct (transmit) an electrical current and it is commonly expressed in units (mS/m). Soil electrical conductivity is an indirect measurement that correlates very well with several soil physical and chemical properties.

F

Farming system: A farming system is defined as a population of individual farm systems that have broadly similar resource bases, enterprise patterns, household livelihoods and constraints, and for which similar development strategies and interventions would be appropriate.

Field capacity: The moisture content of soil in the field as measured two or three days after a thorough wetting of a well-drained soil by rain or irrigation water.

Food security: According to FAO, food security exists when all people at all times have physical and economic access to adequate amounts of nutritious, safe, and culturally appropriate food to maintain a healthy and active life.

G

Global warming: A gradual increase in the overall temperature of the earth's atmosphere generally attributed to the greenhouse effect caused by increased levels of carbon dioxide, chlorofluorocarbons, and other pollutants.

Growth of plants: It is the irreversible increase in size primarily associated with capture and allocation of resources e.g. water, nutrients, CO_2.

H

Hydraulic conductivity: Saturated hydraulic conductivity is a quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient. It can be thought of as the ease with which pores of a saturated soil permit water movement.

I

Integrated crop management: It is a holistic approach to sustainable agriculture. It considers the situation across the whole farm, including socioeconomic and environmental factors to deliver the most suitable and safe approach for long-term benefit.

Integrated soil management: Soil management encompasses a number of strategies used by farmers and ranchers to protect soil resources, one of their most valuable assets. By practicing soil conservation, including appropriate soil preparation methods, they reduce soil erosion and increase soil stabilization.

L

Low tyre inflation pressure: It is a conventional traffic system that can facilitate random trafficking where low inflation pressure tyres are used instead of conventional inflation pressure tyres.

M

Macropores: Equivalent diameters is >30 μm. Plant root growth mostly occur in macropores. It allows water flow during infiltration and drainage and have the significance influence on soil aeration.

Mesopores: Equivalent diameters is 0.2–30 μm. while mesopores and micropores are important for the water retention and storage of water in soils although water in micropores is generally unavailable to plants and impede microbiological activity in soil (Kay and Vandenbygaart, 2002).

Micropores: Equivalent diameters is <0.2 μm. Micropores are fine soil pores, typically a fraction of a millimeter in diameter. They are responsible for the water holding capacity of soil.

Minimum (and zero) tillage: Minimum tillage as defined here is generally a one-pass tillage operation at sowing synchronous with seed placement, typically achieved using full cut-out points, or full cut-out one-way or offset discs to break up the entire soil surface. It may include a shallow cultivation between seasons to control weeds when it may be called reduced tillage.

No-till farming: No-till farming is a way of growing crops or pasture from year to year without disturbing the soil through tillage.

Nutrient cycling: A nutrient cycle is the movement and exchange of organic and inorganic matter back into the production of matter. Energy flow is a unidirectional and noncyclic pathway, whereas the movement of mineral nutrients is cyclic.

O

Organic agriculture: The USDA defines organic agriculture as "a production system that is managed to respond to site-specific conditions by integrating cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biodiversity."

P

Penetration resistance: It is a soil attribute that allows identifies areas with restrictions due to compaction, which results in mechanical impedance for root growth and reduced crop yield.

Permanent wilting point: That point at which a plant is dried so badly that even though put into a humid atmosphere and watered, it will no longer recover.

Plant development: It is the continuous change in plant form and function with characteristic transition stages and mostly related to environmental response such as temperature, photoperiod and light quality (Sadras et al., 2016).

Plant available water: It is the amount of water above the wilting point soil water, the lower limit of water at which plants can uptake water.

Pore circularity: It is a measure of how circular pores are in the scanned. The circularity value lies between 0-1. A circularity value of 1.0 indicates a perfect circle (Kim et al., 2010) while value approaches 0.0 indicates an increasingly elongated polygon (Ferreira and Rasband, 2012).

Pore connectivity: It is quantified as a function of the minimum pore diameter considered leading to a connectivity function of the pore space.

Pore size: It is generally the distance between two opposite walls of the pore (diameter of cylindrical pores, width of slip-shaped pores).

Pore size distribution: The pore size distribution is defined as the statistical distribution of the radius of the largest sphere that can be fitted inside a pore at a given point.

Pore solidity: It is the area of a blob (a common term used in image processing) divided by its convex area (the imaginary convex hull around it).

Pre-compression stress: It is is typically used as a factor to assess the mechanical strength and stability of soil against compaction (Horn and Fleige, 2003).

R

Random traffic farming: The random nature of field trafficking is a conventional traffic farming, covering 80-90% of the field area, is a typical commercial practice and inevitably leads to negative impacts on soil, water and crop (Kroulík et al., 2009),

S

Shallow tillage: It refers to soil tillage four inches deep or shallower. The term "shallow" indicates the tillage equipment is designed to stir or ridge the soil without inverting the soil.

Shear strength: It is a term used in soil mechanics to describe the magnitude of the shear stress that a soil can sustain

Shear stress: Shear deform of soil through the rearrangement of soil microaggregates or particles (Koolen, 1994).

Soil aggregate stability: Aggregate stability refers to the ability of soil aggregates to resist disruption when exposed to external forces such as water erosion and wind erosion, shrinking and swelling processes, and tillage.

Soil aggregate: Soil aggregates are groups of soil particles that bind to each other more strongly than to adjacent particles.

Soil aggregation: It occurs due to interactions of primary particles through the rearrangement, flocculation and cementation (Duiker et al., 2003), enhance the soil organic matter (SOM) against degradation and aggregate stability of soil is used as an indicator of soil structure (Six et al., 2000).

Soil biodiversity: Soil biodiversity reflects the mix of living organisms in the soil. These organisms interact with one another and with plants and small animals forming a web of biological activity.

Soil biota: Soil biota consist of the micro-organisms (bacteria, fungi, archaea and algae), soil animals (protozoa, nematodes, mites, springtails, spiders, insects, and earthworms) and plants (Soil Quality Institute 2001) living all or part of their lives in or on the **soil** or pedosphere.

Soil bulk density: Bulk density of soil is the ratio of the oven dry weight mass of the soil to the bulk volume expressed in g cm^{-3} or Mg m^{-3}.

Soil degradation: It is the decline in soil condition that diminishes the capacity of soil and its ecosystems.

Soil erosion: Soil erosion is the displacement of the upper layer of soil, it is one form of soil degradation.

Soil fertility: Soil fertility refers to the ability of soil to sustain agricultural plant growth, i.e. to provide plant habitat and result in sustained and consistent yields of high quality.

Soil health: Soil health, also referred to as soil quality, is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans (USDA NRCS, 2019a).

Soil morphology: The branch of soil science that deals with the description, using standard terminology, of in situ spatial organization and physical properties of soil regardless of potential use.

Soil particle density: It is the ratio of the mass of oven dry weight of the soil particles to the volume of solid particles not pore space, expressed in grams per cubic cm (g cm^{-3}) or megagram per cubic meter (Mg m^{-3}).

Soil porosity: Refers to the amount of pore or open space between soil particles.

Soil productivity: Soil productivity is defined as the capacity of soil, in its normal environment, to support plant growth.

Soil quality: Soil Science Society of America define in simplest terms, soil quality is "the capacity (of soil) to function". Soil quality can be conceptualized as a three-legged stool, the function and balance of which requires an integration of three major components - sustained biological productivity, environmental quality, and plant and animal health.

Soil resource: Soil resources form a fundamental part of the environment. They provide the physical base to support the productivity and cycling of biological resources, provide the source of nutrients and water for agricultural and forestry systems and fulfil a complex buffering role against environmental variability etc.

Soil stability index: It is described as the relative stability of aggregated soil material when a) it is subjected to a test that usually involves either rapid immersion in water, raindrop impact or disruption with ultra-sound or b) a test that reveals a decrease in permeability or a change in the soil pore volume.

Soil strength: It is defined as the resistance to deformation by the action of tangential (shear) stress.

Soil stress: It is primarily a function of the applied surface load that is given by mechanical loading such as wheeled, tracked vehicles and other agricultural machinery.

Soil structure: Soil structure refers to the arrangement of soil separates into units called soil aggregates.

Soil texture: Soil texture refers to the proportion of sand, silt and clay sized particles that make up the mineral fraction of the soil.

Soil water retention: Soil water retention is the soil's ability to hold water inside its pores and hold onto moisture rather than allowing it simply to obey gravity and pour through the earth's surface

Soil water: Soil water is the term for water found in naturally occurring soil. There are three main types of soil water - gravitational water, capillary water, and hygroscopic water - and these terms are defined based on the function of the water in the soil.

Subsoil compaction: This subsoil compaction results in an increased damage of soil ecological functionality as these layers are less resilient due to less intense swelling and shrinkage, thawing and freezing as well as lower content of organic matter, less biological activity and other aggregating agents (Horn et al., 2000).

Sustainable agriculture: It is a farming in sustainable ways, which means meeting society's food and textile present needs, without compromising the ability of future generations to meet their needs.

T

Tillage pans: A plough pan/tillage pan is a subsurface horizon or soil layer having a high bulk density and a lower total porosity than the soil directly above or below it as a result of pressure applied by normal tillage operations, such as plows, discs, and other tillage implements.

Total pore space and porosity: Porosity is the fraction of the total soil volume that is taken up by the pore space. Percent pore space (PS) is the ratio of the volume of voids in the soil to the total volume of the soil that is expressed by percentage.

Tyre inflation pressure: Tyre is a flexible structure filled with compressed air. Inflation pressure plays an important role in carrying the vehicle load. Inflation pressure is vital to safe use of tyres.

W

Water infiltration: Infiltration is the process by which water on the ground surface enters the soil. The infiltration rate is the velocity or speed at which water enters into the soil.

Water run-off: Runoff can be described as the part of the water cycle that flows over land as surface water instead of being absorbed into groundwater or evaporating.

Water use efficiency: It is the ratio between effective water use and actual water withdrawal. In another word, it is defined as the amount of carbon assimilated as biomass or grain produced per unit of water used by the crop.

X

X-ray Computed Tomography: It is a non-invasive imaging technique and a powerful tool to investigate possible modifications in soil structure and other physical properties of soil (Pires et al., 2005). The technique greatly helps in studies of pore geometry, pore shape, orientation and connectivity, pore size distribution, and improving overall understanding of soil hydrodynamic behaviour (Beckers et al., 2014).

CHAPTER 1: INTRODUCTION

The United Nations has declared the 2030 Agenda for Sustainable Development in 2015 for peace and prosperity for people and the planet at present and the future. Among the 17 iconic Sustainable Development Goals (SDGs), goal 2: End hunger, focuses on food security, nutrition and sustainable agriculture (United Nations, 2018). Conventional modern agriculture is currently dependent on heavy machinery, which reduces the time of field operations and labour costs and helps to promote economically sustainable production. However, the effect of the heavier machinery on soil structure and land degradation and on crop development due to soil compaction is a growing concern (Soane and van Ouwerkerk, 1994a; b; Hamza and Anderson, 2005; Ansorge and Godwin, 2007; Billman et al., 2012) and is the main cornerstone of the present study.

1.1. Background and Motivation

Global food production needs to increase by 70-100% to feed a > 9 billion world population in 2050 (Alexandratos and Bruinsma, 2012). Food habits and growing of crops are also changing across landscapes and societies. Although agricultural production and intensification have increased globally, it is necessary to ensure that the production systems are sustainable to ensure food security for the global population (Pretty, 2008; Godfray et al., 2010; Bommarco et al., 2013; Shen et al., 2013; Shaheb et al., 2016; FAO, 2017a; Bunemann et al., 2018). The Green Revolution that occurred in the 1960's, increased agricultural production worldwide, particularly in the developing world (Hazell, 2009) and saved over a billion people from starvation. Adoption of new technologies, high-yielding varieties of cereals, use of fertilizers and agro-chemicals and irrigation together with improved management techniques and mechanization were the keys that made the Green Revolution successful. However, the depletion of soil fertility, soil erosion, soil toxicity, diminishing water resources, pollution and salinity of underground water, increased incidence of diseases and global warming are some of the negative impacts of over adoption of technologies during these periods (Rahman, 2015). Furthermore, the ability to produce food is being affected due to growing competition for land, water, and energy and overexploitation of fisheries and thus, it is urgent to reduce the impact of the food system on the environment (Godfray et al., 2010).

The question is how can the world adequately feed more than 9 billion people by 2050? What are the measures that the world could implement to ensure economic and social development and minimize pressure on the environment? Potential solutions and strategies are needed to close the food gap between today and by 2050 while contributing to economic opportunities and social development and reducing environmental impacts (Searchinger et al., 2013). The current paradigm of productivity enhancement while reducing environmental impacts should translate into a paradigm where ecological sustainability will constitute the entry point for all agricultural development (McKenzie & Williams, 2015).

The soil is a vital natural component of primary importance for food production and global food security and is considered as a non-renewable resource (Janvier et al., 2007; Stavi and Lal, 2015). The intensity of land use for food production often results in negative impacts on soil quality, such as; reduction in OM, decrease in soil fertility, soil structural damage, increase in erosion (Lal, 1997; Towers et al., 2006). Soil and crop management systems greatly influence the soil quality and may impact the microbial community, affecting long-term economic and environmental sustainability (Hungria et al., 2009; Silva et al., 2014). Advances in engineering and technological knowledge have revolutionized modern farming in the United States (Sassenrath et al., 2008). Technological innovations in agricultural tractors have transformed farming, increased labour productivity and reduced operator's hazards (Cavallo et al., 2014). Sustainable agricultural mechanization reduces manual labour time, relieves labour shortages, improves the productivity and timeliness of agricultural operations and creates new employment opportunities (FAO, 2017b).

However, the use of heavy machinery and field traffic can cause compaction that can change soil structure and reduce the productivity of crops. Soil compaction by machinery traffic in agriculture is a well-recognized problem in many parts of the world (Chan et al., 2006; Hakansson, 1990; Hakansson et al., 1988; Horn & Fleige, 2003) while it is recognized as a serious threat to soil productivity and soil ecological functions in modern agriculture (Hamza and Anderson, 2005; Schjønning et al., 2015). More than one-third of European subsoils are highly susceptible to compaction (Jones, Spoor, & Thomasson, 2003), and a quarter of all European soils were found compacted (Schjønning et al., 2015). Total area compacted was reported to be 68, 33 and 4 M ha worldwide, in Europe, and the Australian wheat belt, respectively (Hamza and Anderson, 2005). Reports show that these may have increased considerably in the past 2 decades (Keller et al., 2017).

Soil compaction is a physical form of soil degradation, which changes the soil structure and influences soil productivity and causes damage to the environment by increasing GHGs emission, soil erosion and pollution (Raghavan et al., 1976; Tullberg, 2010; Mueller et al., 2011). Soil degradation due to compaction is also reported in many areas in the USA (Flowers and Lal, 1998). In fact, soils in all regions of the United States are designated as susceptible to compaction (USDA NRCS, 2004a). Soil compaction concerns have been growing in the temperate region of North America (Lindstrom and Voorhees, 1994) and more recently in Minnesota (Dejong-Hughes, 2018).

The size and continuous increase in the weight of heavier machinery and use, and number of passes in modern intense agricultural production systems have been impacted soil conditions. The average tractor weight has increased threefold from 1950 to 2000 (Soane and van Ouwerkerk, 1998; Sidhu and Duiker, 2006). Axle loads of 10 Mg are common in many countries (Hakansson & Reeder, 1994). The weight of grain cart (single-axle) in the U.S. are of 15 to 45 Mg per axle (Schuler et al., 2000). The weight of tractors was < 3 tons in 1940, which has increased around 6 times for the big 4WD and is approximately 18 Mg (Dejong-Hughes, 2009). Ballasted tractor weight tested at the University of Nebraska-Lincoln showed that there is a persistent trend in increased tractor size and mass (0.41 Mg weight increment per year) over the last 100 years (Billman et al., 2012). A list of the agricultural equipment and their weight currently seen in the farmers' field of the United States and other regions is given in Appendix 1. This increase in equipment size is considered one of the major threats to increase soil compaction (Chamen, 2011; Billman et al., 2012). Traffic and heavy machinery passes can create soil compaction: increasing bulk density, reducing porosity, soil hydraulic properties and soil stability (Alakukku, 1996a; b; Hula et al., 2009). Every passage causes damage to the soil structure (Raghavan et al., 1976). The first tyre pass in the soil increased the bulk density and cone index by an average of 7 and 6%, respectively (Canillas and Salokhe, 2002). The number of tyre passes when ploughing with conventional tillage, contacted more than 86% of the total field area in one cropping season (Kroulík et al., 2011). Increased traffic frequency and high ground pressure had detrimental effects on soil physical properties by increasing higher bulk density and strength, resulting in higher cone index values in soil (Solgi et al., 2016). Increasing both the dynamic load and inflation pressure increased the peak soil stresses and bulk density of soil (Bailey et al., 1996). Subsoil compaction increased with the increased loads to the soil, these increases are difficult or expensive to remove (Kroulík et al., 2009).

Soil compaction due to heavy wheel traffic (multiple passes and higher wheel load), and number of passes and tyre pressure impacts on crop growth, development, and yield. Wheel traffic significantly reduced maize root growth as compared to the un-trafficked (UT) side of the crop row (Kaspar et al., 2001). The resulting compaction creates physical (e.g. damages in soil structure), chemical (e.g. changes in plant water and nutrient availability) and biological change (e.g. decreases of soil biota) in the soil that negatively impact crop performance (Chyba, 2012; Horn et al., 2003). The immediate consequences of soil compaction are decreases in water and fertilizer efficiencies and increased soil erosion (Sudibyo, 2011). Repeated traffic and multiple passes with higher contact pressures and a zero traffic treatment caused maize yield reductions of 30–50% in Quebec (Raghavan et al., 1979) while in soybean, a yield reduction of 0.25-0.45 Mg ha^{-1} was found under light to heavy equipment traffic (Botta et al., 2010).

Soil compaction can prevent crop root systems penetrating through the compacted soil and extracting the soil-water that leads to losses of yield (Ball et al., 1999; Hula et al., 2009). Compaction strongly reduces plant growth as it limits root growth (Rosolem et al., 2002) and accessibility of nutrients due to an increase in bulk density and reduced pore size (Nawaz et al., 2013). This may lead to extremely dry topsoil and eventually causes the soil to crack because the roots absorb water requiring for transpiration from the upper part of the soil where plants can penetrate with their restricted root depth (Batey, 2009). Soil compaction due to vehicular traffic caused a 9 and 19% yield reduction of soybean on poorly drained heavy textured soil with the axle loads of 10 and 20 Mg, respectively (Flowers and Lal, 1998). Up to a 38% reduction in grain yield of wheat was reported when subsoil compaction was present at 0.15 m depth to a bulk density of 1.93 Mg m^{-3} (Ishaq et al., 2001).

Tillage helps to loosen and aerate the soil that facilitates crop production. It’s effect on crop yields in a maize and soybean rotation vary considerably. Higher crop yields have been obtained in conventional tillage using mouldboard plough or chisel plough treatments than in no-till systems, particularly for soils with root-restricting tillage pans (Camp et al., 1984; Busscher et al., 2006). Although the benefit of reduced tillage has also found as it promotes the soil to hold organic matter, soil moisture, and potentially more soil carbon while reducing costs and fuel use (USDA ERS, 2016, 2017). Tillage and traffic enhance soil erosion and soil degradation process (Tullberg et al., 2007). Conventional deep tillage improves soil structure by loosening the compaction and helps to improve soil aeration and water infiltration (Sommer and Zach, 1992). However, extensive cultivation is highly vulnerable to soil erosion. The historic ‘Dust Bowl’ incidence in the USA is one of the best examples in this regards (Huggins and Reganold, 2008).

The 15 years trend of typical tillage systems in the United States showed that 40% of the area is covered by the conventional tillage systems that are characterized by deep tillage with chisel plough followed by shallow tillage while the no-till systems covered only 17% (Simmons and Nafziger, 2009) (Fig. 1.1). According to US Census of Agriculture, conventional tillage, reduced tillage and no-till farmland areas in the US national were 37%, 35% and 28% respectively and Illinois 28%, 43%, 29% respectively (Zulauf and Brown, 2019) (Appendix 2.1).

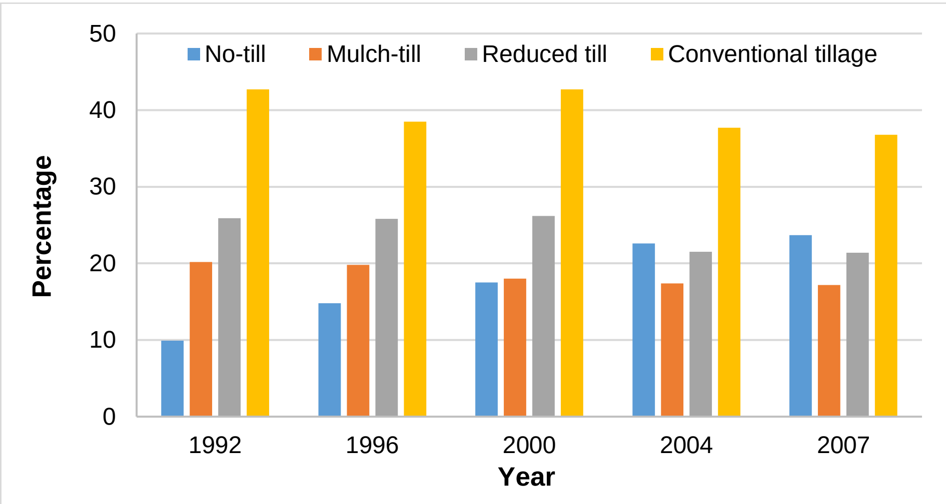


Figure 1.1. Trends of typical tillage systems in the United States. Adapted from Simmons and Nafziger (2009).

Illinois has about 71,000 farms, which covered 10.93 million hectares (27 million acres), which is 75% of the state's total land area. The average size of a farm in Illinois and the United States are 152 and 180 hectares, respectively (USDA NASS, 2018a). The production of maize and soybean for the last 30 years data shows that yield of both maize and soybean are increasing, with average yields of 11.34 and 3.50 Mg ha^{-1} (180.7 and 52.1 bushels $acres^{-1}$), respectively (USDA NASS, 2018b) (Fig. 1.2a-d). Most farm acreage in Illinois is devoted to grain production and Illinois is recognized as a leading producer of soybean (ranked 1st) and maize (2nd) in the United States of America (USDA NASS, 2018b; Illinois Department of Agriculture, 2019) (Fig. 1.2e-f).

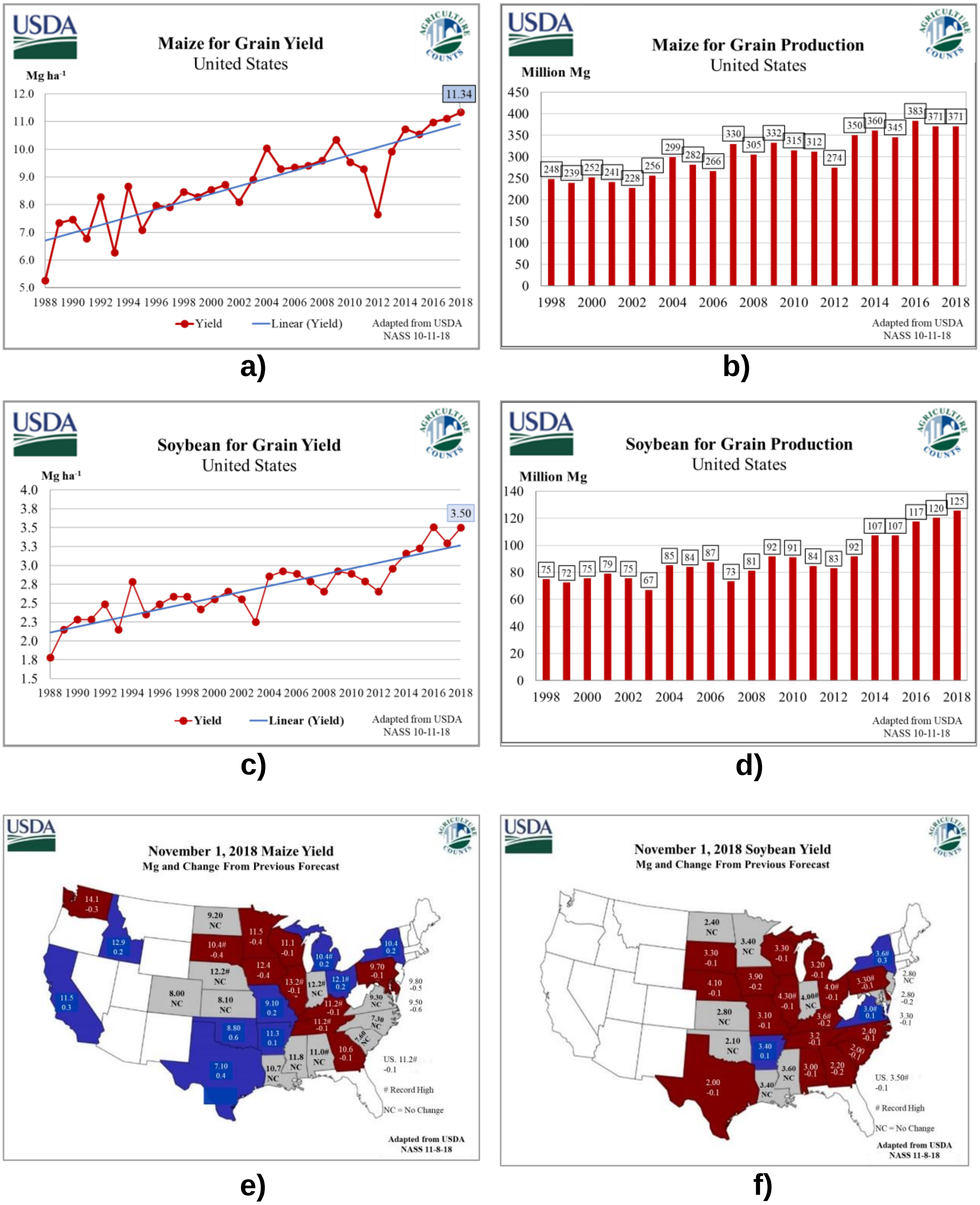


Figure 1.2. Grain yield and production of maize (a, b and e) and soybean (c, d and f) for the last 30 years in the United States (Adapted from USDA NASS, 2018b). Note: 1 Mg grain weight is equivalent to 39.4 and 36.7 bushels for Maize and soybean, respectively.

Meanwhile, shreds of evidence suggest that farm enterprises of all scales due to compaction of agricultural soils could face not only crop yield penalties (Hula et al., 2009; Lamandé and Schjønning, 2018) but also wastage of energy and time required to alleviate compaction (Chamen et al., 1992; McPhee et al., 1995). Thus, to boost up the production and to maintain soil physical health, farmers need to consider viable production systems to deliver on the promise of a sustainable food future. Controlled traffic farming can reduce annual surface area trafficked but this requires: (i) all field machine widths to be matched for crop production (Chamen, 2011) and (ii) navigation and machine guidance systems to be available and reliable (Misiewicz, 2016). Low ground pressure systems with agricultural tracks or specially manufactured tyres that can operate at low inflation pressures have been shown to reduce ground contact stress transmitted during field operations (Ansorge & Godwin, 2007, 2008; Chamen, 2011; Trautner & Arvidsson, 2003). Controlled traffic farming with (30% area trafficked) showed significantly higher yields of winter wheat and spring oats followed by low tyre inflation pressures than random conventional pressure traffic treatment (Godwin et al., 2017). Proper traffic management along with adaptable wheel track widths and operating systems innovation that can reduce soil compaction would help to improve water infiltration rates, reduce energy consumption and improve crop yields (Godwin et al., 2015). Low ground pressure tyre systems that best suit some farming enterprises could be an option as a viable traffic management system (Godwin et al., 2015). Both low-pressure tyres and wheel tracks were both beneficial at minimising soil compaction in a sandy loam soil (Smith et al., 2014a).

Agricultural tyres based on “Ultraflex” technology can carry more load with less pressure resulting in a larger footprint and are aimed at reducing soil compaction and improving crop yield (Michelin, 2017). Apart from the earlier work at Harper Adams University (Smith et al., 2014a; b; Millington, 2019), robust experimental results are not available and these are required to compare this technology with standard radial tyre systems for alternative tillage systems. Notwithstanding several researchers who have studied soil compaction and its effects on soil and crop yield; however, it is difficult to estimate an economic impact because fields vary in soil type, crop rotations, and weather conditions. Currently, no research has been conducted on the effect of Ultraflex low ground pressure tyres with different tillage practices in silty clay loam soils in mid-west farming operations in the United States. Drummer silty clay loam soil is the main productive soil of Illinois which covers more than 0.6 million hectares of land with significant areas in Indiana, Ohio and Wisconsin (USDA NRCS, 2019b) where maize and soybean are the dominant crops. The field-scale studies reported here would improve the understanding of the effect of lower ground pressure systems on soil conditions and crop growth and yield for a typical maize/soybean rotation for three selected tillage systems in the Mid-western United States.

1.2. Hypothesis

It is possible to improve crop development and yield by reducing soil compaction using reduced tyre inflation pressure systems.

1.3. Aim

The aim of the field-scale studies is to improve the understanding of the effect of tyre inflation pressure systems on soil conditions and crop growth and yield for typical maize/soya bean rotation for 3 tillage systems namely: conventional deep tillage, shallow tillage and no-till.

1.4. Objectives

1) To determine the effects of tyre induced ground pressure, by comparing Ultraflex standard[1] and low inflation tyre systems, on soil structure, crop development and yield for a typical maize/soybean rotation for three tillage systems (conventional deep tillage, shallow tillage and no-till) through field-scale studies in silty clay loam Midwest farming system in Illinois, United States.

2) To investigate the effects of tyre inflation pressure on soil properties namely: number of pores, % porosity, pore size and distribution using X-ray Computed Tomography for three tillage systems.

3) To determine the relationship between X-ray Computed Tomography derived porosities and physical soil porosities.

4) To conduct an economic analysis of the farming systems over two cropping seasons.

[1] Standard pressure was used to simulate normal tyres without the need to change the tyres during the experiment as shown by Smith et al. (2014b).

1.5. Structure of the Thesis

The timeline of research works conducted at Champaign County, Illinois, USA from 2016 to 2018 is given in Table 1.1.

Table 1.1. Crop rotation in two adjacent fields in Champaign County, Illinois, USA.

Season	North Field			South Field		
	2016	2017	2018	2016	2017	2018
Year	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
Season	1	2	3	1	2	3
Crop	Maize	Soybean	Maize	Soybean	Maize	Soybean

The thesis consists of ten chapters, an outline of which are given below:

Chapter 1 Introduction

The first chapter focuses on the background of the research study is related to the use of heavy machinery, tyre inflation pressure and different tillage systems effects on soil across the continent and crop development of maize and soybean farming in the Midwest Illinois has described. The main research hypothesis, aim and objectives, and thesis structure are also outlined.

Chapter 2 Review of Literature

This chapter is the review of literature related to soil compaction, the effect from the use of heavy machinery and field trafficking, ground pressure tyres, tracked agricultural vehicles, controlled traffic farming on soil conditions and growth and yield of crops. Moreover, the review investigated the study of soil compaction using X-ray Computed Tomography (CT). A long-term trial of the traffic and tillage systems conducted at Harper Adams University, the UK is also briefly discussed.

Chapter 3 General Methodology

This chapter focuses on the materials and general methodology of the present study. The brief description includes the location of study, materials, treatments, experimental design, and layout of plots. Data recording protocols of soil and crops including collection of soil cores for X-ray CT study and analysis of these data are discussed.

Chapter 4 Study of Soil Properties using X-Ray Computed Tomography

This chapter describes in detail an investigation of the effect of tyre inflation pressure on soil properties for three tillage systems using X-ray CT. Collection of soil cores, protocols and procedures of X-ray CT scanning, image processing, data collection and analysis are discussed. Finally, results and discussion, and conclusions are made.

Chapter 5 Soil Properties and Crop Development of Maize

This chapter focuses on the effect of tyre inflation pressure and tillage systems on soil properties and crop development of maize. Initial soil uniformity assessment, soil properties including compaction measurements, data on growth and yield of maize, and weather data are discussed. Finally, data analysis, results, discussion, and conclusions are made.

Chapter 6 Soil Properties and Crop Development of Soybean

This chapter focuses on the effect of tyre inflation pressure and tillage systems on soil properties and crop development of soybean. Data recording of the initial soil parameters, soil properties during crop growing seasons and crop growth and yield and analysis of these data are discussed. Finally, interpretation of results and discussion, and conclusions are made.

Chapter 7 Economic Analysis of Alternate Tyre Systems in Maize-Soybean Rotation

This chapter focuses on the economic analysis especially tyre costs, annual and total earnings, the payback period of the effect of tyre inflation pressure and tillage systems for maize and soybean farming systems in the Midwestern United States are discussed.

Chapter 8 Discussion

This chapter describes the assessment of the uniformity of experimental fields. Interpretations of the effect of tyre inflation pressure and tillage systems on soil using novel X-ray computed tomography are discussed. The effect on soil properties, growth, and development of maize and soybean, and economic analysis of the farming systems are discussed.

Chapter 9 Conclusions

This chapter focuses on the drawing of conclusions of the study based on the three years of field experimentation and overall findings. Key take-home messages for the farmers and stakeholders are clearly outlined.

Chapter 10 Recommendation for Further Work

This chapter describes the recommendations made from the study of the effect of tyre inflation pressure and tillage systems on soil and crops. Limitations and scopes of a couple of other research areas have addressed for further research.

The References provide the list of reference documents and research articles that have been reviewed.

CHAPTER 2: REVIEW OF LITERATURE

Use of agricultural machinery helps agriculture production systems worldwide to be effective and viable. Notwithstanding the benefit of timeliness of operations and covering the substantial area under cultivation but their negative impact on soil and crops are noticeable. Negative effects on the soil aggregate structure can result in decreased soil quality, increased erosion and decreased crop production (McKenzie, 2010). This chapter summarizes reported effects of soil compaction and it's causes, the effect of heavy machinery, field trafficking on soil properties and crop growth and development and their consequences for crop productivity.

2.1. Soil Resource and its Importance

Soil is a natural non-renewable resource on the surface of the earth that has four components: minerals (45%), organic (5%) water (25%) and air (25%) (Brady and Weil, 1996). The diversity and productivity of plants and animals depend on the soil. Soil stores and regulates water from rain, irrigation etc., sustain plants and animals, and provides, stores, transforms and cycles of carbon (C), nitrogen (N), phosphorus (P), sulphur (S) and other nutrients in the soil. Soil and water are essential natural resources for our domesticated animal- and plant-based food production systems (Parikh and James, 2012). Soil's mineral components and soil biota play an important role as a filter and act as a buffer for potential organic and inorganic pollutants, industrial by-products, and atmospheric deposits. Soil also provides physical support to plant roots and acts as a medium for plant growth (Blum, 1993).

2.2. Soil Health and Structure

According to the USDA, soil health (also referred to as soil quality) is defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (USDA NRCS, 2019a). The discussion between soil quality vs soil health was reported by Bunemann et al. (2018). The paper highlighted that soil quality is more focused on dynamic soil properties that can strongly be influenced by management. In contrast, soil health addresses the ecological attributes of the soil which have implications beyond its quality or capacity to produce a particular crop (Bunemann et al., 2018). Poor soil conditions due to poor soil structure, low organic matter, decreased soil fertility, and high soil compaction increase vulnerability to soil-borne diseases (Abawi and Widmer, 2000). Management practices have an impact on soil physical properties and can increase the diversity of soil microorganisms resulting in improved soil health and reduced disease incidence in the soil in a sustainable manner (Abawi and Widmer, 2000).

Soil health depends on the maintenance of four major functions, namely, C transformations, nutrient cycles, soil structure maintenance, and the regulation of pests and diseases (Kibblewhite et al., 2008). Mechanical tillage, especially intensive tillage, disrupts the spatial organization of soils, increases OM decomposition, and accelerates nutrient cycling, resulting in increased N mineralization and soil C loss as compared with reduced or no-till (Kibblewhite et al., 2008). Soil microorganisms exist in the soil depend on C source for energy. Soil contains about 8 to 15 tons of bacteria, fungi, protozoa, nematodes, earthworms, and arthropods (Hoorman and Islam, 2010). Some soil biota is hardy such as bacteria, actinomycetes, and protozoa and can tolerate more soil disturbance and dominate in tilled soils while others for an example fungal and nematode populations tend to dominate in no-till soils (Hoorman and Islam, 2010). Soil organic matter (SOM) is composed of both living (microorganisms) and non-living dead fractions (fresh residues and humus). Microbes rely on SOM to survive and sustain in the soil.

Organic farming, crop rotation, cover crops and no-till improve soil health. Long-term crop rotations studies were conducted in the US great plains (Anderson, 2015), where rotations included 3 years of a perennial legume and 6 years of annual crops and organized in 2-year intervals of the warm season or cool season crops. Results showed that crop rotations with no-till systems enhanced total porosity and improved nutrient cycling and thus promoted soil restoration in addition to decreasing weed infestation 3 to 4-fold in some annual crops (Anderson, 2015).

Soil structure is referred to as “the size, shape, and arrangement of solids and voids, and forces that affect these characteristics" (Lal, 1991). However, in contrast to agricultural production edaphologically, it is defined as "size, shape, arrangement, and continuity of pores and voids; their capacity to retain and transmit fluids and organic and inorganic substances, and ability to support vigorous root growth and development" (Lal, 1991). Soil with good structure typically has three types of pores macropores, mesopores, and micropores with equivalent diameters are >30, 0.2–30 and <0.2 μm, respectively (Kay and Vandenbygaart, 2002). Plant root growth mostly occurs in macropores that allow water flow during infiltration and drainage, and have a significant influence on soil aeration, while mesopores and micropores are important for water retention and storage of water in soils although water in micropores is generally unavailable to plants and impede microbiological activity (Kay and Vandenbygaart, 2002). Well-structured soils have optimal soil porosity and retain sufficient water and air permeability that create favourable conditions for crop root growth and development and eventually enhance the yield of crops (Kohnke, 1968).

Soil texture is a stable physical property of soil while soil structure can change due to both natural and man-made conditions. Soil structure changes with the management and biological activity in soil (Hillel, 1971) and largely determines the nature of the different physical processes (Kooistra and Tovey, 1994). It is a key factor that enhances the ability of soil to support and sustain plant and animal life, and moderate water quality and soil C sequestration (Bronick and Lal, 2005).

Soil aggregate influences the soil physical and biological processes while optimum conditions retain a large range of pore size distribution. Soil aggregate enhances the ability of soil to resist disruption against external forces such as water and wind erosion, shrinking and swelling and conventional tillage management (Papadopoulos et al., 2009; USDA NRCS, 1996). Soil aggregation occurs due to interactions between primary particles through rearrangement, flocculation and cementation (Duiker et al., 2003), enhance the SOM status against degradation and to improve aggregate stability is used as an indicator of soil structure (Six et al., 2000). Soil structure influences soil water movement and retention, erosion, crusting, nutrient recycling, root penetration and crop yield. The decline in soil structure is increasingly seen as a form of soil degradation (Chan et al., 2003) and is often related to land use and soil/crop management practices.

Compression and shear are the two processes that can lead to deterioration of soil structure. Compression decreases or densifies soil volume through the expulsion of soil air while shear deforms soil through the rearrangement of soil microaggregates or particles (Koolen, 1994). Deep tillage is often used to remove soil compaction but studies suggest that that deep tillage practices might even worsen soil structure if there is no compaction especially if it is conducted in moist soil conditions (above field capacity) that results in hasten soil degradation process and causes double negative in conventional agriculture (McGarry and Sharp, 2003). Tillage encourages decomposition of organic matter, breaks down soil aggregates, and weakens soil structure, thus in the long-term, it may not be a potential solution for minimizing soil compaction (Brady and Weil, 2008).

Compaction damages soil structure and reduces total pore space, and particularly affects the larger pores and voids between soil particles and aggregates. As a result, the continuity of the macropore system is reduced, leading to poor soil aeration, infiltration and transport of water (Hakansson, 2005) and impeded root growth. Macropores are relatively resistant to vertical compression and the structure and functions of macropores can be an effective measure of soil quality (Alakukku, 1996a).

Besides the negative effect of soil structural damage due to imposition of higher stress than soil strength, the presence of a high biological agent (e.g. soil microbes) in the soil sometimes showed a positive response. For an example, soil responds to imposed stresses provided by traffic initially compact but soil when remains undisturbed, even under high loads, some porosity (and therefore reduction in density) is gained due to rooting, biological and fauna activity (Chamen, 2011). To sum up, soils having good structure and high aggregate stability play an important role in enhancing porosity and decreasing erodibility and improving soil health and thus increasing agronomic productivity (Bronick and Lal, 2005).

2.3. Importance of Soil and Agricultural Sustainability

Soil has multiple functions that are vital not only for agricultural and biomass production, natural and environmental resources protection but also to landscaping architecture and urban applications. International Soil Reference and Information Centre (ISRIC) and others reported below are six key soil functions (Blum, 1993; ISRIC, 2019) of which first three are mainly ecological while other three are rather linked to human activity/anthropogenic activates (Blum, 1993).

i) Food and biomass production (soil productivity for agricultural and forest cropping);

ii) Environmental interaction, for an example, filtering water and storage or buffer and transportation of solute, toxic elements etc;

iii) Biological habitat and gene pool;

iv) Source of raw materials, supplying water, clay, sand, gravel, minerals and others;

v) Physical and cultural heritage (e.g. soil serves as the spatial base for technical and industrial structures, forming part of our cultural development, concealing paleontological and archaeological treasures);

vi) Platform for man-made structures: e.g. housing construction, industrial development, transport, and traffic systems.

Soil supports agriculture and is a critical part of sustainable agriculture. Soils provide and regulate a large number of ecosystem services and have a strong relationship with humans, the earth, and food sources (Bommarco et al., 2013; Sanjai and Resources, 2014; Bunemann et al., 2018; Pereira et al., 2018). Soil provides water and nutrients to plants, thus the healthiest soils i.e. good structured and fertile soils produce the healthiest and most abundant food supplies (Sindelar, 2015).

Despite the benefit of the intensification of agriculture, negative responses have emerged to the environment, soil and other natural resources (Pretty, 1997, 2008; Blanke et al., 2017). Decreasing soil fertility, productivity, negative impact on biological diversity, secondary pest outbreaks, agricultural impact on environment etc. are some examples of intensive agriculture (Pretty, 2008; Lichtfouse et al., 2009; Pereira et al., 2018). The concept of sustainable agriculture has become prominent in research, policy, and practice with aims to balance the economic, environmental, and social aspects of farming, creating a resilient farming system in the long-term (Rose et al., 2019).

Agricultural sustainability considers the concept of the economic, environmental and social aspects of farming, while also promoting the resilience and persistence of productive farming landscapes (Garibaldi et al., 2017). The USDA has described the different terms, concepts and practices commonly associated with sustainable agricultural systems, of which some of them are conceptual, while others are strictly methodological. However, most approaches belong to the umbrella of sustainable agriculture (Gold, 2007). Agricultural sustainability can be achieved through several potential concepts. For examples; integrated pest management - an ecosystem based approach intended to grow healthy crops and minimizing the use of pesticides (e.g. FAO, 2019), integrated crop management (e.g. Lançon et al., 2007), agroforestry (e.g. Leakey, 2014), and organic agriculture (e.g. Reganold & Wachter, 2016; Scialabba & Mller-Lindenlauf, 2010), conventional intensification (e.g. Cunningham et al., 2013; Pretty, 2008), diversified farming (e.g. Garibaldi et al., 2017; Kremen et al., 2012), agro-ecological intensification/farming (e.g. Bommarco et al. 2013) are all currently practised.

Researchers view to pursue the aim of the agricultural sustainability through precision farming (e.g. Blackmore, 1994), sustainable intensification (e.g. Garibaldi et al., 2017; Pretty, 2008), climate smart farming - increase the productivity, building resilience to climate change and reducing greenhouse gas emissions (FAO, 2013; Lipper et al., 2014), integrated soil management (e.g. Lal, 2008).

Agricultural sustainability is a broad term that cannot be translated easily into the practical field; however, it is a concept that helps to maintain long-term agricultural productivity as well as protecting the environment (Gold, 2007). It can be understood as "the management and use of agroecosystems in a way that the biological diversity, productivity, regeneration capacity, vitality and functioning capacity are maintained" (Rose et al., 2019). Overall, it can be understood by the way of cumulative use of best management approaches and practices of our agroecosystems. Agricultural sustainability helps to increase agricultural productivity whereby optimum utilization of natural resources will be ensured, soil health and quality will be maintained; environment and social benefit will be guaranteed for the present without compromising the need of the future generations.

2.4. Soil Degradation and its Impact on the Environment

Degradation of soil diminishes the capacity of the soil and its ecosystems. Improper use and poor management of soil usually for agricultural, industrial, or urban purposes are the main causes of soil degradation. Declining soil fertility, loss of organic matter, changes in soil structure (due to compaction), soil erosion, adverse changes in salinity, acidity and /or alkalinity are some of the examples of soil degradation (Oldeman et al., 1991; Soane and van Ouwerkerk, 1995a; Lal, 1997; Eswaran et al., 2001). According to the UN Global Assessment of Land Degradation report, almost 38% of the global land area has been degraded by human-induced land degradation (Nkonya et al., 2011). Land degradation occurs through the physical (e.g. crusting, compaction, erosion), chemical (e.g. salinization, nutrient leaching, N volatilization), and biological processes (e.g. decrease in SOM, soil biodiversity) (Lal, 1993) that decrease in soil quality and reduces in biodiversity.

Soil biota and biological processes are important drivers of change of soil quality and play a significant role in improving soil structure (Russell, 1988). Improper management of soil causes a negative influence on biological soil health by affecting the number and distribution of microbial populations in soil (Chamen, 2011). Reduced root biomass, reduced infiltration, increased runoff, and increased soil temperature due to soil disturbance disrupt habitat for soil biota and eventually can diminish the soil food web (USDA NRCS, 2004b). Microbial biomass and C-mineralization deteriorated with the soil bulk densities of over 1.7 Mg m^{-3} and further burrowing of earthworms can be impeded due to soil compaction (Beylich et al., 2010). Although, field trial results reported that compaction had no significant effect on soil biota (Beylich et al., 2010), however, experiments were highly varied in conditions and situations. The distribution and numbers of microbes were reported to be reduced in the bulk density range 1.32–1.49 Mg m^{-3} whilst both biomass and numbers were reduced drastically when bulk density reached 1.52 Mg m^{-3} (Söchtig and Larink, 1992).

Soil compaction is a physical degradation of soil that reduces soil aeration and increases soil strength. There are three types of physical degradation of soil found in ISRIC's report on the Global Extent of Soil Degradation (Oldeman, 1992). These are; i) compaction (e.g. due to heavy machinery), crusting and scaling of topsoil (e.g. due to raindrops), ii) waterlogging and iii) reduction in SOM that can decline in soil conditions. Soil strength elevated by the application of a loading stress increases bulk density (BD), penetration resistance (PR) or shear strength of soil (Whalley et al., 2008). This reduces the size of pores, pore area and percentage porosity of soil and thus results in degradation of soil structure. "The Thematic Strategy for Soil Protection" published by the European Commission in 2006 identified soil compaction as one of the five most frequent threats to soils in Europe (Houšková and Montanarella, 2008). Compaction causes tighter bonding between soil particles and aggregates, increases soil strength and decreases soil aeration that leads to poorer uptake of water and nutrients and lesser plant root growth (Hakansson, 2005). Increasing soil strength and decreasing storage and supply of water and nutrients results in poorer soil physical properties. This is exacerbated with the use of tillage or grazing at high soil moisture content and low organic matter soil (Hamza and Anderson, 2005).

2.5. Soil Management

Soil management is fundamental to all agricultural systems due to the widespread degradation of agricultural soils (European Commission, 2002). The key challenge is to maintain and conserve ecosystem functions and services while optimizing agricultural yields (Kibblewhite et al., 2008). The soil has both inherent and dynamic properties of which soil texture is the inherent soil quality that does not change easily while dynamic soil properties e.g. SOM, soil structure can be changed by management practices (USDA NRCS, 2019c). Simmons and Nafziger (2009) reported six essential practices involved in soil management: i) amount and type of tillage, ii) maintenance of SOM, iii) proper nutrient supply for plants, iv) soil acidity, v) avoidance of soil contamination and finally vi) control of soil erosion. A typical chart (Fig. 2.1) of soil management showed that adequate time is required for the gradual improvement of soil and environmental quality after initiation of improved management (USDA NRCS, 2018).

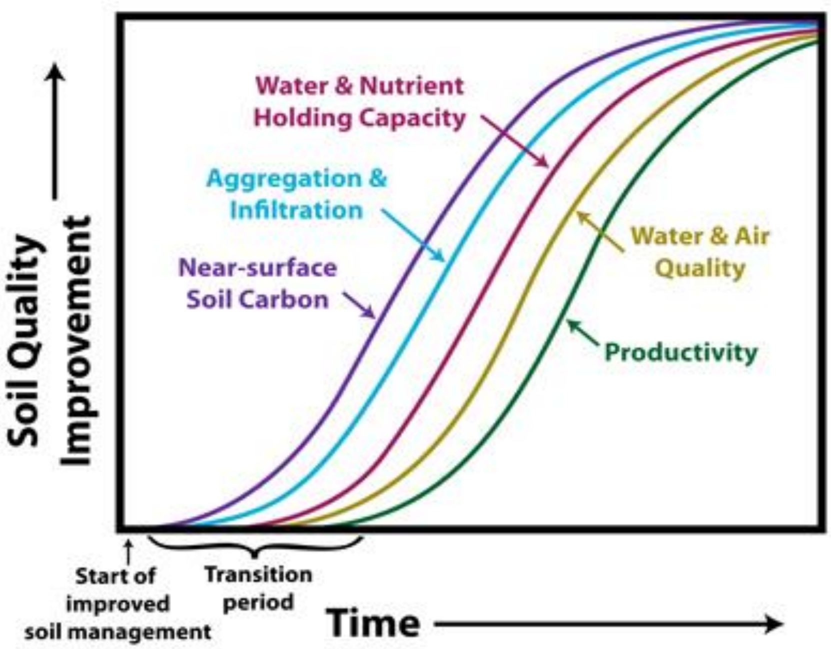


Figure 2.1. Soil quality improvement over time after the start of soil management (USDA NRCS, 2018).

Several management options have been described for minimizing the effect of compaction of soil (Hamza and Anderson, 2005). These include minimum (and zero) tillage, controlled traffic, reduced traffic and number of passes, reduced intensity of grazing, vegetative soil cover, loosening compacted soil by deep ripping and using deep and strong rooting plants in rotation, machines with low axle loads and tyres with high contact area resulting in reduced ground pressure etc. However, the adoption of these practices can be considered depending on soil type, environmental conditions, and farming system perspective.

Reduced or no-till farming practices improve soil health by conserving SOM (Komatsuzaki and Ohta, 2007). Due to its benefit to soil, worldwide around 72 million ha of land mainly to Latin America, USA, Canada and Australia is covered by conservation agriculture (no-till, cover crops, retention of residues) while only 3% of land in the rest of the world are managed with conservation agriculture practices (Benites et al., 2003). Long term no-till soil contains higher amounts of active carbon, SOM and thus has a higher number of soil microbes than conventionally tilled soils (Hoorman and Islam, 2010). Soil is a non-renewable natural resource that provides ecosystem services essential for life (Kragt and Robertson, 2014; Pereira et al., 2018). To feed-ever increasing world populations and provide food, fibre, fuel, and other medicinal products sustainable management of soil is crucial.

2.6. Review of the Effect of Soil Compaction

Definition of compaction and key issues related to compaction such as causes and factors, the effect of compaction on soil properties and crop growth, development and yield are given below.

2.6.1. Soil Compaction

Compaction takes place when soils are subjected to stresses that exceed its inherent strength. Compaction in physical terms can be defined as: "*The modification of the pore volume and pore structure of the soil in which the size and number of macropores are reduced and shape and continuity of pores are changed* (Soane et al., 1980)". The Soil Science Society of America (SSSA) defines compaction as ''the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density'' (SSSA, 2008). Compaction alters the spatial arrangement, size and shape of clods and eventually reduces the pore spaces of soil both inside and outside of clods and aggregates (Defossez and Richard, 2002). Compaction is the reduction of the volume of a given mass of soil, i.e. decrease in void ratio and porosity and, conversely, increase in BD (Keller, 2004) which was considered as a working definition of the present study. Soil compaction is also defined as the "Densification and distortion of soil by which total and air-filled porosity are reduced, causing deterioration or loss of one or more soil functions (Huber et al., 2008)".

Research on compaction has increased with an increase in the mechanization of agriculture in the 1950s (Schafer et al., 1992). Historical conferences organized by ASAE, ISTRO and others held between 1960 to 1988 on compaction concluded that soil compaction is a complex phenomenon and it's solutions are not easily obtainable, and thus the fundamental understanding of compaction is essential to develop sustainable crop production management systems (Schafer et al., 1992).

2.6.2. Causes of Soil Compaction

Soil compaction occurs when the application of a load or stress provided by a vehicle on the soil surface exceeds the soil strength (Sohne, 1958). Degradation of soil structure through the natural (Young et al., 1991) and human-induced (Soane et al., 1980; Soane & van Ouwerkerk, 1995) processes, enhances to incidences of serious erosion and decreases in crop yields. The main causes of soil compaction are overuse of heavy machinery, intensive cropping and inappropriate soil management which is aggravated by working in moist conditions (Hamza and Anderson, 2005). Natural characteristics of soil deformation cause a dense layer, shrinkage of soil owing to drying, trampling by draught and grazing animals, however, the main causes of soil compaction are related to wheels and tracks of machines and vehicles and soil-engaging tools (Canillas and Salokhe, 2002).

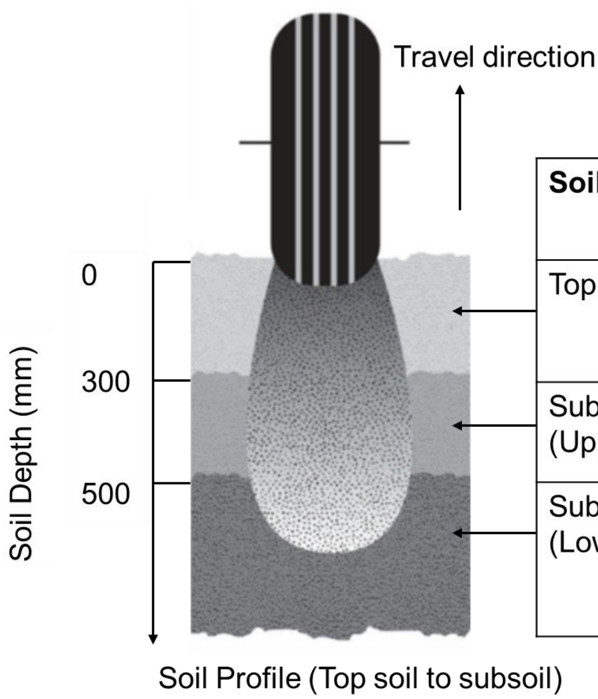
Compaction of agricultural soils can be induced by human and natural process (Kirby, 2007; Houšková and Montanarella, 2008). Natural compaction can be referred as primary compaction, includes soil properties inherited from rock and minerals, environment and climate while, human-induced compaction also known as secondary compaction can be created by the type of soil use and soil management (Houšková and Montanarella, 2008). The compressive forces derived from vehicle wheels, tillage machinery and the trampling of animals, acting on compressible soil are the main causes of soil compaction (Batey, 2009). Human-induced compaction can be the result of using tillage equipment and heavy field machinery while natural soil forming processes can also cause compacted soils with high clay content, and the best example is the Solonetzic soils in Alberta Canada (McKenzie, 2010).

Soil stress is primarily a function of the applied surface load that is given by mechanical loading such as by wheeled, tracked vehicles and other agricultural machinery. Application of loads onto the soil via pneumatic tyred equipment is the major cause of compaction of agricultural soils, which causes damage to the soil-water-air-plant system (Misiewicz, 2010). Soil stresses resulting from a loaded wheel exhibit three types of behaviour: non-deforming, hardening and plastic flow (Koolen, 1994). The non-deforming behaviour occurs when the soil stresses under wheels are low in relation to soil strength. When soil stresses exceed soil strength, soil exhibits hardening types of behaviour, resulted in deformed and more compacted soil until a new state of soil strength is reached. Plastic flow type, involving deformation when a loading induces soil flow at near-constant volume, also degrades soil qualities. However, the increased use of low tyre inflation pressures can help farmers' gain access to soft terrains so that in future plastic flow type behaviour may occur more frequently (Koolen, 1994).

Researchers use the term pre-compression stress to explain soil compaction. The pre-compression stress 'σ_{pc}' is typically used as a factor to assess the mechanical strength and stability of soil against compaction (Horn and Fleige, 2003). Deformation of soil can be elastic or plastic. Soil loading inducing lower stresses than the soil pre-compression stress causes mainly elastic deformation while loading with greater than pre-compression stress causes soil compaction (Koolen and Kuipers, 1983). Soil under elastic deformation at any depth decreases the risk of soil compaction (Horn and Lebert, 1994). Deformation of soil due to elastic can be recoverable but soil under plastic deformation leads to permanent soil compaction (Horn and Fleige, 2003). The results highlighted that soil compaction could be avoided by restricting applied soil stress to <pre-compression stress (i.e. $\sigma < \sigma_{pc}$). However, a number of tyre loading experiments also found that soil deformation occurred when measured stress was smaller than the pre-compression stress (Keller, 2004). A similar study also showed that stress provided by a tyre or track loading vehicle when it exceeded a value smaller than the pre-compression stress, compaction damage could become severe (Kirby, 1991). However, the value of pre-compression stress is dependent upon several factors including the nature of the compression test and the method of its determination (Koolen, 1974; Lebert et al., 1989; Arvidsson and Keller, 2004; Keller et al., 2004). In Sweden, residual deformations of soil were reported despite the lower stress applied on the soil than the pre-compression stress which in turn confirm that reducing the applied load to a value of the pre-compression stress cannot help to fully avoid the soil become compact (Keller & Arvidsson, 2006).

Soil structural deterioration can also be contributed by climate, fertilizers, and biological factors (Koolen, 1994). In areas where climatic and biological influences are strong, adoption of mechanization to minimize soil structural damage will decrease the possibility that field traffic may not be the main cause of such deterioration (Koolen, 1994). The deterioration of soil qualities is higher and becomes more adverse during wet compaction than dry, and hence, it can be avoided by restricting wheel traffic to periods when the soil is dry (Koolen, 1994). Heavy axle loads (> 10 Mg per axle) and wet soil conditions can increase the severity of compaction and up to 0.61 m (DeJong-Hughes et al., 2001) or even more (Billman et al., 2012).

Subsoil compaction is a serious problem because it is expensive and difficult to alleviate. It has been acknowledged as a serious form of soil degradation by the European Union (Jones et al., 2003). Subsoil compaction was also identified as a concern as early as the 1990s and giving the importance, a special issue of Soil and Tillage Research under the title “Subsoil compaction by high axle load traffic” was published (Hakansson, 1994). Subsoil compaction is considered a major problem in modern agriculture (Hamza and Anderson, 2005; Gut et al., 2015). Topsoil compaction is related to the stresses imposed by the tyre, track or hoof on the soil surface, while subsoil compaction associated with excessive stresses induced by the total load of the vehicle (Kirby, 2007). Several experiments conducted in North America and Europe (Fig. 2.2) confirmed that compaction of topsoil is caused by ground contact pressure while axle load is associated with the compaction in subsoil compaction (Duiker, 2004).



Soil layers	Causes of compaction of soil
Top soil	Effect of contact pressure
Sub soil (Upper part)	Effect of contact pressure and axle load
Subsoil (Lower part)	Effect of axle load

Figure 2.2. A typical example of the effect of contact pressure and axle load on top and subsoil. Adapted from Duiker (2004).

High contact pressure on soils (> 100 kPa) and conventional wheel systems with a weigh of 120kN can cause appreciable compaction (Soane et al., 1981). In the Netherlands, a study was conducted to determine the effects of wheel load (32 kN) using low (80kPa) and high tyre inflation pressures (240 kPa) on two loosened topsoil layers with a thickness of 0.35 and 0.55 m (Van den Akker et al., 1994). Reducing tyre pressure resulted in lower deformations and compactions than normal tyre and wheel stresses beneath the low pressure tyres were higher than expected. Although peak penetration resistances caused by both tyres were almost the same, the area involved was much smaller in the case of low tyre inflation pressure system than the high inflation pressure tyre systems. Thus, their recommendation is that use of low pressure tyre could be a good option to prevent soil degradation by excessive compactions and deformations (Van den Akker et al., 1994).

The problem was investigated in the Netherlands and revealed that about 50% of the sandy and sandy loam soils having clay content <18% were found over compaction in the top 0.2 m of the subsoil (Van den Akker, 2006). It was later evident that axle load was responsible for subsoil compaction, not the tyre contact pressure (Botta et al., 2008). At field capacity, stresses applied on the surface of soil were influenced by tyre inflation pressure while vehicle wheel load was influenced in 0.9 m soil depth (Lamandé and Schjønning, 2010). It is hidden damage that affects soil ecosystem services including crop growth and yields, and a range of soil functions that, in turn, can impact on the environment (Lamandé and Schjønning, 2018).

To summarize it can be said that soil compaction due to heavy machinery and wheel traffic is an undesirable condition that threatens the long-term productivity of soils (Soane et al., 1980; Koolen, 1994; Soane and van Ouwerkerk, 1995b; Jones et al., 2003; Hamza and Anderson, 2005).

2.6.3. Factors Affecting Soil Compaction

Many, interacting factors that play a role in the soil compaction process and soil degradation. Factors influencing soil compaction include soil texture, soil moisture, type and weight of equipment, tyre type and pressure and number of traffic passes (Eliasson, 2005; Gerasimov & Katarov, 2010; Han et al., 2009; Labelle & Jaeger, 2012; Naghdi & Solgi, 2014; Sakai et al., 2008). Studies showed that subsoil structure within coarse, medium and medium fine texture class soils are weak and found to be more susceptible to compaction (Spoor et al., 2003). Compaction of soil under conventional pneumatic tyres is related to load, tyre dimensions, contact pressure, wheel slip, carcass construction, inflation pressure including forwarding speed and the number of vehicles passes (Soane et al., 1981). Vehicle wheel load and tyre contact area (machine type), soil moisture condition during field operations (soil wetness) and the number of wheel pass (cumulative stresses) influence the extent of soil compaction (Alakukku et al., 2003). However, the degree of soil compaction is largely influenced by the loads applied to the soil and the resulting surface and subsurface pressure (Misiewicz, 2010).

Soil moisture is an important factor that largely influences the compaction process (Soane & van Ouwerkerk, 1994a). Soil structural deformation due to field trafficking increases with moisture content and the number of passes (Bakker and Davis, 1995; Hakansson and Lipiec, 2000). Water permits soil particles and aggregates to move and pack and reduces air spaces, however, Chamen et al. (2015) reported that wet soils are vulnerable and have a lower ability to resist vehicular compaction. Soil moisture content, number of passes and wheel equipment were found to have the greatest importance to the degree of compaction whilst tyre inflation pressure and weight of the machinery have intermediate importance and tractive power and vehicle speed had little influence on the degree of soil compactness (Arvidsson and Håkansson, 1991). The degree of soil compaction due to the vehicle tyre loading stresses depends on soil strength which is associated with the mechanical strength of soil (determined by soil texture and SOM content), tillage layer and wetness of soil (Hamza and Anderson, 2005).

Soil compactibility depends strongly on soil water content (O'Sullivan and Simota, 1995) which is the principal determinant of the severity and extent of soil structure degradation especially during travelling of vehicles at harvest and primary field cultivation (Kirby and Blunden, 1992; Berli et al., 2003). In wetter climates and when the conditions are wetter than average seasons, drainage becomes restricted, causing the adverse effects of compaction of the soil. Thus, soil moisture below the plastic limit is ideal for successful crop cultivation (Spoor and Godwin, 1978). The most optimum soil moisture content for tillage is considered approximately 0.95 of plastic limit cited by Hamza and Anderson (2005) and 0.9–1.0 of plastic limit as discussed by (Dexter & Czyż, 2000; Mueller et al., 2003).

2.6.4. Effect of Compaction on Soil Properties

Soil compaction due to wheel traffic deteriorates soil structure, forms a fissured structure in the topsoil and massive structure just beneath this layer (Domżał et al., 1991). Compaction disrupts soil structure, accelerates the other threats such as water and wind erosion, water run-off and damages the soil balance with other components of the environment (Houšková and Montanarella, 2008). Soil compaction damages soil structure and changes soil porosity, the best indicator of soil structure quality (Pagliai and Vignozzi, 2002). They reported that quantification of pore spaces in terms of pore size, shape, connectivity, arrangement, and distribution can help to perceive such changes and define the complexity of soil structure. The report showed that porosity of soil decreased with the increase of PR (Fig. 2.3). In Germany, researchers showed that repeated wheeling of heavy machinery and tillage system negatively affected PR of soil, macropore volume and air permeability of topsoil (0.05–0.1 m, 0.18–0.23 m) and subsoil (0.4–0.45 m), resulting in a decrease in the yield of sugar beet (Koch et al., 2008).

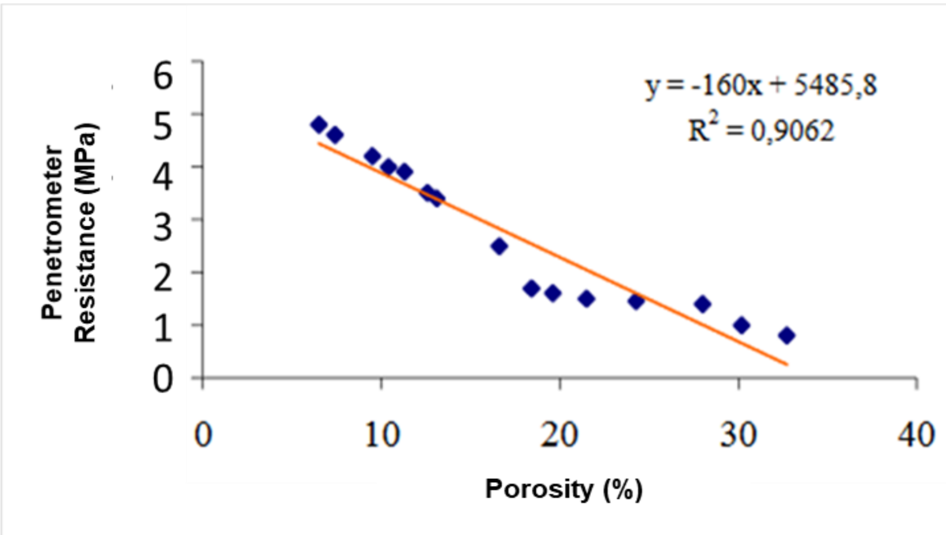


Figure 2.3. Relationship between porosity and penetration resistance at 0-10 cm depth for a clay loam soil (After Pagliai & Vignozzi, 2002).

A recent 4-year study focused on heavy traffic-induced changes in soil structure conducted on a sandy loam soil in Denmark (Pulido-Moncada et al., 2019). Compaction treatments were no compaction, compaction with ~3 Mg and ~8 Mg wheel loads with 4 to 5 multiple wheel passes, and compaction with 12 Mg wheel loads with a single pass. Results showed that 8 Mg wheel loads plus multiple passes treatment significantly increased BD whilst reduced subsoil structural quality, air-filled pore space, air permeability, gas diffusivity and pore volume to >50 cm soil depth (Pulido-Moncada et al., 2019). However, there are divergences in opinion on the seriousness of compaction as a degrading process. Incidence of soil degradation and compaction are found in some agricultural soils in Scotland was there is no evidence of serious threats to soil quality rather the circumstances are recognized to be localized and readily reversed (Towers et al., 2006). Their statement is the opposite of others who found that the severity of incidences of compaction is associated with land use and heavy machinery, indicating that it is the most ubiquitous kind of soil degradation in Central and Eastern Europe (Van den Akker and Soane, 2004). Depending on soil types, a small degree of topsoil compaction is found to be beneficial for root anchorage and crop growth (Bouwman and Arts, 2000; Hamza and Anderson, 2005). Compaction confined to the sub-surface layer led the root growth and spread of soybean to be more in the superficial layer and decreased in the compacted layer; however, no pieces of evidence of decreasing crop yield were reported (Rosolem and Takahashi, 1998).

Investigation of the effects of duals with high (0.17 MPa) and low pressures (0.040 MPa) tyres and tracks on soil compaction were conducted on a silty clay loam soil in Champaign, the USA (Duiker, 2004; Hoeft et al., 2000). The results showed that the total porosity as a measure of compaction was the lowest for the high inflation pressure tyre system as compared to the track and low tyre pressure systems (Duiker, 2004; Hoeft et al., 2000) (Fig. 2.4). However, robust experimental results by incorporating typical tillage systems and quantification of pore characteristics were still scarce.

The ground pressure of 200–250 kPa reduced water infiltration properties of a sandy loam soil by more than 80% in comparison to non–compacted soil (Chyba et al., 2014). To conclude, it can be said that compaction of soil reduces water infiltration rate, hydraulic conductivity, porosity and aeration whilst increases BD and PR and impede root growth and development (Liebig et al., 1993; Li et al., 2001; Radford et al., 2001; Hamza and Anderson, 2005; Raper and Kirby, 2006). A summary of the effect of compaction on soil conditions and the crop is also shown in Appendix 2.2.

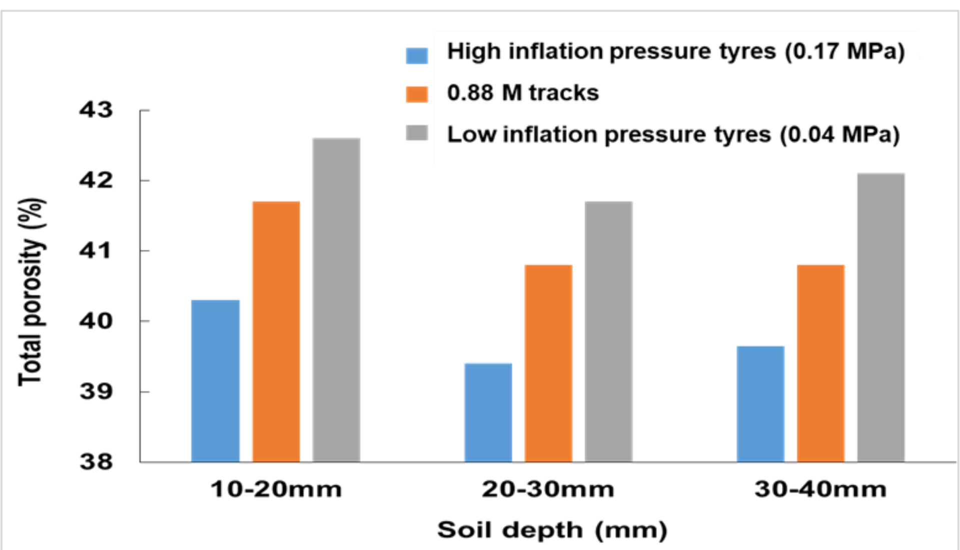


Figure 2.4. Effect of compaction due to high and low tyre inflation pressures and tracks on total porosity of soil. Adapted from Hoeft et al (2000).

2.6.5. Effect of Heavy Machinery and Field Trafficking

Increase in machinery power, vehicle weight and implement size are ongoing and inevitable in industrial agriculture and the negative effect on soil properties due to compaction by the use of heavy machinery are documented (Batey, 2009; Çarman, 1994; McKenzie, 2010). Reports show that the popularity of the number of four-wheel drive tractor in Germany was increased from 33 to 89% between 1977 and 1992 (Renius, 1994) whilst combine harvesters and slurry tankers were more on 25 and 30 Mg, respectively (Hakansson and Petelkau, 1994). The weight of two-axle and three-axle sugar beet harvesters was about 35–40 and 50 Mg or even more (Alakukku et al., 2003). A gradual increment of the weight of farm machinery from 1930 to the present day is given in Fig. 2.5.

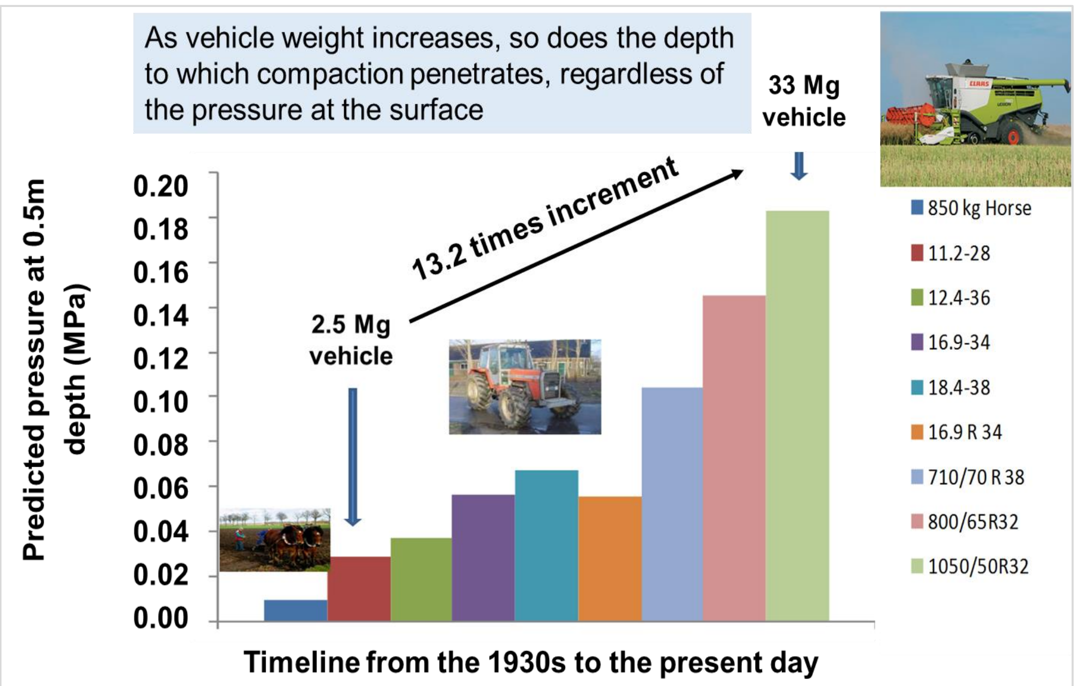


Figure 2.5. Gradual increment of the weight of farm machinery since 1930. (After Chamen, 2015).

The increasing weight of agricultural machinery with a 4-fold mass over the past 30-40 years (Horn et al., 2006) and their effect especially on deep sub-soil compaction have become a great concern, where repeated wheeling has aggravated compaction effects (Kirby, 2007). The relationship between wheel traffic compaction and axle load and moisture content showed that compaction of soil increases with the increase of equipment weight or moisture condition (Fig. 2.6).

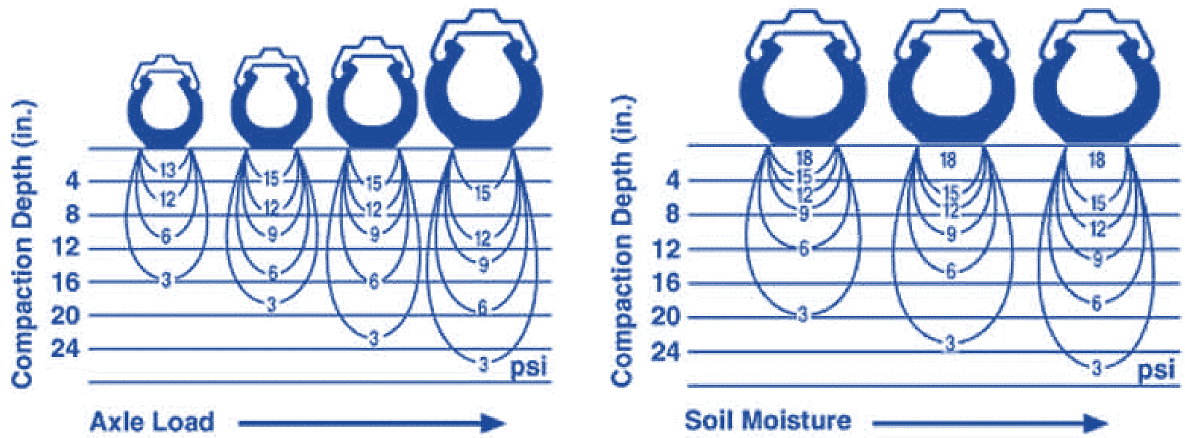


Figure 2.6. Wheel traffic compaction responses to axle load and soil moisture condition. After Sohne (1958).

According to the report of the European Commission published in 2006, 36% of European subsoils belong to the class of high or very high susceptibility to compaction (Van-camp et al., 2004). Estimation by other source found that 33 million hectares of the European land (around 4%, total) being affected by compaction (Van Ouwerkerk and Soane, 1995). About 68 million ha of agricultural land worldwide was damaged due to soil compaction based on an estimation in 1991 and of which 50 % of land (33 million ha) was identified in Europe (Kroulík et al., 2009; Gasso et al., 2014). In Australia, about 4 million hectares of the wheat belt was degraded by soil compaction which accounts for almost 30% of the area of land (Hamza and Anderson, 2005). Wheel traffic accelerates direct cost that is associated with the energy requirements for managing wheeled soil, and reduces water availability to crops, enhances runoff and soil erosion, and hence impacts on the environment and long term agricultural productivity (Tullberg et al., 2007). Their report indicated that soil degradation alone caused approximately AUS$144 million worth of damage of cost in the Murray-Darling Basin which is a large and important agricultural region in Australia (Tullberg et al., 2007).

Salokhe and Ninh (1993) showed that the first tyre wheel pass caused the most soil compaction; compaction due to later passes decreased exponentially. A similar study also confirmed that the first traffic pass caused up to 90% of compaction damages in soil (Badalıkova, 2010).

In Alabama, a study of the effect of wheeling on soil deformation and stress/strain distribution on a Hiwassee clay soil in a soil bin was conducted (Horn et al., 2003). Results showed that the more the tractor wheelings, the lower the hydraulic conductivity, the higher BD at all depths of 0-0.35m were observed. The more rearrangement of soil aggregates or particles caused by repeated wheelings or higher soil stress resulted in deteriorating an existing soil structure (Horn et al., 2003).

The summary of a series of 21 long term field trials investigating the compaction effects concentrated on plough layer was conducted from 1963 to 1999 in Sweden (Arvidsson and Håkansson, 1996; Hakansson, 2005). The experimental annual traffic before autumn ploughing was applied with a vehicle of 9 Mg and an axle load <4Mg. A traffic intensity of 350 Mg km ha^{-1} which was 2 to 3 times more than annual traffic of 150 Mg km ha^{-1} in Swedish cereal fields was consistently applied across all sites. Results show that the effects of annual traffic were not remediated by ploughing and it took nearly 4 years to restore that yield to the non-treatment level, indicating that the effect was caused by the traffic intensity.

Agricultural field traffic resulted in compaction and a significant increase in PR on coarse loamy sand in California while it’s absence on fragile soils on flood irrigated land and found a decrease in BD and PR of soil where controlled traffic farming (CTF) system was used (Carter et al., 1991). Effects of wheel loads (30 and 60 kN) for two tyre widths (560 and 800 mm) inflated to rated pressures was investigated by Lamandé and Schjønning, (2010). The results showed that stresses on the soil surface were influenced by tyre inflation pressure while wheel loads were stressed soil to a depth of 0.9 m (Lamandé and Schjønning, 2010). Canillas and Salokhe (2002) reported that the first tyre pass in the soil increased the BD and cone index at an average of 7 and 6%, respectively compared to zero passes. Kaspar et al. (2001) reported increased bulk density values in all trafficked row centres which were opposite to the untracked row centres in Iowa, USA. Similar results were presented by Hamlett et al. (1990) who obtained values of soil BD of 1.10 and 1.40 Mg m^{-3} for UT and trafficked row centres, respectively. Heavy field traffic applying for multiple passes in agricultural fields with heavy tractor wheel loads (8 Mg) imposes a risk of severe soil structural damage deep into the subsoil (Pulido-Moncada et al., 2019). The critical values of soil PR that can restrict crop root growth were identified to be between 1.5 and 3.0 MPa (Hakansson, 2005) and reported by (Chamen, 2011), however, the value is not constant as the level of resistance is influenced by many variables such as soil structure, soil texture, moisture, clay content and SOM. Soil aeration and penetration resistance are the most critical factors in excessively compacted soils (e.g. Lipiec and Simota, 1994). As per literature, an air-filled porosity of 10% (v/v) and a PR to the soil of 3 MPa often represent critical limits of soil aeration and rootability of crops, respectively (e.g. Hakansson & Lipiec, 2000; Lipiec & Hatano, 2003).

Results of an 8 year long-term study on a Ladysmith silty clay loam in Kansas (Blanco-Canqui et al., 2010) showed that wheel traffic had a more significant influence on soil conditions than intensive cropping systems resulted in increasing BD (from 1.16 to 1.38 Mg m^{-3}), PR of soil (from 1.78 to 3.10 MPa), shear strength (from 23 to 61 kPa), and aggregate tensile strength (from 377 to 955 kPa) over non-trafficked locations at depths 0-75 mm. Moreover, water infiltration, saturated hydraulic conductivity, soil water retention, plant-available water, effective porosity, and volume of pores (>50-μm) were also decreased.

2.7. Tillage Systems and Their Effect

Tillage is used to produce a good seedbed, help to enhance contact with soil. allows good seed germination and reduced soil resistance for seedlings and root development (Hallett & Bengough, 2013). Tillage has both beneficial and harmful effect on soil depending on the methods followed. The positive effect includes controlling of weeds, incorporating manure and fertilizer and crop residue and herbicides and promoting soil aeration. However, it can degrade soil structure, enhance soil erosion, and disrupt soil biota. Tillage helps to remove biological, physical and chemical limitations for crops within soils and provide favourable conditions for their establishment, growth and development (Morris et al., 2010). It also incorporates crop residues and plant nutrients properly, and destroy weeds (Godwin, 2014).

Conventional tillage consists of primary cultivation using a mouldboard plough that inverts the soil and secondary cultivation using tine, disc or rotary cultivator to prepare the field for cultivation (Hallett & Bengough, 2013; Morris et al., 2010). Field traffic associated with different tillage systems is shown in Fig. 2.7.

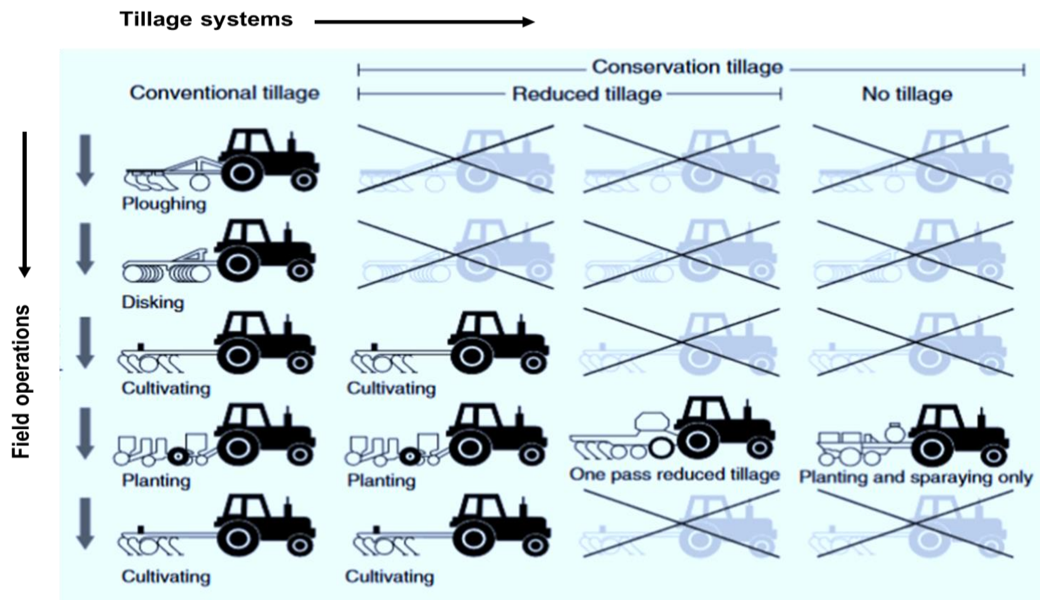


Figure 2.7. Field traffic associated with different tillage systems. After Hallett & Bengough (2013).

It is worth noting that over 30% of ground area is trafficked by the tyres of farm machinery to plant the crop (one pass) in zero tillage systems (Tullberg et al., 2007). Studies found that in one cropping cycle, the percentage of trafficked area is likely to exceed 60% for 2–3 passes under minimum tillage while it would be almost 100% for conventional tillage with multiple passes (Soane et al., 1982). Tillage and traffic enhance soil erosion and soil degradation process and tillage sometimes has been considered a major problem in the agricultural field (Tullberg et al., 2007). Despite the advantage of reduced tillage for addressing such problems (Hallett & Bengough, 2013; Morris et al., 2010), the adoption rate of both reduced and zero tillage is still much lower and practices are seen in CTF farming systems (Tullberg et al., 2007). Conventional deep tillage improves soil structure by loosening the compaction and helps to improve soil aeration and water infiltration (Sommer and Zach, 1992). However, extensive cultivation is highly vulnerable to soil degradation and erosion. The historic 'Dust Bowl' incidence which occurred in the USA in the 1930s, is the best example 'catastrophic wind erosion' where severe drought blew away the cultivated loosen topsoil including nutrients, and polluted water bodies (Huggins and Reganold, 2008).

Routine ploughing in a cropping system can cause compaction of soil at depths of 0.2 – 0.35 m, known as a plough pan and this to remove the compaction periodical subsoiling is needed (Morris et al., 2010). Subsoiling can remove plough pan compaction but undertaking routine field operation without identifying the restricting soil pan or structural problem may increase the risk and vulnerability of a subsoil to re-compaction (Spoor and Godwin, 1981) cited by Chamen et al. (2003). Ploughing deep loosened soils increases the risk of re-compaction of the subsoil and decreases the soil surface bearing capacity (Soane et al., 1986). Similar findings showed that subsoiling of compacted soil results in increased susceptibility to re-compaction from subsequent field traffic (Sommer and Zach, 1992).

Conservation agriculture (CA) is now a well-recognized approach, practised in many parts of the world (Jones et al., 2006; Fonteyne et al., 2019). Minimize/reduce tillage, round the year soil cover, reducing agrochemical inputs and losses can enhance biological processes in soil are the key elements that allow CA to protect soil and water, and contribute to sustainable agriculture (Jones et al., 2006). Non-inversion tillage a form of reducing tillage can be used as an alternative to conventional mouldboard ploughing in a cropping system as this requires less energy and reduces fuel use (Warner et al., 2016).

In the UK, approximately 40% of agricultural land is under a form of reduced tillage system while no-till farming is practised on only 5% of the land (Godwin, 2014). While in the USA, no-till farming is more widely practised and as per a report up to 20% of the total arable area was under no-till agriculture (Lal, 2004). Another report in 2012 indicated that over 20% of the total arable area is devoted to reduced tillage (Hallett et al., 2012).

A 3-year study was conducted on a sandy loam soil in Denmark, where mouldboard ploughing was replaced with no-till farming. Results found that both BD and PR were increased in the no-till farming soil, suggesting that a periodic non-inversion loosening on this soil is needed to sustain a profitable no-till production system (Munkholm et al., 2003). It has been also discussed that recently tilled soil does not have enough inherent strength to withstand the compressive forces exerted by vehicle and thus soil compaction risk is high (Raper, 2005).

It is generally viewed that no-till farming possesses several benefits such as conserving soil and water as compared to conventional tillage practices. Research suggests that plant available water and water use efficiency in no-till soils is higher than conventional ploughing cropping systems (Grabski et al., 1995). It was also evident that no-till farming has some positive effects on soil such as soil porosity which is evident at depths of 0.12m to 0.35 m, increases in the percentage of pores > 50 μm, which improved water infiltration rates (Tebrugge and During, 1999). A 14-year study of the effect of conventional (0.2m) and no-till farming on soil structure and crop development in a soybean and cereals rotations showed that soil properties such as macroporosity and saturated hydraulic conductivity were higher in the no-till system (Cavalieria et al., 2009).

A recent study showed that hydraulic properties in a silty clay soil under no-till, chisel plough, disk, and mouldboard plough systems after 35 years of management did not differ among tillage systems except for water infiltration which was found to be higher in the mouldboard plough tillage system (Blanco-Canqui et al., 2017). However, available reports e.g. Intergovernmental Panel on Climate Change (IPCC) show that intensive and continued tillage practices have an enormous contribution to the losses of soil organic carbon (SOC) and N pools (IPCC, 1996), leading to the production of GHGs emissions (e.g., CO_2, CH_4, N_2O) into the atmosphere (Blanco-Canqui and Lal, 2008).

Previous tillage history of a given field essentially needs to be taken into account to get the optimum effect when comparing the outcome of compaction with different traffic management practices and intensities (Botta et al., 2012). Although research from elsewhere found that sugar beet harvesting and ploughing representing contemporary heavy agricultural machinery (wheel load 7.8–11.7 Mg and mean ground contact pressure 100–145 kPa) did not show any significant responses in cereal yield (Koch et al., 2008). A similar study was conducted on a silty clay loam soil in Argentina (Botta et al., 2008). The results highlighted that tillage did not affect soil properties; however, conventional tillage had a greater susceptibility to cause subsoil compaction. Tractor wheel load was found to be the most dominating aspect in subsoil compaction and ground pressure was independent, however, topsoil compaction was affected by ground pressure and resulted in increased in BD and PR and rut depth of soil (Botta et al., 2008).

Soil compaction can be influenced by both climatic and soil conditions. An example was found in temperate climates in Northern Europe where the yields of winter crops recorded in no-till or reduced tillage systems were comparable to those of conventional tillage with ploughing, while for spring crops, yields were decreased (Soane et al., 2012). An experiment looking at the effect of 5 different tillage systems (conventional tillage-CT, reduced tillage-RT, conservation tillage I-CP, conservation tillage II-CM and no-till-NT) on physical properties of a silty loam soil in a soybean/winter wheat rotation was conducted in Croatia from 1997-2000 (Husnjak et al., 2002). The results indicate that significant differences were observed between some tillage systems in-terms of BD, total porosity, air capacity and soil moisture in the case of soybean seasons but no significant differences were found for wheat. The deterioration trend of physical properties of soil was generally increasing in the following order CM, CT, CP, NT. In year 1, the yield of soybean was the highest under the CT system, while for the rest of the years the highest yield of winter wheat and soybean was recorded for the in CM tillage system (Husnjak et al., 2002).

A long-term study of the effect of 4 and 7 years of conventional tillage (CT) and no-till (NT) systems on soil physical properties, root growth, and wheat yield was conducted in Central Chile (Martínez et al., 2008). The results showed that the effect of NT was more evident near the soil surface and the mean-weight diameter of soil aggregates and the PR were higher under NT as compared to CT. Root length density was also greater in NT than the CT system whilst macropores and soil water infiltration were higher under CT rather than under NT. They found enhanced aggregate stability in NT practised for a longer period, however, other soil physical properties were negatively affected. Tillage system did not significantly affect BD or yield (Martínez et al., 2008).

2.8. Effect of Different Traffic System

From field cultivation to harvest of crops, several traverses of tractors and combines are done in modern agriculture. With the advancement of agriculture, innovative and new traffic farming management systems, or techniques such as control traffic farming, traffic farming with tracked agricultural vehicles and use of low ground pressure tyres have been developed. These are discussed below:

2.8.1. Random Traffic Farming (RTF)

The random nature of field trafficking in a conventional traffic farming, covering 80-90% of the field area, is a typical commercial practice and inevitably leads to negative impacts on soil, water and crop (Kroulík et al., 2009) which is, in fact, RTF systems mostly used throughout the world. Study shows that that conventional tillage technologies with ploughing cover a high number of tyre passes and more than 86 % of the total field area trafficked during one season (Kroulík et al., 2011). Further, a high number of repeatedly run-over areas such as twice run-over area 31%, three times run over area 15.6% were detected. The natural repair of the damage incurred due to the conventional traffic farming system on soil structure takes a number of years (McHugh et al., 2009). However, to make agricultural systems productive, cost-effective, practical, and sustainable means of systems are necessary. It was suggested that field traffic in the agricultural field should be restricted to around 20% and a combination of approaches including the judicious loosening of the soil with the use of low ground pressure tyre system might be helpful (Chamen, 2011).

2.8.2. Controlled Traffic Farming (CTF)

Controlled Traffic Farming (CTF) is the term used for a field traffic system that confines agricultural machinery to permanent wheel or traffic lanes that are separate from distinct crop zones (Gasso et al., 2014). Ideally, the CTF system requires all machinery to be capable of being guided by navigation systems (Galambošová et al., 2017). Controlled Traffic Farming emanates from Australia and the USA where, field traffic travels on permanent wheel-ways, significantly reducing total area trafficked to c. 30% depending on working widths used (Tullberg et al., 2007; Chamen, 2011; Antille et al., 2016).

In Australia, the total area devoted to RTF and well-designed CTF systems are around 15% and over 85% respectively (Antille et al., 2016). Adoption of CTF technology as a technically and economically viable alternative enhances the productivity and sustainability benefits in arable and grassland cropping systems (Antille. et al., 2019). The finding of this study also highlighted that these benefits can also be triggered by no-till practices and expedited by adopting precision agriculture technologies. Chamen (2011) describes that the positive effects of CTF system are 60% reduction in fuel use, greater reduction of tillage inputs and reduction in the areas become traffic.

Comparing with RTF, non-organized traffic systems, a well-designed CTF system using commercially available agricultural machinery may reduce the area affected by traffic up to 50%, whereas converting the traffic farming from RTF to CTF can provide a 0.5 Mg ha^{-1} yield increase in cereal yield as compared to RTF (Galambošová et al., 2017). In the UK, CTF with a 30 and 15% trafficked area had given 0.32 and 0.61 Mg higher yield benefit in winter wheat and spring oats as compared with RTF (Godwin et al., 2017).

Despite the benefits, adoption of CTF systems is still relatively low, except for grain production systems in Australia. The main reason of non or less adoption of the CTF systems could be the incompatibilities of working widths between the different farm machinery and equipment used in the field (Tullberg, 2010), indicating the need to modify machinery to suit a specific system design that is often costly and may result in losses of product warranty to the farmers. The

ACTFA (Australian Controlled Traffic Farming Association) in Australia and CTF Europe Ltd. have organisation developed to work with farmers to assist them in the CTF process.

2.8.3. Tracked Agricultural Vehicles

Adoption of tracked tractors can be beneficial to soils as it can produce large contact areas and reduce compaction of soils. Studies show that compacted soil was found to be lower due to the lower loading stress provided by tracked vehicles compare to the similar mass of wheel tractors (Rusanov, 1991; Ansorge and Godwin, 2009a; Smith et al., 2014a). A review of the effect of track tractors over wheel tractors showed that under normal agricultural conditions tracks have some advantages over wheel tractors such as less slip, more tractive efficiency, less rut depth on wet soils and a compact vehicle design (Alakukku et al., 2003). Evidence shows that tracks have a positive effect on clay soil in Italy (Pagliai et al., 2003). However, this research showed that soil strength was lower under wheel tracks at depths of 0-0.35 m after a single pass that led to lower PR but was higher after multiple passes at depths of 0-0.15 m under tracked vehicles.

In the UK, a study of the effect of self-propelled wheels and a rubber track at high axle loads (9-24 Mg) on soil compaction showed that rubber tracks significantly reduced the surface rut depth and lowered PR in the subsoil as compared to wheeled systems (Ansorge and Godwin, 2007, 2008) whilst maintaining the productivity of the soil. The tracks can contribute to forming a hard strength at the soil surface to support subsoil to withstand and protect from further compaction (Ansorge and Godwin, 2008). Results showed that tracked vehicles cause smaller soil displacement and rut depths and found potential ability of the track to reduce compaction at depth while exhibiting similar surface deformation (Ansorge and Godwin, 2009b).

However, opinion and findings are also varied. For example, comparing two agricultural vehicles traffic on sandy soil in Australia, researchers showed that external stress provided by a tracked tractor (15 Mg, contact pressure 58 kPa) was lower on a sandy soil as compared to a wheel tractor (18 Mg, 74–81 kPa). However, the report showed that PR of soil at 0.40 m depth was lower in the wheel tractor (1.48 MPa) than tracked tractor (1.51 MPa) (Blunden et al., 1994).

2.8.4. Low Tyre Inflation Pressure (LTP)

Low tyre inflation pressure traffic system is a conventional traffic system that can facilitate random trafficking where low inflation pressure tyres are used instead of conventional inflation pressure tyres. Tyre contact area and tyre inflation or ground pressure can influence soil compaction. Low pressure tyres and controlling wheel/track loads can effectively prevent soil compaction (Alakukku et al., 2003). A benefit of this tyre system is the flexible structure that can carry more loads at low inflation pressure, generate a greater surface imprint which in turn increases traction (Michelin, 2017). Moreover, it helps to minimize soil compaction while less fuel and more return can be achieved (Michelin, 2017).

Overall, traffic system experiments on a field scale generally show positive responses of the topsoil condition and the yield of most crops to substituting a low tyre inflation pressure traffic system for a conventional traffic system (Chamen et al., 2015). Reduction in soil compaction due to LTP system is often observed and restricted to the topsoil layers while in the subsoil stresses tend to increase due to stress superposition (Sohne, 1958). A detailed review of soil compaction related research and literature, its causes and solutions are discussed (Hamza and Anderson, 2005). The report also shows that reducing tyre inflation pressure on the soil by decreasing wheel loads and increasing contact area and following a CTF system can reduce soil compaction that eventually enhances crop growth and yields as compared to higher (standard) tyre inflation tyres. The contact area of radial tyres was found to be between 30 and 46% higher as compared to the equivalent sized bias-ply tyres (Soane et al., 1981). Reports in 2005 showed that radial tractor tyres had largely been replaced by cross-ply (bias-ply) tyres because of the increased traction performance and larger soil contact area that leads to reduced soil compaction (Raper, 2005).

Studies suggest that soil compaction can be avoided by the use of LTP tyres (low inflation pressure) and the adoption of CTF in the farming systems (Chamen et al., 2015). Due to their role as avoidance of compaction, LTP tyre systems caused less stress mainly on topsoil and have a larger footprint that may help to reduce or avoid compaction of soil, which, in turn, increased crop yield and gross margin as compared to a conventional trafficking system. Similar benefits of using LTP found that LTP systems create more footprint of the tyre and concentrate the applied load on soils towards the outside of the tyre whilst the opposite is true for standard tyre inflation pressure system (STP) systems which cause more compaction (Raper, 2005).

LTP systems reduce the topsoil stresses at depth 0.01 m while increased axle load increases subsoil stresses, with soil stress is always a function of soil conditions, tyre properties, load and inflation pressure (Arvidsson & Keller, 2007). The ground contact pressure of 160 kPa increased BD and consolidation pressure whilst decreasing air permeability and macroporosity on moist soil at depth of 0.12-0.17 m. Cone index under zero traffic was significantly lower than those of reduced ground pressure traffic and conventional system to a depth of 0.24 m; at greater depths, no significant differences were found (Dickson and Ritchie, 1996). However, reduced ground pressure (130 kPa) showed a marginal change in soil structure at a depth of 0.32–0.37 m and 0.52–0.57 m (Gysi et al., 1999).

Reducing tyre pressure indeed increases ground contact area but it also increases the total area of field trafficked as compared with STP systems, meaning that there is more compaction of the topsoil over a whole field with LTP. Nonetheless, Hamza and Anderson (2005) reported that the damage to the soil was greater with the narrower tyres at higher tyre inflation pressure. A significant reduction in the negative effect of soil compaction was achieved with a larger diameter type with reduced contact pressure rather than a wider tyre (Ansorge and Godwin, 2007). Tyre contact pressure is a good indicator of the potential amount of soil compaction a wheeled machine can exert on the upper layers of the soil (Sohne, 1958). A study confirmed that the influences of low ground pressure tyres tend to be most significant in the topsoil while severe compaction in subsoils is caused by large axle loads (Botta et al., 2010).

Heavy machinery considerably increases the risk of rutting and soil compaction under unfavourable soil conditions. In Sweden, the effect of 3 levels of tyre inflation pressure (300, 450 and 600 kPa) and machine passes (1, 2 and 5) on rutting and soil compaction were studied (Eliasson, 2005). Machine weight for the 1st pass was 19.7 Mg only for a combine harvester and the rest of the passes were with a fully loaded forwarder with 37.8 Mg. The results suggested that both rut depth and soil BD significantly increased with the increase in the number of passes but was not influenced by tyre inflation pressure. The research concluded that reducing tyre inflation pressure with a single pass may reduce soil compaction but when the soil under heavy wheel traffic with multiple passes, soil compaction cannot be avoided (Eliasson, 2005). This was explained by the fact that the low tyre pressure examined was much higher than the usual low tyre pressure (≤ 100 kPa) used in agriculture.

A survey conducted in Germany showed that the main benefits of the controlling of tyre inflation pressure are an improved tyre potential, reduced soil compaction and drawbar pull, enhanced fuel economy and crop yield (Renius, 1994).

2.9. Growth and Development of Crops and the Effect of Soil Compaction

Growth of plants is the irreversible increase in size primarily associated with capture and allocation of resources e.g. water, nutrients, CO_2, sunlight. Albeit development is the continuous change in plant form and function with characteristic transition stages and mostly related to environmental response such as temperature, photoperiod and light quality (Sadras et al., 2016).

Growth and development of crops depend on both abiotic and biotic factors especially soil, and environment and climate factors greatly influence these processes. Growth and yield reductions of crops due to soil compaction have been found in several studies throughout the world. Compaction of soil due to wheel traffic significantly reduced maize root growth as compared to the UT side of the row (Kaspar et al., 1991). Compaction induced by the use of heavy machinery, repeated tractor wheeling etc. creates physical, chemical and biological changes in the soil that negatively impact crop performance (Chyba, 2012; Horn et al., 2003).

2.9.1. Growth and Development of Maize

Maize and soybean are the two main crops grown in the Midwestern United States. These two crops are commonly cultivated in rotation. The growth and development of maize and soybean are briefly described below and in the following section, respectively.

Maize is the most extensively cultivated crop after wheat and top produced crop in the world in 2018 (FAO, 2019b). The total production of maize was more than 1 billion Mg from an area of almost 200 million hectares in 2018. The U.S. Maize Belt produces 38% of the world's total, followed by China (18%), Brazil (8%), Argentina (8%), Baltic States (9.5%), India (5%), and Mexico (3%) (FAO, 2018). In 2018, U.S. maize growers produced 0.366 billion Mg (14.4 billion bushels), down 1 percent from 2017 and are estimated at 11.07 Mg ha^{-1} (176 bushel $acre^{-1}$) from an area harvested, of 33.1 million hectares (1 percent down from 2017). Weather data depict that cooler than average summer months but a warmer spring kept the maize harvest just 1 percent below than 2017 (USDA NASS, 2019a)**.** Crop yields are the result of environmental factors such as soil, climate, and management inputs (Garcia-Paredes et al., 2000). Temperature and moisture have a direct influence on the developmental aspects of the crop, and thus on the physiological processes such as leaf initiation, shoot and root growth. The most susceptible phenological phases to temperature are emergence, anthesis, and grain filling of maize (García-Lara and Serna-Saldivar, 2019).

Maize plants undergo a series of developmental stages throughout the growing season. These stages are separated into two groups: vegetative (V) and reproductive (R) and are distinguished by the appearances of silks (Ritchie et al., 1993). The vegetative stage starts with the emergence of the seed which is known as VE. V1 stage starts when the collar of the first developed leaf becomes fully visible. Eventually based on the uniqueness of the number of fully developed leaves V2-V10/V15 stages are identified. For example, V6 is the stage when six leaves along with their visible colours are fully developed. Tillers start to become visible at this stage. At V10 or sometimes at V15, plant ear shoots develop, tassel formation starts, and nutrient and dry weight accumulation are greatly increased. A plant reaches VT (Vegetative tasselling) stage when the tassel completely extends before silking. VT stage is signified by the maximum vegetative growth of plant and pollen shed starts in 2-3 weeks. However, crops at this stage are vulnerable to hail damage. The growth stages of maize are shown in Fig. 2.8.

Reproductive stages start with silking (R1) and become visible outside the husk. Pollen grains falls onto the silk, reach the ovule and pollination occurs. Environmental stresses such as lack of moisture can cause the silks to dry and that results in poor pollination or kernel set, and limit the ability of silk to transfer pollen grain into the ovule. Kernels at the blister stage (R2) are very small in size having around 85% water and are white. Milk stage (R3) begins with the milky structure of the kernels with a yellowish colour. The rate of dry matter accumulation is very high at R3. Dough (R4) and Dent (R5) stages appear when ears become brighter yellow to reddish and kernels become dented containing almost 55% moisture, respectfully. Kernel at R5 continues to form dough stage to a much harder texture. Dry matter accumulation reaches at a peak, hard structure, and a black abscission layer forms in the kernels. This is known as the R6 growth stage where maize plants reach at physiological maturity and kernels contain approximately 30-35% moisture. Environmental stresses at R1 limits pollination and can affect the size and number of the kernels (Ritchie et al., 1993). Stresses such as water and nutrient deficits, unavailability of water in the soil or soil compaction reduce growth and development by reducing the amount and the efficiency in the use of resources captured by the crop (Sadras et al., 2016).

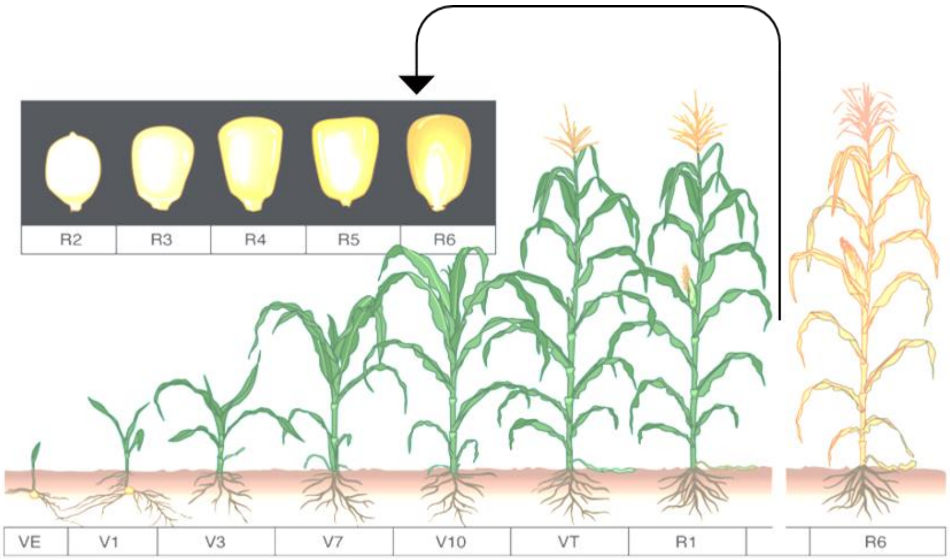


Figure 2.8. Maize growth stages. Adapted from Nafziger (2009).

2.9.2. Growth and Development of Soybean

The USA accounts for 35% of global soybean production, producing annually an 85 MT (Grassini et al., 2015). According to the USDA Crop Production 2018 Summary, the nation's soybean yield was up 5% from 2017, with the planted area down 1% from record 2017 acreage (USDA NASS, 2019b). A record 0.123 billion (4.54 billion bushel) Mg of soybean was produced in 2018 which was up 3% from 2017. With record high yields in Arkansas, Illinois, Indiana, Mississippi, New York, and Ohio, the average soybean yield is estimated at 3.47 Mg ha^{-1} (51.6 bushels acre^{-1}) (USDA NASS, 2019b).

Growth stages of soybean are also divided into vegetative and reproductive stages. Development of trifoliate leaves fully accounted for the vegetative stage whereas, reproductive stages starts at flowering and end at plant maturation (Licht, 2014)**.** VE is the first stage that determines emergences and V1 stage is identified when one set of trifoliate leaves completely appears. Eventually, V2 to Vn vegetative stages are identified based on the appearances of fully developed trifoliate leaves of soybean. The onset of flowering (R1) is the first reproductive stage when at least one flower is found at any node. Eventually, the final stages are pod formation stage (R4) to maturity stage (R8). The growth stages of soybean are shown in Fig. 2.9. The unfavourable environment at conditions such as changes in temperature and rainfall may greatly affect the height of soybeans without greatly affecting initial reproductive growth stages such as flowering (Naeve, 2018).

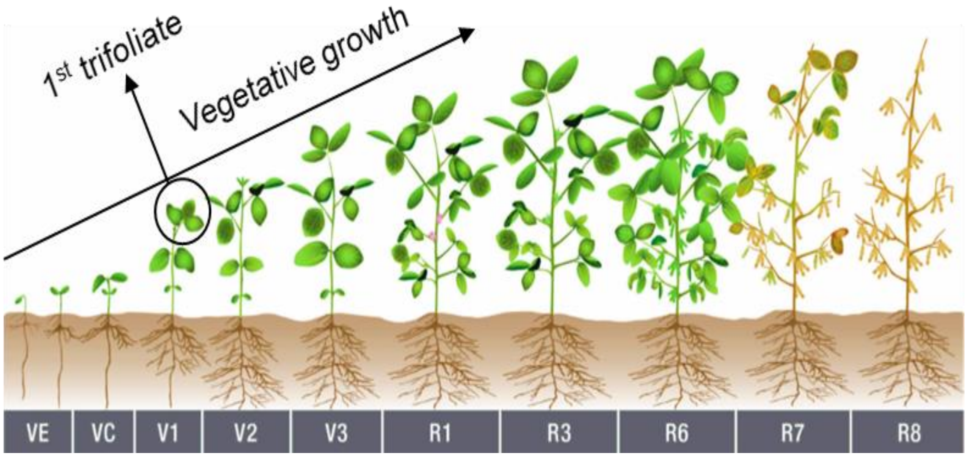


Figure 2.9. Soybean growth stages. Adapted from the figure of the University of Illinois as reported (DEKALB, 2018)

2.9.3. Effect of Soil Compaction on Crop Growth and Yield

Soil compaction leads to yield losses because it prevents crop root systems penetrating through the compacted soil and extracting soil-bound water (Ball et al., 1999; Hula et al., 2009) and has adverse effects on ecology. The consequence of soil compaction is an increase in deep tillage/subsoiling and energy requirement for soil treatment. Several studies indicated that these extra soil treatments adversely affect the germination of subsequent crops (Chamen et al., 1992; (Ishaq et al., 2001a; Defossez and Richard, 2002; Gelder et al., 2007; Hula et al., 2009). Soil compaction, caused primarily by heavy machinery, can lead to crop yield losses of 9-19%, flooding and soil erosion on arable land. Up to 38% reduction in grain yield of a wheat crop was reported when the subsoil compaction was present at 0.15 m depth to a BD of 1.93 Mg m^{-3} (Ishaq et al., 2001b).

Compaction of soil generally increases with the increase or repeated number of vehicle passes during field operation (Raghavan et al., 1976). Repeated wheel traffic (1, 5, 10, and 15 passes) with different contact pressures (31, 41, and 62 kPa) and a zero traffic treatment experiment was conducted on a St. Rosalie clay soil in Quebec, Canada. Results indicated that yield reductions of crops were almost 40–50% with higher contact pressures and multiple passes (Raghavan et al., 1979).

Soil compaction prevents crop root systems penetrating through the compacted soil and extracting the soil-water and nutrients. This leads to losses of yield (Ball et al., 1999; Hula et al., 2009). In the UK, a long-term traffic and tillage study showed that compaction lowered the plant establishment and reduced root dry mass of winter barley in highly trafficked areas as compared with UT areas (34 and 41% more). Millington et al. (2016) reported that anaerobic conditions in compacted areas due to the reduction in the size of the soil pores were associated with compaction and might be the reason for the reduced yield observed. Reduction in root and crop growth and yield are associated with the high annual traffic intensity, which causes reduced soil aeration and limited oxygen in the root zone and further boosting undesirable gaseous exchanges (Chamen, 2011; Hakansson, 2005) (Fig. 2.10).

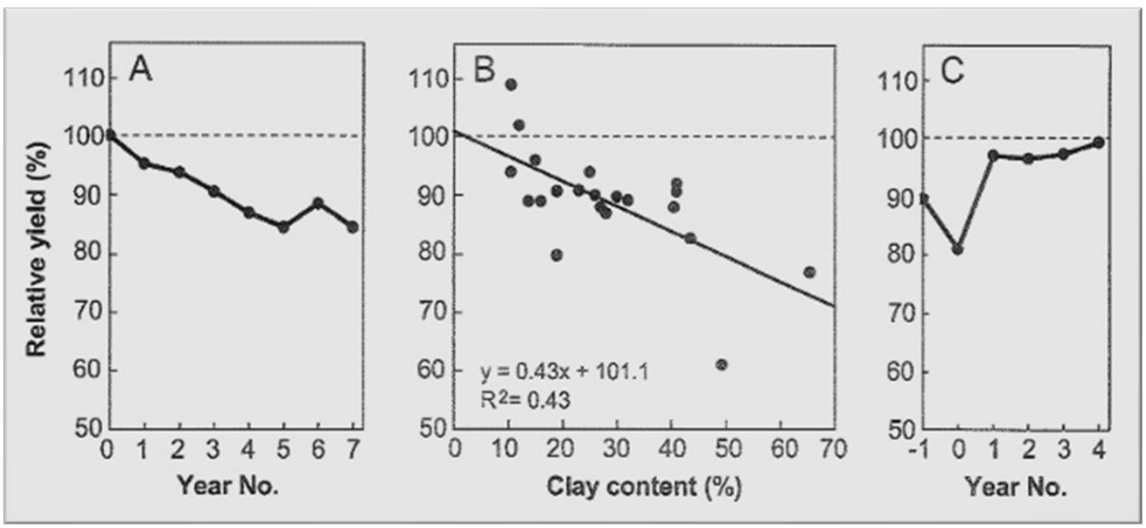


Figure 2.10. Relative crop yield in a series of 21 long-term field trials in Sweden. After Arvidsson & Håkansson (1996) and redrawn by Hakansson (2005).

a) Mean relative yield in compacted plots in the whole series of trials during the first seven years.

b) Mean relative yield from year 4 to the year after the last compaction treatment in each trial as a function of the clay content of the soil.

c) Mean relative yield in compacted plots in the whole series of trials after the termination of the experimental traffic.

Year No. 0 is the last year with annual compaction treatment.

A five-year study to determine the effect of wheel tracks on BD, PR, and wheat yield on a Webster clay loam soil in Minnesota was conducted (Voorhees et al., 1985). They found that compaction from vehicular traffic on both sides of the row caused increased BD and PR values to depths of 0.3 m. Grain yield of wheat decreased by 27% for wheel tracked soil in comparison with no tracked soil. Cotton plants development under different BD, soil strength and moisture tension were studied in the sandy soils of the Southern Great Plains, USA (Taylor & Gardner, 1963). They concluded that soil strength, not soil BD, was the critical impedance factor controlling root penetration in soils. Their findings showed that no roots penetrated into the soil with a resistance larger than 2.96 MPa, which was valid whether the soil strength was caused by an increase in BD or by a decrease in soil moisture. Later in 1966, results of another study on soil strength measurements as an indicator of resistance encountered by cotton seedlings showed that no taproots penetrated through soil cores with strengths greater than 2.5 MPa for four soil types (Taylor et al., 1966).

A four-year compaction study evaluated the effect of using different axle loads of 8 and 12.5 Mg on maize on a silt loam and silty clay soil in Wisconsin, USA (Lowery and Schuler, 1994). Results showed that BD and PR dramatically increased and hydraulic conductivity was decreasing in trend with increasing levels of compaction. Plant height was found to be a good indicator of compaction as it was lower in the compacted areas in all years. Maize grain yields decreased in the first year at both sites in the compaction treatments and the second and fourth years at the silt loam site and silty clay site (Lowery and Schuler, 1994). A 25 and 50% yield reduction in maize were recorded in field induced with severe compaction (BD of 1.82 Mg m^{-3}) and moderate compaction (BD of 1.69 Mg m^{-3}), respectively (Gaultney et al., 1982). Both root length and depth of rooting, and yield of spring barley were retarded due to compaction (Domżał et al., 1991).

The effect of a given level of compaction is related to both weather and climate (Batey, 2009) and can have both negative and positive effects. A four years soil compaction study induced by wheel traffic using 10.6 Mg axle loads for three traffic managements (wheel traffic over the entire soil surface, on alternate rows, and control) was conducted on a Thorp silt loam, Champaign county, USA (Bicki and Siemens, 1991). The results showed that compaction induced by wheel traffic had increased yields of maize in dry years (1^{st} and 3^{rd} year) and decreased yields in wetter years (2^{nd} and 4^{th} years), however, there was no individual years effect on soybean and no net overall effect from compaction of both crops. They also indicated that compaction was found to decrease yields with more favourable moisture conditions. Earlier germination, more rapid early growth, and more intensive root system of the maize plants in no extra compaction as compared with adjacent compacted rows might be the reasons for such yield differences (Bicki and Siemens, 1991). Compaction had a positive influence on the crop yield in dry years, as such grain yields were recorded higher in moderately compacted soils but reduced in wetter years compared to non-compacted soils (Raper, 2005). It has been also discussed that the effect of compaction becomes severe in the event of large soil moisture deficits which restricts rooting depth but may have a negligible effect at the same degree of compaction, where moisture deficits are small (Batey, 2009). Reduced crop growth can occur due to stresses such as water deficits or soil compaction which decreases the capacity and efficiency of the crop canopy and root systems to capture the use of the resources such as H_2O, CO_2, radiation and nutrients (Sadras et al., 2016).

Plant root systems are often affected by increased soil BD because of compaction. There is a non-linear relationship between root elongation and soil resistance in the majority of plants (Misra and Gibbons, 1996). Plant total root length of primary and lateral roots decreased with an increase in BD and soil strength (from 0.4 to 4.2 MPa) however, results indicated primary roots to be more sensitive to high soil strength than the lateral roots. Compaction strongly reduces plant growth as it limits root growth (Young et al., 1997; Rosolem et al., 2002; Lipiec et al., 2012).

In Poland, experiments were conducted on tractor wheel induced compaction and showed that increasing the number of wheel traffic passes cause increased compaction, leading to increased BD and decreased aeration that eventually reduced the number of plants after emergence, root system development and the grain yield of spring barley (Czyż, 2004). Aeration is the limiting factor in strongly compacted soil and optimum BD of 1.43 Mg m^{-3} was found for on a sandy loam soil for root growth and yield of spring barley (Czyż, 2004). Soil compaction may lead to extremely dry topsoil and eventually causes soil to crack because the roots absorb water requiring for transpiration from the upper part of the soil where plants can penetrate with their restricted root depth (Batey, 2009). The main physical negative effects of soil compaction to plants are restricted root growth and accessibility of nutrients and water owing to an increase in BD and reduced pore size (Nawaz et al., 2013).

Field traffic significantly increased soil PR at depths of 100mm and 250mm, it reduced water infiltration rates and decreased the grain yield of winter wheat in the UK (Smith et al., 2014b). A summary of long term trials investigating the effects of different tillage with traffic systems (RTF conventional, LGP and CTF) showed that CTF with a 30% trafficked area significantly increased yields than RTF conventional and LGP traffic for the winter wheat and spring oats (Godwin et al., 2017). However, proper traffic management along with adaptable wheel track widths and operating systems innovation that reduces soil compaction would help to improve water infiltration rates, increase crop yields, reduce energy consumption (Godwin et al., 2015).

An investigation of the effect of repeated traffic (1, 5, 10, and 15 passes) with contact pressures (31, 41, and 62 kPa) and a no traffic treatment was established on a St. Rosalie clay soil in Quebec (Raghavan et al., 1979). Results showed that maize yield reductions were up to 50% in severely compacted plots due to high contact pressures and multiple passes. They concluded that reduced air-filled porosity, higher PR, BD and moisture stress are associated with the higher contact pressure with a higher number of traffic passes that causes a high level of compaction (Raghavan et al., 1979). An experiment conducted on a poorly drained Fincastle silt loam in Indiana, USA showed that growth and yield of maize were severely affected by subsoil compaction (Gaultney et al., 1982). Up to 50 and 25% reduction in maize yield were reported with severe compaction and moderate compaction, respectively.

A five years compaction study in Minnesota showed that compaction from vehicle traffic on both sides of the row increased BD and cone index values to depths of 0.3 m (Voorhees et al., 1985). Grain yield of wheat in wheel-tracked crop rows was reduced by 27% as compared to non-trafficked crop rows. It was later documented that the lack of crop response to wheel traffic may be due to increased root growth on the UT side of the row that compensates for decreased root growth on the trafficked areas (Reeves et al., 1992).

An experiment conducted in Norway found that damage to topsoil structure caused by a compaction treatment of 4 wheelings with of an axle load of 26 Mg traffic, resulting in significant yields reduction of barley (*Hordeum vulgare*) and carrot (*Daucus carota*) (Riley, 1994). A similar seven years experiment was conducted in Quebec, Canada, where 12 and 20 Mg per axle loads were applied in four and two passes, in addition to control (Gameda et al., 1994). Results showed that the compaction treatment increased soil BD, decreased total plant dry matter of maize whilst grain yield reduction was persistent and reduced by 20.5, 8.4 and 13.9% for the three consecutive years.

In Ohio, effects of harvest traffic (single axle loads grain cart loaded with 0, 10 and 20 Mg maize) and tillage systems (no-till, chisel plough, and mouldboard plough) on soil and crop development of soybean on a poorly drained heavy textured soil was studied (Flowers and Lal, 1998). Results showed that soil compaction due to harvest traffic increased soil BD and decreased grain yield of soybean. Reductions in yields were of 9 and 19% when axle loads were imposed by 10 and 20 Mg, respectively.

Experiments of the effect of subsoil compaction were conducted on a sandy clay loam soil in Pakistan and results showed that compaction treatment significantly reduced the nutrient uptake of wheat and sorghum with an increase in BD from 1.65 to 1.93 Mg m^{-3} and PR from 1.00 to 4.83 MPa (Ishaq et al., 2001). Up to 38 and 8% reduction in grain yields of wheat in Year 1 and 2 while in sorghum the yield reductions were 22 and 14% when subsoil compaction was present at 0.15 m depth to a BD of 1.93 Mg m^{-3} (Ishaq et al., 2001a). The effect of compaction due to the use of heavy machinery and tyre inflation pressures for various soil types and crops is presented in Table 2.1.

Table 2.1. Effect of compaction of agricultural soils on growth and yield of crops

Crops (Scientific name)	Soil types and location	Tyre inflation pressure/ machinery traffic/axle load	Effects on growth and yield of crops
Corn (*Zea mays*)	Silt loam and silty clay, WI	Axle load 12.5 and 4.5 Mg; 150-220 kPa; 4passes	Decreased plant emergence; yield reduction of 4-14 and 14 - 43%, respectively (Lowery and Schuler, 1991)
	Fine sand soil, MN	PR > 3 MPa; BD 1.57 Mg m^{-3}	Mechanical impedance from 0.15 to 0.35 m deep restrict root growth (Laboski et al., 1998)
	Silt loam and silty clay, WI	8 and 12.5 Mg axle load; BD 1.61 and 1.63 Mg m^{-3}	Reduced growth and yield in year 1 at both sites, and the year 2 at silt loam and 4 at silty clay site (Lowery and Schuler, 1994).
	Clay soil, QC, Canada	31, 41 and 63 kPa; 1, 5, 10 and 15 passes	Higher contact pressure and multiple passes caused 40-50% yield reductions (Raghavan et al., 1979b).
	Silty clay loam soil, OH	0, 10 and 20-Mg axle load	Decreased in yield in year 1 from 37-71% and 14-20% for 3 year period, (Lal, 1996)
	Silt loam soil, PA	700 kPa and 250 kPa; 10-Mg axle load	Yield reductions averaging 17% in 3 years out of 4. Deep tillage after compaction increased yield (17%) in year 1 only (Sidhu and Duiker, 2006)
	Silty clay loam, NE; Vertisol, AUS; others	-	Mechanical impedance restricts root growth (Hamza and Anderson, 2005; Raper and Kirby, 2006; Radford et al., 2007)
	Clay loam soil, ON, Canada	14 Mg axle	Reduced plant growth and productivity; dry matter and yield reduced by 33% and 26% (Gregorich et al., 2011).
	Garden soil, Cracow, Poland	BD 1.10, 1.34 and 1.58 Mg m^{-3}	Root growth heavily restricted and greater damages in physiological characteristics in leaves (Grzesiak, 2009; Grzesiak et al., 2013)
Wheat (*Triticum aestivum*)	Sandy clay loam, Pakistan	BD 1.61 and 1.93 Mg m^{-3}	Decreased crop growth and yield by 38 in year 1 and 8% in year 2 (Ishaq et al., 2001a).
	Beijing, China/Lab study	High and Low strength; 0.75 MPa	Impeded root growth and reduction in total biomass from 71 - 88% (Jin et al., 2015)

Crops (Scientific name)	Soil types and location	Tyre inflation pressure/ machinery traffic/axle load	Effects on growth and yield of crops
	Sodic brown clay, Australia	Wheel track and non-track; PR >2.0 MPa and BD 1.5-1.58 Mg m^{-3}	Root growth reduction; no difference in yield (Chan et al., 2006).
Soybean (*Glycine max*)	Heavy textured soil	Axle loads 10 and 20 Mg	Grain yield reduced by 9 and 19%, respectively (Flowers and Lal, 1998).
	Silty clay loam soil, OH	0, 10 and 20-Mg axle load	Mean reduction in yields were 9 and 20%, respectively (Lal, 1996).
	Clay soil, Argentina	Traffic intensity (0, 60, 120 and 180 Mg km ha^{-1}),	Decreases in yield from 9.8–38% than zero traffic (Botta et al., 2004).
Sorghum (*Sorghum bicolor)*	Sandy clay loam, Pakistan	Sub-soil compaction; BD 1.61 and 1.78 Mg m^{-3}	Crop growth and yield decreased. Yield decreased by 14 and 24% in year 1 and 2 (Ishaq et al., 2001a).
Triticale (*Triticco secale*)	Garden soil, Cracow, Poland	BD 1.10, 1.34 and 1.58 Mg m^{-3}	Impact on root growth and physiological characteristic in leaves relatively small (Grzesiak, 2009)
Potato (*Solanum tuberosum*)	Loamy sand, WI	Compaction with 29.8 and 26.2 Mg; PR >2.0 MPa	Limited root growth and crop rooting (Copas et al., 2009)
	Sandy soil, MN; silt loam, ID	PR > 3 MPa; BD 1.57 Mg m^{-3}	Restricted and ceased root growth, respectively (Laboski et al., 1998; Aase et al., 2001)
Tomato (*Solanum lycopersicum*)	Loamy sand and clay loam, UK	BD 1.20 and 1.60 Mg m^{-3}	Affects root architecture, limiting the soil volume explored (Tracy et al., 2012)
Barley (Hordium vulgare)	Loomy soil	-	Root growth and yield decreased (Lipiec et al., 2003)
	Sandy loam soil, Estonia	Axle load 4.84 Mg; 0,1,3 and 6 passes; PR 1.80-1.96 MPa	Reduction in root dry matter by 74% (Trükmann et al., 2008)
	Sandy loam soil, UK	0.12, 0.15 MPa (high) and 0.07 MPa (low)	Decreased in yield of approximately 25% in year 1 (Millington, 2019)
	Clay loam soil, Jordan	5 and 15 Mg axle load; 200 and 400 kPa	Higher pressure and axle load decreased in yield (Abu-Hamdeh and Al-Widyan, 2000).
Radish (Raphanus sativus)	Elsinboro and Galestown series, MD	Axle load 11.88 Mg with 0, 1 and 2 passes; 5.83 Mg with 0 and 1 pass	Reduction in root dry matter by 31% and biomass by 31.25% (Chen and Weil, 2010)

Crops (Scientific name)	Soil types and location	Tyre inflation pressure/ machinery traffic/axle load	Effects on growth and yield of crops
Rapeseed (Brassica napus)	-do-	-do-	Reduction in root dry matter by 50% and biomass by 62.89% (Chen and Weil, 2010)
Rye (Secale cereale)	-do-	-do-	Decreased total biomass by 32.01% (Chen and Weil, 2010)
Canola (Brassica napus)	Sodic brown clay, Australia	Wheel track vs between the wheel tracks; >2.0 MPa; 1.5-1.58 Mg m^{-3}	Reduced root growth; potential yield loss by 34% in wheel tracks (Chan et al., 2006).
Oat (Avena sativa)	Sandy clay soil, UK	-	Reduced oats yields by 25% in year 2 (Millington, 2019)
	Silty clay loam soil, OH	0, 10 and 20-Mg axle load	Reduction in yields was up to 57 and 77%, respectively (Lal, 1996)
Sugar beet (Beta vulgaris)	-do-	-do-	Reduced growth of root by 7-9%; No significant influence on yield (Lal, 1996)

Hence, from the above discussion, it can be concluded that heavy agricultural machinery, number of traffic passes, higher ground pressures, wheelings etc. cause compaction of soil, and change the soil structure. Increasing BD with decreasing aeration in soil due to such different magnitudes of compaction negatively affect root structure, crop growth and yields of crops in different agro-ecological environments. This view is also supported by the many researchers across continents (Hamza, Al-Adawi, & Al-Hinai, 2011; Liebig et al., 1993; Raper & Kirby, 2006; Yuxia et al., 2001).

2.10. Draft Forces and Economic Impact

Compaction of soil can influence the amount of energy used in agriculture (Chamen et al., 1992). The possible need for additional inputs of fertilizer (e.g. N) or pesticides as energy is needed during the manufacturing process, a greater draught forces requirement for cultivation, and a greater tillage requirement to alleviate compaction (Chamen et al., 1992). Denitrification is the indirect effect of compaction which is likely to lead to N deficiency in crops (Batey, 2009), possibly increasing the need for additional fertilizer and N requirements (Chamen et al., 1992; O’Sullivan and Simota, 1995).

Draft forces required for running agricultural machinery vary for various field operations. Energy is used for tillage which can be a significant cost factor for some cropping systems and soils (McPhee et al., 1995). Compaction events and correction of compaction using heavy machinery and field traffic consume more engine power and draft forces compare to avoidance of compaction, which is, in fact, a waste of money and has a negative impact on the environment. Soil strength as a result of compaction increases the draught requirement of the tractor for primary tillage (Chamen et al., 1992). Tillage depth is positively correlated with draft force requirement and thus draft force increases with the increase of subsoiling depth for primary tillage (Wolf et al., 1981).

Compaction due to one-wheel pass for ploughing increased diesel fuel consumption by 19% (Voorhees, 1979). Primary tillage in compacted soil is not sufficient to produce good tilth and therefore, more secondary tillage is required for compacted soil than un-compacted soil (Dickson and Ritchie, 1993), leading to increased fuel use and consequent GHGs emission to the environment. Tractor engine power can be absorbed in the soil of the wheel tracks which is in fact wasted up to 30% due to compaction, and a single pass of tractor wheels can also increase demand of draft forces by up to 25% (McPhee et al., 1995). The demand for energy consumption for tillage increased in the range 25–40% due to the previous tyre passes on soil, that half of tractor engine power could be wasted due to loosening of compacted soil due to preceding machinery passes (Tullberg, 2000).

Large and heavy machinery save operating costs and timeliness of operations but the economic losses due to compaction of using these machinery may be much more than this savings (Hakansson, 2005). A recent economic analysis of alleviating or avoiding soil compaction showed that the net on-farm cost of different mitigation options is negative, however, avoiding soil compaction is more cost-effective than alleviating it, particularly true in the case of subsoil compaction (Hallett et al., 2012).

It was discussed earlier that subsoil compaction is persistence which is associated with many adverse effects including economic losses such as the decrease in crop yield and soil productivity (Hakansson & Reeder, 1994), increased management costs (Chamen et al., 2003). and increased requirement for greater draught forces for cultivation (Chamen et al., 1992).

2.11. Management of Soil compaction

Prevention of soil compaction is far better than correction of compaction problem (McKenzie, 2010), meaning that there will be win-win possibilities of improving farm productivity while simultaneously reducing environmental impacts (Hallett et al., 2012). Benefits of using CTF have also reported (Spoor et al., 2003) as tractor wheelings always remain in the same wheel track for all field operations and thus less area become trafficked. The CTF restricts the tractor wheelings to the wheel track and reduces annual surface trafficked to around 30% and the concept is found to be successful in Australia (Tullberg et al., 2007). However, it requires all field machine widths to be matched for crop production (Chamen, 2011) and navigation and machine guidance systems to be available and reliable (Misiewicz, 2016).

Researchers suggested some technical solutions that can potentially help to minimize the risk of subsoil compaction. Use of dual and tandem wheels instead of single wheels, low tyre inflation pressure or tracks, reducing axle load are compelling among them (Trautner and Arvidsson, 2003; Hamza and Anderson, 2005; Keller and Arvidsson, 2006). Tijink et al. (1995) reported that avoidance of topsoil compaction could be gained with the tyre pressures <50 kPa and 100 kPa during the crop growing season and out of seasons, respectively. Evidence suggests that LTP systems are very effective in controlling subsoil compaction, and in the topsoil (0 – 0.15m depth) and low pressure tyres showed 40% reduction of maximum pressure peaks than higher pressure tyres (Van den Akker, 1998). LTP systems have shown to reduce ground contact stress transmitted during field operations (Trautner and Arvidsson, 2003) and thus help in reducing compaction of soil under wheels (Batey, 2009). Both low pressure tyres and tracks were suitable to minimize soil compaction in a sandy loam soil in the UK (Smith et al., 2014a). The Michelin Tyre Company has developed agricultural tyres based on Ultraflex technology with the aim of reducing soil compaction. They claimed that these tyre can operate at low inflation pressure and carry more load, resulting in a larger footprint and help in reducing compaction of soil whilst improving crop yield (Michelin, 2017).

Management options such as minimizing or eliminating soil tillage, reducing or minimizing wheel traffic load and field traffic areas, avoiding field traffic when soils are wet, and creating a larger footprint on the soil by using radial tyres at LTP, can avoid the risk of soil compaction (McKenzie, 2010). A protective residue cover on the soil surface to reduce soil crusting after rain or irrigation water and use of best agronomic management practices to improve soil OM and soil structure can help to minimize the risks of soil compaction (McKenzie, 2010). Crop rotation can improve soil structure. Deep-rooted species in the crop rotation was shown desirable to minimize the effects of soil compaction (Ishaq et al., 2001). Growing of fibrous (e.g. pea) and tap rooted (e.g. canola) crops in a rotation help the roots to penetrate soils and develop deep root channels and eventually add organic matter to soil (McKenzie, 2010). An investigation was conducted on a Vertisol soil that was cultivated by conventional farming with random traffic over 50 years (McHugh et al., 2003). At the end of three years, results show that no traffic and crop rotation with winter cereal, a legume and lablab were found to be very effective. PR at the same soil moisture contents decreased by between 0.2 and 1.0 MPa in the depth range of 0-400 mm from greater than 2 MPa (McHugh et al., 2003).

Plants roots can be considered potential tillage tools as they exert forces to penetrate soils and grow through compacted soil layers that may change the soil physical conditions (Elkins, 1985). This happens when roots decay in the compacted layers, resulting in macropores that improve water movement, aeration and gaseous diffusion (Elkins, 1985). The role of tap roots (e.g. Canola plants) in “bio-drilling” can create bio-pores through deeply penetrating the soil and ameliorate the subsoil compaction. This may be helped in the succeeding wheat crop roots to penetrate the soil easily (Cresswell and Kirkegaard, 1995). Such role of tap-root plants in the compacted soil also recognized as “biological tillage tools” (Chen and Weil, 2010).

Tillage systems affect the soil physical and chemical environment, and soil structure and reduces macroaggregates and thus reduces the biological activity of soil biota (Dick, 1992; Kladivko, 2001). The review also evidenced that crop rotation can suppress deleterious microorganisms flourishing in soil especially under monoculture which promotes crop productivity.

There are several possible options that have been proposed that can minimize compaction of the soil. These include (Hamza & Anderson, 2005; Raper, 2005):

- Reducing axle load
- Reducing tractive element-soil contact stress and this can be achieved through using radial tyres, duals, and tracks;
- Increasing soil drying before traffic;
- Following conservation tillage systems which minimize vehicle traffic;
- Using CTF systems which eliminate random vehicle traffic across fields; and
- Subsoiling to eliminate compacted soil profiles such as plough pans

Compaction of soil in a practical sense may not be possible to eliminate rather intelligent management of vehicle traffic can help in reducing and/or controlling of it (Raper, 2005). A detail compaction study was conducted on loamy sand and silty clay soils in Germany (Schäfer-Landefeld et al., 2004). Their observations showed the presence of plough pan layer at 0.3m cm depth can effectively protect the subsoil from high wheel loads (up to 12.5 Mg) but when loosened, causes severe compaction, particularly in the subsoil. Approaches to compaction, matching machines for alleviation or avoidance of compaction is a good soil management tool (Larson et al., 1994). Avoidance of compaction (Hatley et al., 2005) particularly subsoil compaction (Spoor et al., 2003), is beneficial and should be a key issue in future crop production systems (Chamen, 2006).

Loosening of soil can help to reduce the effect of compaction. However, careful assessment of the compaction is needed before operations (Spoor et al., 2003). Evidence within agriculture suggests that shallower loosening of soil at a depth of 0.3 to 0.35 m most of the time were successful but can be upsetting when deeper loosening of soil is done (Spoor, 2006).

Soil compaction may be reduced by natural freezing and thawing events that can play a positive role on soil structure evolution (Etana et al., 2013) but the impact is more evident in the subsoil (Etana and Hakansson, 1994; Voorhees, 2000). However, differences in opinions are also found. Gaultney et al. (1982) disagreed with the concept that natural forces of freezing and thawing may be reliable agents to break plough pan and to minimize compaction. In Sweden where annual freezing is a normal phenomenon to depths of 0.4-0.7m showed that crop yields 11 years after deep compaction were still adversely affected (Etana and Hakansson, 1994). A similar study was conducted on a clay soil in Finland which reported that both crop yields and N contents in the crops were reduced 17 years after a single compaction event (Alakukku, 2000).

To summarize, the possible approaches of minimizing and/or avoiding compaction from the above review of literature: a)_reducing stress on the soil following LTP system b) use of lower wheel load, c) reducing tractive element-soil contact stress using radial tyres, d) use of agricultural tracks, e) minimizing vehicle traffic, f) following crop rotation with deep and shallow-rooted crops, g) adapting practices and cropping to avoid moist soil conditions, h) growing of cover crops in the cropping systems and i) confining field traffic compaction to a narrow strip following CTF system.

2.12. Measurement of Soil Compaction

To characterize the degree of compaction, dry BD and total soil porosity parameters are frequently used. The degree of soil compaction can be expressed by pore space, void ratio, dry volume weight and bulk weight volume (Koolen and Kuipers, 1983). Soil BD and PR are often used as two key parameters to determine and describe the levels of soil compaction and used for soil profile examination (Soane et al., 1987; Duiker, 2002; Hatley et al., 2005; Raper, 2005). PR provides cone index values that are determined by dividing the force required to insert the penetrometer into the soil by the cross-sectional area of the base of the cone. A higher cone index value can have a negative effect on root growth. Cone index values over 2 MPa have been shown to restrict, to varying degrees, crop root development (Taylor and Gardner, 1963; Aase et al., 2001).

Other studies suggested that soil compaction reduces the porosity and increases the BD of soils, and also reduces the water infiltration rate as compared to non-compacted soil (Liebig et al., 1993; Yuxia et al., 2001; Hamza and Anderson, 2005; Raper and Kirby, 2006). Thus, soil BD and cone index have been conclusively proven to increase as the magnitude and intensity of vehicle traffic increased (Solgi et al., 2016).

Dry BD is a widely accepted means of explaining soil compaction and total soil porosity can describe the soil condition concerning vehicular traffic and mechanical tillage operations (Campbell, 1994). Researchers suggested that soil compactness needs to be expressed both by an absolute term and relative terms (Soane et al., 1980). Bulk density, specific volume, void ratio or pore volume for examples are the absolute terms which are the universally and independent method of measurement of compaction. The degree of compactness and relative density of soil on the other hands are the relative terms which are expressed its absolute value as a ratio of that in a reference state of them (Soane et al., 1980).

Compaction reduces root penetration and decreases the ability of soil to infiltrate water into the soil profile (Schoonover and Crim, 2015). Hence, bulk density, infiltration capacity, and penetration resistance of soil can be effectively used to explain soil porosity or degree of compaction.

Visual assessments of soils as per the description of soil profiles by soil survey methods, visual assessment of porosity and strength, and examination of the plant root system, semi-quantitative visual and tactile methods etc. can help to explain compaction of soils (Spoor et al., 2003; Hatley et al., 2005; Batey, 2009). A recent study showed that there were seven soil quality indicators (SQIs) that could help in monitoring of soil condition or quality (Rickson et al., 2012). These are soil depth, surface sealing, visual soil evaluation, packing density (e.g. data on bulk density and clay content), aggregate stability, soil water retention characteristics and soil erosion rate. These would also help to measure changes in soil condition due to compaction of agricultural soils.

A soil compaction model was developed to assess compaction that uses soil cone resistance, dry BD, wheel shrinkage and rut cross-sectional area as measures of the compactive effort of a vehicle (Smith, 1987). The model can predict the changes in dry BD with depths because of vehicle passage and assess the relative contributions of soil and wheel variables to the compaction process. A conceptual model was also developed for predicting soil BD that is considered as a function of soil mineral packing structures and soil structure (Tranter et al., 2007). This model suggests that BD increased with the depth of soil and were influenced by over-burden pressure. A soil compaction profile sensor was developed by Sharifi et al. (2007)

that was consisted of a series of eight instrumented flaps that linking its output to global positioning systems. The sensor can also able to determine the changes in soil strength by different surface-applied loads and tyre inflation pressures (Sharifi et al., 2007).

Besides, some filed criteria specified by researchers can be used to identify compaction including waterlogging, increase in soil strength, reduction in visible porosity, changes to soil structure, soil colour and particularly the distribution of plant roots and soil moisture (Spoor et al., 2003; Batey and McKenzie, 2006).

X-ray computed tomography (X-ray CT) has been used as a potential tool to quantify soil structure, BD and water content (Taina et al., 2008). Moreover, as a non-invasive method, it can also help in analysing soil pore size, porosity and pore size distribution, orientation, and improving overall understanding of soil hydrodynamic behaviour (Rab et al., 2014; Beckers et al., 2014). In the present study, classical soil physical measurements such as BD, PR, the porosity of soil and soil moisture content were recorded to monitor and measure the compaction of the soil. Further, X-ray CT tool which is for the first time used to measure the soil compaction by quantifying soil pore characteristics under different tyre inflation pressures along with three tillage systems for a typical maize/soybean rotation in silty clay loam soil in the US Midwest.

2.13. Harper Adams University Long Term Traffic and Tillage Trial

Harper Adams University, UK has established a long-term experiment in 2012 with an aim to determine the long-term effect of traffic and tillage systems on a sandy loam soil on crop growth and yield and the corresponding effect on soil physical properties. Also, to measure the effect of different traffic management and tillage systems on soil structure using the Novel technique of X-ray Computed Tomography. Treatments are three traffic systems (Random Traffic Farming with standard tyre inflation pressure, Random Traffic Farming with low tyre inflation pressure and Controlled Traffic Farming for soils cultivated) with three tillage systems (deep, 250 mm; shallow, 100 mm and zero, no-till). A randomized 3 x 3 (traffic x tillage) factorial study with four replicated blocks was established at the Large Marsh farm of the University in September 2012. Before setting up the experiment, a mouldboard plough/power harrow at a depth of 250 mm treatment was applied uniformly to all plots of the whole field. Thus, the first year such activates is recognized as a normalisation year. However, these field operations were done to allow the field site to stabilise after the installation of a gravel back-filled drainage system at 13 m spacing followed by subsoiling operations to a depth of 0.6m, to remove traffic and tillage related any residual deep compaction from the field (Smith et al., 2014b).

The first trial crop was winter wheat (*Triticum aestivum* var. Duxford) with the three tillage x three traffic treatments, planted in November 2012. The date on plant establishment (plants m^{-2}) based on growth stages mark at GS11/12 was recorded using a quadrant method. Photographic crop assessment at GS37/39 and immediately prior to harvest were also observed. Analysis of data showed that traffic and tillage treatments had no significant effect on plant establishment of wheat. The visual assessment showed that plant establishment of wheat was poor or limited in primary wheel ways and non-uniformity in the no-till plots. The harvested data showed that the interaction of tillage and traffic treatments at 5% probability level did not show any significant effect on the grain yield of wheat. This indicating that the experimental field was uniform that led into a good uniformity in wheat yield with a coefficient of variation of 6% (Godwin et al., 2015). The CTF traffic treatment had the highest mean yields (7.7 Mg ha^{-1}). Among the combinations, CTF with shallow tillage treatment was found to have the highest grain yield of 8.39 Mg ha^{-1} of wheat in 2013 which was 14% higher than the mean of the other treatments (7.47 Mg ha^{-1}). The yield was significantly higher at 10% level of probability by 15% (1.1 Mg ha^{-1}) to standard tyre inflation pressure (STP) with deep tillage mean yield. STP with zero tillage combination had the lowest mean yield of 6.87 Mg ha^{-1} (Smith et al., 2014b; Godwin et al., 2015). Thus, the overall findings suggest that CTF farming provide higher grain yield of winter wheat with less area trafficked, indicating that wheelings were confined in the specific wheel tracks and one of the management practices of compaction 'avoidance' was accomplished. Further, soil compaction produced by RTF farming and not subject to remedial tillage can reduce yields of winter wheat.

Continuation of the experiment with the same treatments' factors was examined on other cereal crops such as winter barley, spring oat and spring wheat from 2015 to 2018. Effect of traffic and tillage systems on growth and yield of these crops and the corresponding effect on soil physical properties using the innovative technique of X-ray Computed Tomography were also studied (Millington et al., 2016; Godwin et al., 2017). Overall crop yields result suggest that reducing tyre inflation pressure tyres gave a yield improvement of 2.90% compared to standard inflation pressure tyres. Adopting CTF combined with a reduced tillage depth (100 mm), resulted in increased yields by 6.3% over a five year period (Millington, 2019). However, deep and shallow tillage did not show any significant difference in crop yield. The deep tillage significantly ($P = 0.030$) reduced the soil shear strength, leaving soils prone to compaction by subsequent field traffic. Interestingly, shallow tillage had lower fuel costs than deep tillage which provides an opportunity to saves fuel by reducing the draft force required for the tillage operations (Millington, 2019). Significantly reduced crop yield was observed in Zero tillage treatment ($p<0.001$) which was lower by 15% than shallow tillage. Study of soil cores using a novel technique for determining the total porosity allowed a comparison of soil porosities derived from bulk density measurements and X-ray CT measured porosities. Results found that a constant of 31% could be added to the X-ray CT porosities to give the total physical soil porosity of sandy loam soil in the UK (Millington, 2019). Research is also underway in Zambia to tackle the recent problem of soil compaction and results showed that compaction of soil leading to poor crop growth and compounding food availability problems in Sub-Saharan Africa (Bwembya et al., 2017).

2.14. X-ray Computed Tomography

X-ray computed tomography (X-ray CT) is a non-invasive imaging technique that is extensively used in the medical field. However, it has been shown to be a powerful tool to investigate possible modifications in soil structure and other physical properties of soil (Pires et al., 2005). The first applicability of X-ray CT in Soil Science was in early 80's (Petrovic et al., 1982; Hainsworth and Aylmore, 1983; Crestana et al., 1985; Vaz et al., 2011). They proved that X-ray CT can be effectively used to measure the spatial distribution (2D and 3D) of BD and water content in soil (Taina et al., 2008).

Studies show that as a non-destructive 3D imaging technique, X-ray CT can effectively be used to quantify soil pore size and pore size distribution (Rab et al., 2014). The technique greatly helps in studies of pore geometry, pore shape, orientation and connectivity, pore size distribution, and improving overall understanding of soil hydrodynamic behaviour (Beckers et al., 2014). Evidence from a field-scale study in Missouri, USA showed that X-ray CT can help to quantify the effect of different management in soil relative to environmental benefits, water storage and transport (Udawatta and Anderson, 2008). The results suggested that there is a close relationship between CT measured pore parameters and saturated hydraulic conductivity (Udawatta and Anderson, 2008). Investigation of the effect of compaction using medical GE Genesis-Zeus X-ray CT scanner on a silt loam soil in Missouri, USA was also conducted (Kim et al., 2010). They found that CT measured porosity in compacted soils was reduced significantly by 64 % as compared to the un-compacted soil while the number of pores was decreased by 71% with an increase of 8% BD of soils. Katuwal et al. (2015). reported that quantification of pore characteristics such as pore size distribution and connectivity were key variables helped to understand air-flow and transport behaviour of soils and there was stronger preferential flow in samples with low macroporosity when pores were less dense and interconnected (Katuwal et al., 2015).

Soil compaction reduces larger pores and thus affects soil porosity for a given mass (Berisso et al., 2012) by increasing BD and reducing the proportion of large to small pores in soil (Kim et al., 2010). It is evident that these large volumes of small pores are more susceptible to waterlogging and eventual anaerobic conditions that lead to denitrification and reduction in root growth (Czyż, 2004). Dal Ferro et al. (2014) observed that tillage systems (conventional tillage and a no-till system) significantly influenced the macroporosity of soil measured by X-ray CT while microporosity measured by mercury intrusion porosimetry, had no significant effect between the treatments. Conventional tillage disrupts macropore structure, resulting in a greater number of smaller pores (100-250 μm) than no-till soil (Dal Ferro et al., 2014). A typical X-ray CT tomography setup of both fan-beam and cone-beam configurations are given in Fig. 2.11.

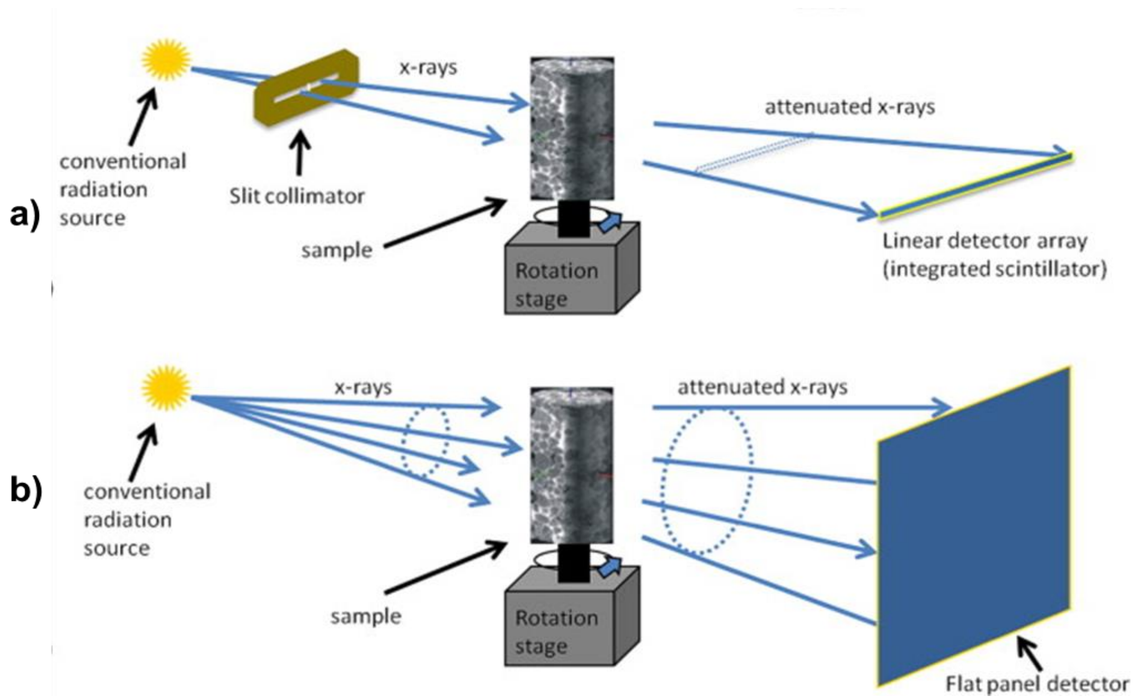


Figure. 2.11. Typical tomography setup of fan-beam (a) and cone-beam configurations (b) a microCT system. After Wildenschild and Sheppard (2013).

X-ray CT provides 2D cross-sectional images to compose stacks of 3D representation of the internal structure of natural porous materials (e.g. soils) through the uses of mathematical reconstructions from attenuation of ionizing electromagnetic radiation (Vaz et al., 2011). Using CT-segmented data of Brazilian Oxisols soils they successfully determined soil porosities and pore-size distributions (Vaz et al., 2011). However, the whole X-ray CT process involves a sample such as soil core being rotated incrementally through 360° in X-ray beams, producing a series of radiograms which are then algorithmically reconstructed to produce 2D images (slices) and then stack images of producing 3D attenuation map of soil (Beckers et al., 2014). Based on the X-ray resolution, each image is made up of 3D pixels which are called voxels (Calistru and Jităreanu, 2015). Appropriate resolution of CT scanning is an important factor to get desired 2D and 3D stacked images. CT-derived porosities may underestimate physically measured porosity values if the resolution is high and 1.0 μm is considered to be the maximum resolution for soil samples (Vaz et al., 2011).

CT-segmentation can differentiate two or more different elements (Taina et al., 2008) and thus to quantify pore space the reconstructed images are segmented using a threshold tool on an 8-bit greyscale image (Taud et al., 2005). A simple histogram of the greyscale values of the image explains three main phases of pore space, organic material and mineral grains (Lamandé et al., 2013). The threshold tool is applied to separate the pore spaces from the mixture of other phases of soil (Helliwell et al., 2013). Finally quantified values less than the threshold are air-filled pore space and values above on that are others (Kim et al., 2010). Quantification of soil pore networks is easily done as the X-ray attenuation of soil solids and soil pores have a large contrast between them (Taina et al., 2008). Manual thresholding of images is not performed well as user bias may affect the thresholding results (Baveye et al., 2010), hence assistance of CT experts may be warranted.

X-ray CT imaging is a powerful tool that helps to understand the nature and spatial configuration of soil components, and their relationship with soil behaviour and processes (Taina et al., 2008). Mooney et al. (2012) demonstrated the impressive progress and enormous potentiality of X-ray CT as a tool to observe and quantify in situ root-soil interactions. They also cited findings of various studies of the application of X-ray CT as a powerful means of exploring the structure and function of roots and soils e.g. (Heeraman et al., 1997; Gregory et al., 2003), characterisation of pore space and BD, spatial correlation of tortuosity and porosity (Heijs et al., 1995). Research on soil-water and soil-root interactions have been found, however, many of them concentrated mainly on the development of the technique for soil analysis and problems associated with segmenting images. Recent studies in sandy loam soil in the UK evidenced that low tyre pressure systems had a measurable CT derived porosity comparable to high tyre inflation pressure systems (Millington, 2019). However, apart from this and to the present knowledge, there are no data on the relationship between the X-ray CT derived porosities and soil physical porosities. Besides, field-scale studies of the soil pore structure using X-ray CT as a potential tool of studying the effect of high flexion tyre and tillage induced compaction are unavailable on a silty clay loam soil in the Midwestern United States.

2.15. Literature Review Conclusion

The main aspects of this review of literature were to explore the impact of farm machinery with different traffic systems on soil compaction and degradation, factors under different tillage systems and their further effect on soil properties and growth and yield of crops. Global food demands are projected to double in the 21st century, which further increases the pressure on the use of land, water, and nutrients. To increase food productivity and hence economic returns, significant improvement of the cropping system is essential (Nazrul et al., 2013; Shaheb et al., 2014). Sustainable, safe and nutritious food productions are the major challenges for global food security to meet dietary needs and food preferences for an active and healthy life (Shaheb et al., 2016). Soil supports agriculture and is a critical part of sustainable agriculture as it provides water and nutrients to plants.

Degradation of soil means the declining the capacity of the soil and its ecosystems. Improper use or poor management of soil in agricultural, industrial, or urban purposes leads to declining soil fertility, loss of SOM, changes in soil structure, increased erosion, and many other adverse changes. Intensive mechanization in agriculture is one of the components of the Green Revolution that helped agricultural production be successful. Development of larger and heavier machinery was inevitable in industrial agriculture as it increases the timeliness of operations, saves operating costs, reduces labour costs, and covers substantial areas under cultivation within short periods. The intensification of agriculture and the use of these heavy machinery have had significant negative effects on soil structure and quality. Soil compaction is caused by the use of heavy machinery and high axle load, high tyre inflation pressure, multiple traffic passes and conventional tillage systems damages and alters soil structure, and reduces soil quality (Hamza and Anderson, 2005).

Research efforts to address soil compaction and possible approaches either through avoidance or reduction are crucial. Research on CTF, track agricultural vehicles, LTP systems, cover crops, reduced tillage practices, ecosystem services and sub-soiling are needed in diverse ecosystems. While the use of reduced tyre inflation pressures has been recommended for several decades, quantification of these benefits for high flexion tyres by linking the resulting soil conditions to crop yield and the economic benefit is not available. Moreover, research works on the magnitude the soil compaction and the consequences of the use of heavy machinery on soil condition and growth and yield of the two main crops maize and soybean grown in the Midwest farming system in Illinois are scarce. Furthermore, a farming system based economic analysis of the use of the low pressure tyres technology that can help in preserving soil and provide economic benefit to the farmers whether or not are unavailable. The present study is a part of this research where efforts are made to address the key issues related to soil compaction, and to quantify, the effect of high flexion tyres run at standard and low tyre inflation pressures systems under various typical tillage practices on soil properties, crop development and yield in a maize-soybean rotation in Central Illinois. Moreover, X-ray CT technique was used to determine the effect of compaction on soil pore characteristics throughout the soil profile. An economic analysis of the farming systems has also been conducted. As it is essentially important that potential solutions must be farmer oriented, easily adaptable, and economically profitable.

CHAPTER 3: GENERAL METHODOLOGY

3.1. Introduction

This chapter focuses on the materials and general methodology of the study. It provides a concise description includes sites the study sites, traffic and tillage system treatments and experimental design, and laying out of blocks and plots, farm equipment and agricultural tyres. Detail approaches of field operations to apply treatments, soil sampling, and data recording of soil and crops and their statistical analysis have been discussed. Procedures of soil X-ray CT study are also described. However, chapter wise brief methodologies for the experiments carried out from 2016 to 2018 are also described in the appropriate chapters (i.e. Chapters 4, 5 and 6).

3.2. Details of the Study Area

The experiment was established at the Agricultural Engineering farm of the Department of Agricultural and Biological Engineering, the University of Illinois at Urbana-Champaign (UIUC), Champaign County, Illinois, the United States (latitude/longitude: 40.070965, -88.217538) from November 2015 – October 2018. Two adjacent fields (North and South) each of 3.24 ha were selected for the study. The farm is a representative site for a typical maize/soybean rotation in a Midwest farming system in the United States where both fields being in use with alternative rotations of these two crops (Fig. 3.1)

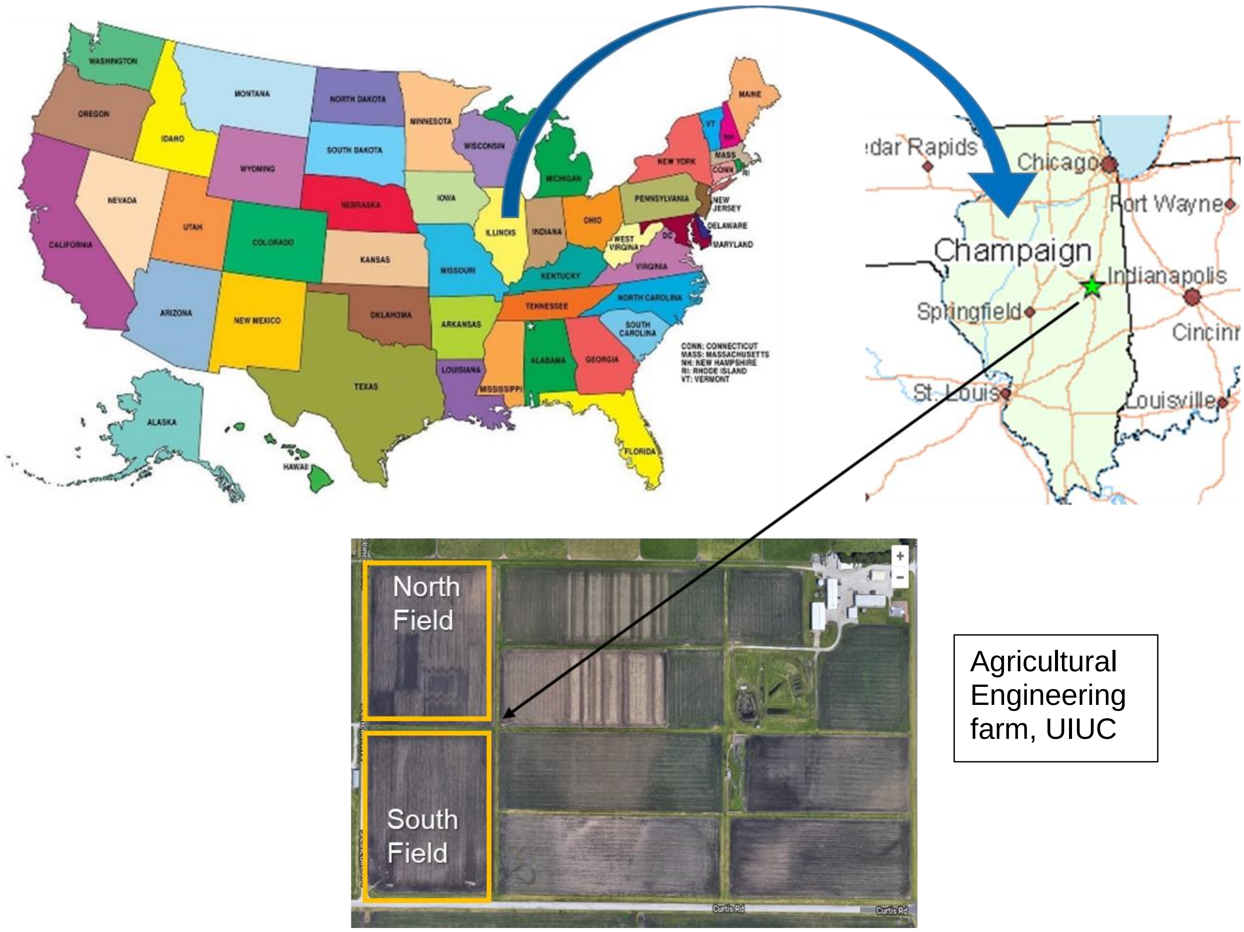


Figure 3.1. Location of the study in Champaign County, Illinois, United States (Source: Google search for US maps/Google maps)

3.3. Soil and Climate

The soil of the experimental site consists of two soil series. Drummer soil (152A) series characterised as a silty clay loam (59% silt, 33% clay silt and 7% sand) is the prime soil series with small areas of the field mainly in Northern field that are Thorp (206A) silt loam series (USDA NRCS, 2015a). The Drummer series consists of soils that formed in 1m to 1.5m of loess or other silty material and in the underlying stratified, loamy glacial drift. Drummer silty clay loam soil is one of the major extensive and productive soils and is designated as the official state soil of Illinois. It occurs on more than 0.6 million hectares in the state in which maize and soybean are the principal crops (USDA NRCS, 2019b). Both soil series have 0 to 2% slope and are poorly drained. The capacity of the most limiting layer to transmit water (Kstat) is moderately high to high (15-50 mm/hr) in the Drummer soil while in the Thorp series it is ranked moderately low to moderately high (1.5-5 mm/hr). The surface layers are a thick, black silty clay loam and subsurface layers are a very dark grey silty clay loam while the subsoil is reddish-brown and a grey silty clay loam are main characteristics of the soil (USDA NRCS, 2015a). According to the Illinois State Water Survey (ISWS), the average annual precipitation ranges from 838 to 1092 mm and the average annual air temperature ranges from 7.78 to 12.2°C (ISWS, 2016).

3.4. Details of Materials and Experimental Design

The experiment was laid out in a split-plot, factorial randomized complete block design, with five blocks where the tyre inflation pressure (TIP) and tillage systems (TS) were the main plots and the 8 crop rows (crop rows 1-8) and a central non-trafficked inter-row of 4 and 5 were allotted in the sub-plots in the year 2017 and 2018. In October 2015 prior to year 1 (2016), both experimental fields were deeply tilled (450 mm) using a disc ripper with deep tines to remove any residual compaction. Thus, each block with three replications where tyre inflation pressure was the main plot and crop rows (crop row 1 to 4) as specified by traffic intensity (number of vehicles passes) were the sub-plots. The treatments in the year 2016 comprised two tyre inflation pressures for the main equipment involved i.e. standard tyre inflation pressure (STP) (tillage tractor: front/rear @ 0.121/0.14 MPa; planter tractor: front/rear @ 0.12/0.12 MPa and combine harvester: front/rear @ 0.20/0.16 and low tyre inflation pressure (LTP) (both tillage and planter: front/rear@ 0.06/0.06 MPa and combine harvester: front/rear @ 0.15/0.16 MPa), and four crop rows (crop row 1- 4, as both sides of the central line of the plot are symmetrical) which were different traffic intensity levels as a result of vehicle passes on the plots.

In 2017 and 2018, revised tyre inflation pressures as per vehicles weight verified and recommended by the manufacturer (Michelin) were recommended. The treatments comprised two tyre inflation pressures i.e. the standard tyre inflation pressure (tillage tractor, planter tractor and combine harvester @ 0.14, 0.12 and 0.21 MPa, respectively) and low tyre inflation pressure (tillage tractor, planter tractor and combine harvester @ 0.07, 0.05 and 0.14 MPa, respectively) and three tillage systems viz. deep tillage (DT) (450mm), shallow tillage (ST) (100mm) and no-till (NT). The 2 × 3 factorial tyre inflation pressure and tillage system treatments arrangement is shown in Table 3.1. Typical tillage practices of Illinois used in the present study is given in Appendix 3.1.

Table 3.1. Tyre inflation pressure and tillage systems treatments arrangement in 2017 and 2018

Tyre inflation pressure (2)	Tillage system (3)
Standard tyre Inflation pressure (STP)	Deep tillage (DT): 450mm Shallow tillage (ST): 100mm No-till (NT)
Low tyre inflation pressure (LTP)	Deep tillage (DT): 450mm Shallow tillage (ST): 100mm No-till (NT)

3.5. Block and Plot Layout

Google Earth Pro and MATLAB 2014b software were used to determine the geographic locations (coordinates) of the centre lines (AB lines) of each plot and subsequently, a Trimble RTK-GPS rover was used to identify these points in the fields (Appendix 3.2). Different coloured flags for each treatment were then positioned to mark the 30 plots. Individual plots were 6 m wide by 180 m long with a headland of 10m, to avoid any edge effects. Hence, the unit plot area was 160m x 6m = 960m^2 with 8 crop rows per plot for both maize and soybean. The plots were orientated in an East-West direction. The layout of the experimental design in 2016 and the years 2017 & 2018 are given in Figs. 3.2a - b.

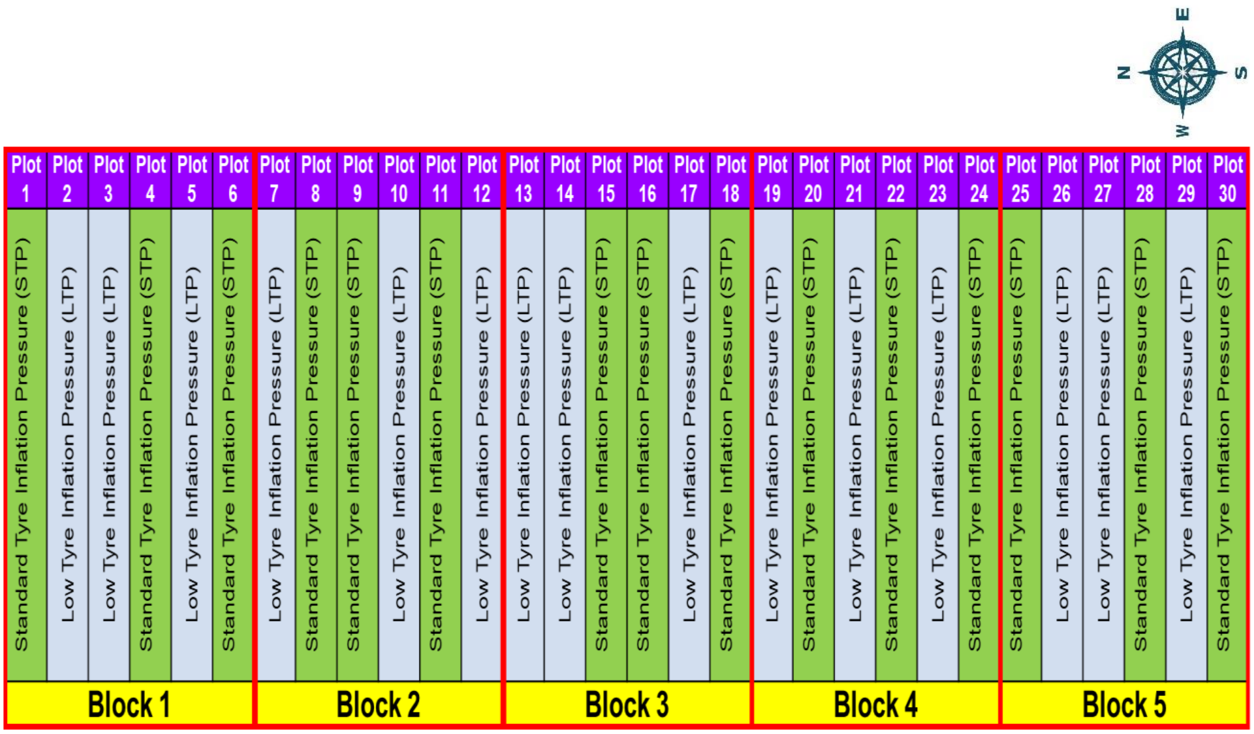


Figure 3.2a. A typical layout of the experiment in 2016.

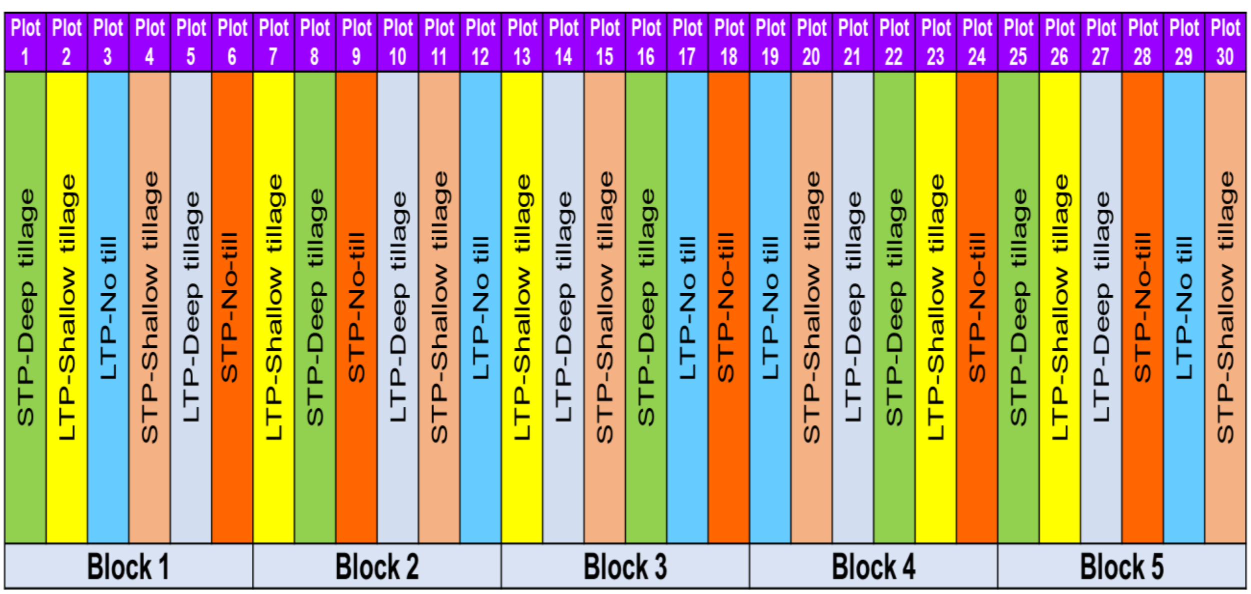


Figure 3.2b. A typical layout of the experiment in 2017 and 2018

3.6. Farm Equipment

The equipment available at The Agricultural Engineering farm, UIUC: consisted of tractors for tillage and planting operations (Model JD 7930 and JD 7700 respectively), a combine harvester (Model JD 9410), spring tillage tools (Model Sunflower/AGCO 6221-20"), a disc ripper with deep tines (Model Case/IH ET 527B) and 8 row planter (0.75m distance between rows) (JD 7200 Max Emerge 2). A self-propelled sprayer (model JD 4930) was used for pre and post-emergence spraying of chemicals. The equipment and tools along with their manufacturer and specifications are shown in Table 3.2, Figs. 3.3 -3.4 and Appendix 3.3.

Table 3.2. Specifications of farm equipment

Equipment	Manufacturer	Model	Power (kW)	Inner/outer wheel spacing (m)		Axle load (Mg)	
				Front	Rear*	Front	Rear
Tillage tractor	John Deere	7930	164	1.47/2.18	1.36/2.29	3.81	6.49
Planting tractor	John Deere	7700	94	1.30/2.03	1.12/2.11	3.12	5.51
Combine	John Deere	9410	306	2.58/4.13	2.58/3.39	18.14	-
Spring tillage Tool	Sunflower /AGCO	6221-20	-	-	-	-	-
Disc Ripper (Autumn tillage tool)	Case/IH	ET527 B	-	-	-	-	-
Planter	John Deere	7200 Max Emerge 2					
Self-propelled sprayer	John Deere	4930		Boom width 36.5m			

*For dual wheels used in 2016, the inner and outer wheel spacings were 2.69 and 3.58 m, respectively.

a)

b)

c)

Figure 3.3. Farm equipment, a) tillage tractor (JD 7930), b) planter tractor (JD 7700) and c) combine harvester (JD 9410)

Figure 3.4a. Deep tillage operations during fall after harvest of crops (Disc ripper model: CASE/IH ET 527B). Tines used are shown top corner of the picture.

Figure 3.4b. Shallow tillage operations during autumn in April (Tillage tool model: Sunflower/AGCO 6221-20)

Figure 3.4c. Seed planting in mid-May (Planter model: JD 7200 Max Emerge 2)

Figure 3.4d. Self-propelled sprayer (model: JD 4930)

3.7. Agricultural Tyres Used

Manufacture Française Des Pneumatiques Michelin supplied a range of Ultraflex tyres to fit on the equipment for the experiment and specified the appropriate STP and LTP pressures based on the load of the equipment. The specification of both front and rear tyres and their recommended inflation pressures used in the experiment are given in Table 3.3. Different manufacturer tyres comparable with Michelin Ultraflex radial tyres are also presented in Table 3.4. Tyres were fitted on the tractors and combine harvester before conducting the experiment in mid - April 2016.

Table 3.3. Ultraflex radial tyres and recommended tyre inflation pressures

Equipment	Model	Front tyres	Rear tyres	Pressure mode	Tyre inflation pressure (Front and Rear, MPa)			
					2016		2017 - 2018	
Tillage	JD	Yieldbib VF	Yieldbib VF	STP	0.12	0.14	0.14	0.14
tractor	7930	380/85R34	480/80R46	LTP	0.06	0.06	0.07	0.07
Planting	JD	Yieldbib VF	Yieldbib VF	STP	0.12	0.12	0.12	0.12
tractor	7700	380/85R34	480/80R46	LTP	0.06	0.06	0.05	0.05
Combine	JD	Cerexbib	Cerexbib	STP	0.20	0.16	0.21	0.21
Harvester	9410	800/65/R32	14.9R24	LTP	0.15	0.16	0.14	0.14

Source: Michelin (2017)
Note: STP and LTP represent the standard and low tyre inflation pressure, respectively.

Table 3.4. Different manufacturer tyres comparable with Ultraflex radial tyres

Equipment	Front/Rear	Tyres of Different Manufacturer		
		Michelin tyre	Firestone	Titan/Goodyear
Standard Tyre				
Tractor	Front	Yieldbib VF 380/85R34	Radial All Traction 380/85R34	Dyna Torque Radial 380/85R34
	Rear	Yieldbib VF 480/80R46	Radial All Traction 480/80R46	Dyna Torque Radial 480/80R46
Combine	Front	Cerexbib 800/65R32	Radial All Traction DT 800/65R32	Dyna Torque Radial 800/65R32
	Rear	Cerexbib 14.9R24	All Traction 2 14.9R24	Hi-traction Lug Radial 14.9R24
Improved Tyre				
Tractor	Front	Yieldbib VF380/85R34	Performer EVO 380/85R34	Optitrac TL 380/85R34
	Rear	Yieldbib VF480/80R46	Performer EVO 480/80R46	Optitrac TL 480/80R46
Combine	Front	Cerexbib 800/65R32	Radial All Traction DT 800/65R32	no offering
	Rear	Cerexbib 14.9R24	All Traction 2 14.9R24	no offering

Source: T. Lecher, Personal communication, 24 October 2019.

3.8. Crops and Varieties

The main crops in the Midwest farming system are soybeans (*Glycine max* L.) and maize (*Zea mays* L.). Maize is a C4 plant and in respect of day length, it is considered to be either a day-neutral or a short-day plant. Maize is grown across temperate to tropic climates and the daily favourable temperatures are above 15°C. The most susceptible phenological phases to temperature are emergence, anthesis, and grain filling of maize (García-Lara and Serna-Saldivar, 2019). Soybeans are originally cultivated in East Asia and presently, have been adapted to diverse environments around the world. Soybean is a C3 plant and responds to the length of days and begins to flower as nights become longer. The number of plants per hectare, pods per plant, seeds per pod and grain weight are the determining factors of soybean yield. Illinois State is recognized as a leading producer of soybean (ranked 1st) and maize (2nd) in the USA (Illinois Department of Agriculture, 2019). Thus, these two crops were selected to implement for the present experiment. The varieties of maize and soybean were P1221AMXT (Pioneer seed) and P35T58R, respectively. Seed rate of maize and soybean were approximately 86076 seeds/ha and 307406 seeds/ha, respectively. Maize and soybean were grown in rotation (maize-soybean-maize in North field and soybean-maize-soybean in South field) for the three years.

3.9. Field Traffic and Tillage Operations and Crop Production Technology

Deep tillage operation as autumn tillage is the typical tillage system in Illinois during autumn after harvest of maize and soybean and thus both fields were deeply tilled (450 mm) using ripper tines in October 2015. Before cultivation, tyre inflation pressures were adjusted and checked for the respective compaction treatment as per the recommendation of Michelin. The tillage tractor attached with spring tillage tool, fitted with the Ultraflex tyre as per tyre inflation pressure (Table 3.3) was then cultivated by shallow tillage (100 mm) on April 2016 in an East-West direction, following an AB/Centre line of each plot. In May 2016, the field was then levelled using the same tillage tractor with recommended tyre pressures for STP and LTP plots. In 2016, as both fields had been deeply tilled, tillage was not a factor and therefore the only factor was tyre inflation pressure so,15 STP and 15 LTP plots of the North field were allotted for maize production and another 15 STP and 15 LTP plots of South field were cultivated for soybean production (Fig. 3.5). But in 2017 and 2018, besides the two tyre inflation pressures, three tillage systems were included (Figs. 3.6 - 3.8). Thus, deep tillage was undertaken on the deep tillage plots only of both north and south fields by Michelin Ultraflex tyres fitted to the tillage/compaction tractor (JD 7930) in Autumn 2016 and 2017. All deep and shallow tillage plots of both fields were then cultivated by shallow tillage (100 mm) using the same tillage tractor with revised recommended tyre pressures for STP and LTP plots following an AB line/centre line in April 2017 and 2018. To study the compaction effect closely on each row and to simulate grain cart chase-bin, extra compaction was applied in the 2nd week of May 2017 and 2018 using the planting tractor running on crop rows 1 and 3 to all plots as per STP and LTP modes, respectively. For pre-emergence spraying, a self-propelled sprayer (Model JD 4930) with boom widths of 36.6m was used to spray 32% urea ammonium nitrate (UAN) @ 563 L ha^{-1} fertilizer with herbicide Harness extra @ 5.27 L ha^{-1} in the maize field and Authority Assist 250 GL @ 0.42 kg ha^{-1} in the soybean field perpendicular (North-South) to the direction of the plots in May 2017 and 2018. The tillage tractor was then used to mix chemicals in soils and level the cultivated plots as per recommended tyre pressures for STP and LTP plots. Maize and soybean were planted in mid-May maintaining the row-to-row spacing of both crops 0.75 m following the recommended STP and LTP pressures. All field operations were conducted using a Real-Time Kinematic (RTK) tractor guidance system combined with autosteer technology. The post-emergence spray was applied at 30 days after planting (DAP) with the herbicides Calisto 4SC @ 0.14 kg ha^{-1} and Round-up @ 2.24 kg ha^{-1} in the maize and Cobra @ 0.70 kg ha^{-1}, Select Max @ 0.42 kg ha^{-1} and Warrant @ 0.21 kg ha^{-1} in the soybean field were sprayed perpendicular (North-South) to the direction of the plots so that all plots receive an equal amount of sprayer wheel traffic. No major disease or insect incidences were observed. All necessary data related to soil and crops were recorded over time. Hand sampling of both crops was conducted before plot-wise harvest. Finally, maize and soybean were harvested in October at 135-160 DAP using a JD 9410 combine harvester, which was run as per the specified STP and LTP pressures treatments. Details timescale and sequence of field operations, and crop and soil data recording during 2016 - 2018 were given in Appendices 3.4a – 3.4c. Further, a summary of the width of area trafficked and un-trafficked (%) in DT, ST and NT plots and the number of vehicles passes/wheel traffic of each crop row was calculated using AutoCAD (Table 3.5 and Appendices 3.5 – 3.7). Trafficked and un-trafficked crop rows/zones were identified by the number of vehicles trafficked/passes they received. Based on the tyre and vehicle configuration, the number of vehicle pass in each row of each tillage system was calculated by adding the tyre pass/wheel traffic on the crop row, the edge of the tyre at the centre line of crop row and the edge of tyre 60 mm from the centre line of crop row.

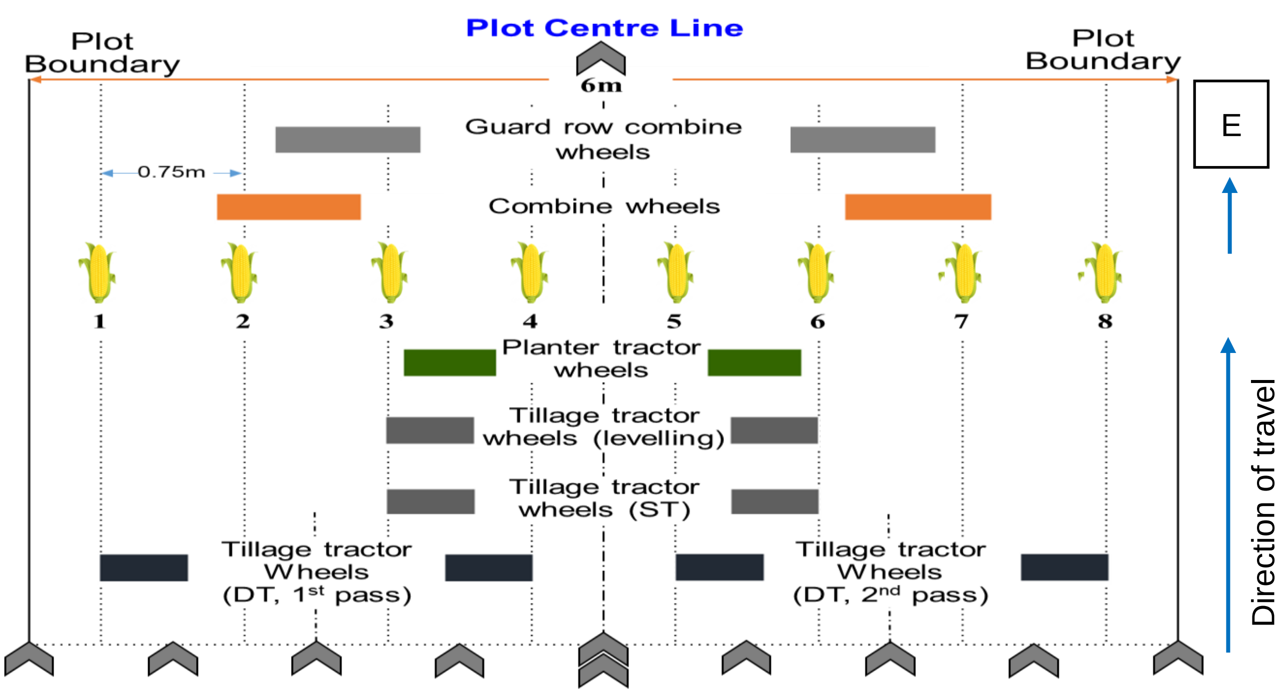


Figure 3.5. A typical plot layout in 2016, indicating deep tillage operations to all plots in Fall, 2015 followed by shallow tillage in spring, levelling the plots and planting of crops.

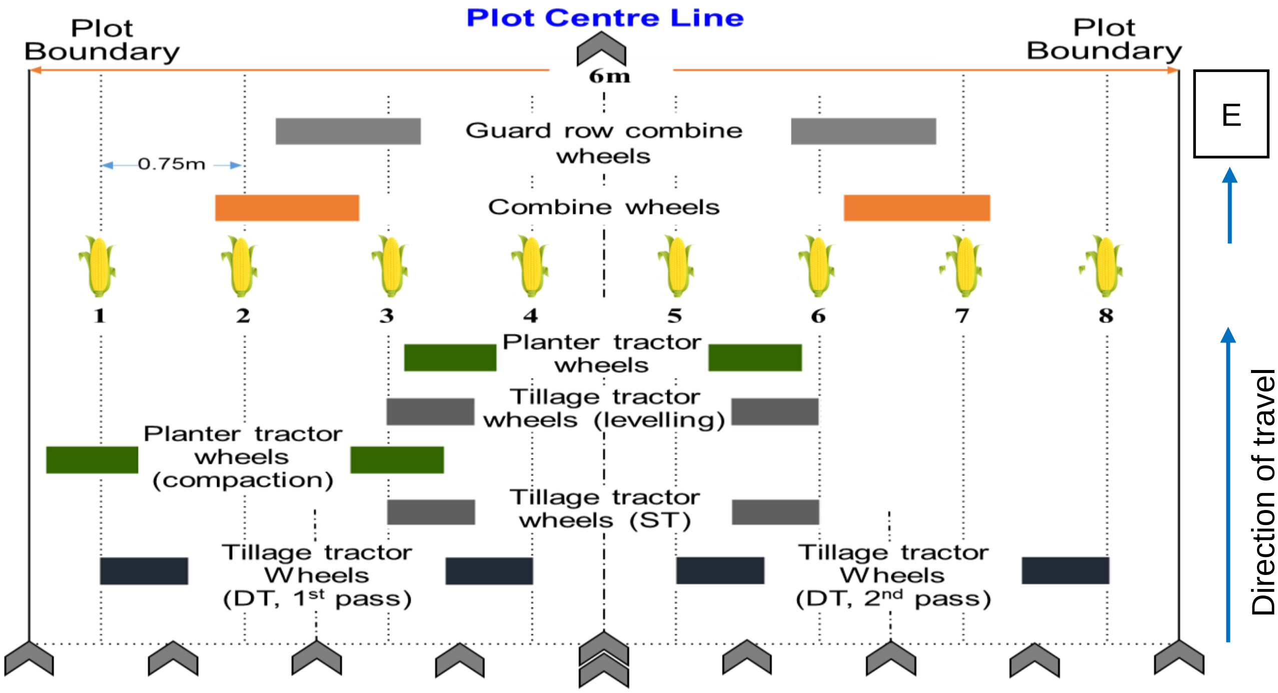


Figure 3.6. A typical deep tillage plot layout in 2017 and 2018, where 1 to 8 indicate crop rows (CR1 to CR8) showing tractors and combine harvester wheels positions.

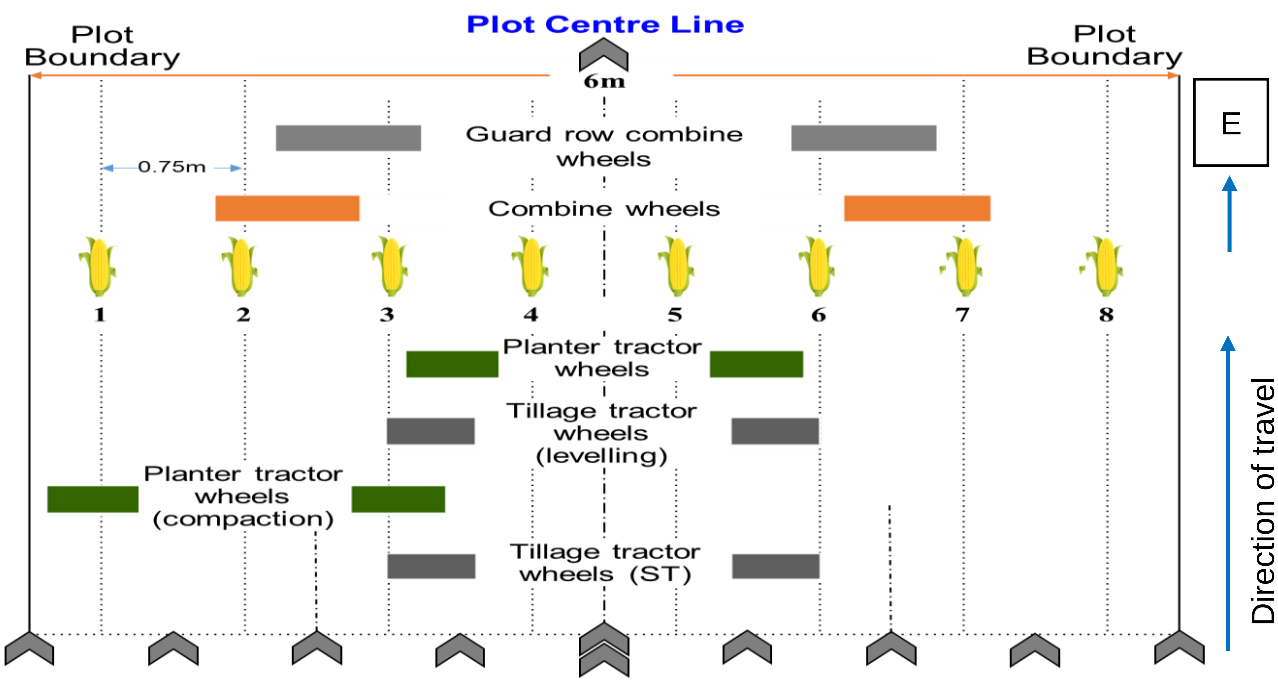


Figure 3.7. A typical shallow tillage plot layout in 2017 and 2018, where 1 to 8 indicate crop rows (CR1 to CR8) showing tractor and combine harvester wheel positions.

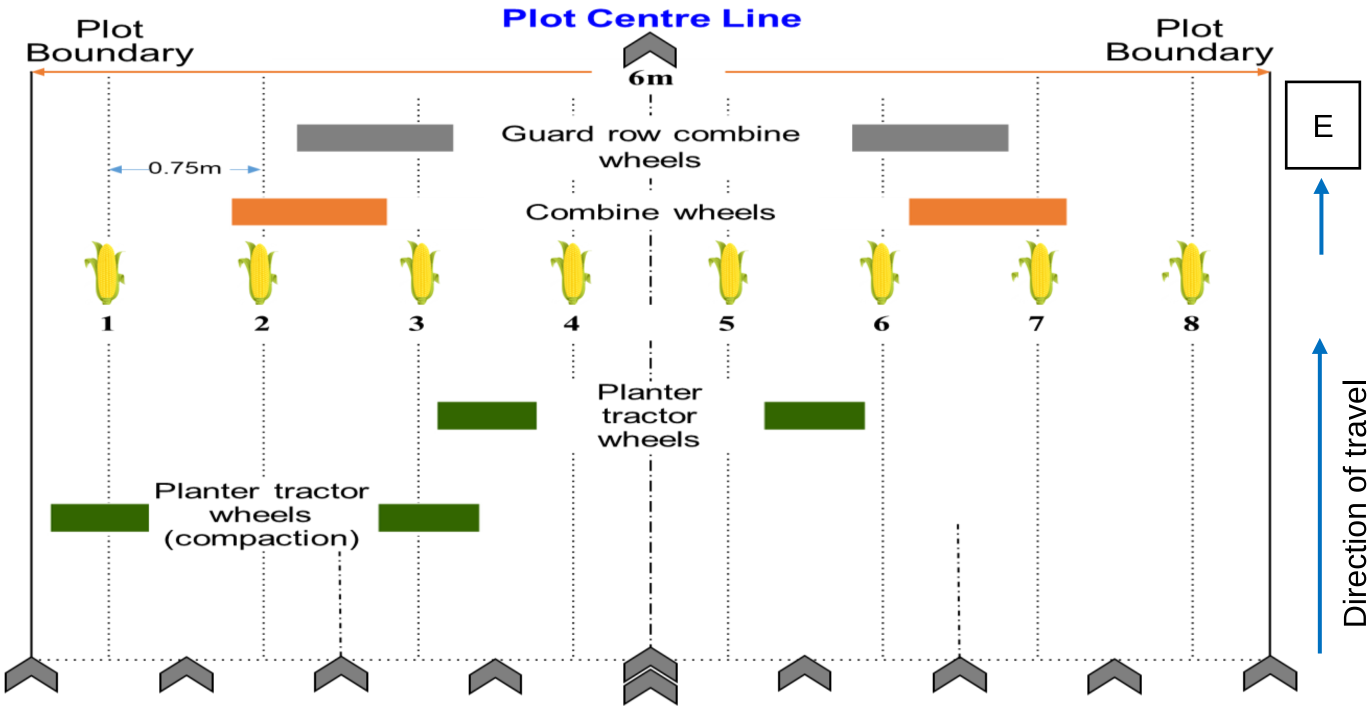


Figure 3.8. A typical no-till plot layout in 2017 and 2018, where 1 to 8 indicate crop rows (R1 to R8) showing tractor and combine harvester wheel positions.

Table 3.5a. Number of vehicles passes in deep tillage, shallow tillage and no-till plot in 2017 and 2018

Crop Row/plot	Number of vehicles passes			Remarks
	Deep tillage plot	Shallow tillage plot	No-till plot	
Crop row 1	2	1	1	HT
Crop row 2	1	1	1	
Crop row 3	5	4	3	HT
Crop row 4	1	0	0	
Inter-row of 4 and 5	0	0	0	Centre line, UT
Crop row 5	1	0	0	
Crop row 6	3	3	2	
Crop row 7	1	1	1	
Crop row 8	1	0	0	

Note: HT and UT denote heavily trafficked and un-trafficked locations/zones, respectively. Crop row 1 and 3 received higher vehicle traffic and considered as HT while other rows were identified as less trafficked crop row. Inter-row 4 and 5 was the centre line of the plot and receive no traffic at all.

Table 3.5b. % area of the width of the trafficked and un-trafficked zones of the experimental plot under different tillage systems

Tillage systems	Trafficked Areas (%)	Un-trafficked Areas (%)
Deep tillage	75.2	24.8
Shallow tillage	57.6	42.4
No-till	57.5	42.5

Note: Detail information is shown in Appendices 3.5 to 3.7.

3.10. Data Recording

Weather data, soil properties, crop growth and development and yield were recorded. These are described below.

3.10.1. Weather Data

The daily maximum (max.) and minimum (min.) temperatures (˚C), rainfall and snowfall (mm) over the growing seasons from November 2015 to November 2018 were collected from a weather station located 500m from the experimental site. These data were processed as per monthly average max. and min. are shown in Fig. 3.9 -3.11. In addition, 30 years' weather data from 1981 to 2010 are given in Table 3.6. Further, air and soil temperatures and rainfall data from 16 October – 4 November 2017 during soil sampling collection for X-ray CT study were also given in Appendix 3.8. Weather data shows that temperatures of all three years were almost similar in range except in 2018 where in May, the mean max. temperature was nearly 30°C. Total annual precipitation was recorded the highest in 2016 (1168 mm) followed by 2018 (1024 mm), while in 2016 it was 883 mm. All three figures show that the mean temperature peaked in July to around 30°C after which it gradually decreased to October. The lowest temperatures were recorded below 0°C during the months from December to April, in which January was the coldest month. However, monthly total rainfall data shows that average nearly 85 mm of rainfall was recorded throughout the year. Rainfall was recorded more in May and June, and then September. However, mean temperatures, precipitation and snowfall data during 2016 to 2018 were showed marginally higher with some fluctuations when compared with the 30 years annual average weather data (ISWS, 2016) (Figs. 3.9 - 3.11 and Table 3.6).

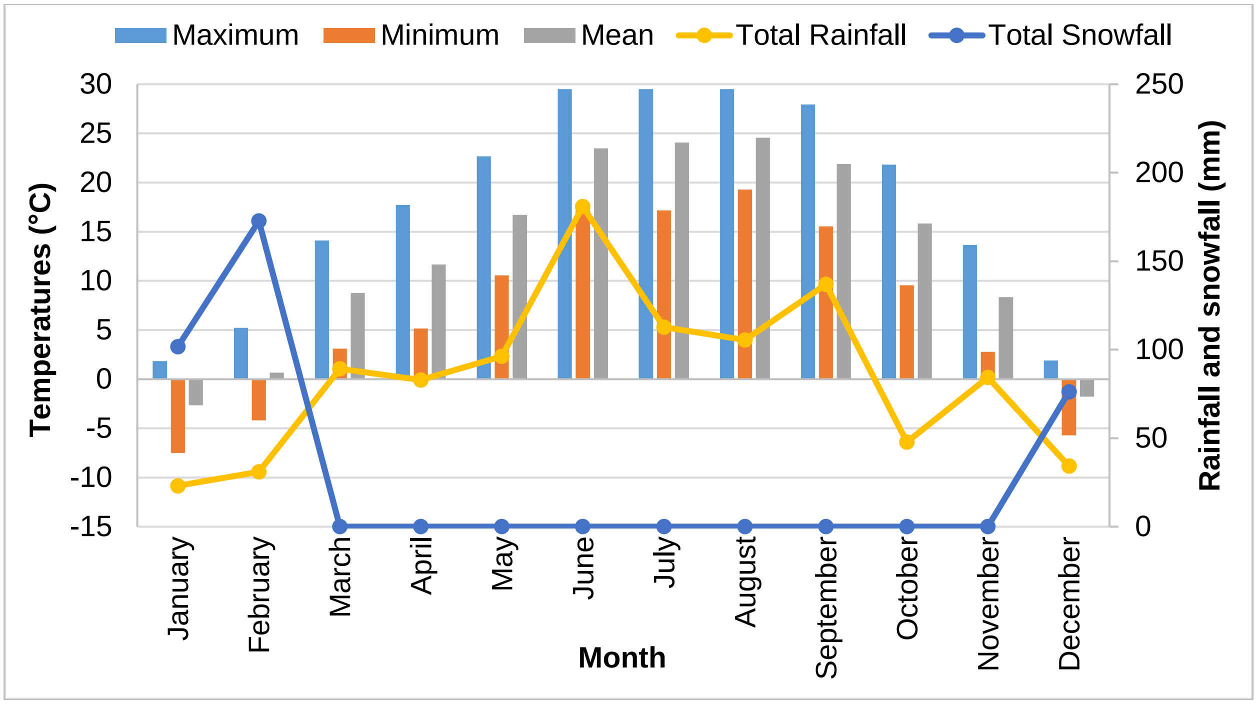


Figure 3.9. Monthly mean, max. and min. temperatures (°C) and total rainfall (mm) at Champaign County, Illinois, 2016

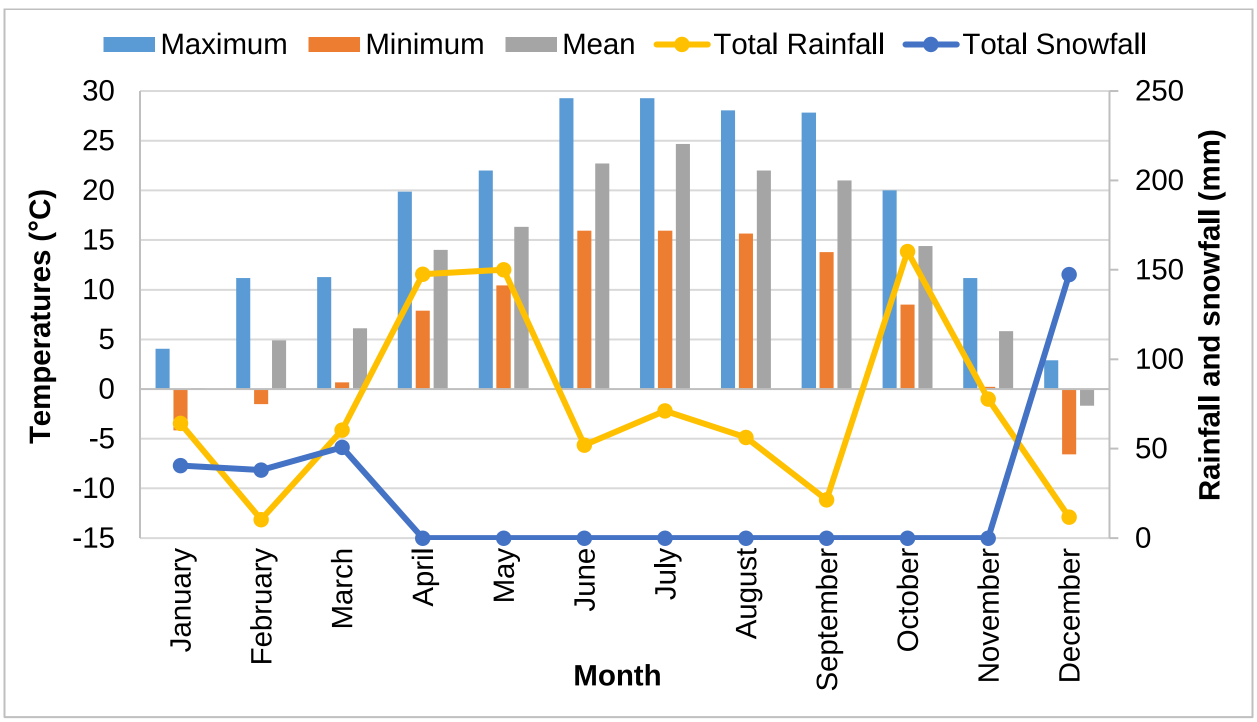


Figure 3.10. Monthly mean, maximum and minimum temperatures (°C) and total rainfall (mm) at Champaign County, Illinois, 2017

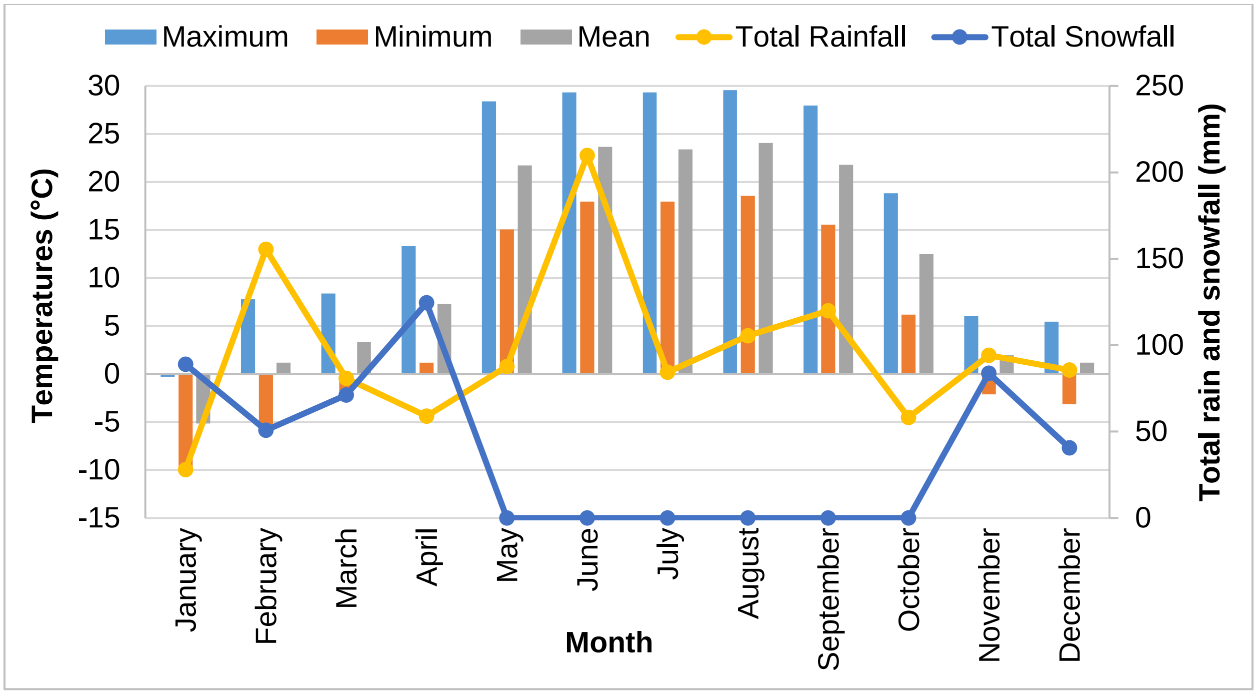


Figure 3.11. Monthly mean, maximum and minimum temperatures (°C) and total rainfall (mm) at Champaign County, Illinois, 2018

Table 3.6. Monthly average max. and min. temperatures, rainfall and snowfall from 1981 to 2010.

Month	Temperatures (^{0}C)			Precipitation (mm)	Snowfall (mm)
	Max.	Min.	Mean		
January	0.50	-8.50	-4.00	52.1	172.7
February	3.20	-6.60	-1.67	54.1	147.3
March	9.90	-1.10	4.44	72.6	66.0
April	17.1	5.10	11.1	93.5	10.2
May	23.0	10.9	16.9	124.2	0.00
June	28.1	16.6	22.3	110.2	0.00
July	29.4	18.3	23.8	119.4	0.00
August	28.7	17.3	23.0	99.8	0.00
September	25.7	12.3	19.0	79.5	0.00
October	18.4	5.90	12.2	82.8	2.54
November	10.3	0.00	5.17	93.5	22.9
December	2.60	-6.00	-1.72	69.3	167.6

Source: ISWS (2016)

3.10.2. Soil Properties

Soil properties in both initial and during the crop growing periods were recorded as listed below:

I. Initial soil parameters (prior to establishing the experiment)

- Electrical conductivity (mS/m)
- Penetrometer resistance (MPa)
- Soil moisture content (%)
- Soil particle density (Mg m^{-3})
- Soil bulk density (Mg m^{-3})
- Total porosity (%)
- Soil pH
- SOM (%)
- Cation exchange capacity (CEC),
- Soil nutrients: Nitrate N (NO_3^-N), Ammonium N (NH_4^+N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Hydrogen (H), Sulpher (S), Zinc (Zn) and Boron (B)

II. Soil parameters during crop growing periods

- Penetrometer resistance (MPa)
- Soil moisture content (%)
- Soil bulk density (Mg m^{-3})
- Total porosity (%)

III. Data on pore characteristics of soil from X-ray CT study

- Number of soil pores
- Total pore area
- Total CT-porosity
- Average pore size
- Pore size distribution
- Perimeter
- Circularity
- Solidity etc.

3.10.3. Crop Growth Parameters and Yield

Data on crop growth and yields of maize and soybean recorded over time are listed below:

a) Plant establishment (%)

b) Number of plants (plants ha^{-1})

c) Days to 50% flowering (days)

d) Plant height (m)

e) Ear height of maize (m)

f) Ear length of maize (m)

g) 1000 Grain weight (g)

h) Seed moisture content (%)

i) Grain yield (Hand harvest) (Mg ha^{-1})

j) Grain yield (Combine harvest) (Mg ha^{-1})

3.10.4. Economic Analysis

The cost and benefit analysis for the use of Ultraflex tyre system (LTP) over the standard tyre system (STP) for the maize and soybean production achieved for two years study from 2017-2018 (four crop seasons), were calculated based on the market price of Ultraflex and standard tyres, tyre depreciation costs, and 2018 annual mean price of the products. Typical farm size of the University of Illinois farm and State of Illinois farm was of 200 and 809 ha (500 and 2000 acres) were considered for the growing of maize-soybean in a rotation. Machinery costs, machinery depreciation, overhead cost, repair, and ownership costs, tillage tools purchase costs, labour cost, were assumed equal for both tyre inflation pressure systems. Fuel use cost and fuel usage rate were considered similar to both systems which are confirmed by the findings of Arslan et al. (2014) who showed that there was no significant difference in fuel use between the standard tyre and Ultraflex tyre systems. Similarly, seed, herbicide, and fertilizer costs were the same as these were applied equally to all plots. Finally, annual cost and earnings increased of using ultra tyre system and the mean economic benefit were determined.

3.11. Data Recording Approach of Soil Properties

Soil core samples from 25 sampling points identified as per coordinates following a grid sampling method (spacing 25 m) from each field (i.e. 2 samples × 25 sampling points = 50 samples/field × 2 fields = 100 samples), were collected in April 2016 before establishing the experiment. A Gator (0.67 Mg) mounted Giddings machine was used to collect soil core samples using 58 mm diameter by 300 mm long tubes. The collected soil cores/tubes were marked at three depths (0-100, 101-200 and 201-300mm) and subjected to soil physical (50 samples) and chemical properties (50 samples) analysis.

3.11.1. Soil Nutrients

To analyse soil nutrient status, 50 soil samples (25 samples/field) were used. The analysed chemical properties of soil and their methods were pH by pH meter (McLean, 1982; Peters et al., 2015), OM (%) by loss of weight on ignition method (Schulte and Hopkins, 1996; Combs and Nathan, 2015), CEC (Warncke and Brown, 2015), Nitrate-N (NO_3^-N) by Nitrate Electrode Method (Millham et al., 1970; Dahnke, 1971; Gelderman and Beegle, 2015), Ammonium-N (NH_4^+N) by Kjeldahl method (Bremner, 1960), P by Bray and Kurtz P-1 method (Bray and Kurtz, 1945), K, Ca, and Mg by Mehlich 3 Extractant method (Mehlich, 1984; Warncke and Brown, 2015), H, S by Monocalcium phosphate extraction method (Franzen, 2015), Zn by DTPA – Diethylene triamine penta acetic acid method (Lindsay and Norvell, 1978; Whitney, 2015) and B by Hot-Water Extractable Boron method (Watson, 2015).

3.11.2. Electrical Conductivity

Electrical conductivity (EC, mS/m) of each field was mapped, every second equivalent to approximately one sample per 3.6 m, using a Veris EM38 sensor drawn behind a John Deere Gator vehicle (0.67 Mg) on 28 April 2016 (Fig. 3.12). The EC maps were then overlaid onto NRCS soil survey maps for both fields.

Figure 3.12. JD Gator, Veris EM38 Sensor and data recording for EC measurement

3.11.3. Penetrometer Resistance

Cone penetrometer resistance (PR) was measured (MPa) as per ASABE Standards of S313.3 and EP542 (ASAE, 1999a; b) in 25 mm increment from 0 mm to approximately 450 mm depth of soil with varying degrees of replication using a hand-held cone penetrometer (Model: Field Scout SC 900 Soil Compaction Meter, Spectrum Technologies Inc.) with a cone angle of 30° and a base area 130 mm^2 (Fig. 3.13). PR readings were taken when the soil was near to field capacity (Arvidsson and Keller, 2007).

Figure 3.13. Field Scout SC 900 Soil Compaction Meter (Spectrum Technologies)

PR data was recorded before establishing the experiment and during the active vegetative stage of growth of crops. In 2016 and 2017, PR data were recorded at approximately 35-40 days after planting (DAP) for both maize and soybean and in 2018 at 95-100 DAP and 55-60 DAP for maize and soybean, respectively. Initial PR data was replicated 3 times to a depth up to 450 mm at each soil core sampling point in both fields (Fig. 3.14). In 2016, PR data were recorded from the left half of the plot from the centre line, as both halves of the plot were symmetrical in terms of field traffic and compaction. To determine the effect of compaction a total of 720 readings (3 readings/row x 4 crop rows/plot x 30 plots/field = 360 times/field x 2 fields = 720 readings) from each 30 plots were recorded from both for maize and soybean fields. While in the year 2017 and 2018, PR was replicated 5 times to the same depth (450 mm) at each sampling point from crop row 1 to 8 including the UT centre line of the plot. A total of 1350 readings (5 readings/sampling locations x 9 locations (8 rows and the centre line of each plot) x 30 plots/field = 1350 times) PR data per field were recorded from the maize and soybean fields, respectively. Finally, the average of the 5 readings per crop row (location) was calculated.

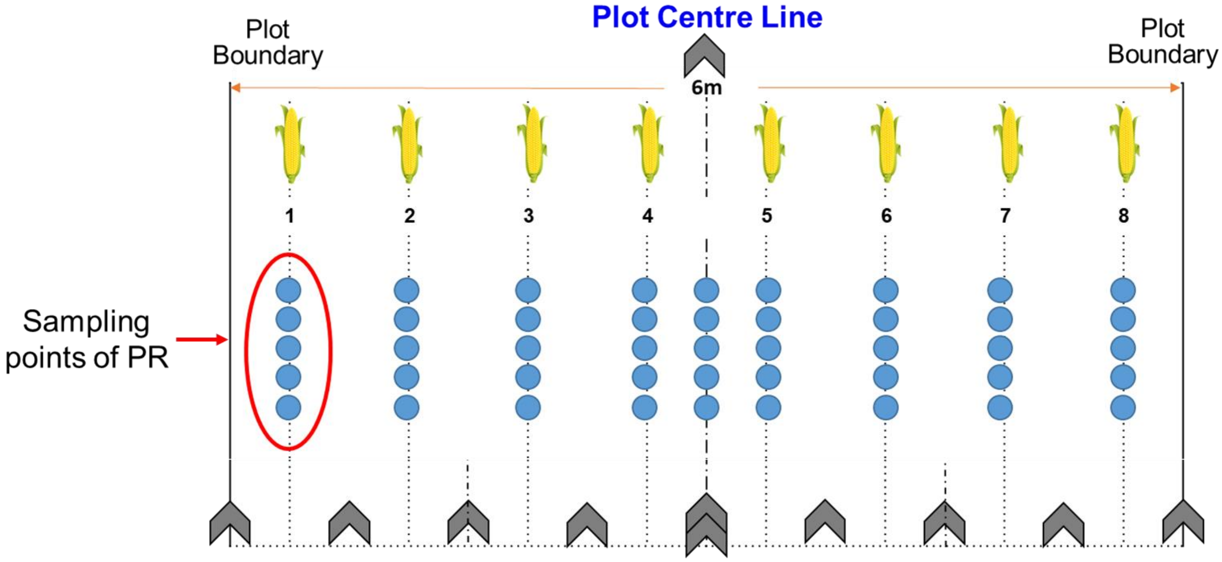


Figure 3.14. A typical plot layout showing sampling points for PR and Soil MC data reading

3.11.4. Soil Moisture Content

Soil moisture influences soil structure and compaction. Plant nutrient availability, nutrient transformation, and soil biological activities, and finally crop growth is affected by soil moisture. Soil moisture content % (Soil MC) was calculated using the following equation:

$$\text{Soil moisture } (\theta) = \frac{W_1 - W_2}{W_2} \times 100 \qquad [3.1]$$

Where,

θ = Soil moisture content

W_1 = Weight of wet soil (g)

W_2 = Weight of dry soil (g)

Initial soil moisture contents were measured from the soil samples collected from the same location during PR data recording from both fields following gravimetric methods. To see the compaction effect on the soil after Year 2 (2017), a total 30 soil cores from the heavy trafficked (HT) area between the crop row 3 and 4 and 30 cores from UT centre line (Interrow of crop row 4 and 5) were collected and gravimetric soil moisture contents were measured at five different depths with a 60 mm increment from 0 – 300 mm depth in the soil lab. Moreover, on the occasion of each PR data recording during the crop growing period for all three years, the volumetric water content in soil was taken from the same location indicated in Fig. 3.14 using a TDR (time-domain reflectometry) 300 soil moisture meter to a depth 200 mm (Fig. 3.15).

Figure 3.15. Field Scout TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc.)

3.11.5. Soil Particle Density

Soil particle density (PD) is the ratio of the mass of oven dry weight of the soil particles to the volume of solid particles not pore space, expressed in grams per cubic cm (g cm^{-3}) or megagram per cubic meter (Mg m^{-3}) and calculated by the following equation. Soil PD differs from BD because the volume used does not include pore spaces. The volume of soil is determined by measuring the volume of water displaced by the particles. The Graduated Cylinder Method was used to measure the PD of soil.

$$\text{Particle Density } (\rho_s) = \frac{M_S}{V_s} \quad [3.2]$$

Where,

ρ_s = Soil particle density (Mg m^{-3})

M_s = Mass of oven-dry soil (g)

V_s = Volume of solid soil without air (g)

3.11.6. Soil Bulk Density

Bulk density (BD) of soil is the ratio of the oven-dry weight mass of the soil to the bulk volume expressed in g cm^{-3} or Mg m^{-3}. BD is a parameter that indicates soil structure and void space and is often used to describe compaction. The degree of magnitude of soil compaction can be measured using soil BD and PR (Raper, 2005). BD was measured using the following formula:

$$\text{Dry Bulk Density } (\rho_d) = \frac{M_S}{V_t} \quad [3.3]$$

Where,

ρ_d = Soil dry BD (Mg m^{-3})

M_s = Mass of oven-dry soil (g)

V_t = Volume of soil (g)

Soil BD was measured both before and after implementing the experiment. Initial soil samples (50 soil cores, 25 from each field) at field capacity moisture content conditions were collected which were taken to the laboratory and separated at three depths of 0-100 mm, 101-200 mm and 201-300 mm. Soil samples were then put in the oven for oven dried at 105°C for 72 hrs as per the American Society for Testing and Materials standard (ASTM) (ASTM International, 2019). Finally, as per the gravimetric method, dry basis BD and soil MC% were determined. Soil cores from the south field immediately after harvest of maize in 2017 from the HT (Between crop row 3 and 4) and UT centre (Between crop row 4 and 5) locations of the plots were collected for X-ray computed tomography study. These undisturbed soil cores after completion of X-ray CT scanning were taken to the soil lab and separated into 5 different depths (0-60 mm, 61-120 mm, 121-180 mm, 181-240 mm and 241-300 mm) and eventually BD and soil MC% were measured.

3.11.7. Total Pore Space and Porosity

The porosity of soil is the fraction of the total soil volume that is taken up by the pore space. Percent pore space (PS) is the ratio of the volume of voids in the soil to the total volume of the soil that is expressed by percentage. PS is filled with air and water, found between adjacent sand, silt and clay particles and between aggregates. Texture and structure are the main factors governing the amount of PS in the soil. Total pore space and porosity (%) are measured by the following formulas (Hallett & Bengough, 2013):

$$\% \text{ Porosity of Soil } (\varphi) = \frac{\rho_d - \rho_s}{\rho_d} \times 100 \qquad [3.4]$$

Where,

φ = Total pore space/porosity (%)

ρ_d = Soil BD (Mg m^{-3})

ρ_s = Soil particle density (Mg m^{-3})

The total porosity of soil was measured from the results of BD and PD for both initial soil samples and samples collected for X-ray CT study in the year 2017.

3.11.8. Pore Characteristics of Soil from X-ray CT

Application of X-ray CT to study soil physical properties has recently been used by a number of researchers, for example (Mooney et al., 2012; Rab et al., 2014; Beckers et al., 2014; Baveye et al., 2018). It is considered to be a powerful tool to explore possible modifications to the structure and other physical properties of soil (Pires et al., 2005). Soil cores from the south field immediately after harvest of maize in 2017 from the HT (between the crop row 3 and 4) and UT centre (between the crop row 4 and 5) locations of all traffic and tillage plots were collected using a Giddings machine. These undisturbed soil cores were then CT scanned in a resolution of 98 µm at the Molecular Imaging Laboratory, Beckman Institute for the Science and Technology, UIUC, IL (Fig. 3.16) Eventually images were processed using Image J as per the working protocols and pore spaces and particles were segmented by Yen threshold. The Image J processing produced data spreadsheets, each containing different pore parameters. Detail procedures of the investigation of soil cores using X-ray CT are discussed in Chapter 4.

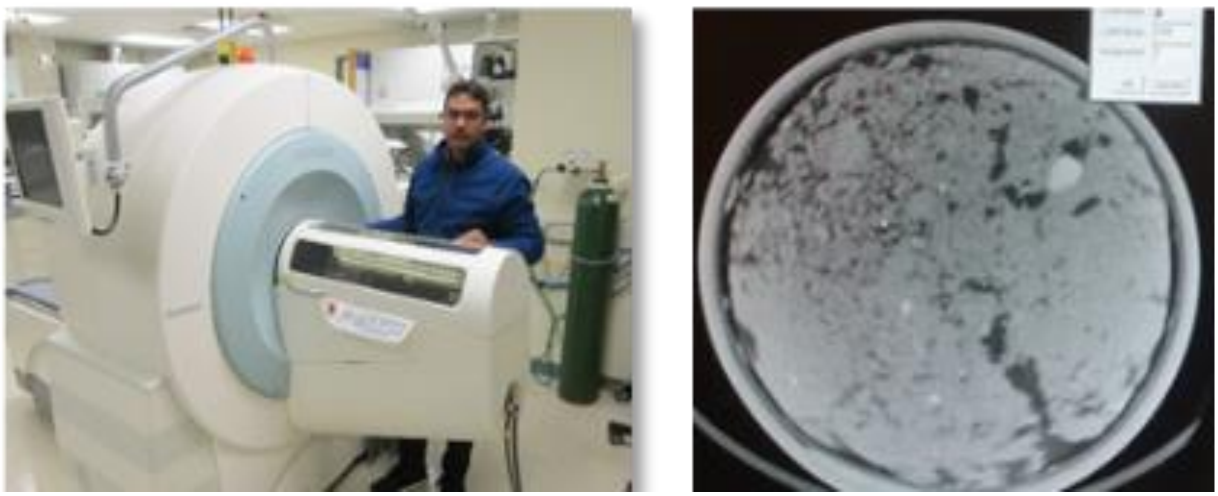


Figure 3.16. Soil cores X-ray CT scanning and top view of the image stack.

3.12. Data Recording Approach of Crop Parameters

Growth and development stages and days to 50% flowering of maize and soybean were closely observed and recorded. There were no significant differences were observed between treatments and thus these data and results were not included in the present thesis. Main crop parameters recorded in terms of growth and yields of maize and soybean are described below.

3.12.1. Plant Establishment

Plant establishment (%) of maize and soybean per hectare (ha) was recorded at 15-18 DAP using the 1/1000th-acre method (University of Wisconsin, 2010). To determine plant counting, a 5.31 m (17′ 5″) long pole was placed alongside crop rows and the number of plants in each crop row per plot were recorded. The number of plants was multiplied by 1000 provided plant population per acre (Plants/17′ 5″ × 1000 = Plants/acre). Measurements were replicated in triplicate per row from all 240 rows of both crops from all STP and LTP plots. Plant establishment (%) was then calculated based on the seed rates applied for maize and soybean per ha.

3.12.2. Number of Plants Per Hectare

To estimate the number of plants per unit area, the 1/1000th acre method was repeated and the number of plants in each crop row per plot was recorded in triplicate at 30-35 DAP. The number of counted plants was multiplied by 1000 to get plants per acre. Finally, the number of plants were then converted to the number of plants per ha.

3.12.3. Plant Height

Plant heights of maize and soybean (m) were recorded from five plants in each crop row at 30 and 45 DAP in 2016 while in 2017 and 2018, to get compaction effect of the whole crop season, these were recorded prior to the harvest (at approximately 130-135 DAP). A linear scale was used to record the plant height of maize from the base to flag leaf angle. Plant height of soybean was recorded from the base to tip of the main stem using a linear meter scale. Data on plant height was recorded in triplicate from each row of 30 STP and LTP plots.

3.12.4. Ear Height and Length of Maize

Ear height of maize (m) was recorded only in 2018 at 130-135 DAP using a linear scale from the base of the plant to ear. The ear height was recorded from the same five plants that were measured for plant height of maize. The ear length of maize (m) was recorded after hand harvest of ears in 2018.

3.12.5. Rooting Depth

For the rooting depth study, an un-replicated one STP and one LTP plots were investigated for both maize and soybean at 60-65 DAP in 2016. To do so, 4 crop rows of one side (both sides of the plot were symmetrical from the centre AB line) profile pits were dug to a depth of 1.5 m using a Caterpillar excavator, then spade and trowel were used carefully to uncover roots and rooting depths (m) of both crops into the soil were recorded. Approximately 6-7 hours were needed to dig and uncover the soil profile of each plot. Although, it was initially planned that rooting depth study will be conducted to all plots, however, the time required per plot would have hampered the collection of other soil and crop parameters. Therefore, this un-replicated rooting depth study was conducted to get a general idea of how far the roots of maize and soybean can penetrate under the different tyre inflation pressure treatments.

3.12.6. 1000 Grain Weight

Grains used to measure 1000 grain weight (g) were cleaned and all cracked and abnormal grains were removed. The 1000-grain weights of maize and soybean of each crop row from all 30 STP and LTP treatments were then recorded using a seed counter.

3.12.7. Grain Moisture Content

Grain moisture content percentage of both maize and soybean were recorded using a seed moisture meter (Model: John Deere grain moisture tester GT-30300). Moisture content (%) of grains of all plots harvested using combine harvester and plant samples of each crop row harvested by hand were recorded when shelled (maize)/threshed (soybean).

3.12.8. Grain and Biomass Yield (Hand Harvest)

To determine treatment effects in each row of all traffic treatments plots, hand harvest sampling of ten plants of soybean and five ears of maize per row were harvested before the plot combine harvest. In 2016, hand harvest sampling was from crop row 1 to 4 (both sides of the centre line were symmetrical) while in 2017 and 2018, these were from all eight crop rows of all STP and LTP plots. Hand harvest sampling of soybean and maize were conducted in the first week and the second week of October, respectively. In 2018, ear length of maize was recorded, and maize ears were then shelled and cleaned. Sample grain weight, 1000 grain weight and seed moisture content of maize were then recorded. Soybean samples per row were dried in a room dryer and then threshed using a soybean thresher. In 2018, hand harvest sampling of soybean included leaves, pods, and stems/branches. Before threshing, the total sample biomass weight was recorded and then samples were threshed. Finally, sample grain weight, seed moisture content and 1000 grain weight of soybean were recorded. The grain moisture contents were then adjusted to 15.5% for maize (Lauer, 2002) and 13% for soybean (Iowa State University, 2008) and final grain weight/yield were converted to Mg ha^{-1}. Harvesting of soybean and threshing are shown in Fig. 3.17.

3.12.9. Grain Yield (Combine Harvest)

Maize and soybean were harvested using a combine harvester with a header width of 6 and 4.5 m respectively on at 135-160 DAP in October. The combine harvester harvested all 8 soybean rows and the centre 6 maize rows of each plot and yield data were recorded accordingly. At first, the 15 STP plots were harvested as per the STP treatment for the combine and those were considered for the final plot yield. For maize, to harvest the two edge rows, 3 adjacent STP plots, STP plots 1 and 30 were harvested as per the STP mode. Subsequently, tyre pressures were lowered to LTP pressures and 15 LTP plots were harvested followed by 4 LTP plot boundaries. After that, 2 edge rows of adjacent plots of the remaining 22 plot boundaries were harvested as per STP and LTP treatments (left and right tyres of the combine were run in STP and LTP mode). Extra compaction by the combine harvester was also conducted to all plots as per STP and LTP modes to all plots boundaries in the soybean field to make both fields symmetrical in terms of field trafficking. The grain yield and seed moisture content (%) per plot were recorded using a weigh wagon (Model: Par-Kan GW 200A) and John Deere grain moisture tester (GT-30300), respectively. Seed moisture contents were then adjusted to 15.5% (Lauer, 2002) and 13% for maize and soybean (Iowa State University, 2008), respectively. Finally, grain yields of both maize and soybean were then converted into Mg ha^{-1}**.**

a) Hand harvesting of soybean

b) Threshing of hand harvest samples

c) 1000 grain weight (g)

d) Crop row sample weight (g)

Figure 3.17. Hand harvesting and threshing of soybean

3.13. Statistical Analysis

The experimental data were analysed by two way ANOVA for the main effect of tyre pressure and tillage systems on combine harvested yield and General ANOVA for hand-harvested data on growth and yield of both crops using software Genstat 18th Edition (VSN International, 2015). Data on PR, BD and total porosity of soil and pore characteristics throughout the soil depth (0 – 450 mm) were analysed using repeated measures of ANOVA. The treatment structure was of tyre inflation pressure x tillage system x crop row and the block structure of block/whole plot (main plot)/crop row. Tukey HSD multiple range tests (P = 0.05) was used to determine significant differences between treatments. However, means, total count, standard deviation, standard error, maximum and minimum data etc. were also calculated by Microsoft Excel 2016 software.

CHAPTER 4: STUDY OF SOIL PROPERTIES USING X-RAY COMPUTED TOMOGRAPHY

4.1. Introduction

The structure is an important physical property of soil which regulates and influences the nature of the different physical processes (Kooistra and Tovey, 1994). It enables the soil to support and sustain plant and animal life, and moderate water quality and soil carbon sequestration (Bronick and Lal, 2005). Soil with good structure typically has three types of pores macropores, mesopores, and micropores with equivalent diameters are >30, 0.2–30 and <0.2 μm, respectively (Kay and Vandenbygaart, 2002). Compaction alters soil structure, reduces total pore space, particularly macropores (> 30 μm) and voids between soil particles and aggregates (Berisso et al., 2012). It increases soil BD and reduces the proportion of large to small pores in the soil (Kim et al., 2010). Reduction in macroporosity due to compaction can restrict root growth (Rab et al., 2014) which leads to a reduction in crop growth and yield (Pagliai and Vignozzi, 2002; Czyż, 2004). Soil physical measurements such as BD, PR, and total porosity are widely used indicators of changes in soil compaction, but these are unable to provide quantification of soil pores, pore sizes and their distribution within the soil.

X-ray computed tomography (CT) facilitates quantification of soil structure such as pore size distribution, porosity, and tortuosity of the porous network at the micrometre scale. It is a non-invasive three dimensional (3D) imaging technique that can be used to measure and quantify soil pore size and distribution (Rab et al., 2014). Its ability to visualise the internal 3D image structure of soil greatly helps the current understanding of the hydrodynamic behaviour of soil (Beckers et al., 2014). The technique has been applied in the field of soil science since the early 1980s (Petrovic et al., 1982; Hainsworth and Aylmore, 1983; Crestana et al., 1985; Beckers et al., 2014). Others refer to the technique as a state of the art in soil science research (Taina et al., 2008; Pires et al., 2010; Baveye et al., 2010).

The heterogeneous nature of soil makes the assessment of structure challenging (Munkholm et al., 2013). The CT technique has offered a non-destructive means of the quantification and visualization of soil in 3D that has provided fundamental insights regarding soil features and function (Helliwell et al., 2013). The process involves a sample (e.g. a soil core) being rotated through 360^o in X-ray beams, which produce successive projections of pixels based on the attenuation, that are reconstructed into cross-sectional 2-D images (tomo/slice) yielding a 3-D object (Mooney et al., 2012). Based on the X-ray resolution, each image/slice is made up of 3D pixels called voxels (Calistru and Jităreanu, 2015). It produces stacked 2D images to create 3D models of the sample using the mathematical reconstructions from attenuation of radiation (Vaz et al., 2011), allowing the researcher to quantify and visualise changes in pore system structure throughout the soil profile. In line with soil compaction, soil structural changes by heavy field traffic using X-ray CT with 90 a μm resolution were investigated (Schäffer et al., 2007). The results showed that both porosity and connectivity of the macropores decreased and that macropore size distribution was distinctly affected by compaction. Qualitative assessment of compacted soil using a medical CT at 750 μm resolution showed that larger vertical pores of soil disappeared due to compaction at 10 to 20 cm depth but more pores persisted at a depth of 30 to 40 cm (Wiermann et al., 2000).

Changes in soil structure due to compaction can be explained by changes in pore size, shape, orientation and connectivity of soil (Pagliai and Vignozzi, 2002). Pore size distribution (PSD) and continuity regulate infiltration and storage of water into the soil (Kutilek and Nielsen, 1994; Hillel, 1998; Kodešová et al., 2011) and available water and aeration for uptake by plants (Cary and Hayden, 1973). However, segmentation (the process of converting a grayscale image to a binary image) method and processing selection are subjective, which, in turn, can have a strong impact on results and conclusions (Beckers et al., 2014). The reconstructed images are segmented to detect pore space of the sample (Taud et al., 2005) using a threshold tool on an 8-bit greyscale image. Values lower than the threshold are considered air-filled pore space and above are considered the solid matter (Kim et al., 2010) or non-pores. However, due to the limitation of X-ray CT resolution, CT derived pores are classified as macropores (Scott, 2000). Smaller macropores and a higher number of smaller macropores indicate the existence of many unconnected pores in the soil (Pires et al., 2017). X-ray CT technique helps to explore possible modifications in the structure and other physical properties of soil (Pires et al., 2005). A recent pore structural study conducted on sandy loam soil in the UK using X-ray tool showed that pore structures in soil significantly varied between the traffic and tillage treatments (Millington, 2019). Apart from this, to the present knowledge, there are no data on the changes in pore characteristics due to the effect of high flexion tyre and tillage induced compaction of soils and the relationship between the X-ray CT derived porosities and soil physical porosities. X-ray CT technique and image analysis may help to cover these gaps.

4.2. Hypothesis

Reduced tyre inflation pressure maintains soil macroporosity, number of pores, pore area and size of pores for three tillage systems.

4.3. Objectives of the X-ray Computed Tomography Study

To determine the effect of standard and low tyre inflation pressure on:

a) Soil structure in terms of pore number and size of pores, and percentage pore area for three tillage systems (deep, 450 mm; shallow, 100 mm and no-till).

b) Soil pore area, pore size and distribution, circularity, and solidity of pores.

c) The relationship between X-ray CT porosity and physical porosity of the soil, PR, and BD of soil.

4.4. Methodology

An investigation of the effect of tyre inflation pressure and tillage systems on soil properties using X-ray computed tomography (CT) was conducted at the Molecular Imaging Laboratory, the Beckman Institute for Advanced Science and Technology, at the University of Illinois at Urbana-Champaign during 2017-2018. The experiment was part of the long-term study of the effect of tyre inflation pressure on soil properties and crop development for three tillage systems, which was implemented in Champaign County, Illinois, USA (lat/lon: 40.070965, -88.217538) from November 2015 – October 2018. The soil of the experimental site consists mainly of Drummer soil (152A) series characterised as a silty clay loam (USDA, 2015). The experiment was a 2 × 3 factorial randomized complete block design, with five blocks. The treatments comprised two tyre inflation pressures: standard tyre inflation pressure (STP) and low tyre inflation pressures (LTP) and three tillage systems: deep tillage (DT, 450mm), shallow tillage (ST, 100mm) and no-till (NT). Details of the study area, experimental design and treatments, field operations as per treatment structure and crop production of maize and soybean in rotation are presented in Chapter 3: General Methodology.

4.4.1. Soil Sampling

Soil samples were collected immediately after harvest of maize on November 4, 2017 (second year of the crop rotation) from the heavily trafficked (HT, between crop row 3 and 4) and UT locations (between crop row 4 and 5) which was the centre line of the plot (Fig. 4.1). HT location of each plot received an equal amount and the same vehicle passes under the two different tyre inflation pressure treatments. Therefore, the soil core collection of these areas and afterwards using X-ray CT study, a fair comparison between two tyre inflation pressure systems were made possible. A Gator (0.67 Mg) mounted Giddings machine was used to collect 60 soil cores (2 trafficked locations × 30 plots) in PVC liners of 58 mm diameter × 300 mm length from the 30 plots (Fig. 4.2). Soil cores were covered with red (top) and black (bottom) lids and then stored in a cool room in an upright position in the dark at 4°C to avoid drying out and to reduce microbial activity.

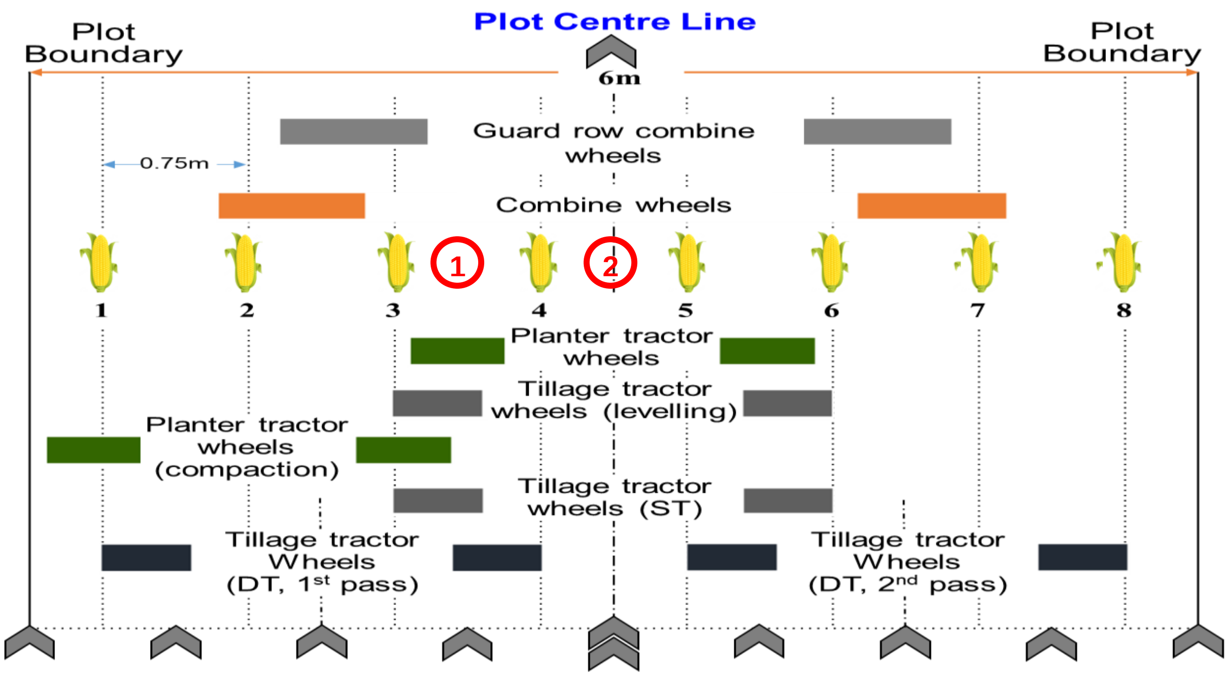


Figure 4.1. Typical plot layout showing vehicles wheeling and soil core sampling locations (red circle) for X-ray CT study.

Note: Red circles 1 and 2 are the locations of sampling of soil cores corresponded to the heavily trafficked (HT, between crop row 3 and 4) and un-trafficked area (UT, between crop row 4 and 5), respectively.

Deep tillage: Applied only to DT plots, shallow tillage: Applied to both DT and ST plots and No-till: NT plots receive no tillage at all.

Figure 4.2. Gator mounted Giddings machine (left) and soil cores (right) collected for X-ray CT scanning.

4.4.2. X-ray Computed Tomography Scanning

The soil cores were scanned using a microCT Preclinical scanner (Model: Hybrid Siemens Inveon triple-modality microPET/SPECT/CT scanner[2]). The system is equipped with multiple pinholes and parallel hole collimators, acquisition, and image processing workstations, and BioVet monitoring system, which allows for rapid evaluation of radiotracers. X-rays were emitted from the source and passed through the sample, which rotated incrementally through 360°. A flat panel detector collected the attenuated X-rays. The CT system parameters were 80 KV, 500 µA and 98 µm resolution. As this was a comparative study thus, the compromise between resolution, sample size and CT scanner beam time was considered acceptable. Studies showed that higher resolutions can provide a smaller field of view and can miss pore structure information due to heterogeneity in the larger sample (Peng et al., 2012). CT scanning of the soil cores was then conducted. Image acquisition and then reconstruction of images were automatically performed by the image acquisition and image reconstruction software installed in the controlling computer/workstation. Three scans were required (0-100 mm, 100-200 mm and 200-300 mm depth) to cover the full length of the soil core. These three scan files were exported as volume files were combined and reconstructed, and the resultant 3D X-ray attenuation maps were exported as top view (cross-sectional area). X-ray CT scanner and a representative whole

[2] PET - Positron Emission Tomography, SPECT - Single Photon Emission Computed Tomography and CT – Computed Tomography.

CT scanned image are shown in Figs. 4.3 and 4.4. A flow diagram of the whole CT scanning procedures of soil cores is also given in Fig. 4.5. The reconstructed image stacks consisted of 3053 slices per soil sample and were then stored in tagged image files format (tiff) for further processing.

Figure 4.3. X-ray CT scanner at the Molecular Imaging Laboratory, Beckman Institute

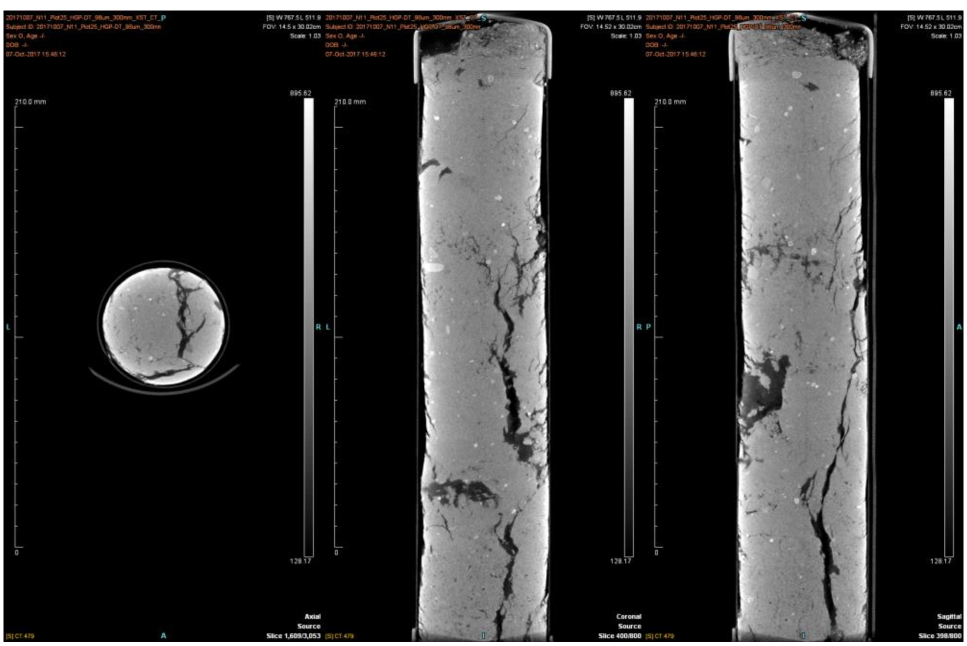


Figure 4.4. A representative whole X-ray CT scanned image with a top view (left) and side view (right).

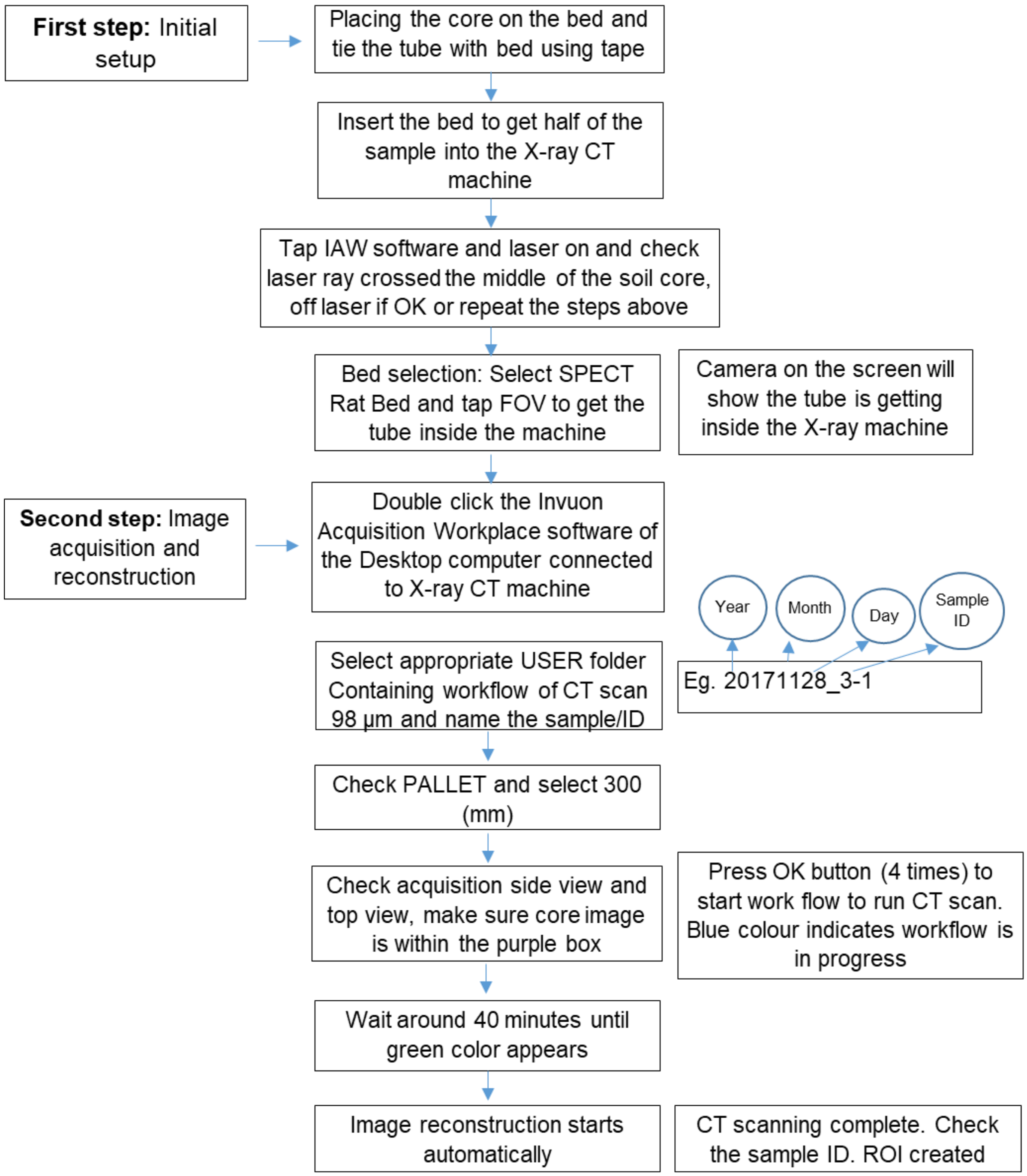


Figure 4.5. Stepwise CT scanning protocol of soil cores at MIL, Beckman Institute.

Note: FOV – Field of View. It is the extent of the observable object (e.g. soil core) that can view on the display screen.

4.4.3. Image Processing and Segmentation

Tiff files of the stack images were processed by Fiji-ImageJ (Schindelin et al., 2012). Before processing the image stacks, a cylindrical region of interest (ROI) of 535-pixel x 535-pixel per slice in the centre of the images was selected. The ROI was extracted to reduce disruption artefacts at the boundary of the samples and to reduce any effect from beam hardening (the most commonly encountered artefact in CT scanning) and deformation from the soil core tool (Li et al., 2016). Beam hardening causes the edges of a scanned object to appear brighter than the centre because of greater attenuation of lower energy photons relative to high energy photons. The effect can be reduced by the use of a filter between the x-ray source and the sample (Helliwell et al., 2013; Rab et al., 2014). In a first step, the topography of each image stack was determined by discarding the top 100 slices or voxels (approx. 10 mm) and the bottom 120 slices or voxels (approx. 12 mm) to avoid including possible wall artefacts introduced by the sampling process. Later, the ROI of 535-pixels x 535-pixels per slice in the centre of the image stack (2832 slices) was cropped that served as a basis for all further processing steps (Fig. 4.6).

The soil core image stacks had large beam hardening effects especially at the centre and on the edges. To remove the noise, the median, mean, Gaussian Blur and minimum filters as potentials tools were applied. However, these background filters did not improve the ability of the image quality to threshold all pore space. Sample CT images for the study of the same parameters for comparison were analysed and compared at the Hounsfield Facility, The University of Nottingham, UK, however, similar observations were found. Therefore, three options were considered for segmenting the soil pore space: (1) subtracting the background of the image stack first and then apply an automatic Li thresholding algorithm (Li & Tam, 1998), however, due to huge beam hardening, the results observed overestimated porosity; (2) perform manual threshold such as Otsu, Li, MaxEntropy, RenyiEntropy and Yen on all samples, which resulted in an underestimation of porosity; (3) creating 2X image stacks (black and white backgrounds), adjusting the background to grey and running an automatic threshold with Yen method, which resulted in slightly underestimated porosity values ([3]S. Mooney and B. Atkinson, Personal communication, 7 March 2018). Finally, option 3 was adopted and the Yen threshold (Yen et al., 1995) was applied to the original cropped image with the knowledge that the pore space was being underestimated (Vaz et al., 2011). However, few image stacks were not able to perform an automated threshold due to higher level of beam hardening. To solve the issue, at

[3] Scientists of the Hounsfield Facility, The University of Nottingham, UK.

first, all automated threshold was run to the cropped image stacks. Then from the log window, the value of Yen was taken and input manually by setting up the value as close as possible to the Yen automated method. Finally, the pore space of these image stacks was segmented.

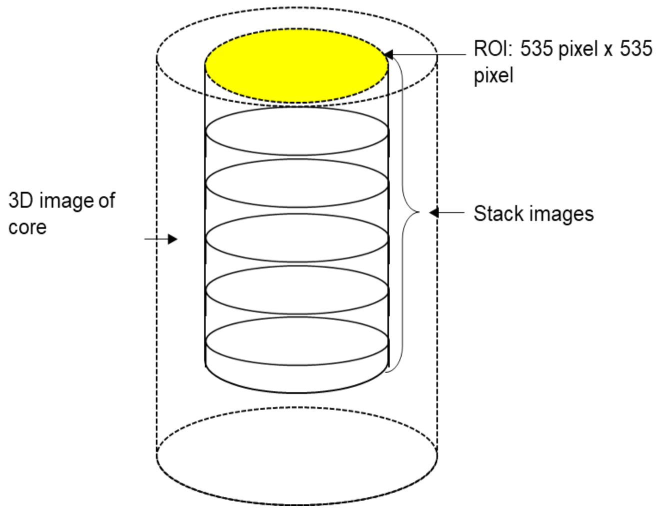


Figure 4.6. A cylindrical ROI selected in stacked images of 535 pixel x 535 pixel per slice.

4.4.4. Image Analysis

ROI image stacks of each sample were further analysed by Fiji ImageJ software (Schindelin et al., 2012) which is similar to that analysed in a macroporosity study of soil (Rachman et al., 2005). After segmentation using the Yen threshold method, binary (8 bit) images were produced and values below the threshold were identified as soil pore space. The image processing produced an HT and UT excel spreadsheet, each containing sheets for the various soil pore parameters across the cores being pore count, pore size, total pore area, circularity, solidity etc. Data visualization and analysis algorithms were written using MATLAB R2018b programming software. The detail procedures/protocol of the X-ray CT analysis is shown in Fig. 4.7.

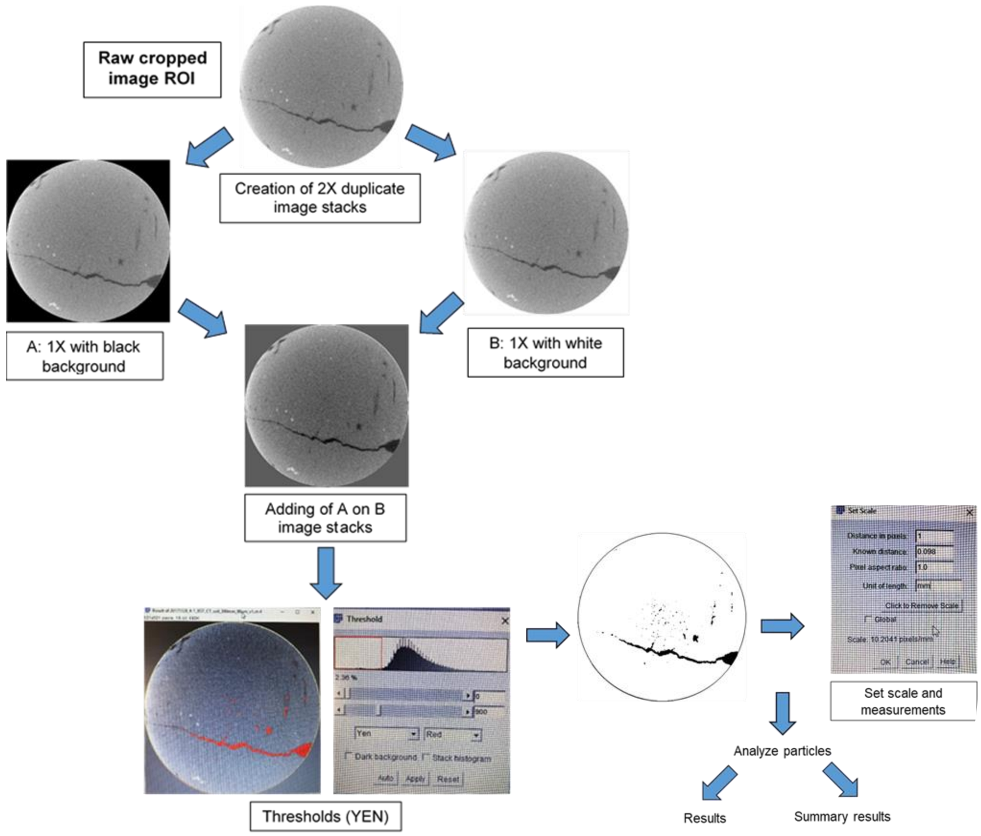


Figure 4.7. Procedures of soil cores X-ray CT images analysis.

4.4.5. Bulk Density, Total Porosity and Penetrometer Resistance of Soil

Bulk density (Mg m^{-3}) and total porosity percentage (BDp) of the X-ray CT soil cores after CT scanning were measured at 5 depths; 0-60 mm, 61-120 mm, 121 – 180 mm, 181 – 240 mm and 241- 300 mm (Detailed methods are described in Chapter 3). During soil core collection for the X-ray CT study, a total of 300 readings of PR data were recorded from the HT and UT locations of all 30 plots in 25 mm increments from 0- to approximately 450 mm depth of soil using a hand-held cone penetrometer as per the ASABE standards of S313.3 and EP542 (ASAE, 1999a; b).

4.4.6. Data Collection

Soil pore space parameters such as total pore count, total pore area (TPA), the average size of pores, CT measured porosity percentage (CTp), perimeter, circularity, solidity, FeretX, FeretY, were collected (Fig. 4.8). Moreover, the cumulative frequency of pore size distribution was plotted. Pore perimeter is defined as the length of the outside boundary of a given selected pore. Pore circularity is a measure of how circular pores are. The circularity value lies between 0-1. A circularity value of 1.0 indicates a perfect circle (Kim et al., 2010) while value approaches 0.0 indicates an increasingly elongated polygon (Ferreira and Rasband, 2012). Solidity is the area of a blob (a common term used in image processing) divided by its convex area (the imaginary convex hull around it). Feret diameter is defined as the distance between the two parallel planes restricting the object perpendicular to that direction. FeretX and FeretY are the lengths of the object's projection in the X and Y directions, respectively. Image J calculates circularity and solidity by the following equations:

$$\text{Circularity} = 4\pi \times \frac{[\text{Area}]}{[\text{Perimeter}^2]} \qquad [4.1]$$

$$\text{Solidity} = \frac{[\text{Area}]}{[\text{Convex Area}]} \qquad [4.2]$$

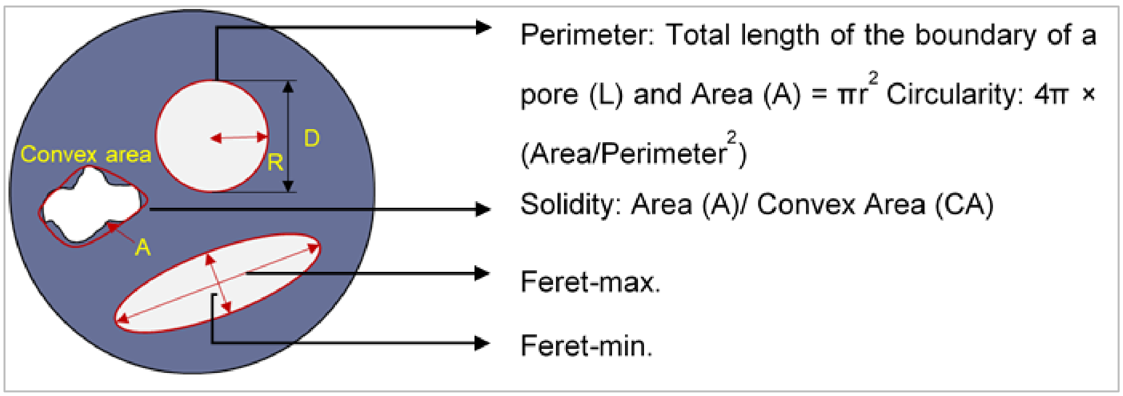


Figure 4.8. An example of a typical image of soil pores, explaining key pore parameters (A - Area, D - Diameter and R - Radius).

4.4.7. Statistical Analysis

Data were analyzed by General ANOVA and repeated measures of ANOVA using software Genstat 18th Edition (VSN International, 2015). The treatment structure was of tyre inflation pressure x tillage system x trafficked location while the block structure was of block/whole plot (main plot)/ trafficked location. Tukey HSD multiple range tests (P = 0.05) were used to determine significant differences among treatments.

4.5. Results and Discussion

The effect of tyre inflation pressure and tillage systems on soil cores by observing image stacks (2832 slices per sample) of HT and UT locations using X-ray CT is shown in Figs. 4.9 and 4.10. Their effect on various pore parameters along with BD and PR are described below:

4.5.1. Qualitative Observation of X-ray CT Images

Figs. 4.9 and 4.10 represent HT and UT locations and show longitudinal slice sections of the sample images produced from the X-ray CT attenuation maps using the slicer function of the ImageJ. Overall, visual observation of these image stacks shows that soil structural differences between cores of HT soil are evident. Comparing this, soil structural variations are smaller in UT locations whilst loose and open structures with a larger volume of pores were seen in the LTP. Fig. 4.9 showed that the soil was in a compacted and dense condition in the samples of STP especially in the HT location, which might be evidence of possible re-compaction after tillage. Moreover, some vertical and horizontal cracks and pore spaces are more prominent in LTP as compared to STP and in UT compared to the HT treatment (Figs. 4.9 and 4.10). Load and pressure induced by agricultural machinery traffic on soil cause cracks and reduced voids on arable soils (Kooistra and Tovey, 1994). However, images of both STP and NT appear to show a more dense structure throughout the profile with the presence of vertical cracks, which agree with the findings of (Millington, 2019).

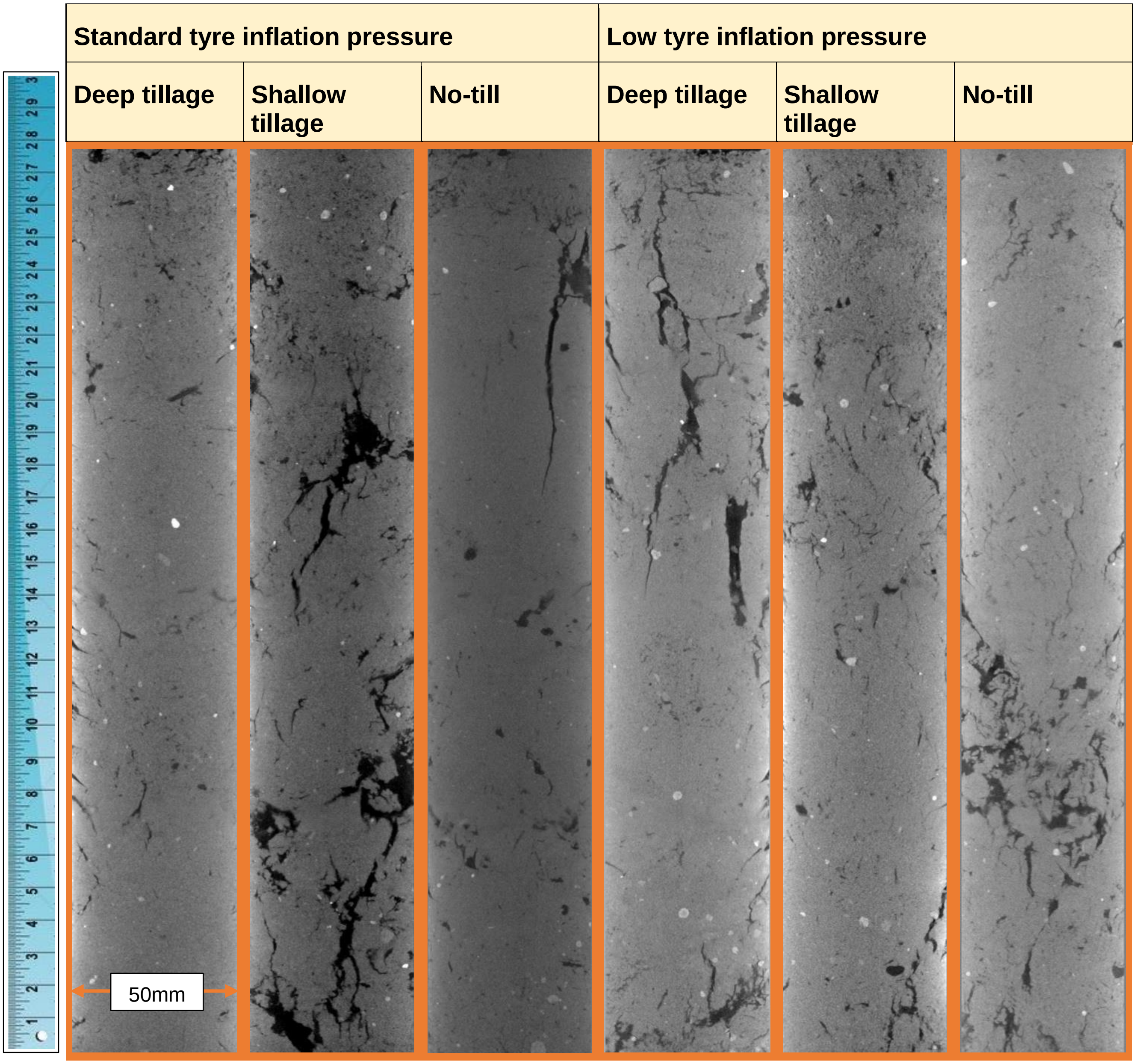


Figure 4.9. Side view of soil cores X-ray CT image stacks (280 mm × 50 mm) of heavily trafficked locations as influenced by tyre inflation pressure and tillage systems.

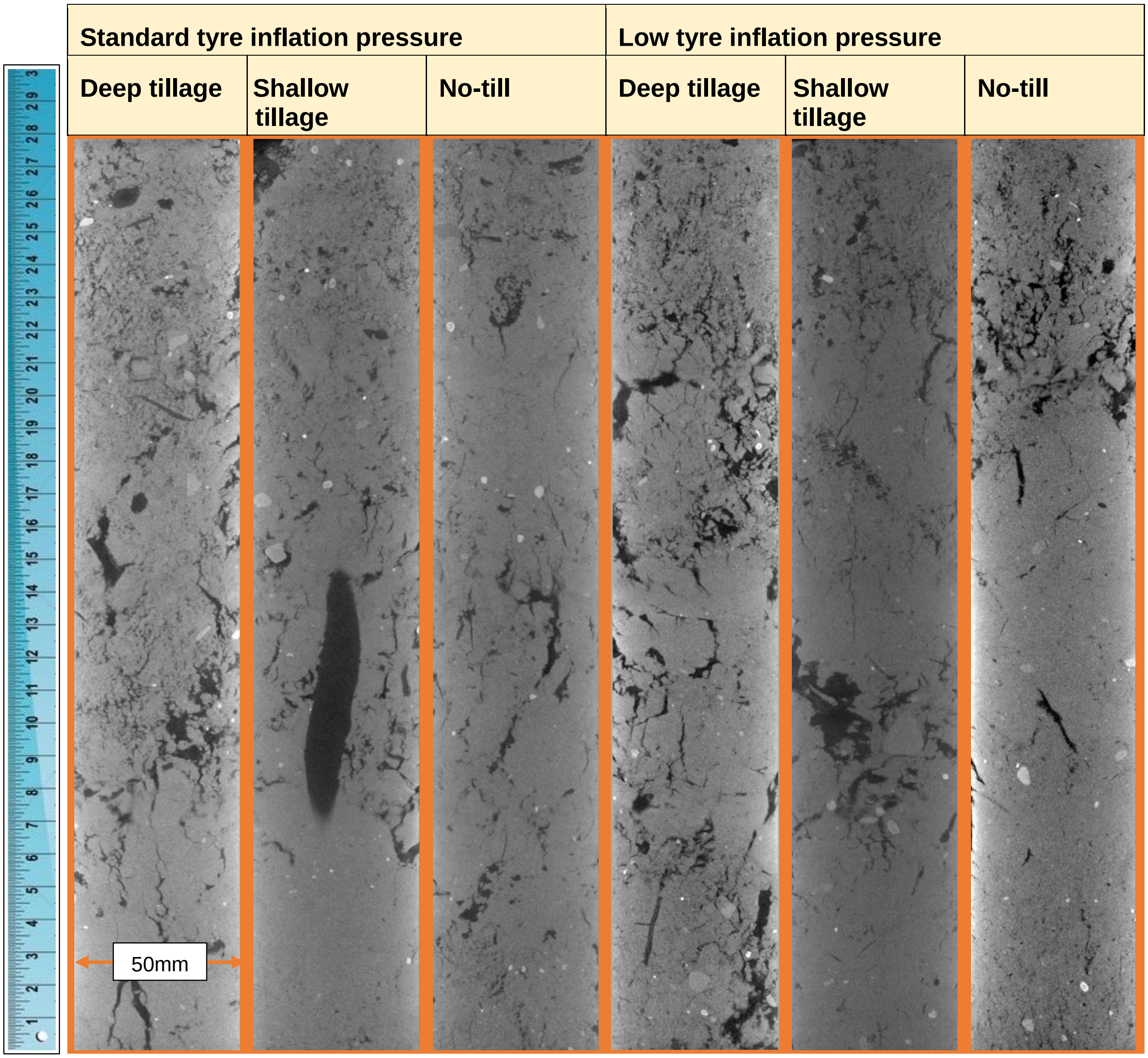


Figure 4.10. Side view of soil cores X-ray CT image stacks (280 mm × 50 mm) of un-trafficked locations as influenced by tyre inflation pressure and tillage systems.

4.5.2. Number of Pores

Total pore count of STP and LTP plots and HT and UT locations in different tillage systems, histograms of the frequency of pores (HT location) and statistical results between treatments are presented in Table 4.1 and Figs. 4.11 – 4.19. Fig. 4.11 shows STP vs LTP in different tillage systems and HT and UT locations, where colour lines are represented as replications of the field experiment. It shows that pore count in LTP was recorded more in all five replications than pore counted in STP. Visualization of pore count in HT vs UT showed that pore count in UT location was higher as compared to the HT location (Fig. 4.12). A histogram of the frequency of pores showed that a right-skewed distribution of pores was observed in HT location of the tyre inflation pressure and tillage systems plots (Fig. 4.13). The mean pore count of LTP and STP for three tillage systems in the HT and UT locations and pore count of UT and HT for various tyre inflation pressures and tillage systems are shown in Figs. 4.15 -4.16. These figures show that pore count was more in the LTP treatment plots than the STP while between trafficked locations, UT location across tire inflation pressure and tillage treatment had shown a higher pore count than HT.

Statistical results show that tyre inflation pressure (P = 0.05), tyre inflation pressure and soil depth (P = 0.010), the interaction effect of tyre inflation pressure and tillage system in HT (P = 0.030) in HT location, and trafficked location and soil depth (P = <0.001) had a significant effect on the number of pores of soil (Table 4.1 and Figs. 4.17-4.18). The tillage system was not significant on the mean pore count of soil (P = 0.95; Fig. 4.17b). Table 4.1 shows that the mean number of pores was recorded to be significantly 38.8% higher in LTP (105.2) than in the STP plots (75.8) (n = 75). The interaction effect of LTP and DT treatments in HT location had a higher number of pores (118) which was significantly different from the treatment combination of STP and NT (70) and STP and DT (59.10) (n = 25). A higher number of pores were also observed in all depths in the LTP treatment; however, the significant differences were observed in the soil depth of 60-120 mm and 120-180 mm (n = 15; Fig. 4.17a and Appendix 4.1). Irrespective of tyre inflation pressure, the mean pore count of all slices was recorded to be significantly higher in UT location (164) than HT areas (91) (n = 150; Appendix 4.2). Mean pore count at different soil depths showed that topsoil (0-60 mm) had the higher pore count that was followed by the depth 60-120mm, however, UT had higher pore count as compared to the HT location. Mean pore count was decreased in the subsequent soil depths and the lowest mean pore count was recorded in soil depth of 180-240 mm (Fig. 4.18). The combined effect of tyre inflation pressure, tillage system and the trafficked location was not significant at 5% level but was found to be significant at the 20% level (P = 0.06; n = 25), where the highest number of pores was obtained in the combination of LTP × ST × UT which was significantly different from others except LTP × DT × UT, STP × ST × UT and STP × ST × UT (Fig. 4.19).

Table 4.1. Effect of tyre inflation pressure and tillage system on the number of pores in the heavily trafficked location

Treatments	Number of pores			Mean
	DT	ST	NT	
STP	59.1[a]	98.3[bc]	70.0[ab]	75.8[a]
LTP	118.0[c]	86.7[abc]	110.9[c]	105.2[b]
Mean*	88.6[a]	92.5[a]	90.5[a]	
20 and 96 DF	SEM	P value	LSD	CV (%)
TIP	7.31	0.05	21.56	31.30
TS	8.95	0.95	26.41	
TIP × TS	12.66	0.03	37.35	

Note: TIP, TS, STP, LTP, DT, ST, NT and DF represent tyre inflation pressure, tillage systems, standard tyre inflation pressure, low tyre inflation pressure, deep tillage, shallow tillage, no-till and degree of freedom, respectively. Means with the same letter are not significantly different (P = 0.05) from each other.

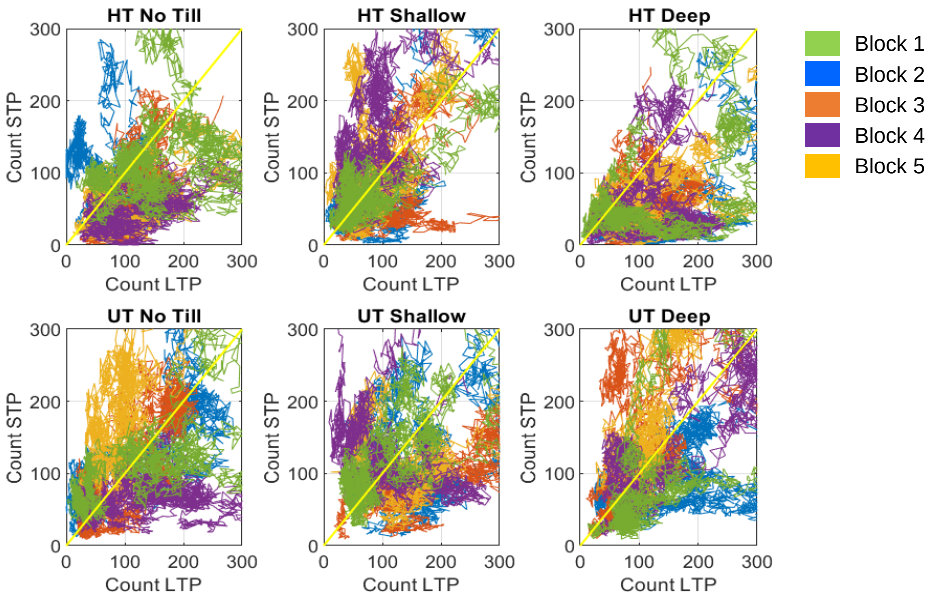


Figure 4.11. STP vs LTP pore count for HT (top row) and UT (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios. Indicating that the majority of pore counts data points lie below the yellow equality line.

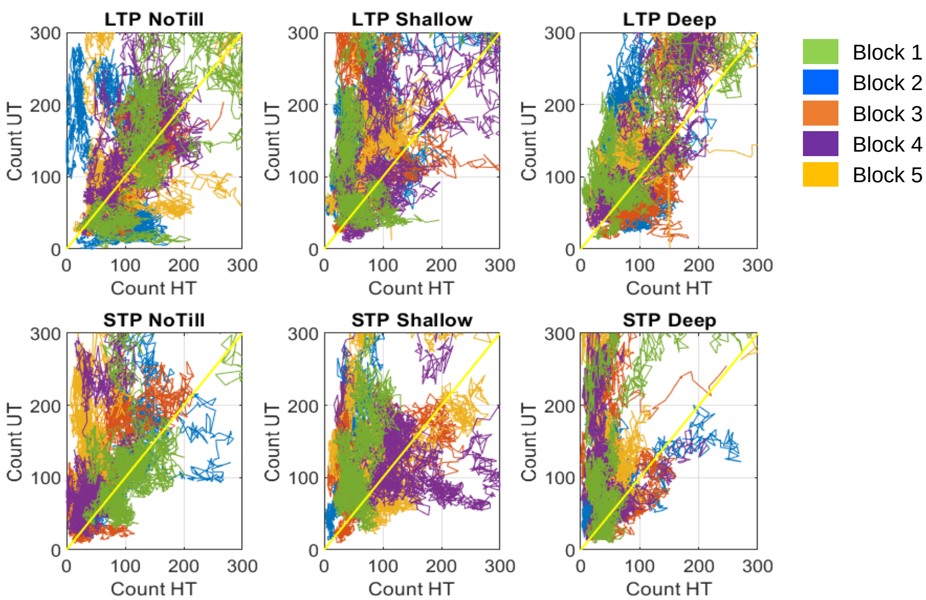


Figure 4.12. UT vs HT pore count for LTP (top row) and STP (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios. Indicating that the majority of pore counts data points lie below the yellow equality line.

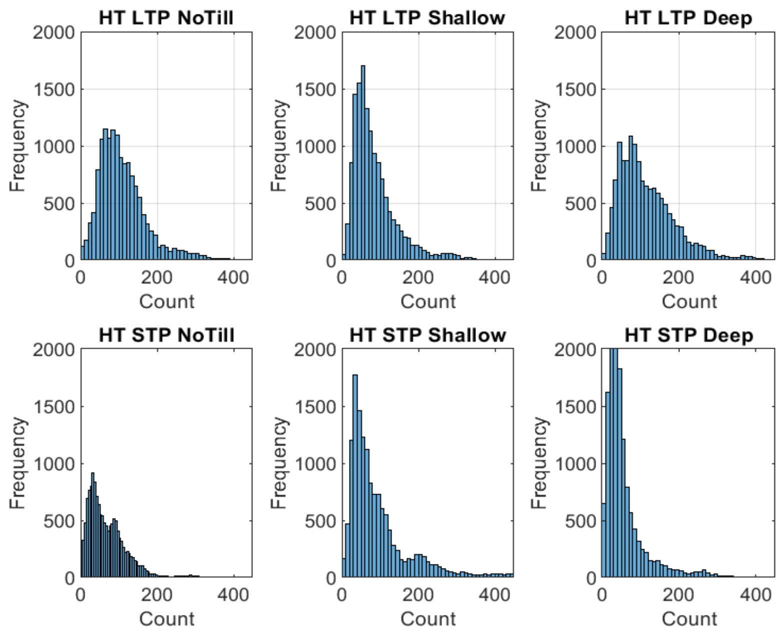


Figure 4.13. Frequency vs pore count for LTP (top row) and STP (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios in the HT location.

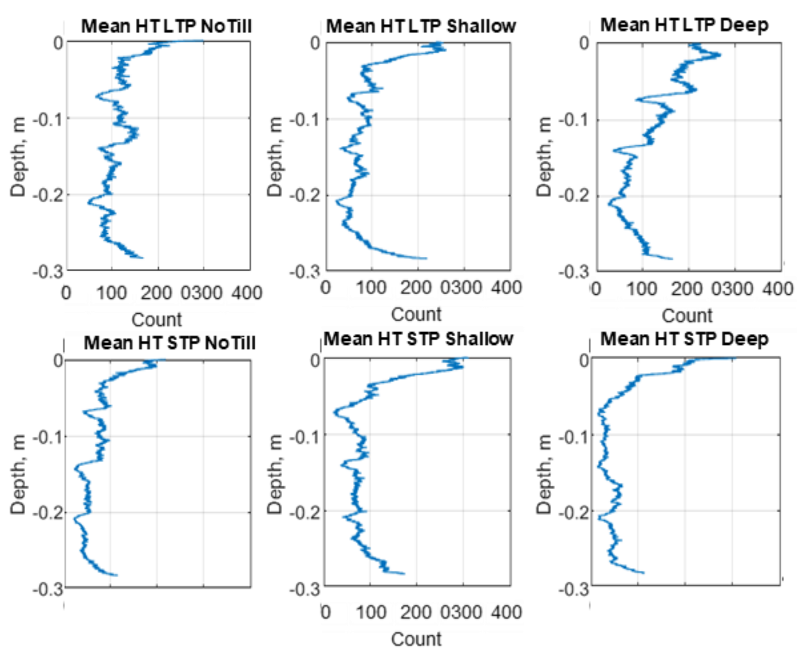


Figure 4.14. Pore count vs soil depth for LTP (top row) and STP (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios in the HT location.

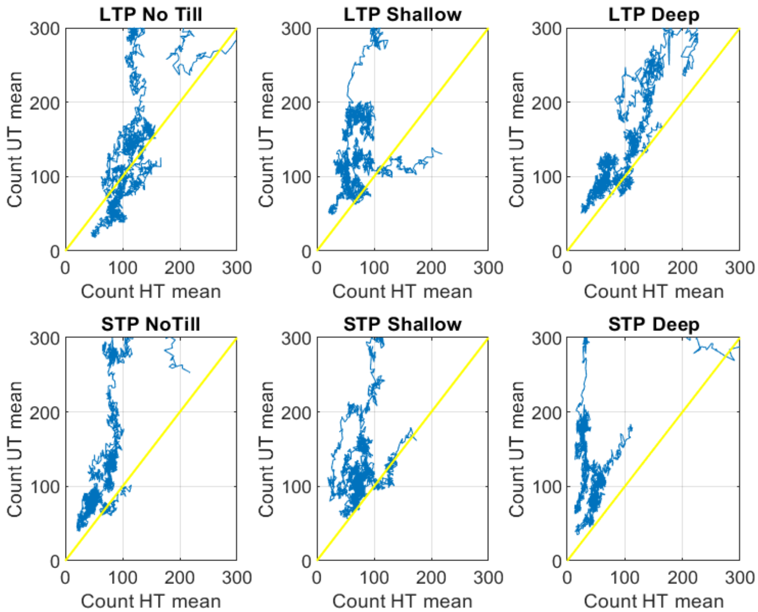


Figure 4.15. UT vs HT pore count for LTP (top row) and STP (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios. Indicating that the majority of pore counts data points lie above the yellow equality line.

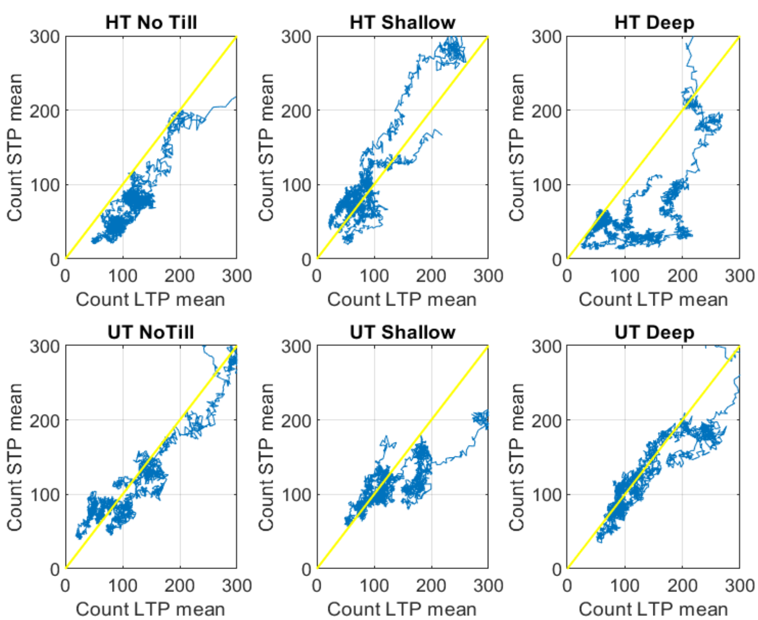


Figure 4.16. STP vs LTP pore count for LTP (top row) and STP (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios. Indicating that the majority of pore counts data points lie below the yellow equality line.

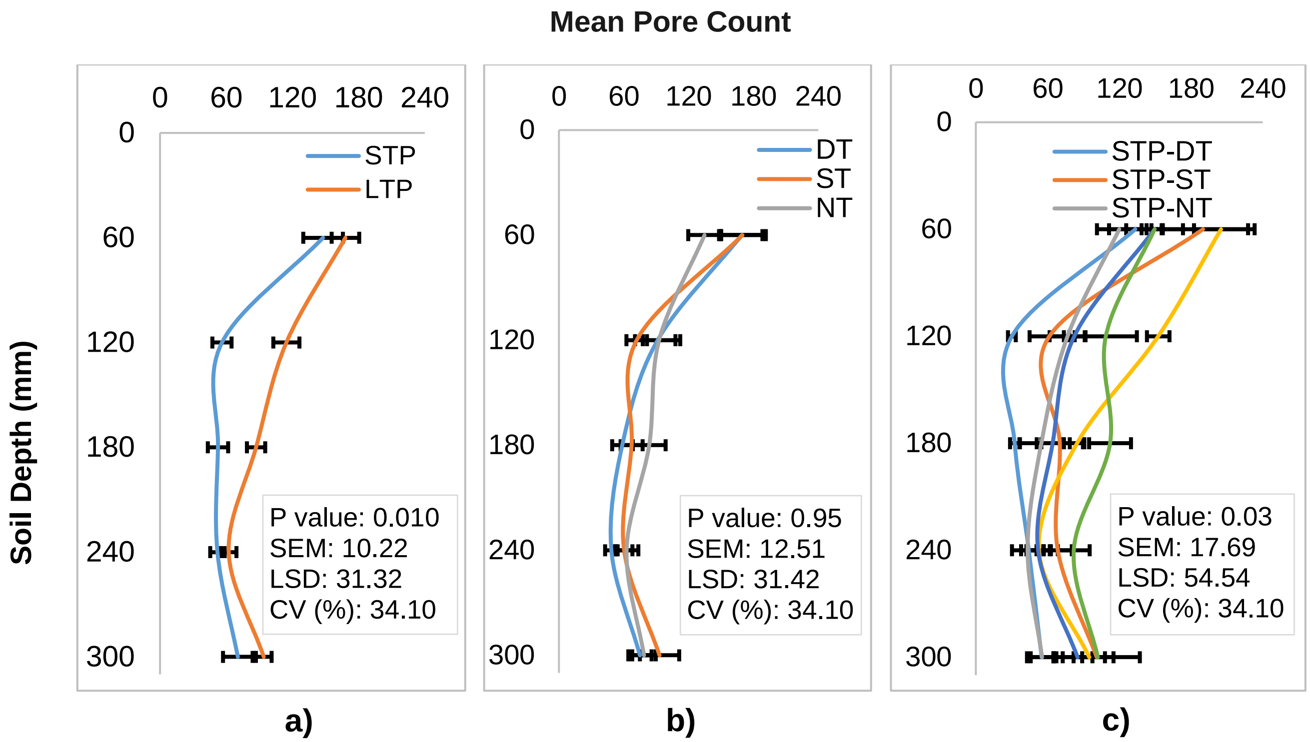


Figure 4.17. Effect of tyre inflation pressure (a), tillage system (b) and their combined effect (c) on the mean pore count of soil in the HT Location. Error bar indicates the standard error of mean.

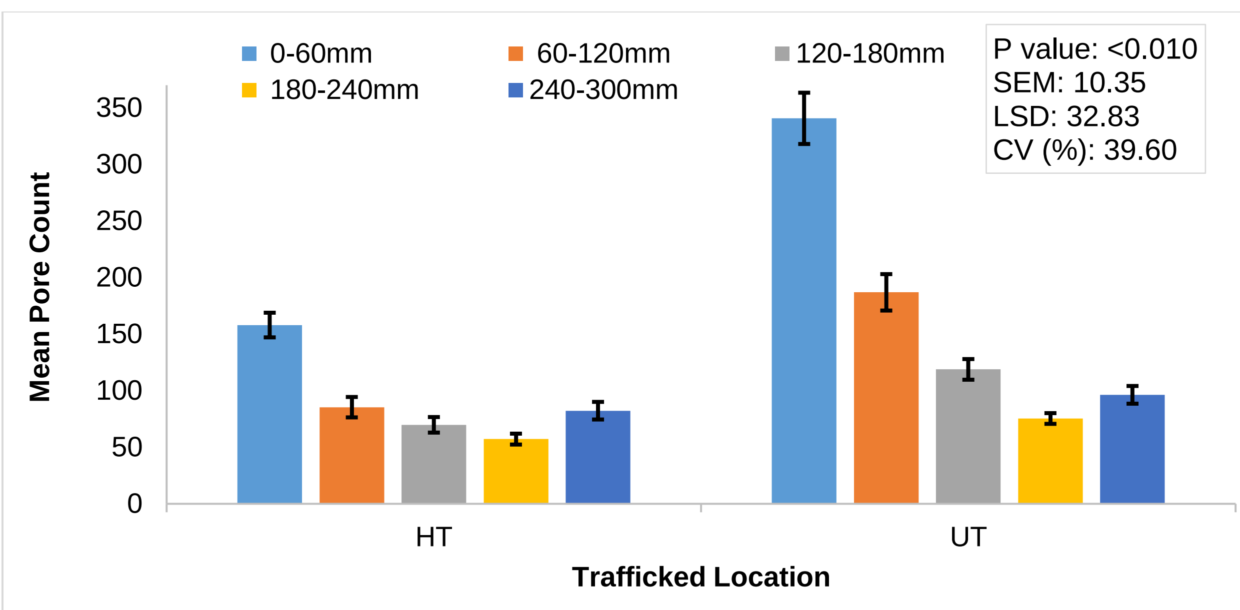


Figure 4.18. Mean pore count vs trafficked location at different soil depths. Error bar indicates the standard error of mean.

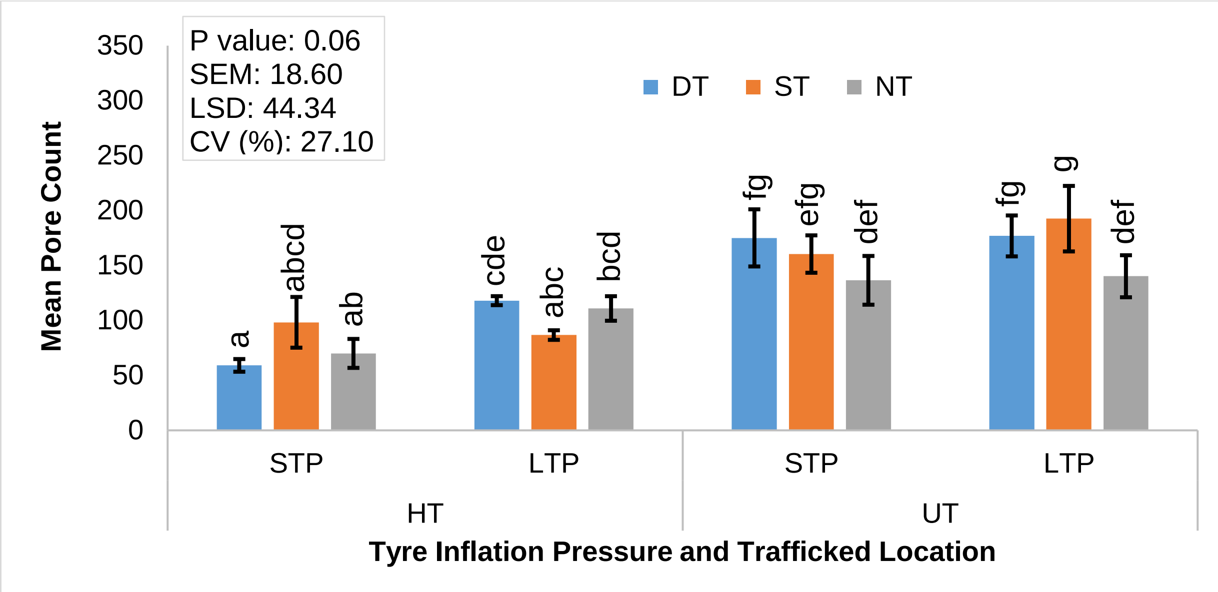


Figure 4.19. Mean pore count vs. tyre inflation pressure and trafficked Locations for different tillage systems. Error bar indicates the standard error of mean.

4.5.3. X-ray CT Measured Percentage Macroporosity (CT_P)

X-ray CT results showed that tyre inflation pressure (P = 0.004), trafficked location (P = <0.001), soil depth (P = <0.001), tyre inflation pressure and soil depth in HT location (P = 0.004), tyre inflation pressure irrespective of trafficked locations (P = 0.014), and interaction effect of trafficked location and soil depth (P = <0.001) had a significant effect on the CT_P of the test soil (Table 4.2 and Figs. 4.20-4.22 and Appendix 4.3). The effect of tillage system and interaction with tyre inflation pressures were not significant. In HT location, the CT_P was recorded as significantly 62.4% higher in LTP (4.66%) compared to STP mode (2.87%) (P = 0.004 and n = 75; Table 4.2). Fig. 4.20a shows that the LTP treatment throughout soil depth had a higher CT_P than the STP, as, it was significantly increased at depths of 60-120mm (5.54%) and 120-180mm (5.08%) (n = 15). Like pore count, the highest CT_P was observed in the soil depth of 0-60mm (6.25%) and decreased with depths with the lowest CT_P of 3.93% was recorded in the depth of 240-300mm. Even though upper soil strata (approx. 0-60mm soil depth) in both UT and HT locations had a higher CT_P, however, the CT_P was recorded to be higher in UT than HT. The trend of CT_P presence in the soil profile is similar to the trend of the number of pores and thus indicating that the number of pores and CT_P are inversely proportional to soil depth. Similarly, the mean CT_P across trafficked locations was recorded as 55.4% higher in LTP (5.84%) than

STP (4.36%) (n = 150). When considering the trafficked locations, the HT had a 41.5% lower CTp (3.77%) than the UT location (6.44%) (n = 150; Fig. 4.21), however, the differences between them throughout soil depths were higher as shown in Fig. 4.22.

Mean CT_P throughout the soil profile plotted as STP vs LTP in different tillage systems and trafficked locations, and UT vs HT in different tyre inflation pressures and tillage systems and CT_P across soil profile are shown in Figs. 4.23 - 4.26. Fig. 4.23 shows that pore percent area (CT_P) data points were more bountiful in the UT locations compared to HT. Similarly, visualization of CT_P distribution was greater in LTP plots not only across five replications of the experimental field than that of STP but also more throughout the soil depth (Figs. 4.24 and 4.26).

Table 4.2. Effect of tyre inflation pressure and tillage system on the CT measured macroporosity in the heavily trafficked location.

Treatments	CT Measured Macroporosity (%)			Mean
	DT	ST	NT	
STP	2.69[a]	3.05[a]	2.87[a]	2.87[a]
LTP	5.03[a]	4.16[a]	4.80[a]	4.66[b]
Mean*	3.86[a]	3.60[a]	3.83[a]	
20 and 96 DF	SEM	P value	LSD	CV (%)
TIP	0.38	0.004	1.13	39.50
TS	0.47	0.91	1.38	
TIP × TS	0.67	0.65	1.96	

Note: TIP, TS, STP, LTP, DT, ST, NT and DF represent tyre inflation pressure, tillage systems, standard tyre inflation pressure, low tyre inflation pressure, deep tillage, shallow tillage, no-till and degree of freedom, respectively. Means with the same letter are not significantly different (P = 0.05) from each other.

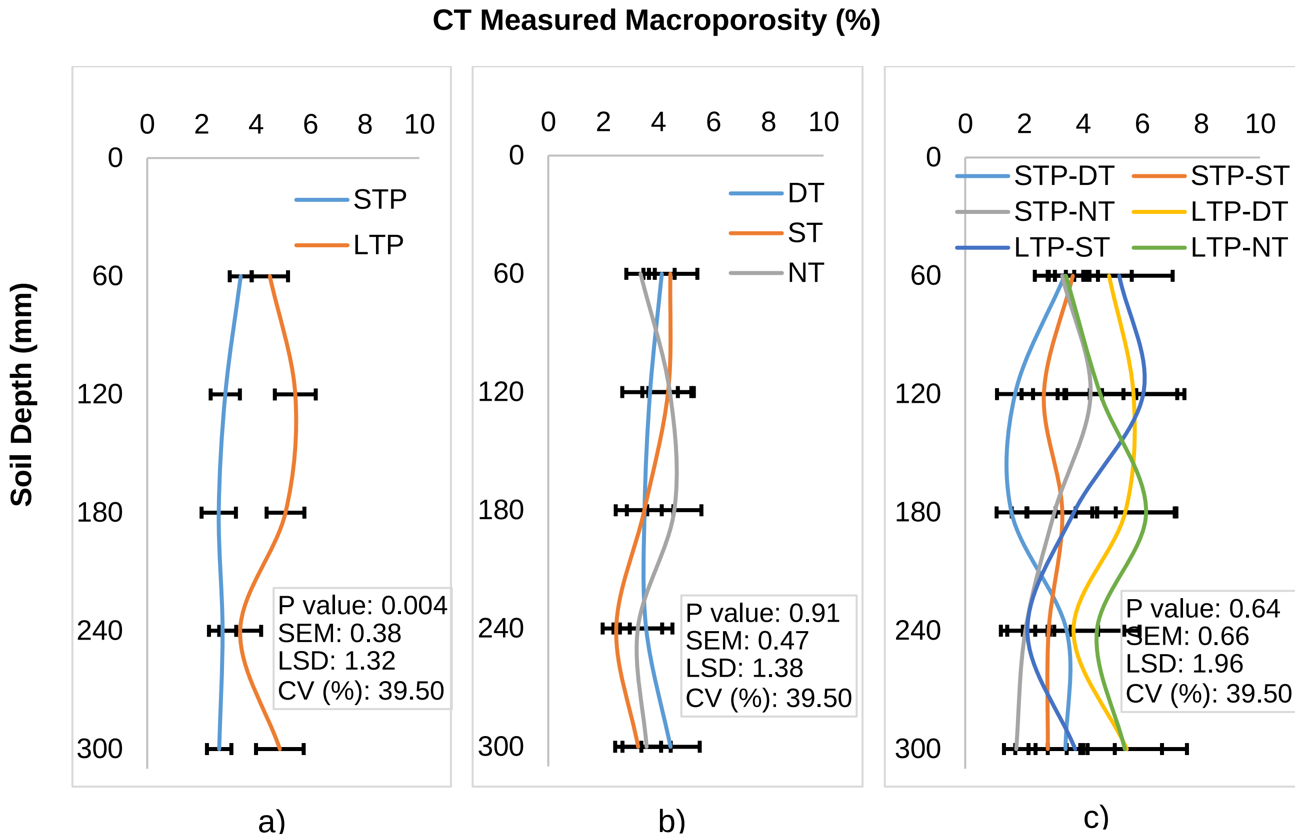


Figure 4.20. Effect of tyre inflation pressure (a), tillage system (b) and their interaction (c) on the CT measured macroporosity of soil in HT location. Error bar indicates the standard error of mean.

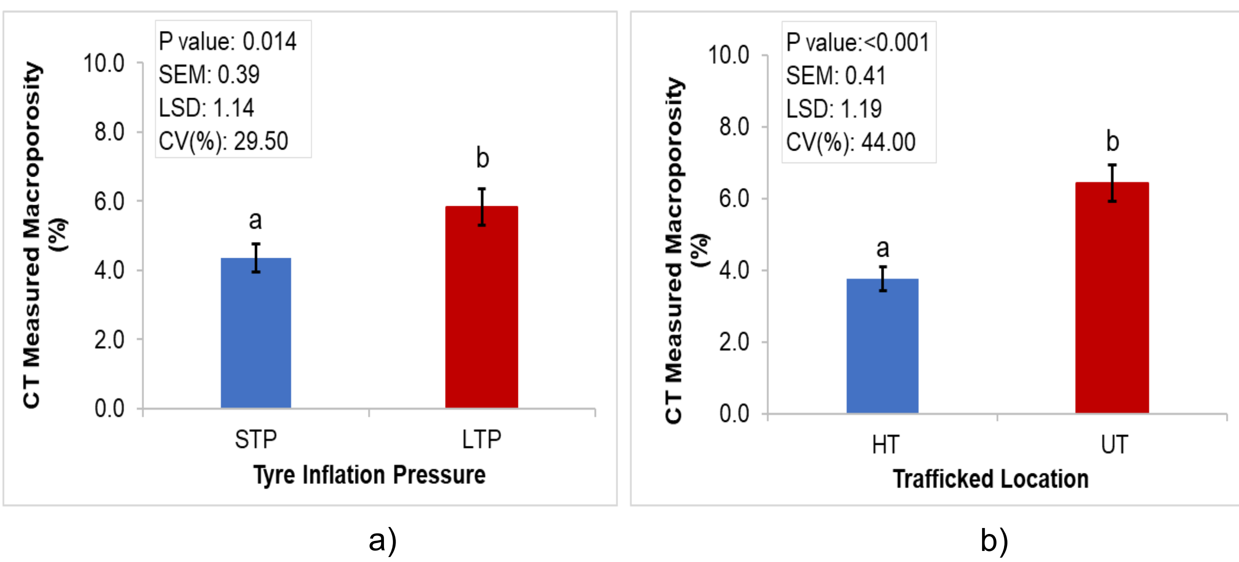


Figure 4.21. Effect of tyre inflation pressure (a) and trafficked location (b) on CT measured macroporosity of soil. Error bar indicates the standard error of mean.

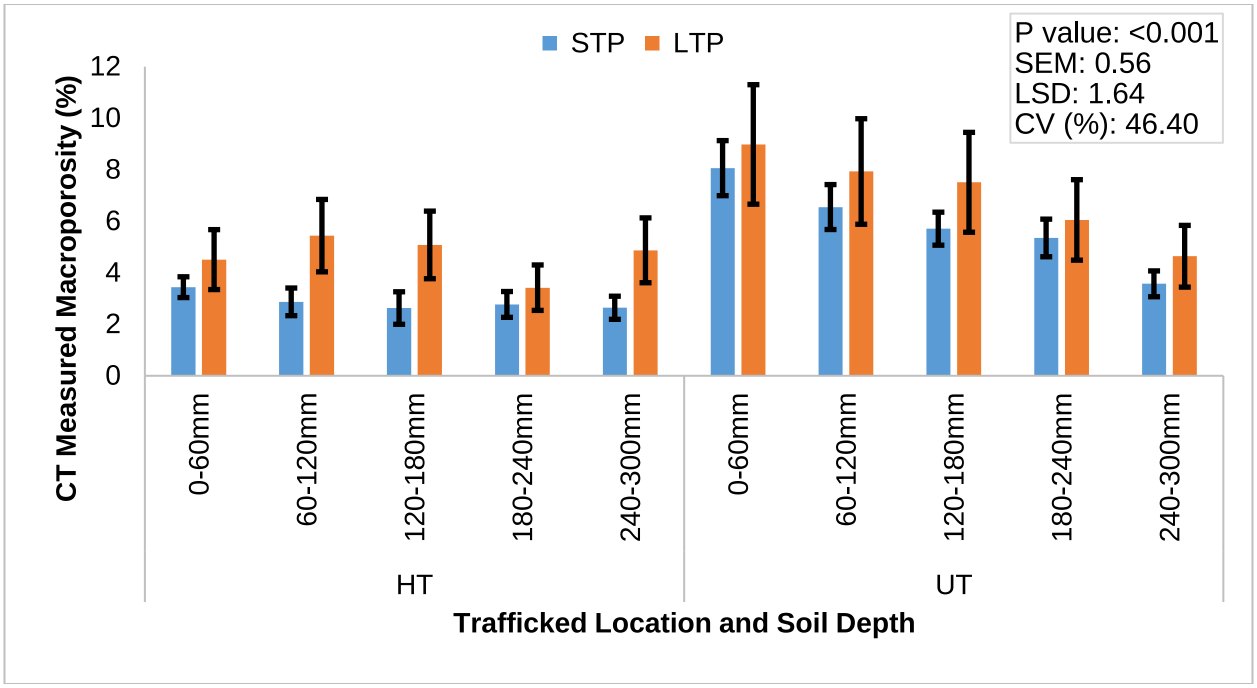


Figure 4.22. Effect of trafficked location and soil depth on the CT measured macroporosity of soil. Error bar indicates the standard error of mean.

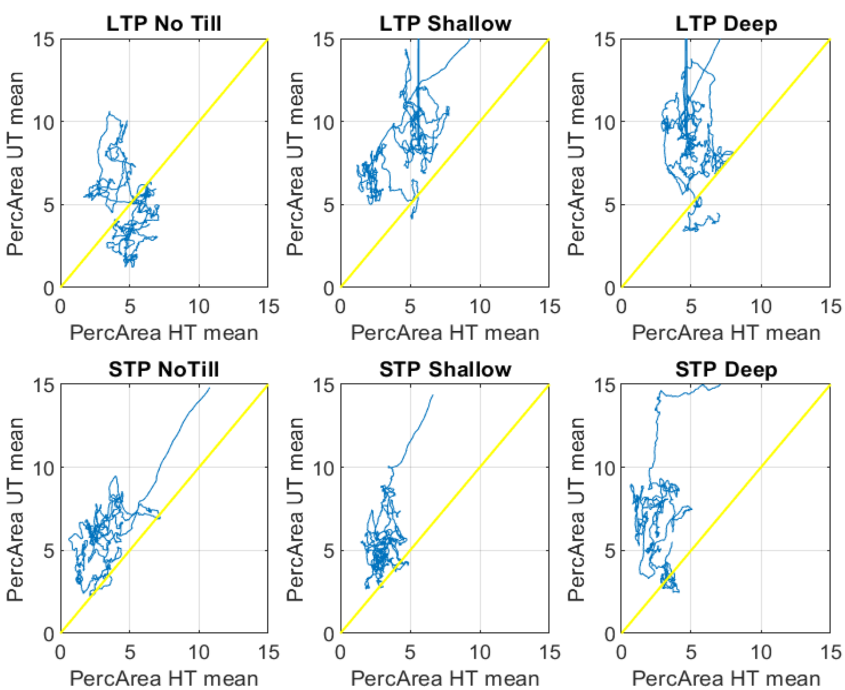


Figure 4.23. UT vs HT percent area (CT_P) for LTP (top row) and STP (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios. Indicating that the majority of percent area data points lie above the yellow equality line.

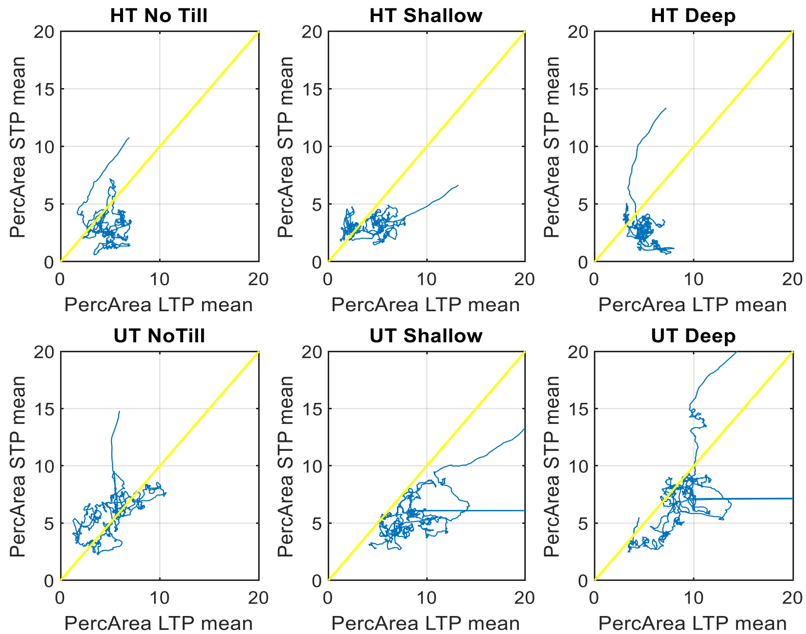


Figure 4.24. STP vs LTP percent area (CT_P) for HT (top row) and UT (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios. Indicating that the majority of percent area data points lie below the yellow equality line.

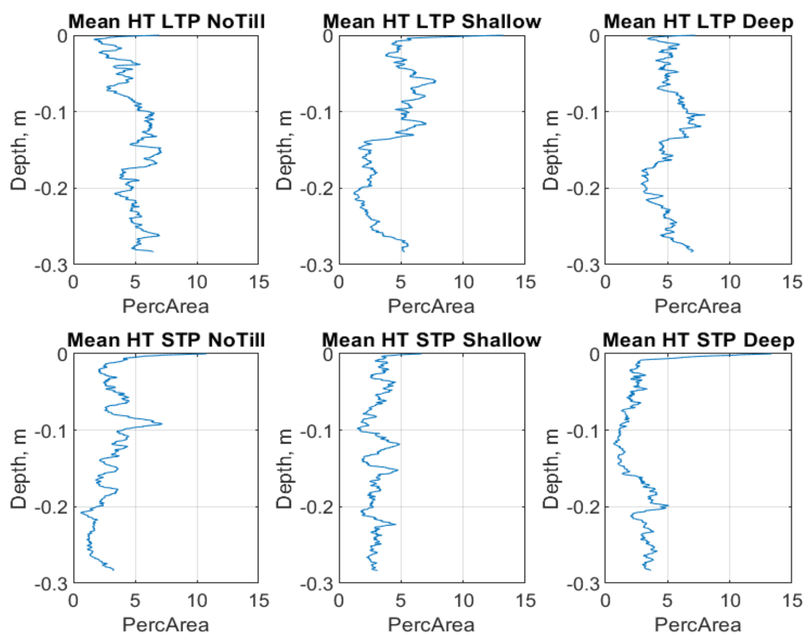


Figure 4.25. Depth vs percent area (CT_P) for LTP (top row) and STP (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios in HT Location.

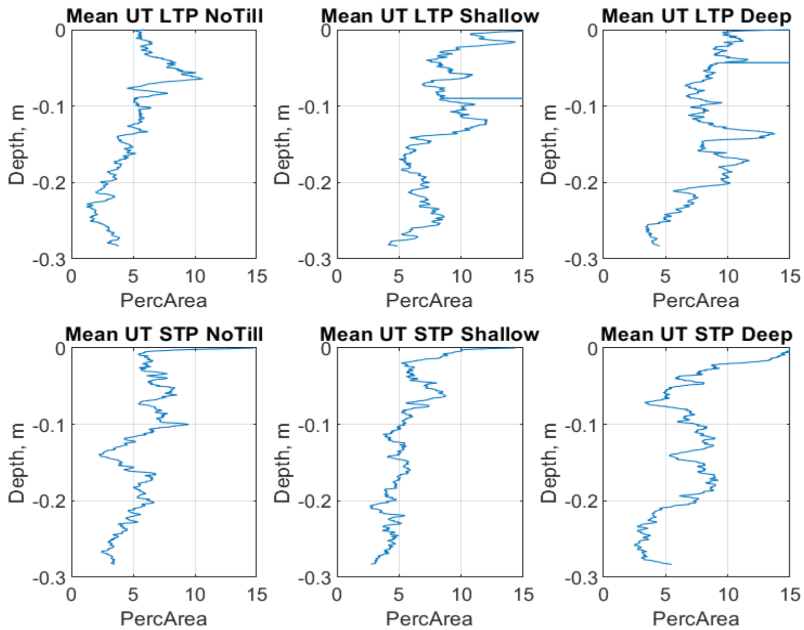


Figure 4.26. Depth vs percent area (CT_P) for LTP (top row) and STP (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios in UT location.

4.5.4. Total Pore Area (TPA)

The results showed that tyre inflation pressure (0.004), tyre inflation pressure across depth (P = 0.004) in HT location, tyre inflation pressure irrespective of trafficked locations (P = 0.014), trafficked location (P =<0.001), soil depth (<0.001) and the combined effect of trafficked location and soil depth (P =<0.001) had a significant effect on the mean total pore area in soil (Table 4.3, Figs. 4.27a and 4.28, and Appendices 4.4 - 4.5). However, the tillage system and its interaction with tyre inflation pressure were not significant (Fig. 4.27b-c). Table 4.3 shows that the mean TPA in the HT location was recorded as 63.6% higher in the LTP (92.60 mm^2) than the STP treatment (56.60 mm^2) (n = 75). Similarly, across depths, the LTP had an increased TPA than STP, however, significantly higher mean TPA was recorded in soil depths of 60-120 mm and 120-180 mm in which LTP treatment had almost double TPA (108.03 and 100.88 mm^2, respectively) than the STP treatment (56.77 and 52.14 mm^2, respectively) (n = 15; Fig. 4.27a). Irrespective of trafficked location, higher TPA was recorded in LTP (116 cm^2) than STP (86.5 cm^2) (n = 150) while between trafficked locations, the HT location had a lower mean TPA (74.7 mm^2) as compared to the UT location (127.8 mm^2) (n = 150; Appendix 4.5) with a lower TPA throughout soil depths than UT (n = 30; Fig. 4.28). In contrast, among soil depths, the mean TPA was observed to be significantly higher in soil depth of 0-60mm (124 mm^2) that all subsequent soil depths, while the lowest mean TPA was recorded in the depth of 240-300mm (78 mm^2) (n = 60; Appendix 4.5). The trend in mean TPA was found to be similar to that observed in CTp, indicating that both CTp and mean TPA were inversely proportional to soil depth (0-60 mm> 60-120 mm> 120-180 mm> 180-240 mm> 240-300 mm). These findings confirm that deeply tilled soils have lower soil strength and less ability to support field trafficking which increases susceptibility to re-compaction (Soane et al., 1986).

To visualize mean TPA across the whole soil profile, TPA data plotted as STP vs LTP for HT and UT locations showed that the mean TPA was higher on average in LTP than that of STP plots (Fig. 4.29). Similarly, HT vs UT TPA for STP and LTP in different tillage systems indicated that UT had a higher mean TPA than the HT locations (Fig. 4.30). The mean TPA across soil depths in both HT and UT locations also indicates a higher mean TPA throughout the soil profile for the UT rather than HT locations and mean TPA decreased with increased soil depths (Fig. 4.31).

Table 4.3. Effect of tyre inflation pressure and tillage system on the total pore area in the heavily trafficked location.

Treatments	Total Pore Area (mm^2)			Mean
	DT	ST	NT	
STP	53.5^a	60.0^a	56.9^a	56.8^b
LTP	100.0^a	82.5^a	95.3^a	92.6^a
Mean	76.7^a	71.3^a	76.1^a	
20 and 96 DF	SEM	P value	LSD	CV (%)
TIP	7.65	0.004	22.59	39.70
TS	9.37	0.90	27.67	
TIP × TS	12.49	0.66	39.14	

Note: TIP, TS, STP, LTP, DT, ST, NT and DF represent tyre inflation pressure, tillage systems, standard tyre inflation pressure, low tyre inflation pressure, deep tillage, shallow tillage, no-till and degree of freedom, respectively. Means with the same letter are not significantly different (P = 0.05) from each other.

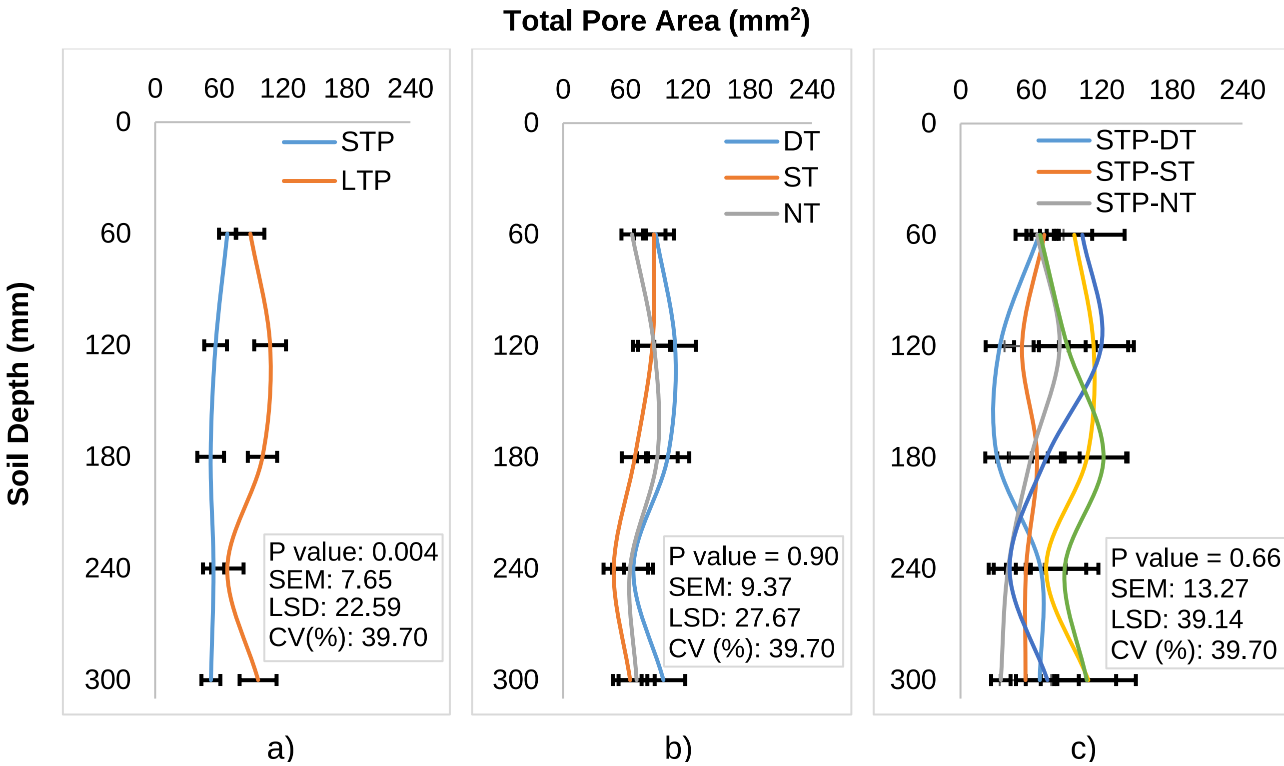


Figure 4.27. Effect of tyre inflation pressure (a), tillage system (b) and their interaction (c) on the total pore area (Soil Depth vs. TPA). Error bar indicates the standard error of mean.

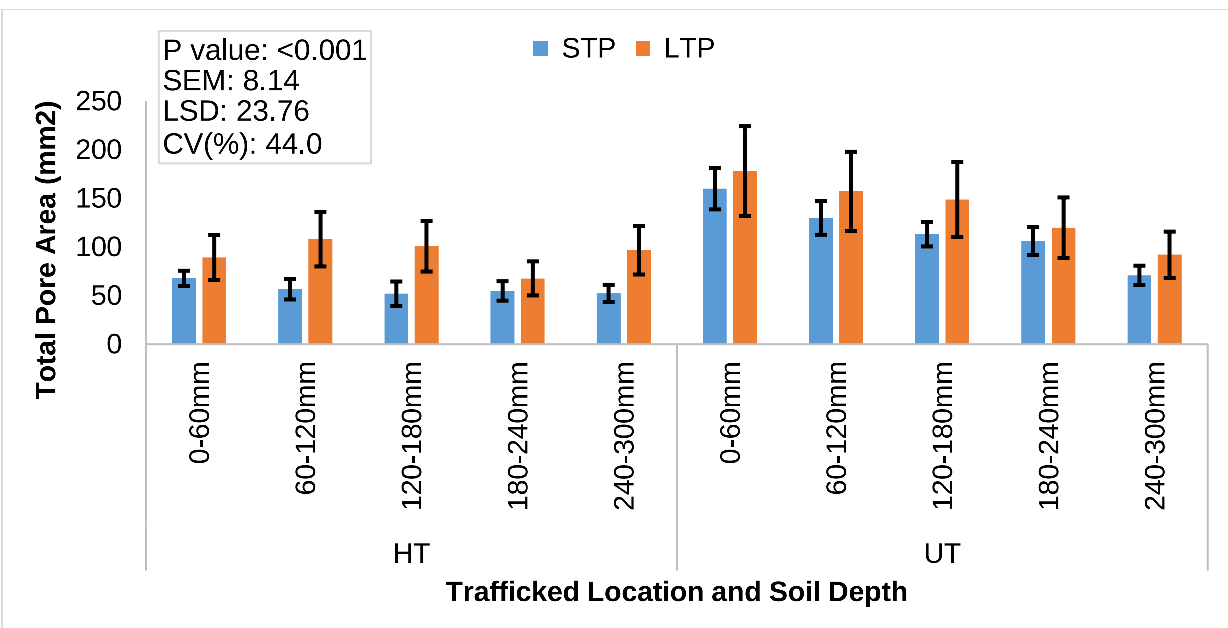


Figure 4.28. Effect of trafficked location and depth on the total pore area of soil. Error bar indicates the standard error of mean.

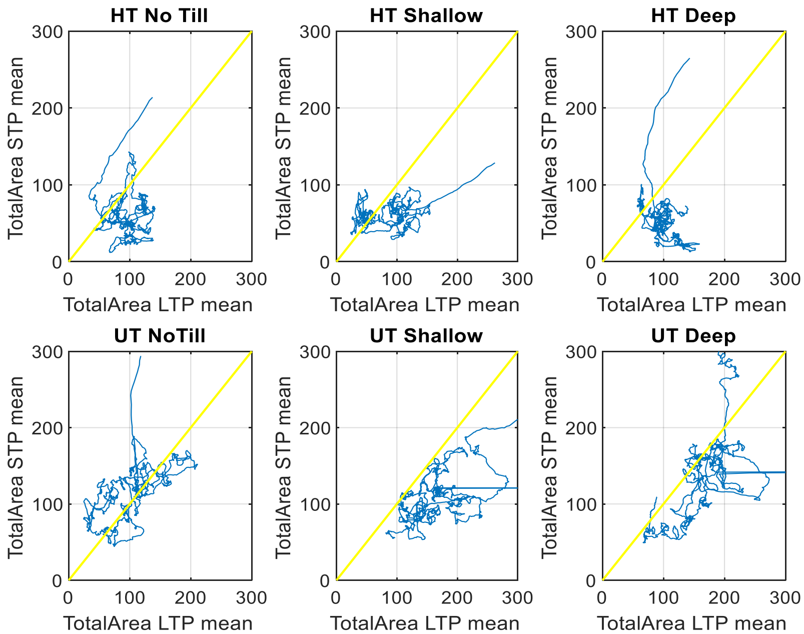


Figure 4.29. Total area STP mean vs total area LTP mean for HT (top row) and UT (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios. Indicating that the majority of data points lie below the yellow equality lines.

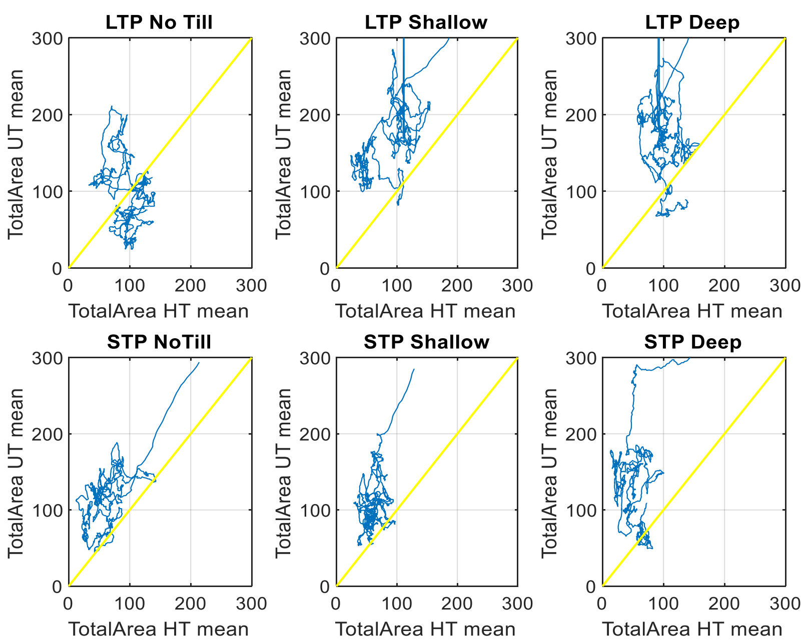


Figure 4.30. Total area UT mean vs total area HT mean for LTP (top row) and STP (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios. Indicating that the majority of total area data points lie above the yellow equality line.

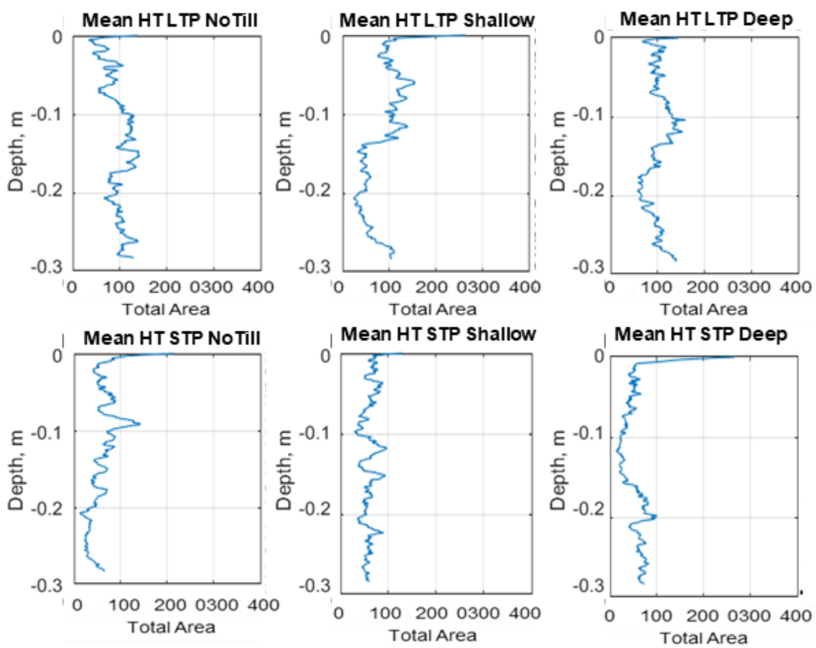


Figure 4.31. Depth vs total area for LTP (top row) and STP (bottom row) in NT (left column), ST (centre column) and DT (right column) scenarios in HT Location.

4.5.5. Average Size of Pore and Pore Size Distribution

The average pore size and pore size distribution in the soil are given in Figs. 4.32 – 4.36. Results showed that only soil depth had a significant effect on the average sizes of pores (P = 0.001, n= 60) while the combined effect of trafficked location and soil depth had a significant effect at 10% level (P = 0.06, n = 30) (Fig. 4.32-4.33). The main effect of tyre inflation pressure, tillage system and their interaction, however, were not significant. It was observed that the average size of pores was recorded to be significantly higher at a soil depth of 180-240 mm (1.35 mm^2) that was followed by the depths of 120-180 (1.24 mm^2) and 240-300 mm (1.11 mm^2), respectively. The lowest average size of the pore was obtained at a depth of 0-60mm (0.66 mm^2, Fig. 4.32). It indicates that the average pore area was proportional to depth. Likewise, Fig. 4.33 shows that the UT location at depth 180-240 mm (1.60 mm^2) had the highest average size of pores which was followed by the same location at depth 120-180mm (1.29 mm^2) while the lowest average size of pores was recorded in the treatment HT at depths of 0-60 mm (0.65 mm^2). As trafficked location had no significant effect on the average size of pores, such differences in location × depth combination are presumably due to the effect of soil depth, indicating again that average pore size was proportional to soil depth.

Pore size distribution is often considered one of the most relevant soil structure characteristics as it affects plant growth (Cary and Hayden, 1973). It highlights the complexity of soil structure between treatments as compared with percentage porosity (Nimmo, 2013). The pore size distribution of tyre inflation pressure, tillage system and their interaction, are shown in Figs. 4.34 and 4.35. The mean pore size distribution cumulative frequency of tyre inflation pressure and tillage system treatments and their combined effect is also shown in Fig. 4.36. These graphs show that the differences in pore size distribution were not affected by tyre inflation pressure. However, the difference in mean pore size frequency among tillage systems became visible with mean values of DT, ST and NT were of 1.26, 1.1.03 and 0.95, respectively (P = 0.10 and n = 100; Fig. 5.36b) which was also likely to have been affected by the combination of tyre inflation pressure and tillage system treatment (Fig. 5.36c). The results are in agreement with the findings that the average pores in tilled soil were twice (0.52 mm^2) as large as pores in no-tilled soils (0.27 mm^2) (Mangalassery et al., 2014). Similar findings of having larger pores in deeply tilled soils are also reported at a depth of 100-150 mm with higher mean pore size frequency (Millington, 2019). However, the findings were varied. For example, a study showed that no-till treatment had a higher number of macropores than tilled soils possibly due to the influence of weather and microbial activity (Kay and Vandenbygaart, 2002). Lipiec et al. (2006) reported that the effect of crop roots and soil fauna may in large part be the reasons for the creation of macropores in no-till soils.

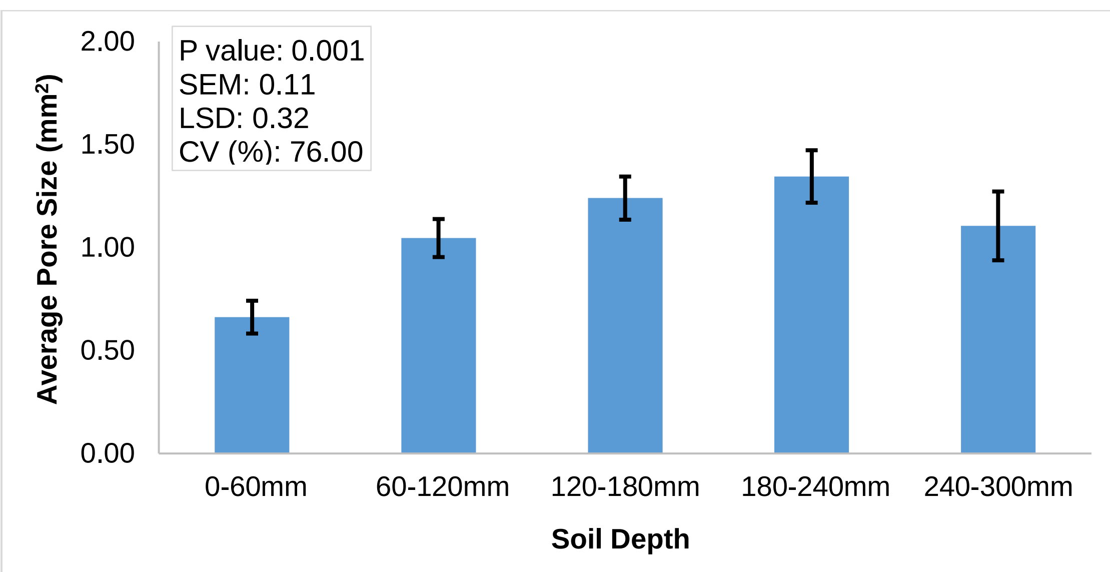


Figure 4.32. Average pore size vs soil depth. Error bar indicates the standard error of mean.

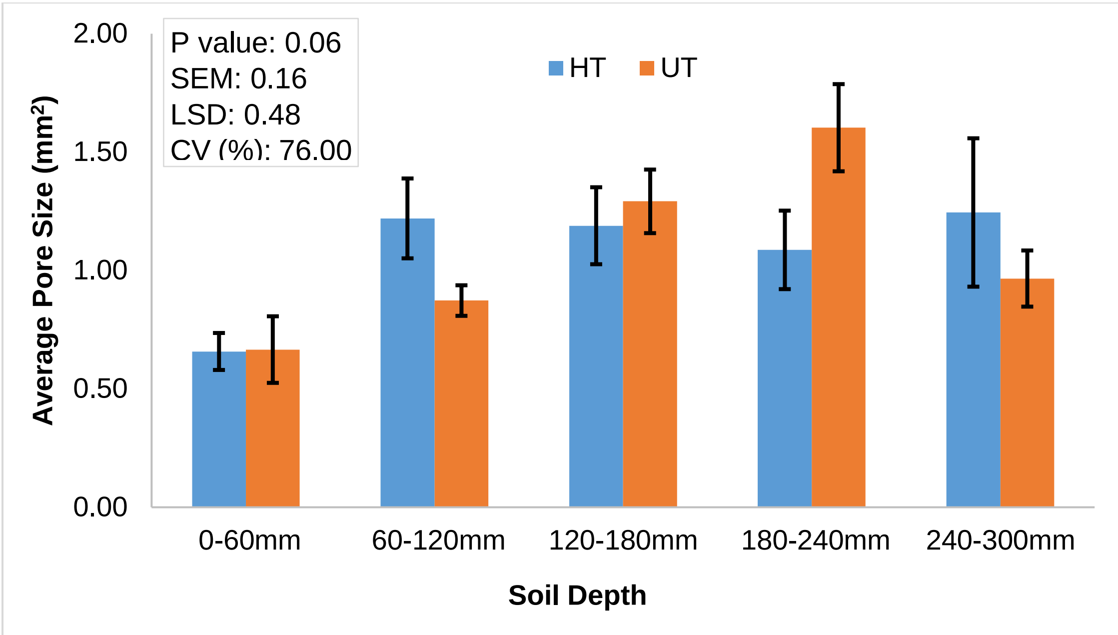


Figure 4.33. Average pore size vs soil depth for HT and UT locations. Error bar indicates the standard error of mean.

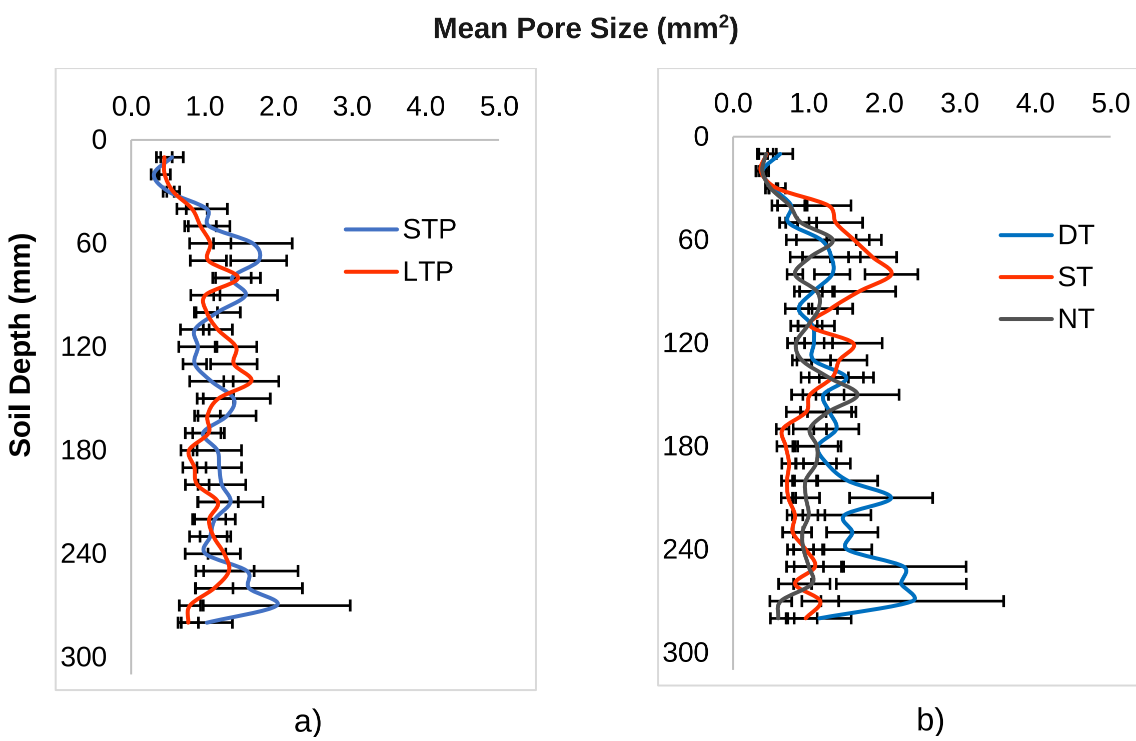


Figure 4.34. Mean pore size distribution as influenced by tyre inflation pressure (a) and tillage system (b). Error bar indicates the standard error of mean.

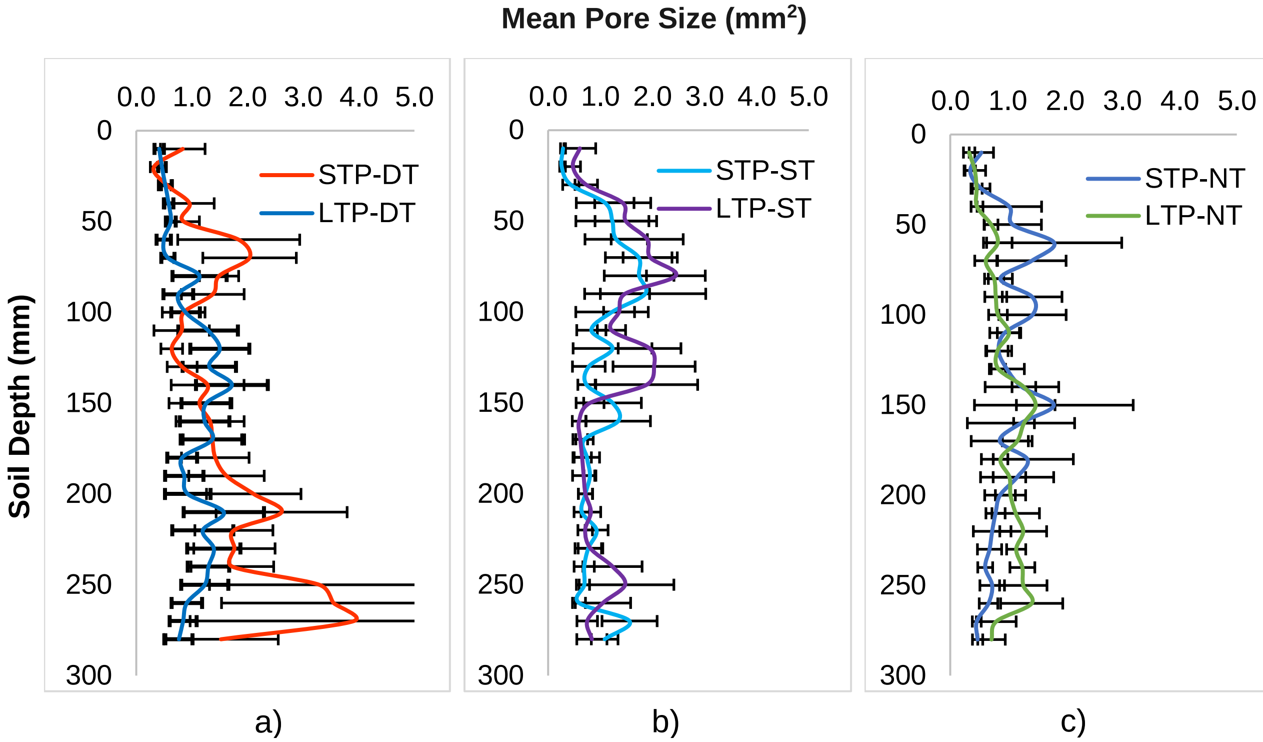


Figure 4.35. Mean pore size distribution as influenced by tyre inflation pressure and tillage system (a: DT, b: ST and c: NT). Error bar indicates the standard error of mean.

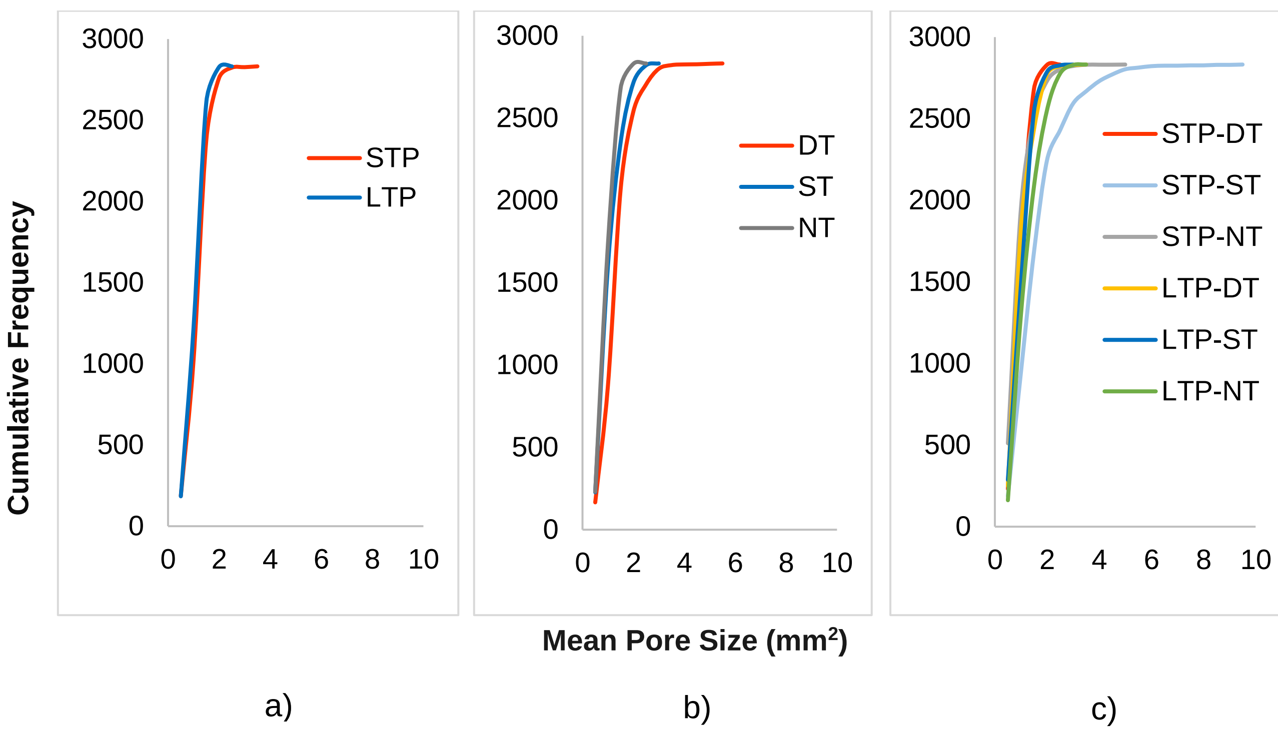


Figure 4.36. Mean pore size (mm^2) cumulative frequency of 280 mm soil core as influenced by a) tyre inflation pressure, b) tillage system and c) their interaction.

4.5.6. Pore Perimeter

Results showed that the mean pore perimeter was significantly affected by both soil depth and the combined effect trafficked location and soil depth (P =<0.001 and 0.007, respectively; Fig. 4.37 and 4.38) while tyre inflation pressure, tillage system and their interaction had no significant effect. Fig. 4.37 shows that significantly the highest mean pore perimeter was recorded at a soil depth of 180-240 mm (3.59 mm) followed by the depths of 120-180 (3.46 mm) (n = 60). The lowest average size of the pore perimeter was obtained at a depth of 0-60mm (2.35 mm). Conversely, among the combination of location and depth, the highest pore perimeter was recorded in UT treatments at a soil depth of 180-240 mm (4.00 mm) and the lowest average perimeter was recorded for the UT treatments at depths of 0-60 mm (2.31 mm) and the treatments HT at the same depths (2.39 mm) (n = 30). These results are similar to the results found in case of the average sizes of the pore that both average sizes of pores and pore perimeter increased with an increase in depth of soil.

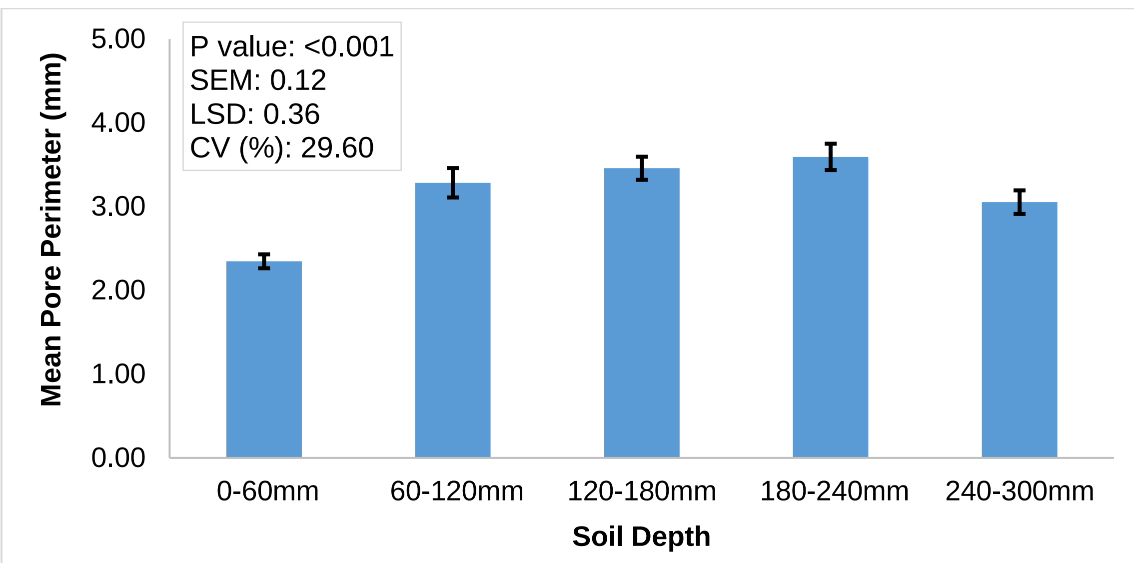


Figure 4.37. Mean pore perimeter vs soil depth. Error bar indicates the standard error of mean.

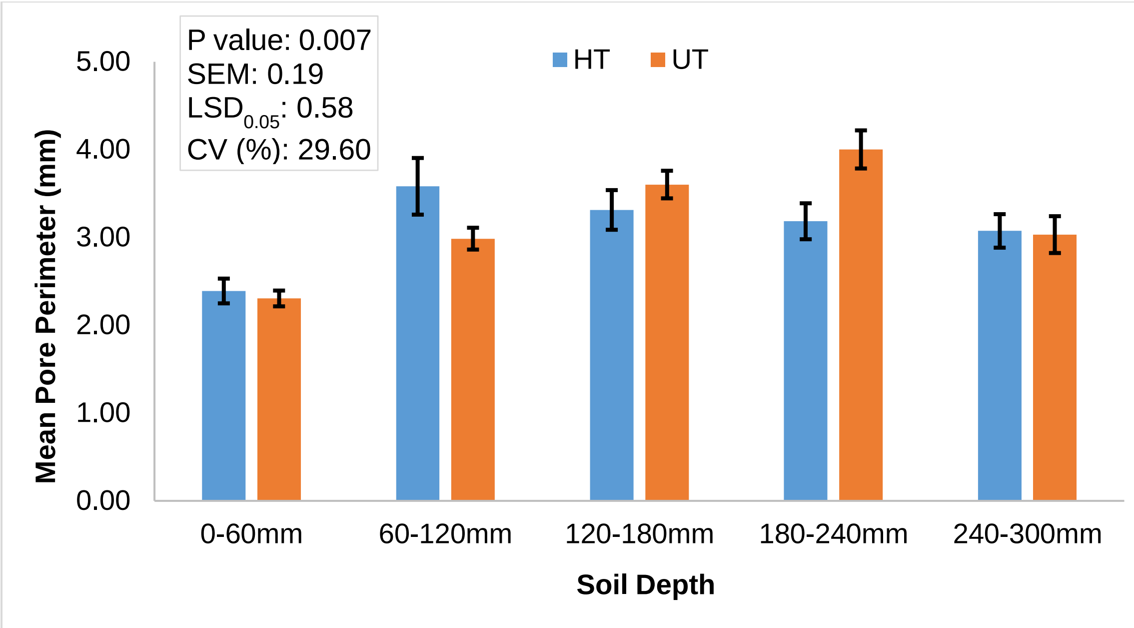


Figure 4.38. Mean pore perimeter vs trafficked location and soil depth. Error bar indicates the standard error of mean.

4.5.7. Pore Circularity

Fig. 4.39 shows that soil depth had a significant effect on the circularity of pores (P =<0.001) while its interaction with trafficked location had a significant effect at the 10% level of significance (P = 0.08, Fig. 4.40). However, there were no significant effect of tyre inflation pressure, tillage system and their interaction on the circularity of pores. The highest circularity of pores was recorded a topsoil depth of 0-60 mm (0.846) followed by the depths of 240-300 mm (0.830) (n = 60). Circularity, in general, decreased with the depth however, a further increase in trend was observed at depths of 240-300mm. The lowest circularity was obtained in the depth of 180-240 mm (0.806 mm). Likewise, the highest circularity was recorded in HT treatment location at depths of 0-60 mm (0.852 mm) that was followed by UT at the same depth of soil (0.834). The lowest circularity was observed in UT treatment locations at depths of 160-180 mm (0.798) and 180-240 mm (0.799 mm) (n = 30). However, the overall trend was that circularity is inversely proportional to soil depth up to a depth of 180mm then increased to a depth 300 mm and was partially followed the trends found in the case of average size and perimeter of pores in the soil. Circularity is a function of pore area and perimeter. Studies showed that better soil aggregation, root activity and soil flora and fauna affect the perimeter leading to affect the circularity (Rachman et al., 2005). The circularity of pores tended to be higher in both top and deeper soil layers compared to a shallower depth (Rachman et al., 2005) which is partially true to the present study.

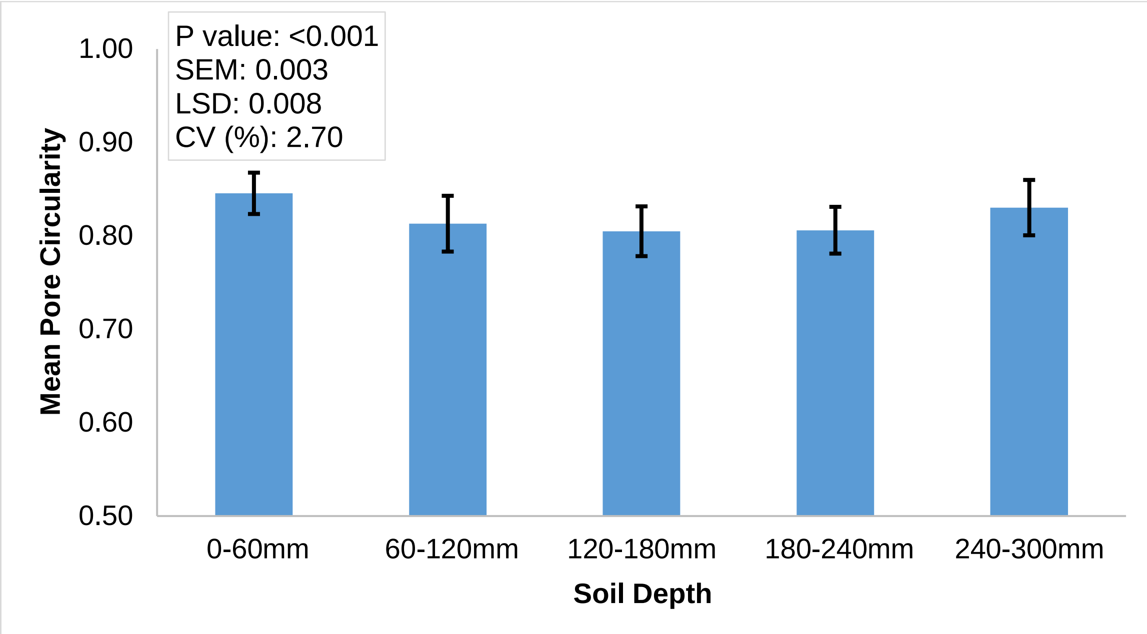


Figure 4.39. Effect of soil depth on the mean pore circularity. Error bar indicates the standard deviation of mean.

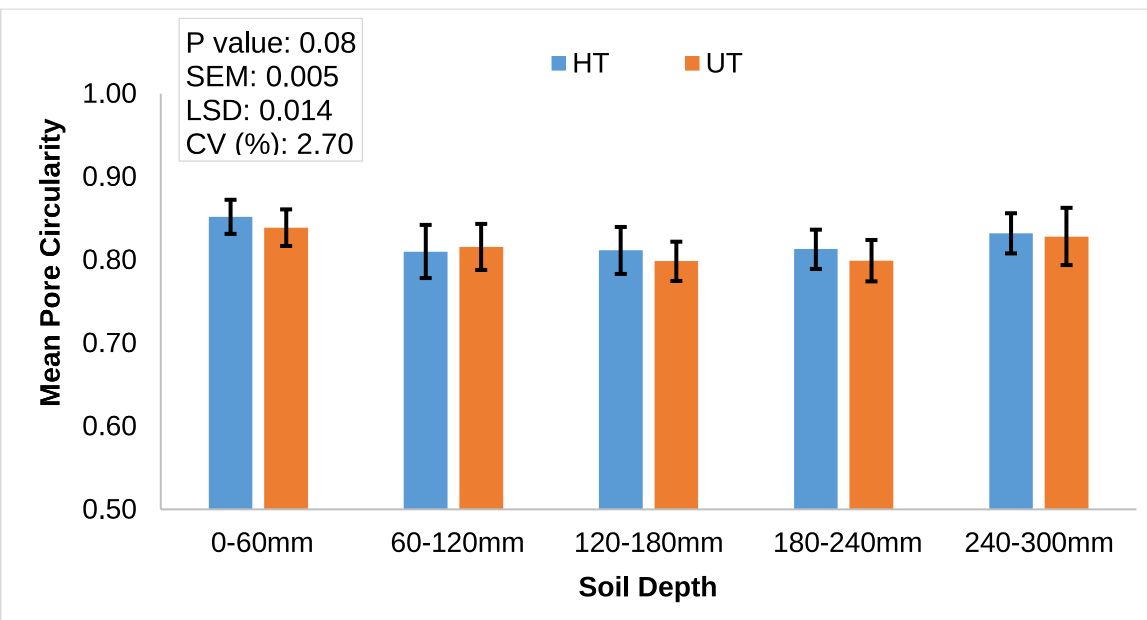


Figure 4.40. Circularity vs soil depth for HT and UT locations. Error bar indicates the standard deviation of mean.

4.5.8. Pore Solidity

Results showed that neither tyre inflation pressure nor tillage system had any significant effect on the solidity of pores. However, trafficked location and soil depth had a significant effect on the solidity of pores (P = 0.04 and P = <0.001, respectively) while their interaction had a significant effect at 10% level of significance on the solidity of pores (P = 0.06) (Figs. 4.41 and 4.42). Between trafficked locations, the solidity of pores was narrowly higher in HT treatments (0.84) than UT treatment locations (0.83) (n = 150; Fig. 4.41a). On the contrary among soil depths, the highest solidity of pores was recorded at a depth of 0-60 mm (0.849) and 240-300 mm (0.846). Similar to circularity, solidity tended to decrease initially up to 120 mm then increased in deeper soil strata to a depth of 240-300 mm. The lowest solidity of the pore was obtained at a depth of 120-180 mm (0.837) (n = 60; Fig. 4.41b).

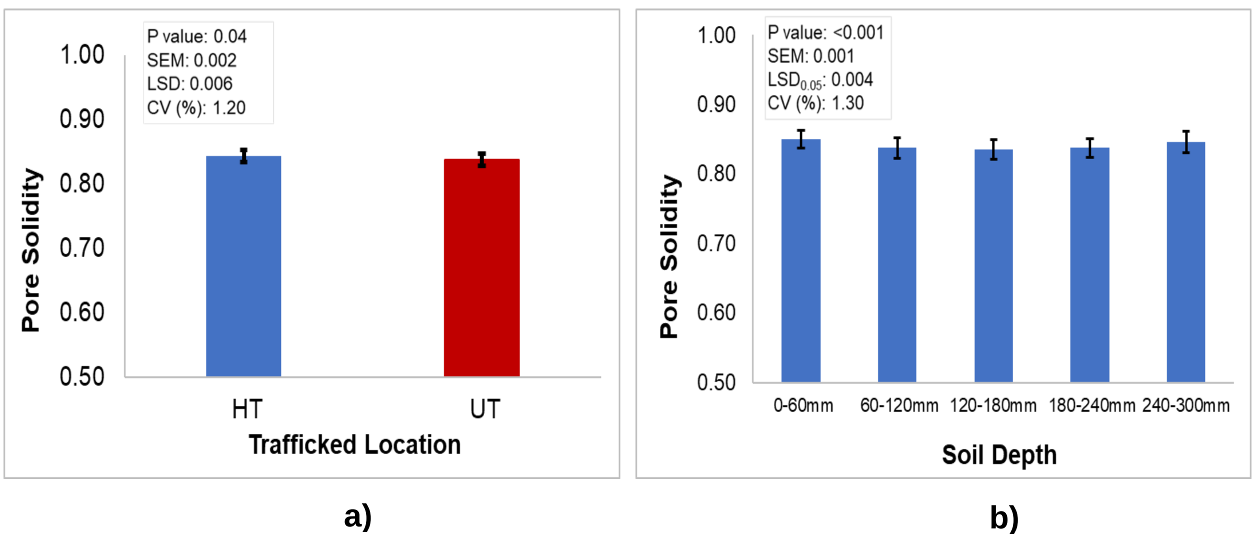


Figure 4.41. Mean pore solidity vs trafficked location (a) and soil depth (b). Error bar indicates the standard deviation of mean.

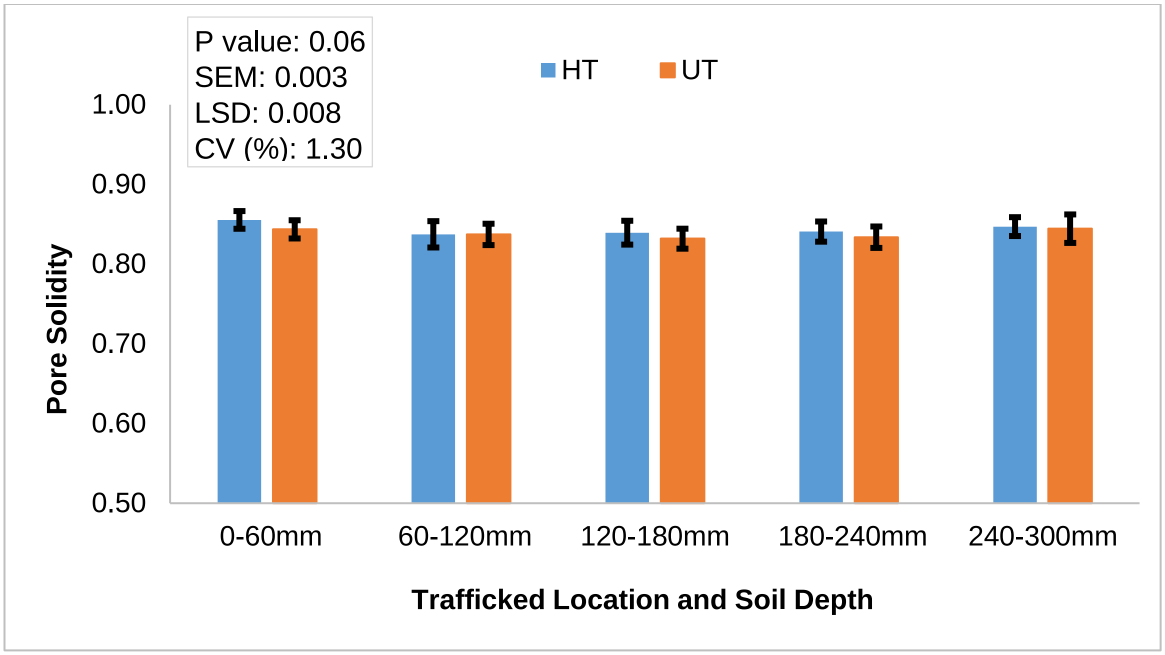


Figure 4.42. Mean pore solidity vs trafficked location (a) and vs soil depth for HT and UT locations (b). Error bar indicates the standard deviation of mean.

4.5.9. Soil Physical Properties at the Location of X-ray CT soil sampling

Dry bulk density and total porosity values of the soils are shown in Figs. 4.43 and 4.44, and Tables 4.4 and 4.5. The results show that tyre inflation pressure (P = <0.001), tillage system (P = 0.04), trafficked location (P = <0.001) and the combined effect of tyre inflation pressure and trafficked location (P = <0.001), all had a significant effect on the BD of soil (Fig. 4.43 and Table 4.4). Irrespective of trafficked location, the BD of soil was recorded to be significantly higher in STP (1.50 Mg m^{-3}) than LTP (1.40 Mg m^{-3}) (n = 150, Fig. 4.43a). Among the tillage systems, the BD of soil (1.47 Mg m^{-3}) was recorded to be significantly the highest in NT whilst both DT and ST had the same BD (1.44 Mg m^{-3}) (n=100, Fig. 4.43.b). Between the trafficked locations, the BD was found to be significantly higher in HT areas (1.49 Mg m^{-3}) than the UT areas (1.41 Mg m^{-3}) (n = 150, Fig. 4.43c). Data in Fig. 4.43d shows that BD was found to be higher in HT location of the STP treatment (1.56 Mg m^{-3}) and was significantly different from others with the lowest BD of 1.42 Mg m^{-3} recorded in the UT areas of the LTP treatment (n = 75). Irrespective of trafficked location, the dry BD of the interaction between tyre inflation pressure and tillage systems showed that LTP treatment at all depths had significantly lower BD (1.39 – 1.41 Mg m^{-3}) than that of the STP (1.49 – 1.51 Mg m^{-3}) (n = 10, Table 4.4).

The results also showed that tyre inflation pressure (P = <0.001), tillage system (P = 0.04), trafficked location (P = <0.001) and the combined effect of tyre inflation pressure and trafficked location (P = <0.001) had a significant effect on the total porosity (BD porosity) of soil (Fig. 4.44 and Table 4.5). The mean porosity of soil was recorded as 4% higher in LTP (46.4 %) than STP treatments (42.6 %) (n = 150, Fig. 4.44a). Between tillage systems, the porosity of soil was to be significantly higher in both DT and ST (45%) whilst the lowest porosity was observed in NT (1.44 Mg m^{-3}) (n = 100, Fig. 4.44b). On the other hand, as expected, the total porosity of soil was recorded as being significantly higher in UT areas (45.9%) compared to HT areas (43.0%) (n = 150, Fig. 4.44c). The total porosity in the HT location of the STP treatment was the lowest (43.3%) which was significantly different from others with the highest porosity of 47% obtained in the UT location of the LTP treatment (n = 75, Fig. 4.44d). Likewise, Table 4.5 shows that porosity of soil among the tyre inflation pressure and tillage systems combination across the five different soil depths had a similar trend, in which across all depths LTP had significantly higher porosity (46.1 – 46.7%) than the STP (42.1 – 43.1%) (n = 10). Field trafficking with LTP tyre system can significantly decrease soil compaction (Boguzas & Hakansson, 2001; Ridge, 2002) which are in line with the present findings. Results of other studies also found agreement with the present findings that compaction increases soil BD whilst reducing the porosity of soil (Hamza and Anderson, 2005).

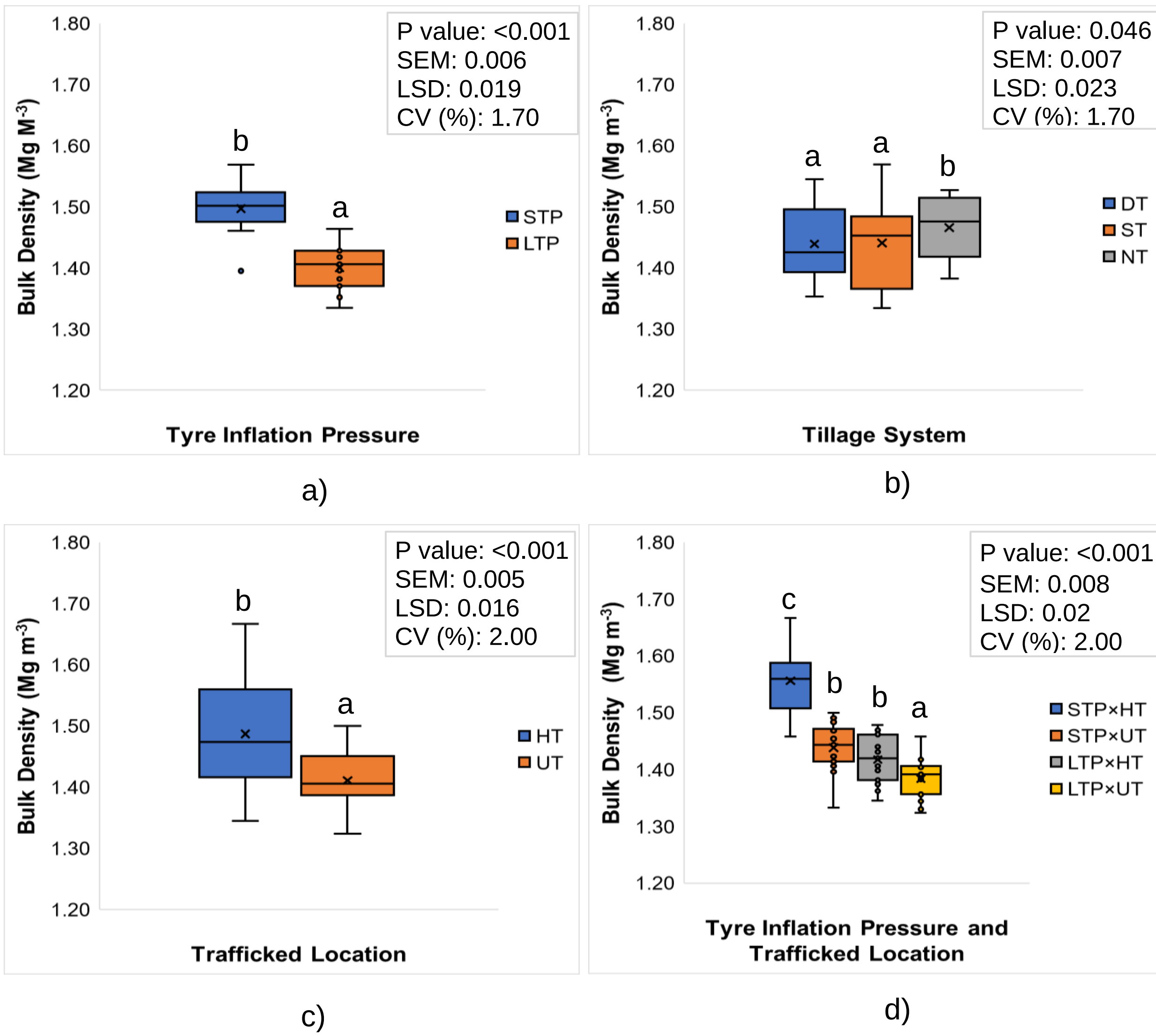


Figure 4.43. Effect of tyre inflation pressure (a), tillage system (b), trafficked locations (c) and tyre inflation pressure and trafficked locations (d) on bulk density of soil. Means with the same letter are not significantly different (P = 0.05) from each other.

Note: The ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

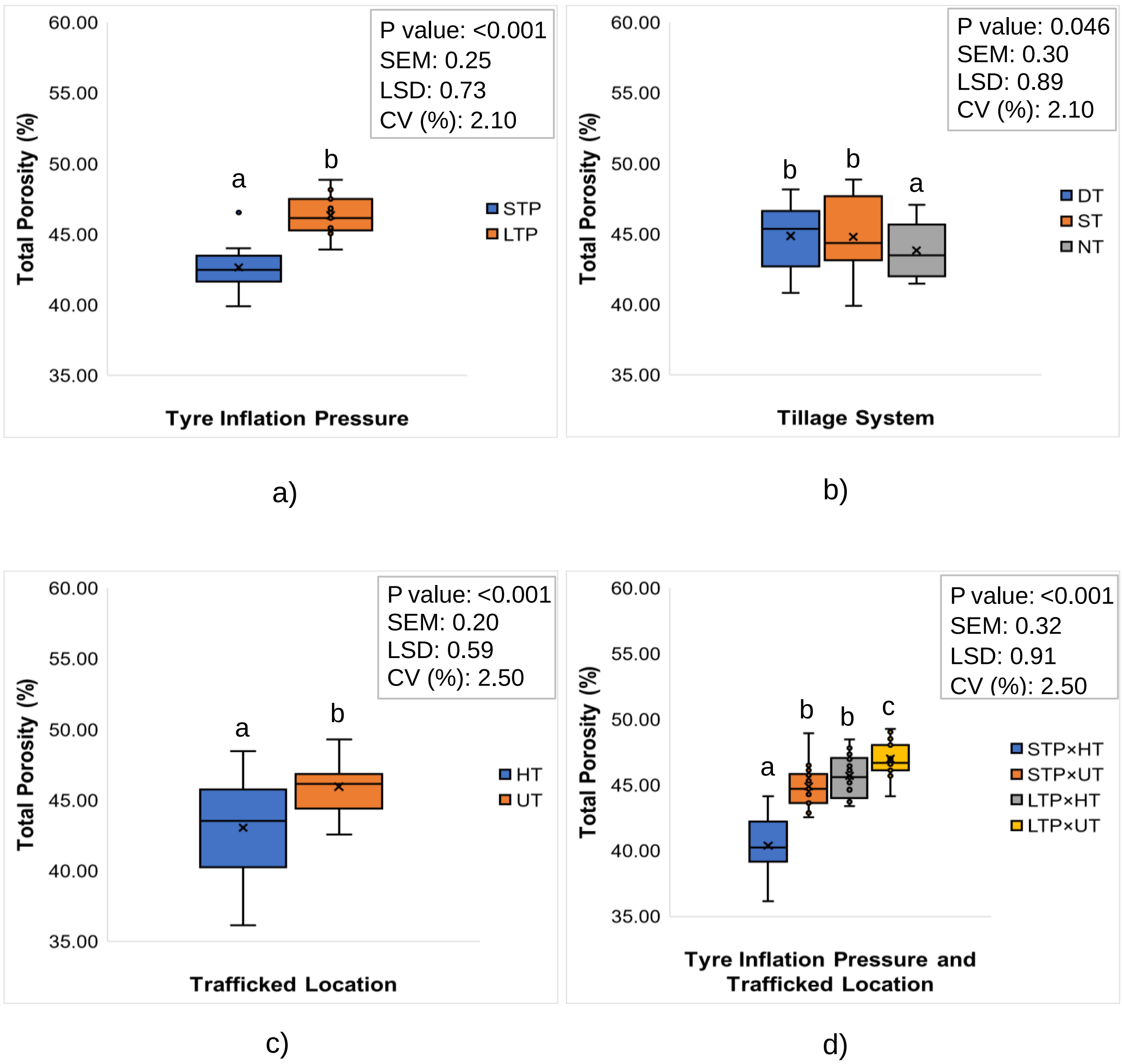


Figure 4.44. Effect of tyre inflation pressure (a), tillage system (b), trafficked locations (c) and tyre inflation pressure and trafficked locations (d) on total porosity of soil. Means with the same letter are not significantly different (P = 0.05) from each other.

Note: The ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

Table 4.4. Effect of tyre inflation pressure and tillage system on bulk density of soil in 2017

TIP	Tillage/ depth	Bulk density (Mg m^{-3})					Mean
		0-60mm	60-120mm	120-180mm	180-240mm	240-300mm	
STP	DT	1.45^{bc}	1.49^{a}	1.48^{a}	1.49^{a}	1.49^{a}	1.48^{a}
	ST	1.52^{d}	1.51^{a}	1.51^{a}	1.46^{a}	1.49^{a}	1.50^{a}
	NT	1.50^{c}	1.53^{a}	1.54^{a}	1.49^{a}	1.49^{a}	1.51^{a}
	Mean	1.49^{B}	1.51^{B}	1.51^{B}	1.48^{B}	1.49^{B}	1.50^{B}
LTP	DT	1.41^{ab}	1.40^{a}	1.38^{a}	1.41^{a}	1.40^{a}	1.40^{a}
	ST	1.34^{a}	1.40^{a}	1.41^{a}	1.39^{a}	1.37^{a}	1.38^{a}
	NT	1.42^{b}	1.43^{a}	1.42^{a}	1.42^{a}	1.42^{a}	1.42^{a}
	Mean	1.39^{A}	1.41^{A}	1.41^{A}	1.40^{A}	1.40^{A}	1.40^{A}
P value	TIP	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	TS	0.137	0.38	0.08	0.02	0.20	0.046
	TIP × TS	<0.001	0.41	0.90	0.74	0.90	0.31
CV(%)		2.40	3.10	2.70	2.30	2.60	1.70

Table 4.5. Effect of tyre inflation pressure and tillage system on total porosity of soil in 2017

TIP	Tillage/ Depth	Total porosity (%)					Mean
		0-60 mm	60-120 mm	120-180 mm	180-240 mm	240-300 mm	
STP	DT	44.4^{ab}	42.8^{a}	43.5^{a}	42.8^{a}	42.9^{a}	43.3^{a}
	ST	41.8^{a}	42.1^{a}	42.2^{a}	43.8^{a}	42.9^{a}	42.6^{a}
	NT	42.5^{a}	41.2^{a}	41.1^{a}	42.7^{a}	42.8^{a}	42.1^{a}
	Mean	42.9^{A}	42.1^{A}	42.2^{A}	43.1^{A}	42.9^{A}	42.6^{A}
LTP	DT	46.0^{bc}	46.9^{a}	47.0^{a}	46.0^{a}	46.2^{a}	46.4^{a}
	ST	48.5^{c}	46.3^{a}	45.8^{a}	46.8^{a}	47.6^{a}	47.0^{a}
	NT	45.7^{b}	45.3^{a}	45.5^{a}	45.7^{a}	45.5^{a}	45.5^{a}
	Mean	46.7^{B}	46.2^{B}	46.1^{B}	46.2^{B}	46.4^{B}	46.3^{B}
Pvalue	TIP	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	TS	0.137	0.381	0.087	0.016	0.204	0.046
	TIP × TS	<0.001	0.410	0.992	0.744	0.985	0.312
CV (%)		2.90	3.10	2.70	2.90	3.20	2.10

Note: Tables 4.5 and 4.6, TIP, TS, STP, LTP, DT, ST and NT represent tyre inflation pressure, tillage systems, standard tyre inflation pressure, low tyre inflation pressure, deep tillage, shallow tillage, no-till, respectively. Means in a column with the same letter are not significantly different (P = 0.05) from each other. Capital and small letters in both tables indicate mean differences between TIP and among TIP × TS treatments, respectively.

4.5.10. Soil Penetrometer Resistance at the Heavily Trafficked and Un-trafficked Locations

The results of PR data in Figs 4.45a-d and appendix 4.6 showed that across soil depth, tyre inflation pressure across ($P = 0.014$, $n = 30$) and trafficked location ($P = <0.001$, $n = 30$) and interaction effect of tyre inflation pressure and trafficked location ($P = 0.023$, $n = 15$), and tillage system and trafficked location ($P = 0.003$, $n = 10$) had a significant effect on the PR of soil. There was no significant effect of tillage system and interaction between tyre inflation pressure and tillage systems across soil depth on the PR of soil. Fig 4.45a shows that irrespective of trafficked location, the PR values in the STP treatment were significantly higher from the depths of 50 mm to 225 mm as compared to the LTP. Between trafficked locations, the PR values of soil were recorded higher in the HT location at all depths as compared to the UT (Fig. 4.45b). The PR values in HT location showed that both STP and LTP had almost similar PR at approximately 0.50 MPa at 25 mm depth, however, the PR values were recorded as being significantly higher in the STP from the depths of 75 mm to 150 mm as compared to the LTP with some minor fluctuations (Fig. 4.45c). The peak PR value in STP in the HT location, however, was recorded at depth of 75mm (1.93 MPa) while the corresponding PR in LTP was 1.61 MPa. Below which, the PR values in both STP and LTP plots gradually increased with a small difference between them and simultaneously reaching their highest value of 2.00 MPa at 450mm depth. As expected, the PR values of STP and LTP of the UT locations were similar, starting at 0.50 MPa at the surface increasing in magnitude throughout the soil profile to a maximum PR of 1.50 MPa a soil depth of 450 mm. Similarly, among tillage systems, PR values were always found to be higher in the HT location as compared to UT location. The PR values were recorded higher in the NT × HT combination that was significantly different from the DT × HT combination from the depths 50 to 75 mm with the peak PR values of 1.94 and 1.54 MPa at depth 75 mm, respectively and different from the combinations of DT × UT, ST × UT and NT × HT from the surface to 250 mm soil depths (Fig. 4.45d). Higher PR values in STP than LTP treatment and HT location than UT could be due to compaction were associated with the vehicle traffic with high tyre inflation pressure. The present findings are in agreement with the findings of others who reported that compaction increases soil BD, PR whilst reducing the porosity of soil (Hamza and Anderson, 2005). Traffic frequency and higher tyre inflation pressure have strong effects on the soil condition, which increased BD and PR of soil (Solgi et al., 2016).

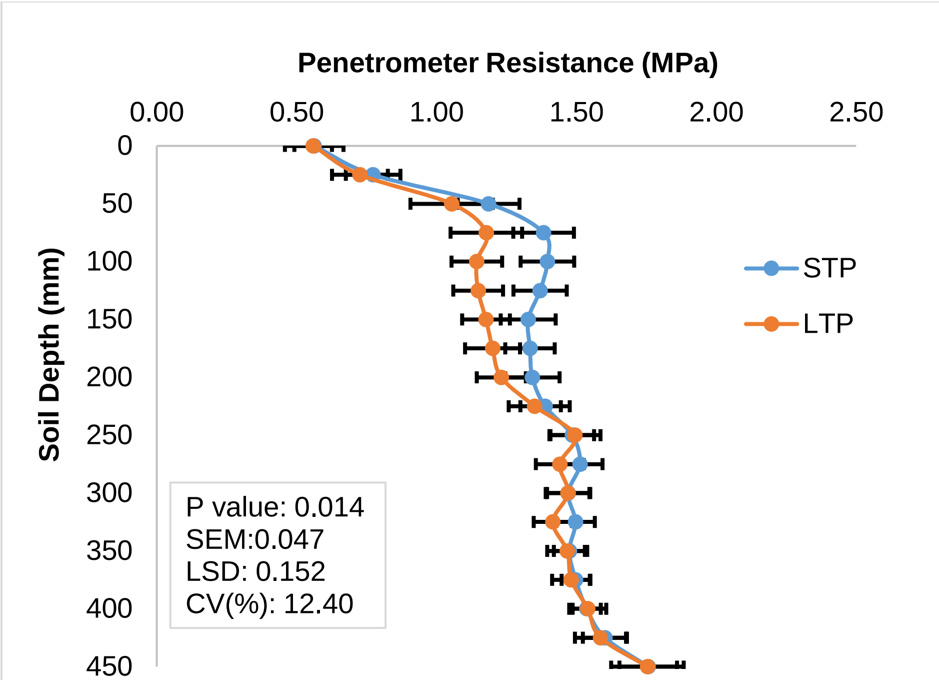


Figure 4.45a. Effect of tyre inflation pressure on penetrometer resistance of soil. Error bar indicates the standard error of mean.

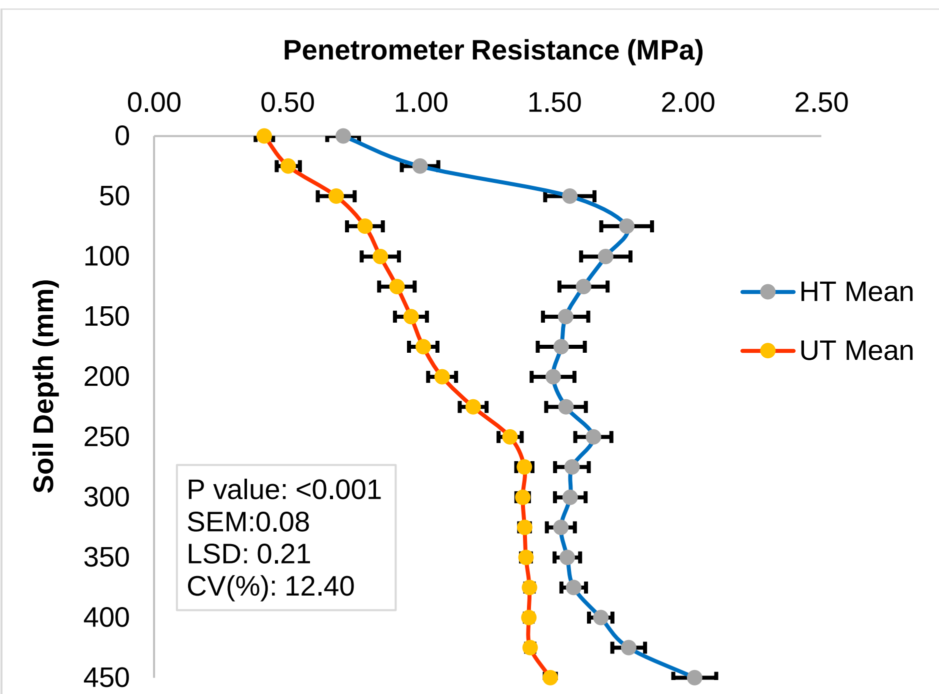


Figure 4.45b. Effect of heavily trafficked and un-trafficked locations on penetrometer resistance of soil. Error bar indicates the standard error of mean.

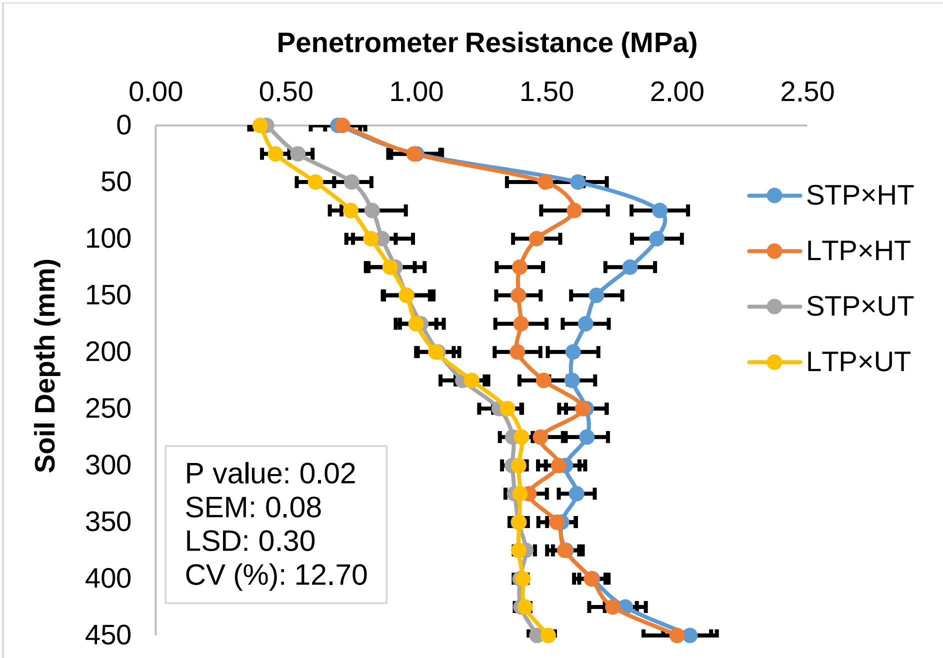


Figure 4.45c. Effect of tyre inflation pressure on penetrometer resistance of soil at heavily trafficked and un-trafficked locations. Error bar indicates the standard error of mean.

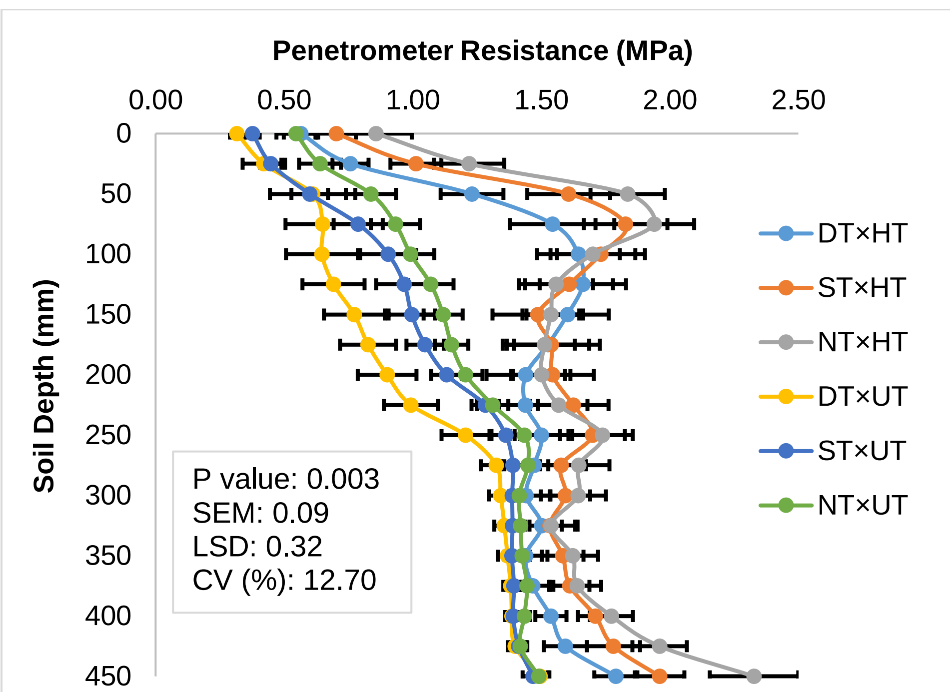


Figure 4.45d. Effect of tillage system on penetrometer resistance of soil at heavily trafficked and un-trafficked locations. Error bar indicates the standard error of mean.

4.5.11. Relationship Between X-Ray Computed Tomography Derived Porosities to Physical Soil Porosity

Earlier, it was described that due to the resolution, X-ray CT scanning can only be used to identify macropores of soil. Tables 4.6 and 4.7 show that the mean total BD_P was recorded as 44.5±2.98 % while CT_P was 5.10±2.68 %. The CT measured macroporosity of the present study was lower than that of total porosity of soil which is an agreement with the findings that X-ray CT derived porosity are macroporosities which underestimate the total soil porosity of soil (Vaz et al., 2011; Marcelino et al., 2007).

There is a high correlation between measured saturated hydraulic conductivity and macroporosity derived from X-ray CT (Kim et al., 2010). The mean difference between BD_P and CT_P under different tyre inflation pressure and tillage systems was found as 39.4±2.87 ≈ or 39 %. This is a constant and adding this with CT_P (5.10 %) can be partially comparable with the findings of Hall et al. (1977), when compared with the air capacity and water retention ability of certain particle-size classes in topsoil. The CT_P derived porosity corresponds to water-filled pore space for a silty clay loam soil (Fig. 4.46). The results are in agreement with the findings of Millington (2019) who found a constant 31 % that was comparable and correspond to the water-filled pore space for the sandy loam soils in the UK. However, the constant value of 39 % for the silty clay loam soil may be dependent on the resolution of the X-ray CT scanning and also the thresholding method used for analysing X-ray CT image stacks. Nevertheless, the constant of 39 % can be compared and well fitted with the findings of Godwin and Dresser (2003) and Brady and Weil (2008) who showed the relationship between soil textural classes and plant available water holding capacity, corresponding to the permanent wilting point, field capacity and saturation (Fig. 4.47). The results suggest that the constant 39 % porosity can be comparable to the field capacity which is approximately equivalent to microporosity of a silty clay loam soil. Therefore, it can be said that CT measured macroporosity is the macroporosity and adding 39 % porosity to it, can be correlated with the air-filled porosity and field capacity for silty clay loam soil.

Table 4.6. Comparison of bulk density and X-ray CT measured porosities for silty clay loam soil (Mean±SD).

Treatments	Tillage System	BDP			CTP			BDP-CTP		
		HT	UT	Mean	HT	UT	Mean	HT	UT	Mean
STP	Deep tillage	41.4±1.93	45.1±2.59	43.2±2.92	2.69±0.94	6.74±3.07	4.72±3.02	38.7±2.16	38.6±4.38	38.5±3.26
	Shallow tillage	40.2±2.55	44.8±0.94	42.5±3.01	3.05±1.21	5.35±0.90	4.20±1.58	37.2±2.92	39.5±1.73	38.3±2.56
	No-till	39.4±0.93	44.7±1.39	42.1±2.96	2.87±1.81	5.45±1.92	4.16±2.23	36.6±1.86	39.2±3.21	37.9±2.83
	Mean	40.3±1.96	44.8±1.66	42.6±2.90	2.87±1.28	5.85±2.10	4.36±2.28	37.5±2.36	39.0±3.09	38.2±2.81
LTP	Deep tillage	45.7±1.51	47.2±1.76	46.4±1.45	5.03±2.73	8.11±3.35	6.57±3.49	40.6±2.49	39.1±2.85	39.8±3.18
	Shallow tillage	46.2±2.00	47.7±1.52	47.0±1.85	4.16±1.71	8.20±3.24	6.18±3.24	42.1±2.11	39.5±2.18	40.8±2.43
	No-till	45.1±1.45	46.0±1.11	45.5±1.31	4.80±0.76	4.76±1.98	4.78±1.41	40.3±1.61	41.2±2.26	40.8±1.09
	Mean	45.7±1.62	47.0±1.37	46.3±1.62	4.66±1.81	7.02±3.30	5.84±2.88	41.0±2.11	39.9±2.84	40.5±2.51
Tyre Inflation pressure mean		43.0±3.22	45.9±1.84	44.5±2.99	3.77±1.79	6.44±2.78	5.10±2.68	39.2±2.83	39.5±2.95	39.4±2.87

Table 4.7. Comparison of bulk density and X-ray CT measured porosities of 0 - 300 mm depth of soil (Mean±SD).

Treatments	Soil depth (mm)	BDP			CTP			BDP - CTP		
		HT	UT	Mean	HT	UT	Mean	HT	UT	Mean
STP	0-60	39.8±2.99	45.9±2.74	42.9±4.19	3.44±1.56	8.06±4.14	5.75±3.87	36.4±2.80	37.9±4.52	37.1±3.77
	60-120	40.5±2.74	45.2±2.60	42.9±3.52	2.87±2.08	6.55±3.38	4.71±3.33	37.7±3.53	38.6±4.73	38.1±4.13
	120-180	39.5±2.92	44.5±2.11	42.0±3.54	2.63±2.44	5.71±2.48	4.17±2.88	36.9±4.76	38.7±3.23	37.8±4.11
	180-240	40.5±2.44	43.8±2.29	42.2±2.86	2.77±1.94	5.35±2.83	4.06±2.72	37.8±2.88	38.5±4.32	38.1±3.62
	240-300	41.3±1.86	44.9±2.17	43.1±2.70	2.64±1.74	3.57±1.94	3.11±1.87	38.6±2.46	41.3±2.69	40.0±2.87
	Mean	40.3±1.96	44.8±1.66	42.6±2.90	2.87±1.28	5.85±2.10	4.36±2.28	37.5±2.36	39.0±3.09	38.2±2.81
LTP	0-60	46.0±2.51	47.4±2.47	46.7±2.55	4.51±2.58	8.98±4.54	6.74±4.28	41.5±2.86	38.5±4.22	40.0±3.87
	60-120	45.9±1.96	47.0±2.65	46.4±2.36	5.44±2.91	7.93±3.85	6.69±3.58	40.4±3.35	39.1±3.38	39.7±3.38
	120-180	45.6±1.64	46.7±2.06	46.1±1.91	5.08±2.69	7.51±3.82	6.29±3.47	40.5±2.77	39.2±3.09	39.8±2.96
	1800240	45.2±2.15	47.0±1.35	46.1±1.98	3.42±2.98	6.05±5.16	4.73±4.35	41.8±2.63	40.9±4.60	41.4±3.71
	240-300	45.6±2.29	46.7±2.61	46.2±2.48	4.87±3.39	4.64±2.46	4.76±2.91	41.7±4.39	42.1±3.95	41.4±4.16
	Mean	45.7±1.62	47.0±1.37	46.3±1.62	4.66±1.81	7.02±3.30	5.84±2.88	41.0±2.11	39.9±2.84	40.5±2.51
Tyre Inflation pressure mean		43.0±3.22	45.9±1.84	44.5±2.99	3.77±1.79	6.44±2.78	5.10±2.68	39.2±2.83	39.5±2.95	39.4±2.87

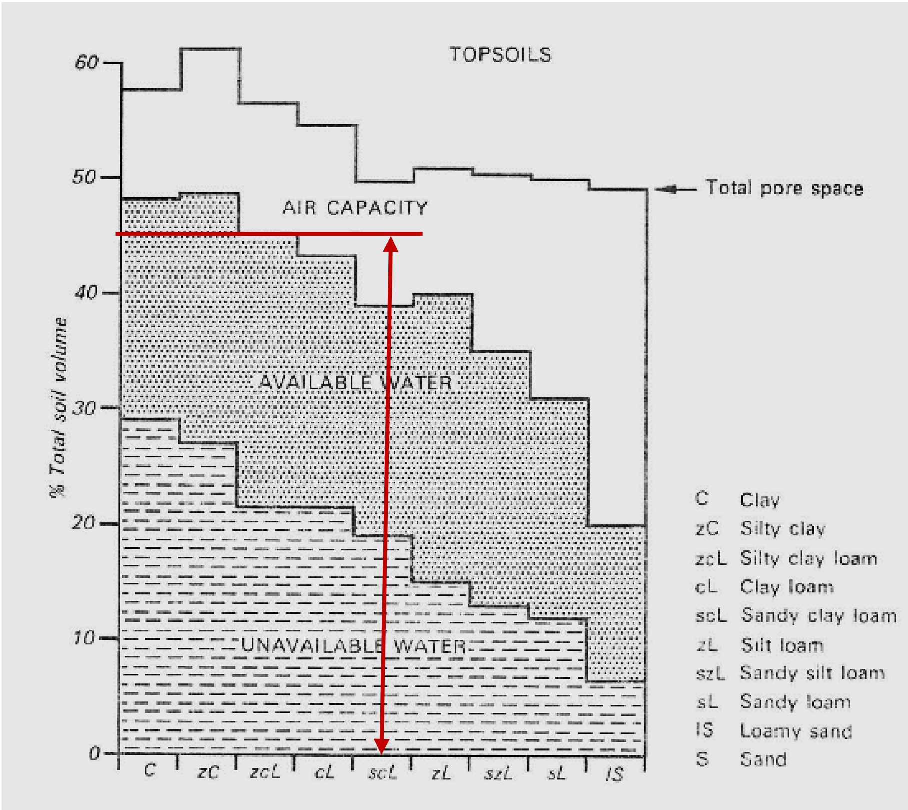


Figure 4.46. Air capacity and water retention ability of certain particle-size classes in topsoils (Adapted from Hall et al., 1977).

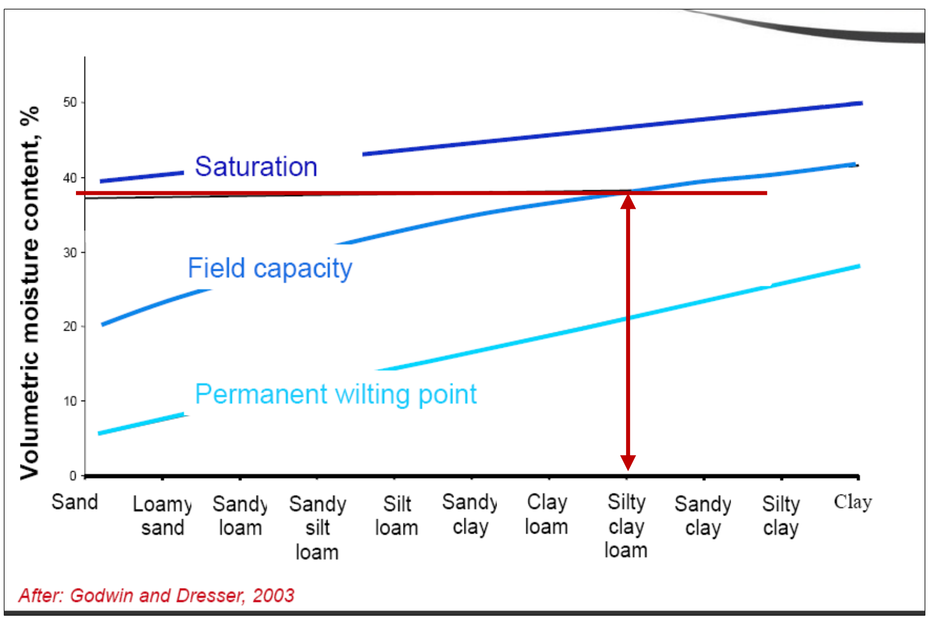


Figure 4.47. Relationship between soil textural classes and plant available water holding capacity (Adapted from Godwin & Dresser, 2003).

4.6. Conclusions

1) X-ray CT has shown to be a valuable tool in determining macroporosity differences with a high resolution among various traffic systems for various tillage practices.

2) The results confirm the hypothesis that the addition of the field capacity porosity with the CT_P gives the total porosity of the soil which is in line with the findings of Millington (2019), as the mean difference between total porosity and CT_P was 39% which is comparable to the field capacity pore space for the silty clay loam soil as shown by Brady & Weil, (2008) and Godwin & Dresser (2003).

3) Observation of the longitudinal view of X-ray CT scanned image stacks showed that there are soil structural differences between cores of HT and UT soil areas. Smaller variations in the UT locations and a more open structure can be seen in LTP mode whilst more compact and dense conditions were observed in STP mode, especially in HT location images.

4) Tyre inflation pressure and its interaction with tillage had a significant effect on mean pore count in HT (P = 0.010 and P = 0.030 respectively) with the higher pore count observed in LTP (105.2) as compared with STP (75.8). Trafficked location (P = <0.001), the combined effect of trafficked location and soil depth (P = <0.001) also had a significant effect on the mean pore count of soil. A higher mean pore count was recorded in the UT location (164) as compared with HT areas (91).

5) Tyre inflation pressure and tyre inflation pressure across soil depths had a significant effect on % CT_P (P = 0.014 and 0.004 respectively) with a greater percentage porosity obtained in LTP (4.66%) than in STP (2.87%) in HT location. The number of pores and CT_P was inversely proportional to soil depth, indicating a possibility to re-compact or subsoil compaction through tillage and tyre inflation pressure increase. Trafficked location (P = <0.001), soil depth (P = <0.001) and trafficked location across depth (P = <0.001) had also a significant effect on the CT_P of soil with no significant effect of the interaction between tyre inflation pressure and tillage system.

6) Results revealed that tyre inflation pressure and its effect across depth (P = <0.001 and 0.014 respectively) in HT, tyre inflation pressure irrespective of trafficked location (P = 0.014), trafficked location (P = <0.001), soil depth (P = <0.001) and combined effect

trafficked location and soil depth (P = <0.001) all had a significant effect on the mean total pore area of soil. In contrasts, tillage systems, the interaction effect of tillage systems and depth, and tyre inflation pressure, tillage systems and depth were not significant. Similar to CT_P, LTP had a higher mean total pore area (116 mm^2) than STP (86.5 mm^2) and mean total pore area was inversely proportional to soil depths in the order 0-60mm> 60-120mm> 120-180mm> 180-240mm> 240-300mm.

7) Soil depth had a significant effect on the average pore size, perimeter, circularity and solidity of pores (P = 0.001, <0.001, <0.001 and 0.04, respectively) while the interaction between trafficked location and soil depth were significant on the perimeter and solidity of pores (P = 0.007 and <0.001 respectively). The main effects of tyre inflation pressure, tillage system and their interaction, however, were not significant. The average pore area, pore perimeter and circularity were proportional to soil depth. The solidity of pores was higher in the heavily trafficked location as compared to the un-trafficked location.

8) The results of the classical gravimetric/volumetric soil physical analysis showed that tyre inflation pressure (P = <0.001), tillage system (P = 0.04), trafficked location (P = <0.001) and the combined effect of tyre inflation pressure and trafficked location (P = <0.001) had a significant effect on the BD and total porosity of the soil. The mean BD of HT location was higher in STP (1.56 Mg m^{-3}) as compared to the LTP treatment (1.42 Mg m^{-3}). The porosity of soil was on average recorded 4% higher in LTP (46.35 %) mode than in STP (42.64 %) mode.

9) The results of PR of soil studies showed that tyre inflation pressure (P = 0.014), trafficked location (P = <0.001) and the interaction effect of tyre inflation pressure and trafficked location (P = 0.023) and tillage system and trafficked locations (P = 0.003) had a significant effect on the penetration resistance of the soil with no significant effect of tillage system and interaction between tyre inflation pressure and tillage systems on the PR of soil. The PR values in the STP treatment were significantly higher from the depths of 50 mm to 225 mm while in HT location higher PR was recorded in the STP from the depths of 75 mm to 150 mm as compared to the LTP with the peak value at depth of 75mm of 1.93 MPa and 1.61 MPa, respectively. Between trafficked locations, the PR values of soil were recorded higher in the HT locations at all depths as compared to the UT locations.

CHAPTER 5: SOIL PROPERTIES AND CROP DEVELOPMENT OF MAIZE

5.1. Introduction

Soil compaction by machinery traffic in agriculture is a well-recognised problem in many parts of the world e.g. (Horn and Fleige, 2003; Chan et al., 2006) and acknowledged as a serious form of soil degradation by the European Union (Jones et al., 2003). Compaction creates physical, chemical and biological change in the soil that negatively impacts crop performance (Chyba, 2012; Horn et al., 2003). Soil compaction reduces the porosity and increases the BD of soils, and also reduces the water infiltration rate as compared to non-compacted soil (Liebig et al., 1993; Li et al., 2001; Hamza and Anderson, 2005; Raper and Kirby, 2006) and restricts root growth and accessibility of nutrients of the plant (Nawaz et al., 2013). Cone index values in excess of 2 MPa have been shown to restrict, to varying degrees, crop root development (Taylor and Gardner, 1963; Aase et al., 2001). Kaspar et al. (2001) found a reduction of root growth of maize in trafficked crop rows due to higher BD as a result of wheel trafficked as compared to the UT rows. Raghavan et al. (1979b) observed that up to 40–50% of maize yield reductions occurred due to high contact pressures and multiple passes. Increased PR and reduced grain yield of winter wheat and spring oats were observed due to random conventional pressure traffic system as compared to other traffic systems (Godwin et al., 2017). Low ground pressure systems with agricultural tracks or specially manufactured tyres transmit reduced ground contact stress (Trautner and Arvidsson, 2003) and showed a positive benefit to minimising soil compaction (Smith et al., 2014a; Godwin et al., 2015). However, research is are scarce on the effect of tyre inflation pressure with different tillage practices in the mid-west farming systems in the United States. Hence, the present experiments were undertaken to assist in understanding the effect of lower inflation pressure systems on soil properties, crop growth and yield of maize.

5.2. Hypothesis

It is possible to increase the yield of maize by improving crop growth and development by reducing soil compaction using reduced tyre inflation pressure systems.

5.3. Aim and objectives

The main aim of the study is to determine the effect of tyre inflation pressure on soil properties, and crop development and yield of maize for three tillage systems. The overall objectives are as follows:

a) To determine the effects of tyre induced ground pressure, by comparing ultra-flex high and low inflation tyre systems, on soil structure, crop development and yield of maize for 2 tillage depths (deep tillage, 450 mm and shallow tillage, 100 mm) and no-till through field-scale studies on a silty clay loam soil in Illinois, the United States.

b) To correlate the effects of the different tyre inflation pressure and tillage systems, on soil conditions and crop parameters.

5.4. Materials and Methods

The study was conducted in Champaign County, Illinois, United States (lat/lon: 40.070965, -88.217538) from November 2015 through October 2018. The treatments comprised of standard (STP) and low tyre inflation pressures (LTP) and three tillage system: deep tillage (450mm), shallow tillage (100mm) and no-till. All machinery was fitted with Michelin Ultraflex radial tyres (Yieldbib and Cerexbib) inflated at standard/high (STP) and low pressures (LTP). The experiment was a split-plot, factorial randomized complete block design with five blocks where the tyre inflation pressure and tillage systems were the main plots and crop rows were sub-plots. The main crop grown in the present farming systems was maize (*Zea mays* L.), the variety P1221AMXT (Pioneer seed), in North field (2016) - South field (2017) - North field (2018) manner where the following crop after maize was soybean (*Glycine max* L.). The detailed methodology of the experiment including tyre inflation pressures for different equipment involved, plot layouts, trafficked and un-trafficked crop rows (Table 3.5 and Appendices 3.5-3.7), field operations, crop description, methods of sampling and procedures for data collection and statistical analysis of soil and crops parameters were described in Chapter 3: General Methodology.

5.5. Results and Discussion

5.5.1. Initial Soil Properties Assessment

Initial soil physical and chemical characteristics have been summarised in Tables 5.1 - 5.2 and Figs. 5.1 - 5.3. The result showed that the mean soil MC (%) of Thorp soil series at three different depths of 0-100, 101-200 and 201-300 mm was approximately 23, 21 and 22%, respectively. While in the Drummer soil series, the soil MC recorded at these three soil depths were 26, 28 and 27 % respectively (Table 5.1). The dry BD at the three depths of 0-100, 101-200 and 201-300 mm in Thorp soil series were 1.23, 1.33 and 1.27 Mg m^{-3} respectively. The BD's of the Drummer soil were 1.14, 1.23 and 1.21 Mg m^{-3}, respectively. Overall, in both soil series, the BD of soil ranged from 1.14 to 1.33 Mg m^{-3} which are well below the BD of >1.40 Mg m^{-3} that can cause a negative effect through soil compaction on root and plant growth in silty clay loam soils (USDA NRCS, 2019d). The mean particle density of both soils was 2.61 Mg m^{-3}. The total porosity of the soil in the Drummer and Thorp soil series was 54% and 51% respectively (Table 5.1). These soil physical properties indicate that the selected site was sufficient for plant establishment and growth.

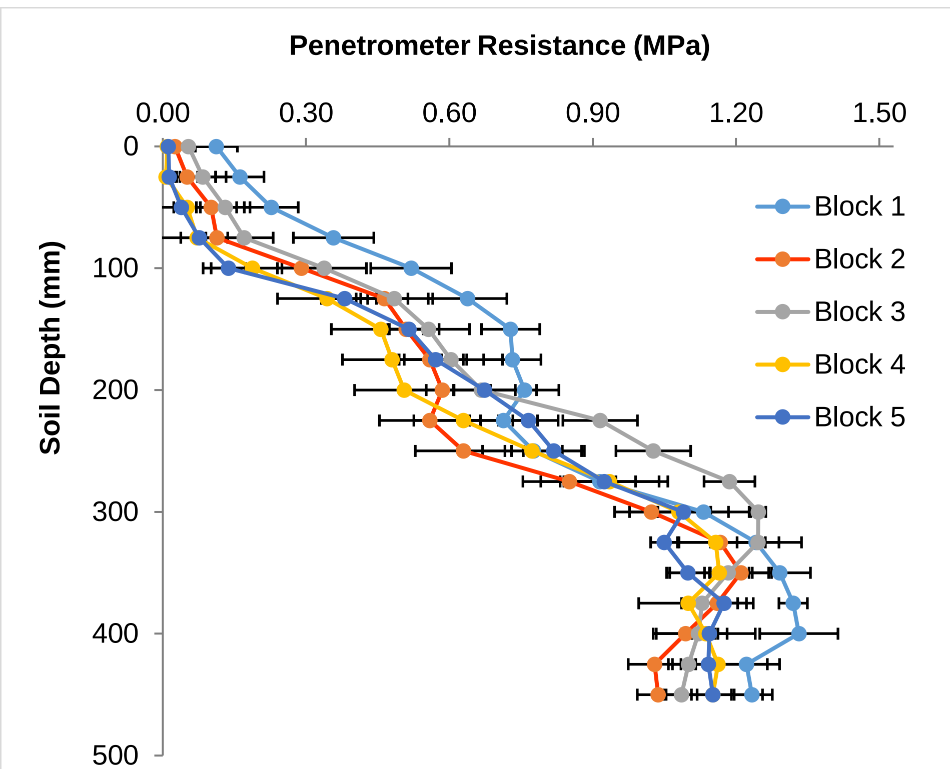
Table 5.1. Initial bulk density and moisture content of soil at three different depths in April 2016

Series	Soil properties	Unit	Depth[a]			Mean
			0-100 mm	101-200 mm	201-300 mm	
206A-Thorp	BD	Mg m^{-3}	1.23±0.02	1.33±0.02	1.25±0.04	1.27±0.03
	PD	Mg m^{-3}	2.61±0.01	2.61±0.01	2.61±0.01	2.61±0.01
	Porosity	%	52.9±0.92	49.1±1.03	52.2±1.50	51.4±0.82
	Soil MC	%	22.8±1.70	20.6±0.80	22.4±1.33	21.9±1.27
152A-Drummer	BD	Mg m^{-3}	1.14±0.03	1.23±0.02	1.21±0.03	1.19±0.03
	PD	Mg m^{-3}	2.61±0.01	2.61±0.01	2.61±0.01	2.61±0.01
	Porosity	%	56.1±1.19	52.4±0.76	52.9±0.85	53.8±0.93
	Soil MC	%	25.5±0.98	27.6±0.92	26.9±1.09	26.7±0.99

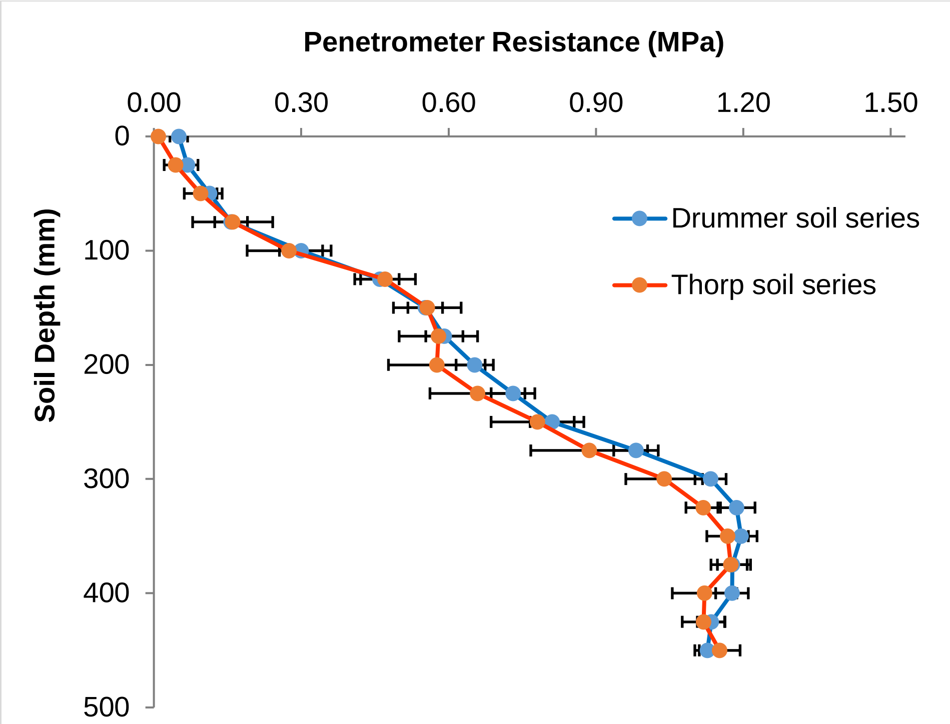
[a]Average of 5 samples for Thorp and 20 samples for Drummer soil series (Mean ± SE)

The initial experimental block (n = 15) and soil series (n = 60 and 15 for Drummer and thorp series, respectively) and overall mean (n = 75) PR of soil in the North field are shown in Fig 5.1a-c. These data showed that PR values gradually increased to values from 0 - 1.33 MPa up to a depth of 400 mm and 0 - 1.20 MPa up to a depth of 350 mm in the blocks and series, respectively then remained constant with some fluctuations to consistent values of 1.03 - 1.23

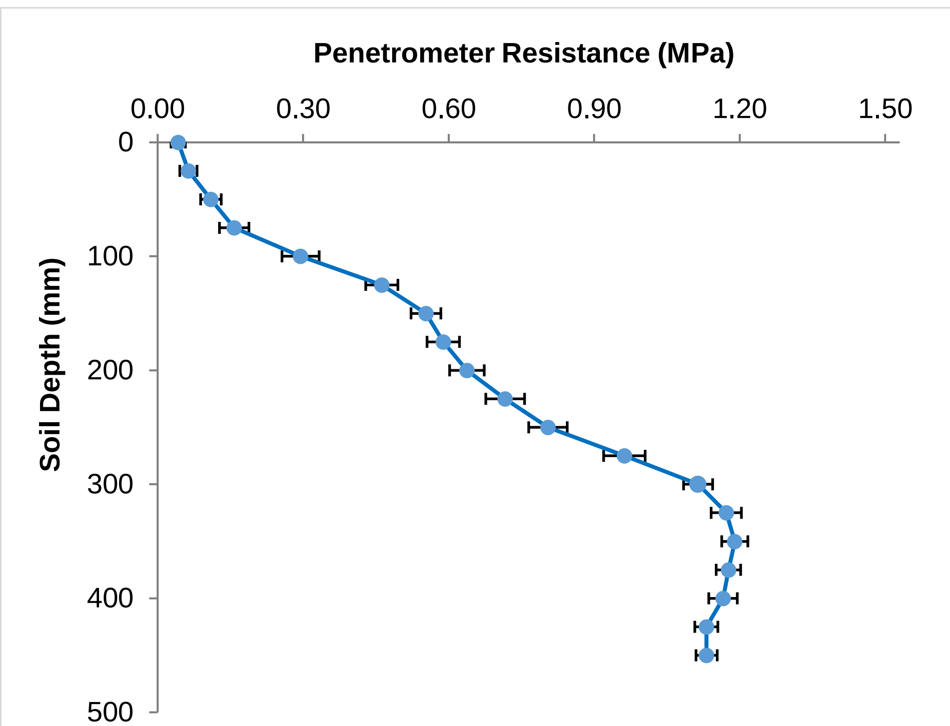
MPa and 1.12 – 1.19 MPa, respectively. The mean data showed that the peak PR of soil (1.19 MPa) was recorded at a depth of 350 mm (Fig. 5.1c). Soil BD and PR are commonly used to determine the level of soil compaction (Raper, 2005). Field traffic with heavy machinery and high tyre inflation pressures increase soil strength and has strong effects on soil physical properties and causes compaction of soil (Solgi et al., 2016) is eventually increases the BD of soil and cone PR to soil. Researchers found that the first tyre pass in the soil increased the BD and PR at an average of 7 and 6%, respectively (Canillas and Salokhe, 2002). Research indicates that the EC values were higher in clay loam soils as compared to sandy loam soils (James et al., 2003). North field had a small difference in soil texture in the northeast section of the field where the Thorp soil series is located, characterised as a silt loam. However, soil physical and chemical properties data showed that there were no significant differences between these two soil series.



a)



b)



c)

Figure 5.1. Initial penetrometer resistance of soil for block (a), soil series (b) and overall mean (c) data in the North field, 2016. Error bar indicates the standard error of mean.

Initial EC data showed that the dominant, silty clay loam Drummer soil series had higher EC values than the Thorp soil series (Fig. 5.2). Regardless of soil series, the EC data ranges from 13.24 - 45 mS/m meaning that both soil series are moderately homogenous with some variation in Thorp series.

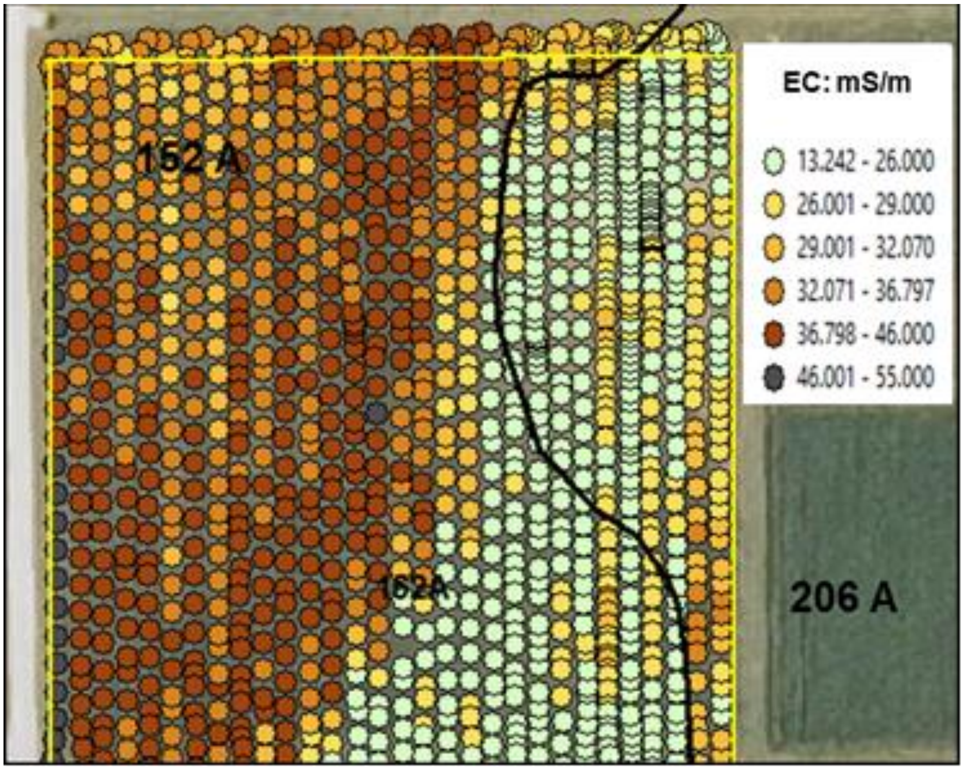


Figure 5.2. Electrical conductivity digital terrain map laid onto the NRCS soil survey map of North field, 2016. 152A - Drummer and 206A - Thorp soil series.

The results of chemical properties of soil showed that soil pH was 6.32 and 6.23 and SOM that were 3.39% and 3.29% at two different depths 0-150 and 151-300 mm, respectively (Table 5.2). Cation exchange capacity (CEC) ranged between 26-29 meq/100g soils. Analysis of soil nutrient showed that Nitrate (NO_3^-N) and Ammonium (NH_4^+N) in soils were found higher at depth 0-150mm (15.4 ppm) as compared with a depth of 151-300 mm (8.4 ppm), respectively. The mean values of P, potassium (K), calcium (Ca) and magnesium (Mg) were around 98, 298, 8243 and 1061 Kg ha^{-1}, respectively. Mean values of base saturation of Ca, Mg, K, H, S were 66%, 15%, 2%, 19% and 17%, respectively. Micronutrients results showed that the mean values of Zinc (Zn) and Boron (B) were 5.85 and 1.32 Kg ha^{-1}, respectively.

Table 5.2. Chemical properties of soil in the North field in April 2016.

Soil properties	Unit	Depth[a]	
		0-150 mm	150-300 mm
Soil pH	-	6.32±0.11	6.23±0.11
OM	%	3.39±0.07	3.29±0.09
CEC	meq/100g	26.0±2.79	29.0±3.29
NO_3^- N	ppm	15.4±1.29	8.40±1.17
NH_4^+ N	ppm	6.20±0.49	4.80±0.38
P^{3-}	kg/ha	129.3±10.12	66.5±7.91
K^+	kg/ha	372.4±118.52	222.7±10.52
Ca^{2+}	kg/ha	8076.4±1032.2	8410.3±1101.7
Mg^{2+}	kg/ha	1024.0±167.0	1098.4±131.7
Ca^{2+} (Base saturation)	%	68.5±3.58	64.1±3.40
Mg^{2+} (Base saturation)	%	14.5±2.17	15.3±2.94
K^+ (Base saturation)	%	2.20±0.57	1.16±0.15
H^+ (Base saturation)	%	18.4±4.32	19.4±3.77
S^{2-}	kg/ha	17.2±0.67	16.1±1.15
Zn^{2+}	kg/ha	6.30±0.99	5.40±0.89
B^{3+}	kg/ha	1.39±0.25	1.25±0.18

[a]Average of 25 samples at each depth (Mean ± SE)

5.5.2. Effect on Soil Properties in Maize Field

In 2016, the PR data recorded at the vegetative stage of maize are presented in Figures 5.3a - 5.3c. The results showed that tyre inflation pressure, the trafficked location had a significant effect on PR in the maize field (at depths of 0-450 mm) (P = 0.006, 0.004 and <0.001) with no significant interaction. The mean PR value was significantly higher in the STP treatment (2.80 MPa) as compared to the LTP treatment (2.51 MPa) (n = 570, Fig. 5.3a). Initially, the PR values across depths in both STP and LTP treatments were similar (0.55 MPa), however, the PR of STP treatment across depths was significantly higher than LTP treatment with peak PR at depths of 300 mm (3.48 MPa) and 275 mm (3.35 MPa) respectively (n = 30; Fig. 5.3b). Fig. 5.3c shows that, not unsurprisingly the PR of HT location had significantly higher compaction levels to a depths of 275 mm as compared to the UT, with peak PR values of 3.49 MPa and 3.30 MPa respectively (n = 30). Below 275 mm, the PR values decreased with depth for both UT and HT locations.

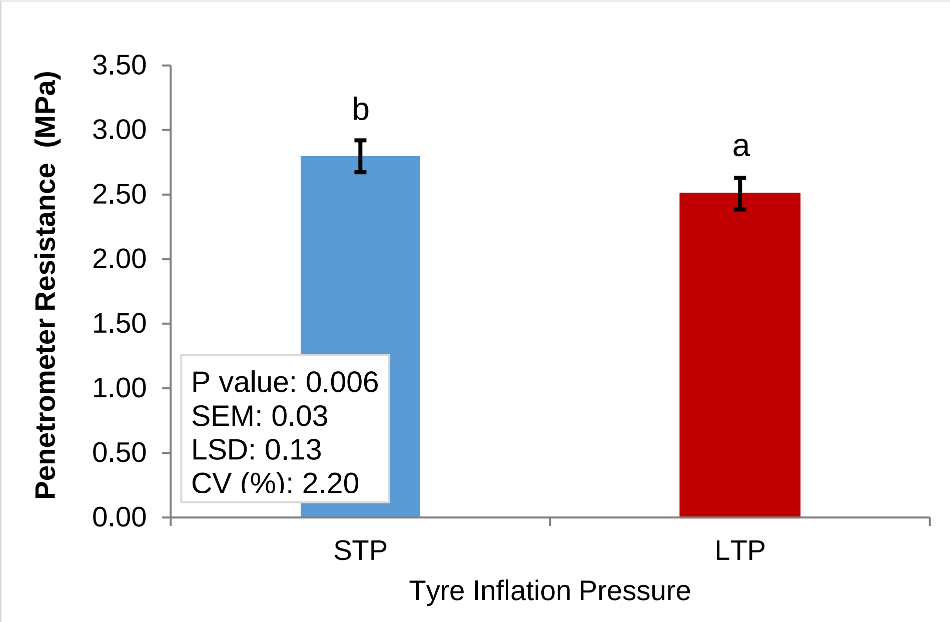


Figure 5.3a. Effect of tyre inflation pressure on the mean penetrometer resistance in the North field in 2016. Error bar indicates the standard error of mean.

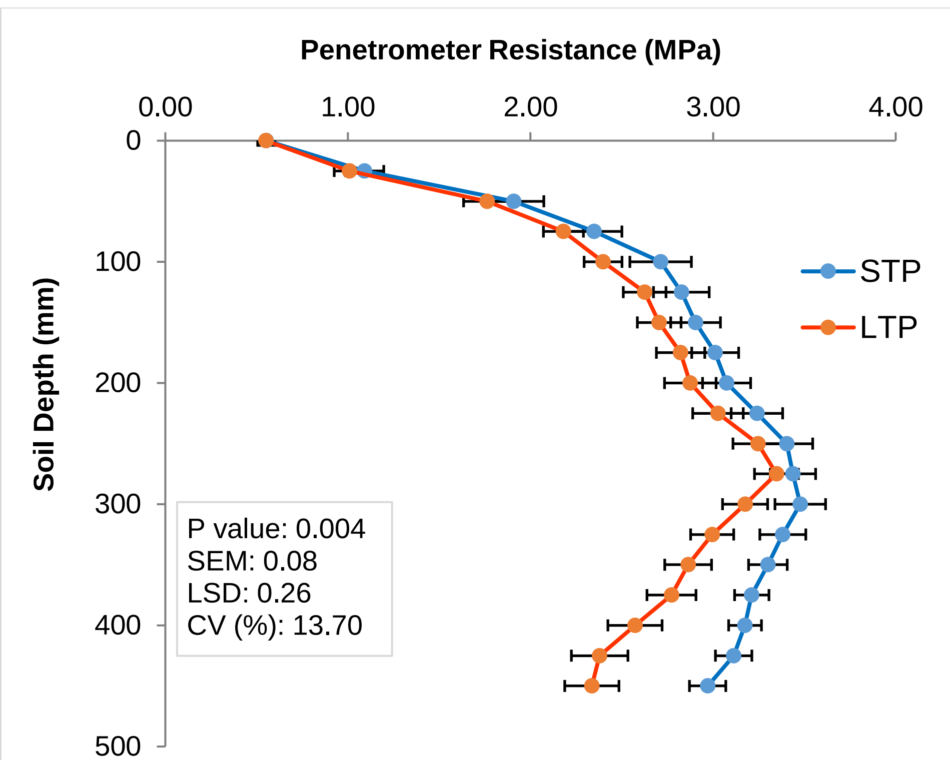


Figure 5.3b. Effect of tyre inflation pressure on the penetrometer resistance in the North field in 2016. Error bar indicates the standard error of mean.

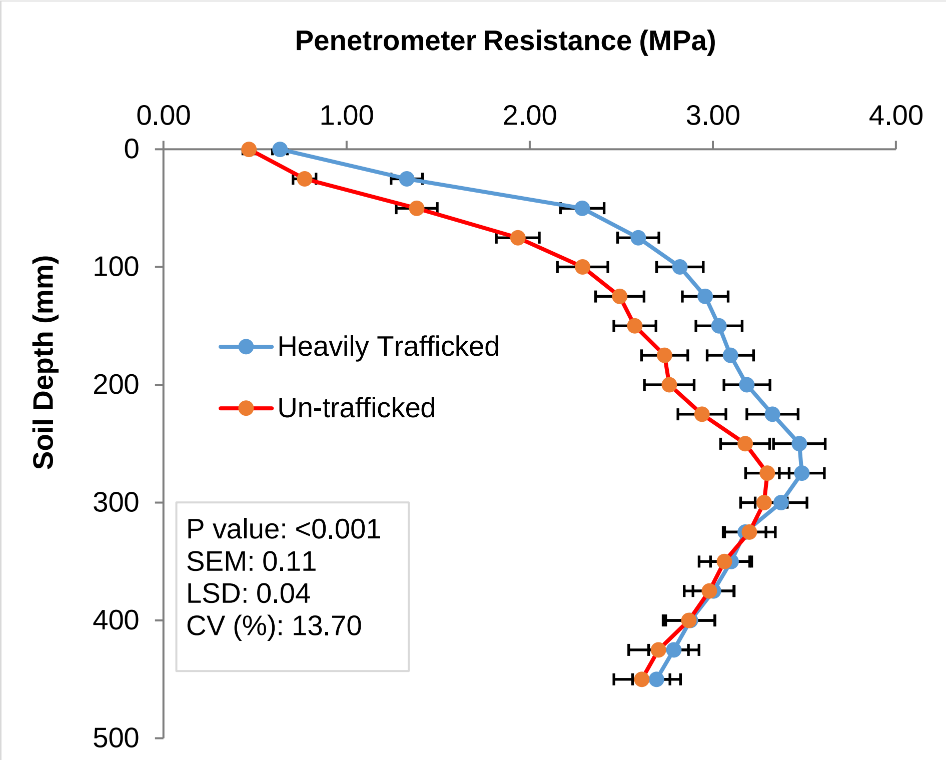


Figure 5.3c. Mean penetrometer resistance of the heavily trafficked and un-trafficked locations in the North field in 2016. Error bar indicates the standard error of mean.

Soil parameters of BD, MC, and total porosity at 3 depths of 0-80mm, 81-160mm and 161-240mm from the crop row 1 to crop row 4, are presented in Appendices 5.1-5.3. These non-replicated data show that the mean BD of the soil was higher in STP treatment plot (1.52 Mg m^{-3}) than LTP treatment (1.42 Mg m^{-3}), while the mean soil MC was recorded more in LTP plot (16.47%) than that of STP plot (14.05%). Similarly, the mean total porosity of soil was recorded higher in LTP treatment plot (46%) than STP (42%). Higher BD and lower soil porosity were recorded in STP plots as a result of compaction of soil as compared to LTP plots are in agreement with the findings that compaction reduces porosity and increases soil bulk density (Liebig et al., 1993; Li et al., 2001).

The soil MC and PR of the soil in 2017 are presented in Figs. 5.4a-b and 5.5a-d. The results showed that the effect of crop row was significant on Soil MC ($p = <0.001$, $n = 30$) however, tyre inflation pressure, tillage system and their interaction had no significant effect on the soil MC in the maize field. The mean highest soil MC was recorded in un-trafficked inter-row between 4 and 5 (37%), which was significantly different from all other rows (Fig. 5.4a). The mean soil MC in LTP and STP treatments were 32 and 31% respectively while in the tillage system, the mean values of soil MC in DT, ST and NT were similar (32%) (Fig. 5.4b).

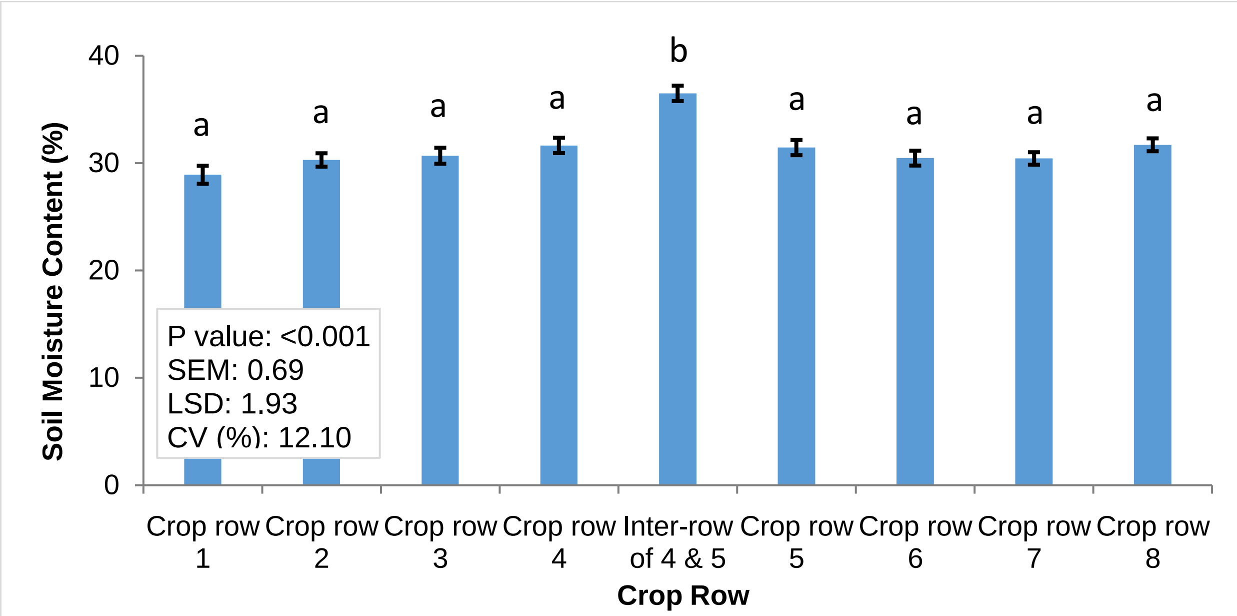


Figure 5.4a. Effect of crop row on soil moisture content in the South field in 2017. Means with the same letter are not significantly different (P = 0.05, n = 30) from each other. Error bar indicates the standard error of mean.

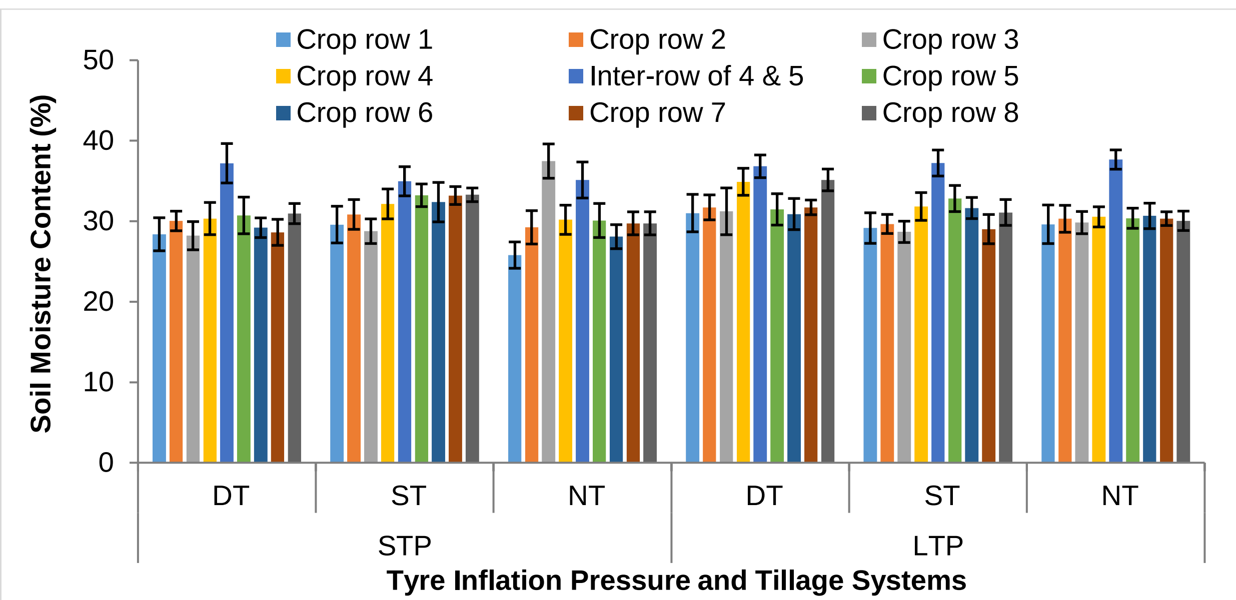


Figure 5.4b. Effect of tyre inflation pressure, tillage systems and crop row on soil moisture content in the South field in 2017 (n = 5). Error bar indicates the standard error of mean.

Figures 5.5a and 5.5b show that the tillage system and crop row had a significant effect on the PR of the soil (P = 0.001 and <0.001, respectively). However, tyre inflation pressure and interaction with tillage systems and crop row were not significant on PR of the soil (Figs. 5.5c and 5.5d). The PR values of soil were recorded the highest in NT than both ST and DT treatments with a maximum PR of soil 1.87 MPa in NT and 1.58 MPa in DT (n = 90), however, the PR of soil was overall in the order of NT>ST>DT. In all cases, PR values increased with soil depth down to 100mm, after which they generally reduced in value and remained relatively constant down to 400mm. The PR values then again increased at depths of 450 mm (Fig. 5.5a). The highest PR values were measured in CR3 at soil depths from 50 to 200 mm, with a peak PR of 1.77 MPa at a depth of 75 mm. These were higher than all other crop rows with a maximum PR of 1.90 MPa at depth 450 mm (P = <0.001, n = 30). The lowest PR values were recorded in the non-trafficked inter-rows 4 and 5, which was the UT zones of the plot (Fig. 5.5b).

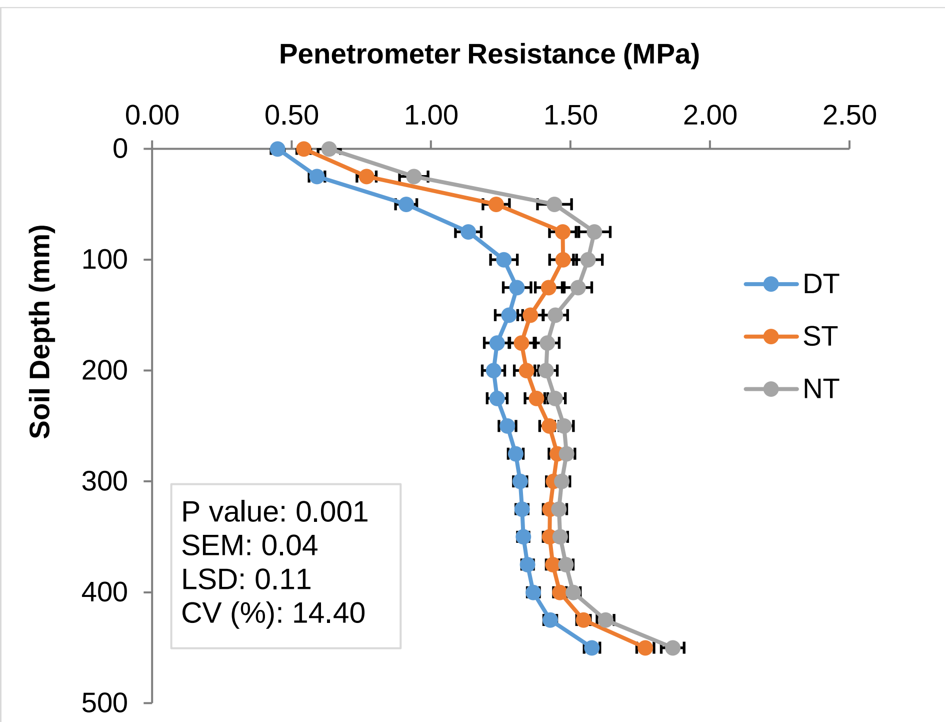


Figure 5.5a. Effect of tillage system on the penetrometer resistance in the South field in 2017. Error bar indicates the standard error of mean.

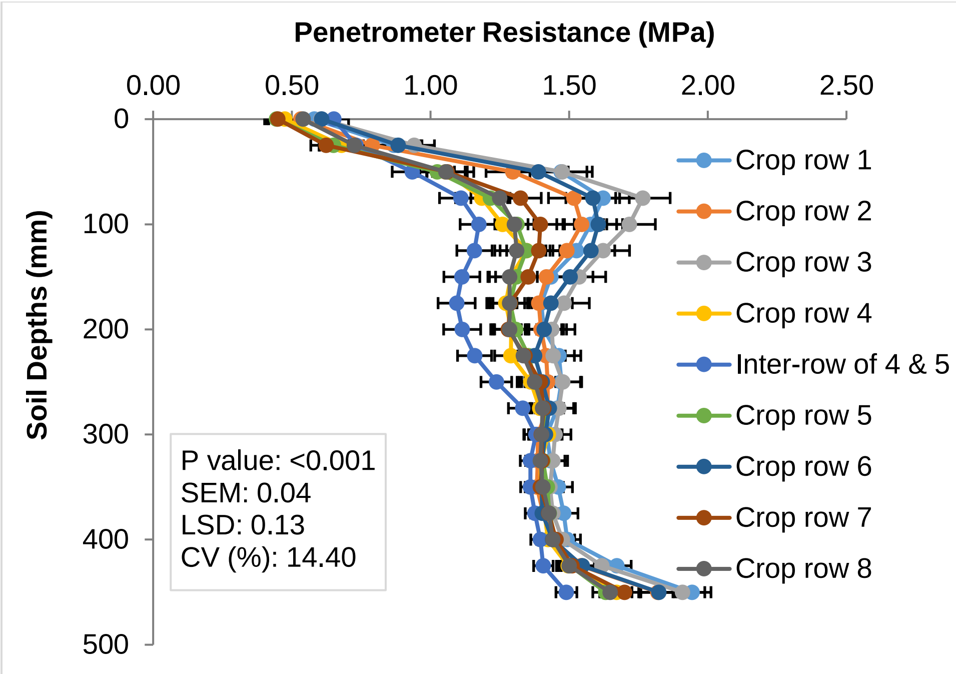


Figure 5.5b. Effect of crop row on the penetrometer resistance in the South field in 2017. Error bar indicates the standard error of mean.

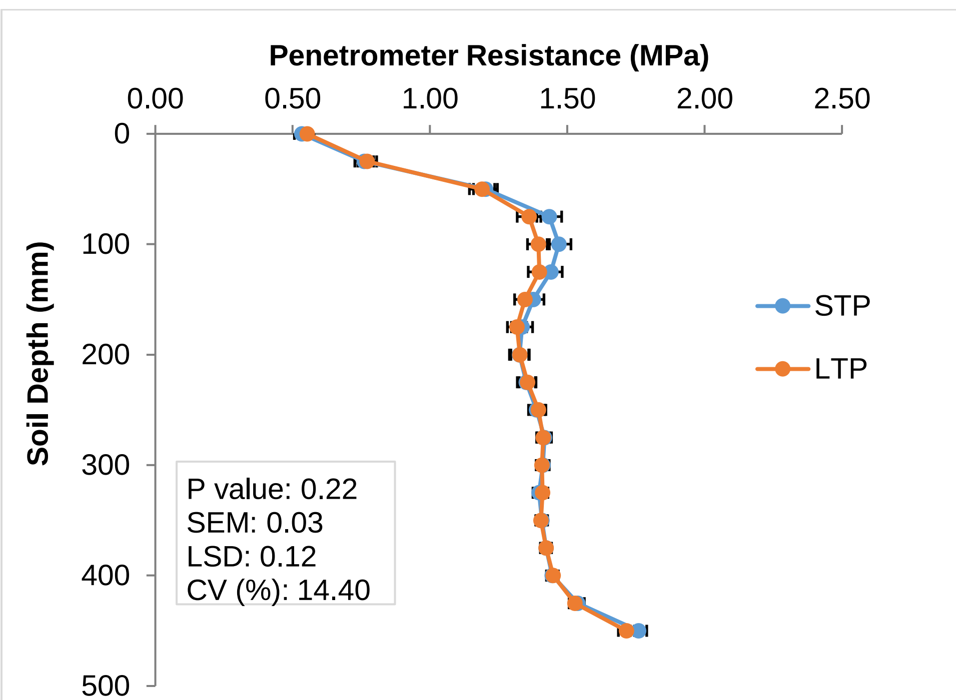


Figure 5.5c. Effect of tyre inflation pressure on penetrometer resistance in the South field in 2017. Error bar indicates the standard error of mean.

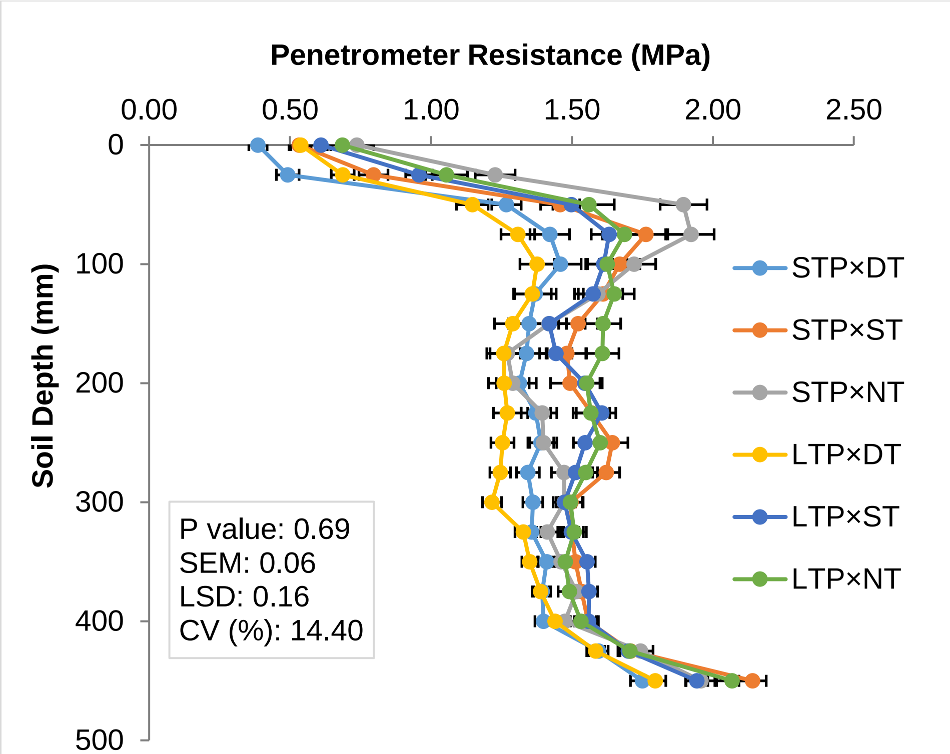


Figure 5.5d. Effect of tyre inflation pressure and tillage system on the penetrometer resistance in the South field in 2017. Error bar indicates the standard error of mean.

In 2018, the subplot effect of crop row was significant on soil MC at a depth of 200 mm in the maize field (P = <0.001, n = 30). Intercrop row of 4 and 5 (centre line of the plot) associated with significantly higher soil MC (36%) than crop rows 1, 3, 4 and 5 (Fig. 5.6a). However, the main effect of tyre inflation pressure, tillage system and interaction between them and crop row were not significant on soil MC (Fig. 5.6b).

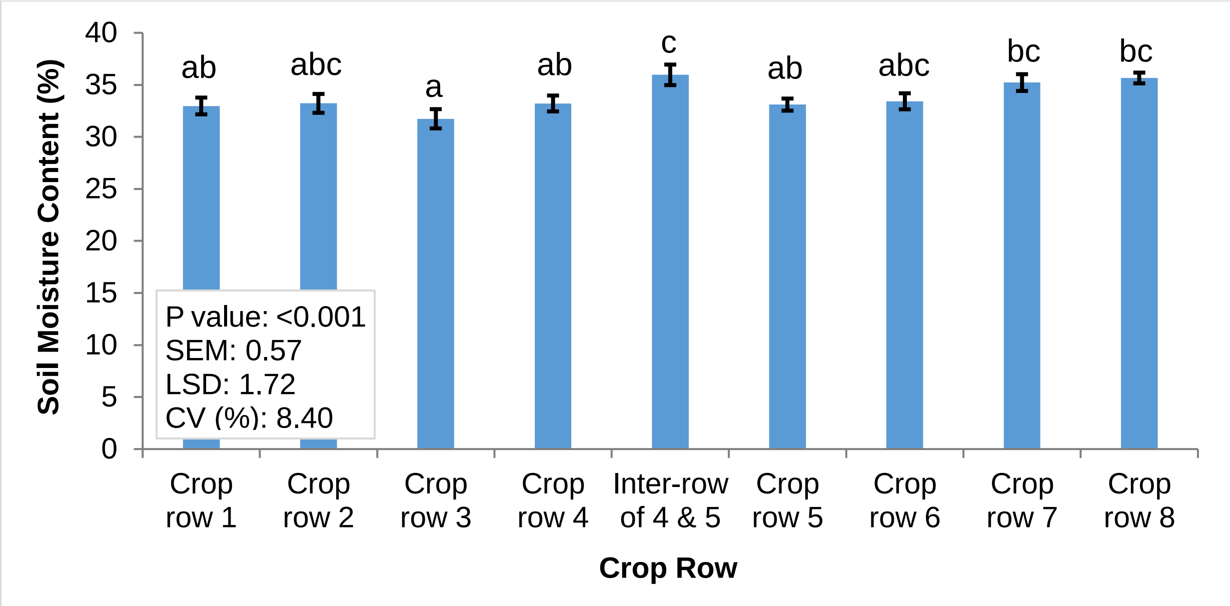


Figure 5.6a. Effect of crop row on soil moisture content at 200 mm depth at 95-100 DAP in the North field in 2018. Means with the same letter are not significantly different (P = 0.05, n = 30) from each other. Error bar indicates the standard error of mean.

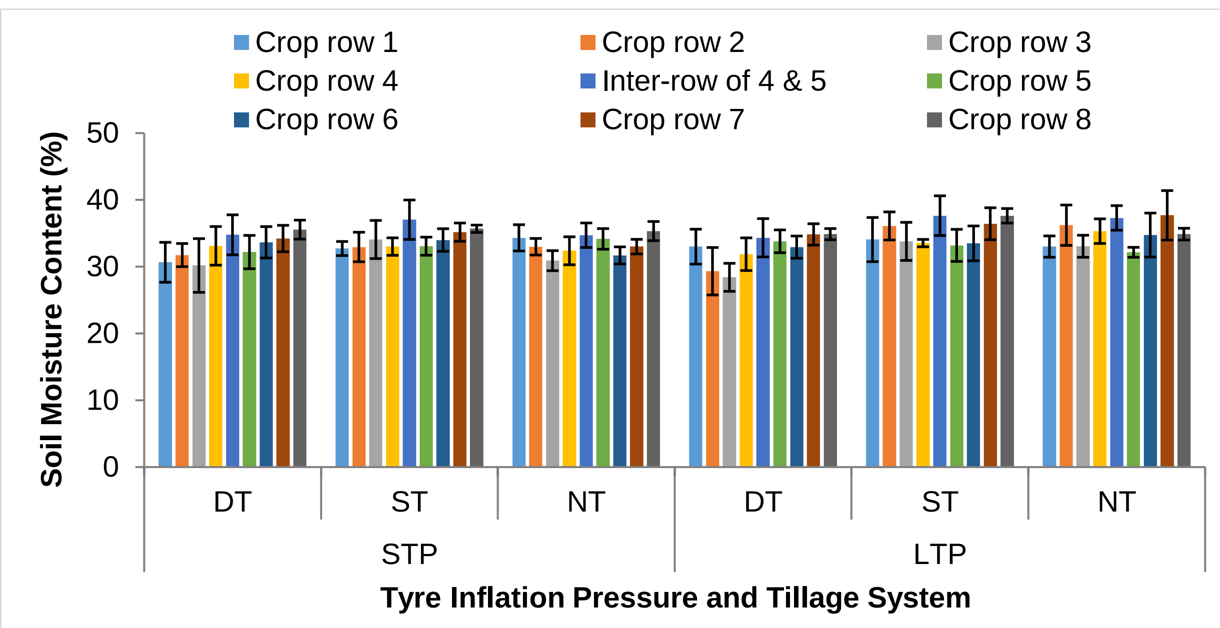


Figure 5.6b. Effect of tyre inflation pressure, tillage system and crop row on soil moisture content at 200 mm depth at 95-100 DAP in the North field in 2018 (n = 5). Error bar indicates the standard error of mean.

The results showed that tyre inflation pressure and its effects across depth and tillage system across depth had a significant influence on PR of soil in the maize field (P =<0.001, Figs. 5.7a-c) with no significant interactions between them (P = 0.06, Fig. 5.7d). The subplot effect of crop row, its effect across depth, and interaction effect of tyre inflation pressure and crop row had also a significant effect on PR of soil (P = <0.001, <0.001 and 0.004; Figs. 5.7e-g). The mean PR values were recorded significantly lower in the LTP treatment (2.39 MPa) than the STP treatment (2.71 MPa) (n = 2565; Fig. 5.7a). PR values in STP and LTP similarly increased from the soil surface to a depth of 50mm, after which the PR values were significantly higher in STP than LTP up to depth 275 mm where PR values were 3.16 and 3.39 MPa, respectively (n = 135). PR values then declined in the same trend up to 450 mm depth of soil where STP had higher values of PR than that of LTP treatment (Fig. 5.7b). Among tillage system, at the beginning across depth, PR values were 0.21 MPa then increased significantly in NT at depths from 25 to 75 mm than ST and DT and almost the same in all three tillage system to a depth of 100mm (n = 90). The increments of PR values were then recorded higher in DT and ST treatments to a depth of 150 mm than NT. After that PR values of soil were in the order of DT>ST>NT, however, significant differences were recorded between them from the depths of 325 mm to 450 mm (Figs. 5.7c).

Fig. 5.7e shows that the mean highest PR was recorded in CR3 (2.95 MPa) that was significantly different from others while the lowest mean PR value was ascertained in CR8 (2.32 MPa) (n = 570). PR values in varying depths were higher in the highly trafficked CR3, however, a significant increment of PR was recorded at depths 50 to 175 mm than other crop rows (P = <0.001, n = 30; Fig. 5.7f). PR values significantly increased from 0.32 MPa to a peak of 3.28 MPa in CR3 at a depth of 275 mm then PR values in all crop rows were gradually decreased to a depth of 450mm. The interaction between STP and crop row 3 had the highest PR of soil (3.30 MPa) that was statistically different from other crop rows in both tyre inflation pressure treatments (n = 285; Fig. 5.7g).

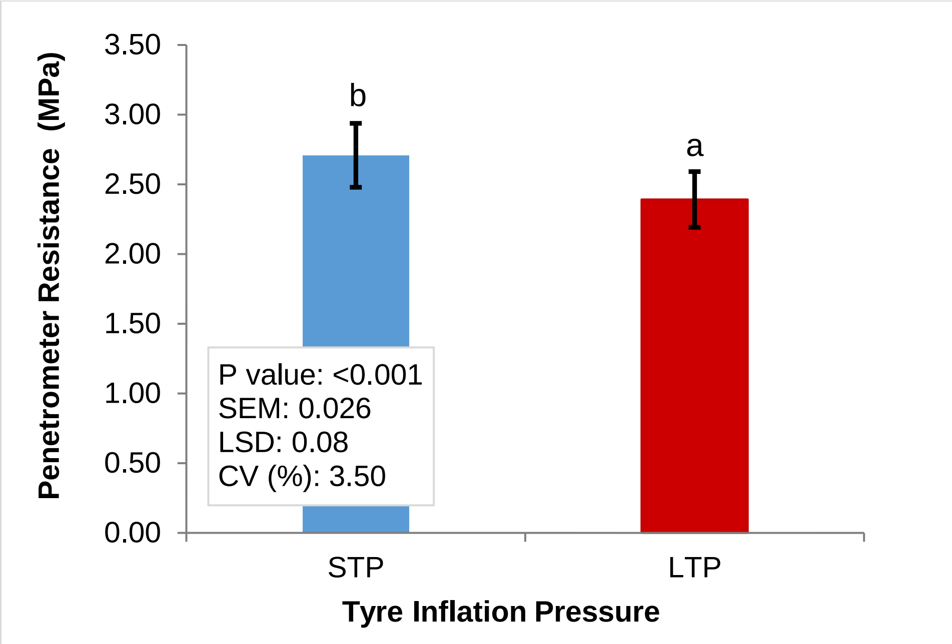


Figure 5.7a. Effect of tyre inflation pressure on the mean penetration resistance down to 450 mm depth in the North field in 2018. Error bar indicates the standard error of mean.

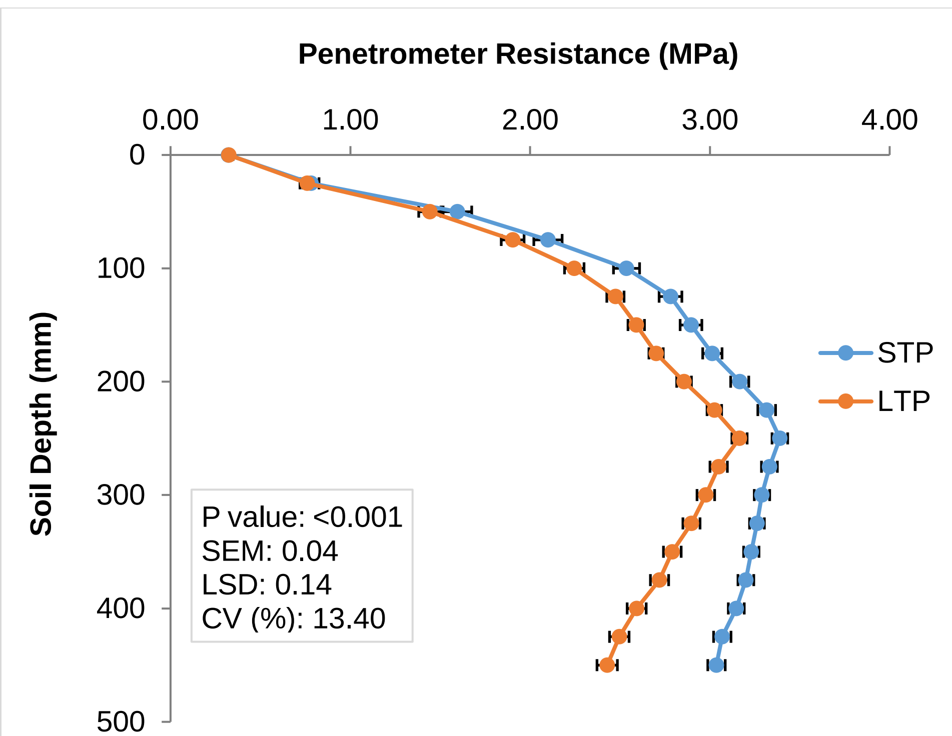


Figure 5.7b. Effect of tyre inflation pressure on the penetration resistance in the North field in 2018. Error bar indicates the standard error of mean.

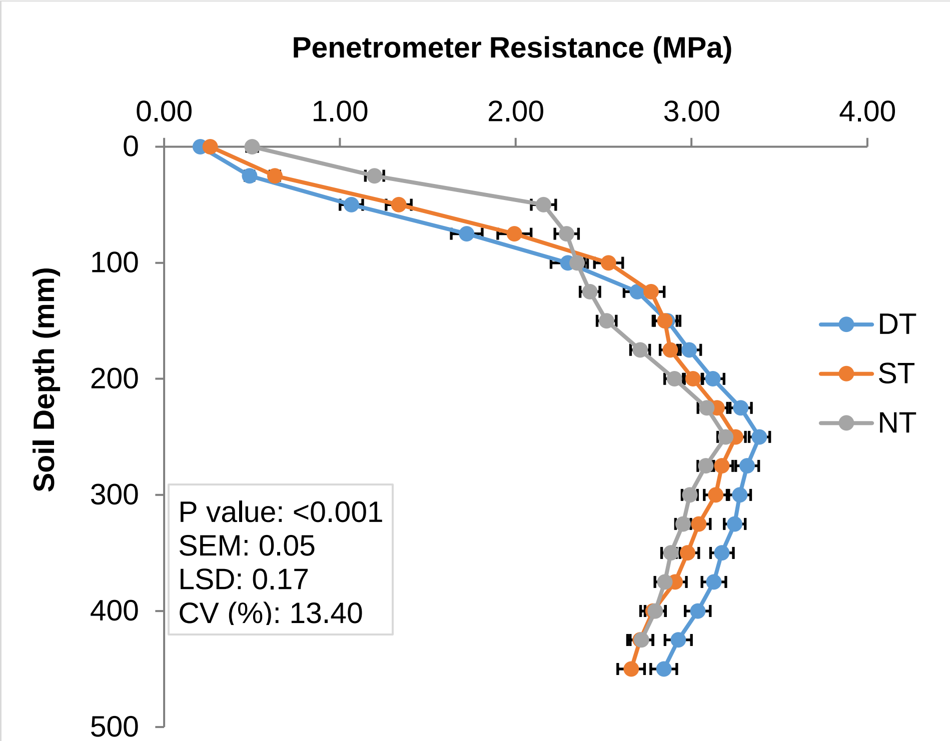


Figure 5.7c. Effect of tillage system and depth on the penetration resistance in the North field in 2018. Error bar indicates the standard error of mean.

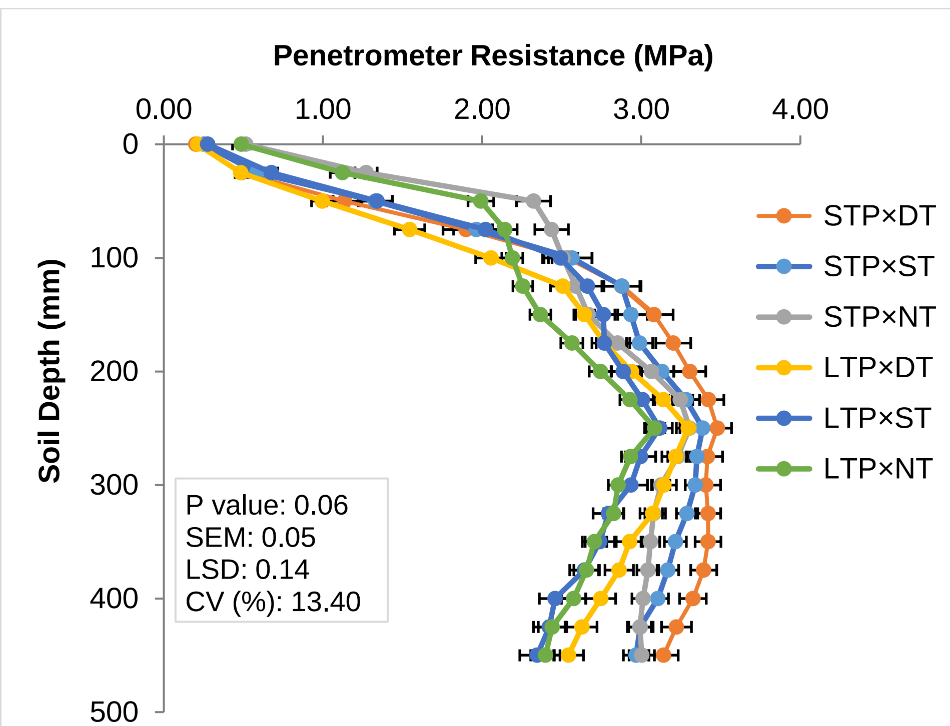


Figure 5.7d. Effect of tyre inflation pressure and tillage system on the penetration resistance in the North field in 2018. Error bar indicates the standard error of mean.

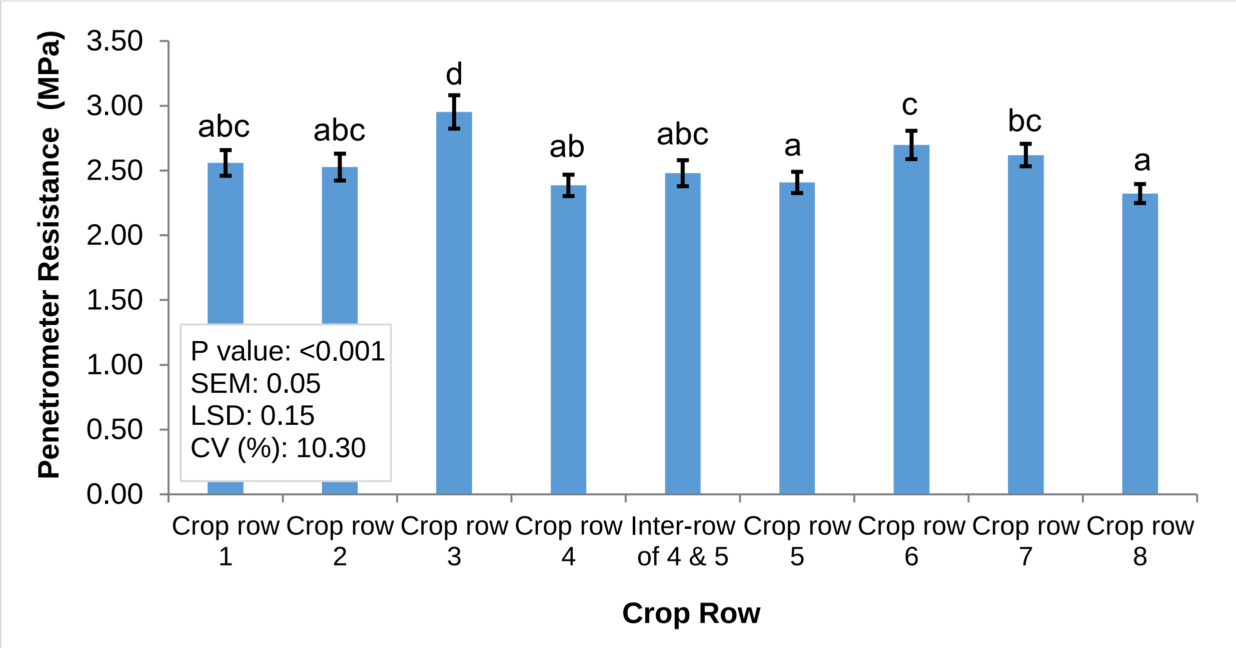


Figure 5.7e. Effect of crop row on the mean penetration resistance down to 450 mm depth in the North field in 2018. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

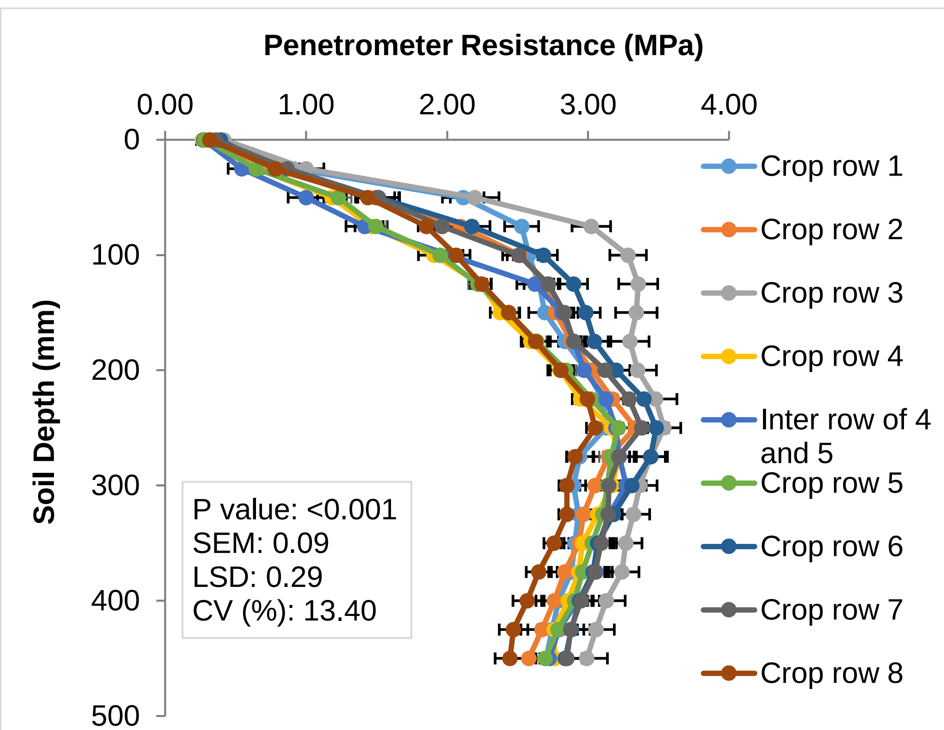


Figure 5.7f. Effect of crop row and depth on the penetration resistance in the North field in 2018. Error bar indicates the standard error of mean.

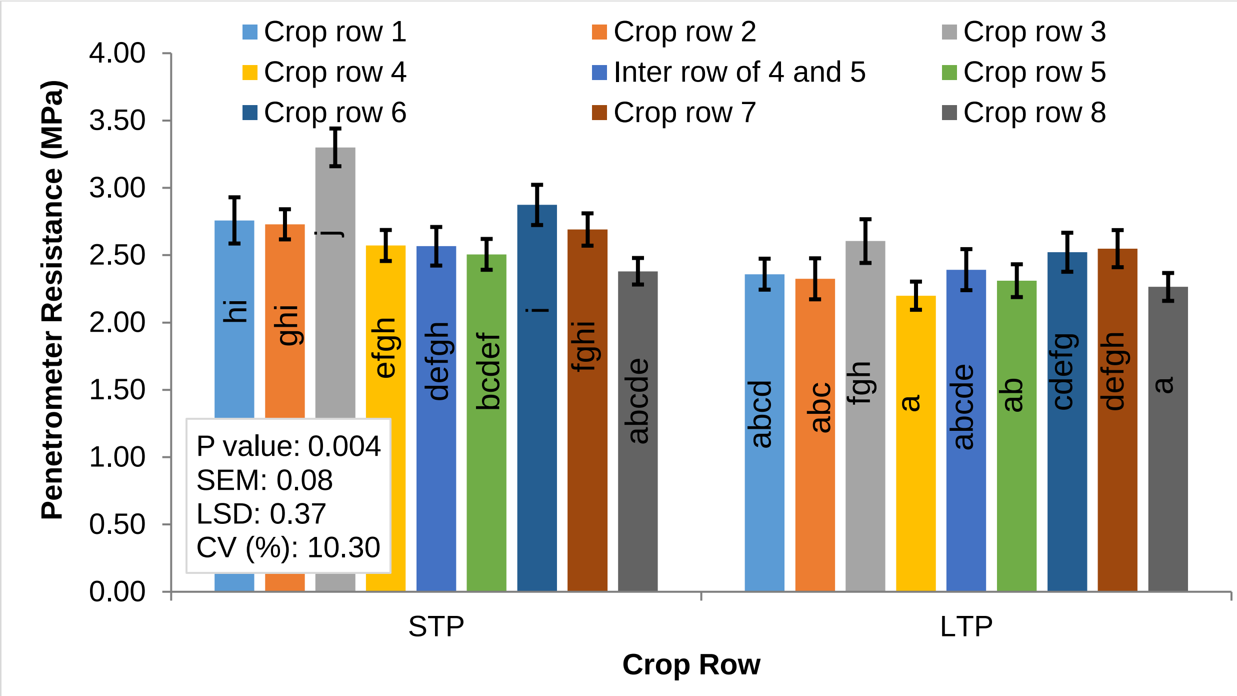


Figure 5.7g. Effect of tyre inflation pressure and crop row on the mean penetration resistance down to 450 mm depth in the North field in 2018. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

5.5.3. Effect on Growth and Yield of Maize

5.5.3.1. Growth Parameters of Maize

The data in 2016 shows that tyre inflation pressure had a significant effect on plant establishment (%) (P = 0.013, n = 60) and number of plants per ha (P = 0.012, n = 60) but had no significant influence on plant height at 30 DAP (P = 0.08) and 45 DAP (P = 0.757 and 0.009) of maize (Table 5.3 and Appendix 5.4). The mean plant establishment (%) across crop rows in LTP treatment was observed slightly higher i.e. 1.0 % (95.8%) compared to STP treatments (95.0%). Similarly, more plants per ha were recorded in LTP (89038) than that of STP treatment (88368, Table 5.3). The mean values of plant height of maize in STP treatment at 30, 45 DAP (base to flag leaf) and 45 (base to tip) were 1.26 m, 1.30 m and 1.89 m, respectively. Plant heights at these three different DAP of maize in the LTP treatments were 1.27 m, 1.29 m and 1.89 m respectively (Appendix-5.5). The results showed that the crop row had a significant effect on the plant height of maize at 30 DAP (P = <0.001) but had no significant effect on plant establishment (%, P = 0.60) and the number of plants ha^{-1} (P = 0.60) of Maize, and no interaction with tyre inflation pressure on any of these parameters (P = 0.59, 0.82 and 0.34, respectively). The plant height of maize at 30 DAP was significantly shorter in the crop row 3 (1.24 m) and 4 (1.25 m) than rows 1 and 2 (1.29 and 1.28 m, respectively) (1.25 m).

Table 5.3. Effect of tyre inflation pressure and crop row on plant establishment, number of plants ha^{-1} and plant height of maize, in the North field in 2016

Treatments	Plant establishment (%)					Number of plants ha^{-1}					Plant height at 30 DAP (m)				
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Mean	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Mean	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Mean
STP	95.5^{a}	95.3^{a}	94.2^{a}	95.3^{a}	95.0^{a}	88577^{a}	87573^{a}	88577^{a}	88745^{a}	88368^{a}	1.29^{a}	1.28^{a}	1.24^{a}	1.24^{a}	1.26^{a}
LTP	96.2^{a}	95.5^{a}	95.6^{a}	95.8^{a}	95.8^{b}	89080^{a}	88912^{a}	88745^{a}	89415^{a}	89038^{b}	1.28^{a}	1.28^{a}	1.25^{a}	1.27^{a}	1.27^{a}
Mean	95.8^{a}	95.4^{a}	94.9^{a}	95.5a		88829^{a}	88243^{a}	88661^{a}	89080^{a}		1.29^{b}	1.28^{b}	1.24^{a}	1.25^{a}	
24 and 80 DF	SEM	P value	LSD	CV (%)		SEM	P value	LSD	CV (%)		SEM	P value	LSD	CV (%)	
TIP	0.11	0.01	0.46	0.30		108.8	0.01	427.0	1.60		0.004	0.08	0.016	1.50	
CR	0.47	0.60	1.39	1.60		444.3	0.60	1296.0	2.60		0.005	<0.001	0.015	2.20	
TIP × CR	0.59	0.82	1.73			555.0	0.82	1614.0			0.008	0.34	0.021		

[†]TIP- Tyre inflation pressure, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, CR-Crop row, DF-Degree of freedom. Means with the same letter are not significantly different (P = 0.05) from each other.

It was observed that the vegetative stage started with emergence (VE, 5-7 DAP) and ended with tasselling (VT) from 65-80 DAP, respectively. The reproductive stage (R) of maize began when silk was visible outside the husks (R1 stage) at 70 DAP and ended with physiological maturity i.e. a black layer in the seed (R6) stage at 125-130 DAP. Days to 50% flowering of maize (silking and tasselling) was observed at 60-65 DAP. There was no visible difference on the days to 50% flowering between the tyre inflation pressures and crop row. The non-replicated rooting depth investigation showed that the maize rooting depth was 1.28 - 1.30 m (Appendix 5.6), which is comparable to typical maize effective rooting depths of 0.91 to 1.22 in the Midwest soils with a maximum depth of 1.52 to 1.82 m (Abendroth et al., 2011; Irmak and Rudnick, 2014). Vegetative growth and harvesting of maize are shown in Fig. 5.8.

a) Vegetative stages

b) Rooting depth investigation

c) Harvest of maize

Figure 5.8. Vegetative stage, rooting depth study and harvesting of maize.

The data in Fig. 5.9 shows that there was no significant main effect of tyre inflation pressure, tillage system or their interaction on plant establishment (%) of maize in 2017 (P =0.349, 0.105 and 0.501, respectively). The subplot effect of crop row of maize was also not significant; the mean plant establishment (%) of maize was recorded to be 97%. The mean plant establishment (%) in both tyre inflation pressure treatments was similar (97%). Tables 5.4 - 5.5 and Appendix 5.7 show that only tillage system had a significant effect on the number of plants ha^{-1} of maize (P = <0.001, n = 80) while tyre inflation pressure and crop row had a significant influence on the plant height of maize (P = 0.04 and 0.002, respectively) and others were not significant. The highest number of plants ha^{-1} was found in NT (91676) which was significantly different from ST (91215) and DT (90744). Table 5.5 shows there was a small (1%) but significantly greater plant height in the LTP treatment (2.15 m) in comparison to the STP treatment (2.13 m, P = 0.045, n = 120). Among crop rows, the heavily trafficked crop row 3 had the shortest plant height (2.11 m) that was 2% shorter than some, but not all the remaining crop rows (n = 30).

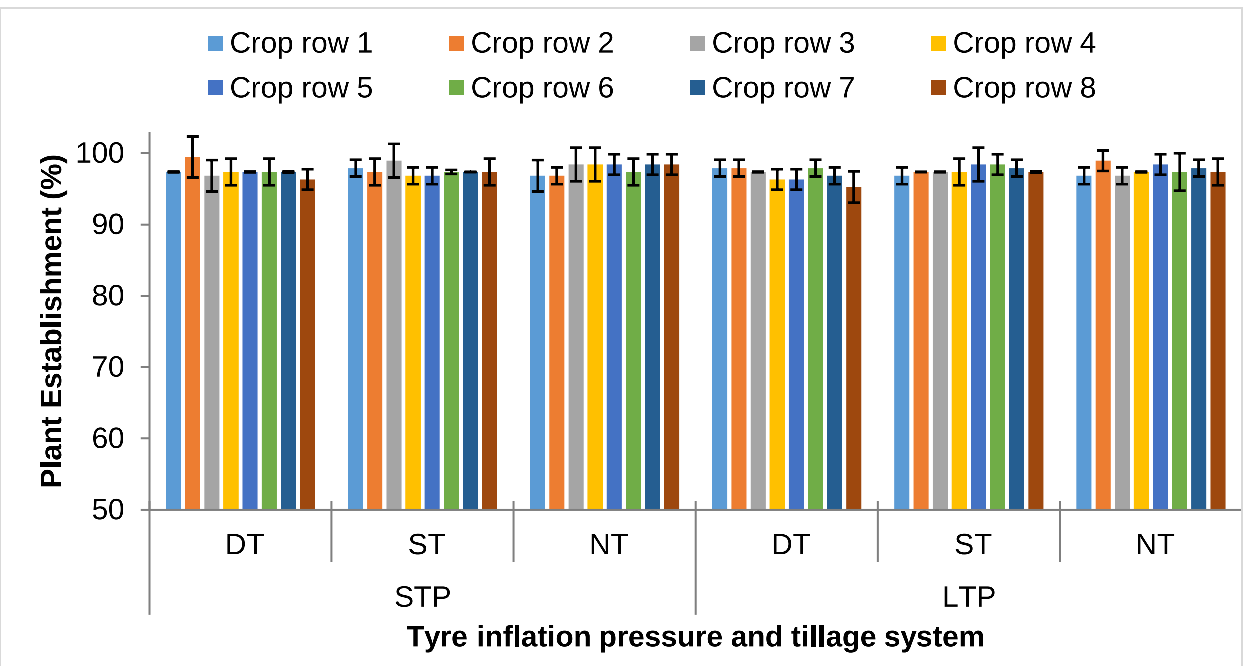


Figure 5.9. Effect of tyre pressure, tillage system and crop row on plant establishment of maize, in the South field in 2017 (n = 5). Error bar indicates the standard deviation of mean.

Table 5.4. Effect of tyre inflation pressure and tillage system on the number of plants ha^{-1} of maize, in the South field in 2017

Treatments†	Number of plants ha^{-1}			Mean
	DT	ST	NT	
STP	90964[a]	91173[a]	91864[a]	91334[a]
LTP	90524[a]	91257[a]	91487[a]	91089[a]
Mean	90744[a]	91215[b]	91676[c]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	100.0	0.09	294.9	0.40
TS	122.4	<0.001	361.1	
TIP × TS	173.1	0.27	510.7	

†TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 5.5. Effect of tyre inflation pressure and crop row on plant height of maize at harvest, in the South field in 2017

Treatments†	Plant height (m)								Mean
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Crop row 5	Crop row 6	Crop row 7	Crop row 8	
STP	2.11[a]	2.15[a]	2.09[a]	2.14[a]	2.14[a]	2.13[a]	2.14[a]	2.13[a]	2.13[a]
LTP	2.16[a]	2.17[a]	2.13[a]	2.15[a]	2.15[a]	2.13[a]	2.14[a]	2.15[a]	2.15[b]
Mean	2.13[ab]	2.15[b]	2.11[a]	2.15[b]	2.14[b]	2.13[ab]	2.14[ab]	2.14[b]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)					
TIP	0.007	0.04	0.02	1.20					
CR	0.007	0.002	0.02	1.70					
TIP × CR	0.013	0.34	0.03						

†TIP- Tyre inflation pressure, CR-crop row, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure. Means with the same letter are not significantly different (P = 0.05) from each other.

The data in Tables 5.6 to 5.8 and Appendix 5.8 revealed that in 2018, tyre inflation pressure had a significant effect on plant establishment (%) (P = 0.007, n = 120), number of plants ha^{-1} (P = 0.005, n = 120) and plant height (P = 0.004, n = 120) of maize while tillage system significantly influenced the plant height of maize (P = 0.047, n = 80) with no significant interaction between tyre inflation pressure and tillage system. The result showed that plant establishment (%) of maize was recorded marginally higher in LTP (91.3%) than STP treatment plot (90.4%). The mean plant establishment (%) of maize across all three tillage systems was approximately 91% (Table 5.6). A small but significantly 0.6% higher number of plants ha^{-1} (84775) and 2% higher plant height (2.57 m) were recorded in LTP as compared to the STP treatment with the number of plants ha^{-1} of 84273 and plant height of 2.52 m. Among tillage system, across both tyre inflation pressures, the plant height was marginally higher in DT plots (2.56 m) that was significantly different from NT (2.55 m) and ST treatment plots (2.52 m, Table 5.8).

Table. 5.6. Effect of tyre inflation pressure, tillage system and crop row on plant establishment of maize, in the North field in 2018

Treatments†	Plant establishment (%)			Mean
	DT	ST	NT	
STP	90.1[a]	90.6[a]	90.5[a]	90.4[a]
LTP	91.0[a]	91.6[a]	91.3[a]	91.3[b]
Mean	90.5[a]	91.1[a]	90.9[a]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	0.28	0.007	0.59	0.90
TS	0.35	0.26	0.73	
TIP × TS	0.49	0.95	1.03	

†TIP- Tyre inflation pressure, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure, DT-deep tillage, ST-shallow tillage, and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table. 5.7. Effect of tyre inflation pressure and tillage system on the number of plants ha^{-1} of maize, in the North field in 2018

Treatments†	Number of plants ha^{-1}			Mean
	DT	ST	NT	
STP	84538[a]	83994[a]	84287[a]	84273[a]
LTP	84517[a]	84810[a]	84998[a]	84775[b]
Mean	84527[a]	84402[a]	84643[a]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	111	0.005	328.6	0.50
TS	136	0.47	402.5	
TIP × TS	193	0.08	569.3	

†TIP- Tyre inflation pressure, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure, DT-deep tillage, ST-shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Data of the effect of tyre inflation pressures, tillage system and crop row, and their interaction effects on the ear height and ear length in 2018 are shown in Table 5.9 - 5.10 and Appendix 5.9. Table 5.9 shows that tyre inflation pressure, tillage system and interaction between tillage system and crop row had a significant effect on ear height of maize (P = 0.05, 0.02 and 0.001, respectively). There was no significant effect of interaction between tyre inflation pressure and tillage system and crop row on the ear height of maize (P = 0.63 and 0.32, respectively). In comparison to standard tyre inflation pressures (1.20 m), the low inflation pressure tyre systems had higher ear height of maize (1.23 m, n = 120) in 2018. The ear height of maize was also recorded higher in DT (1.2 m) that was significantly different from NT and ST plot (1.20 m) (n = 80). Higher ear height of maize was recorded in crop row 3 in DT (1.29 m) that was significantly different from the crop rows 2, 4, 5, 7 and 8 in ST and crop rows 3 and 6 in NT (1.17 m) with the lowest ear height in crop row 3 of NT (Table 5.9b) (n = 10). In the case of ear length, LTP had a 6.29% higher ear length of maize (0.186 m) as compared with STP treatments (0.175 m) (n = 120; Table 5.10).

Table 5.8. Effect of tyre inflation pressure and tillage system on plant height of maize at harvest, in the North field in 2018

Treatments†	Plant height (m)			Mean
	DT	ST	NT	
STP	2.53[a]	2.49[a]	2.55[a]	2.52[a]
LTP	2.59[a]	2.55[a]	2.56[a]	2.57[b]
Mean	2.56[b]	2.52[a]	2.55[a]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	0.009	0.004	0.03	1.40
TS	0.012	0.04	0.03	
TIP × TS	0.016	0.32	0.05	

†TIP- Tyre inflation pressure, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure, DT-deep tillage, ST-shallow tillage, and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 5.9a. Effect of tyre inflation pressure and tillage system on the ear height of maize at harvest, in the North field in 2018

Treatments†	Ear height (m)			Mean
	DT	ST	NT	
STP	1.23[a]	1.18[a]	1.21[a]	1.20[a]
LTP	1.25[a]	1.22[a]	1.21[a]	1.23[b]
Mean	1.24[b]	1.20[a]	1.21[a]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	0.007	0.05	0.021	2.30
TS	0.009	0.02	0.026	
TIP × TS	0.013	0.63	0.037	

†TIP- Tyre inflation pressure, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure, DT-deep tillage, ST-shallow tillage, and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 5.9b. Effect of tillage system and crop row on the ear height of maize, in the North field in 2018

Treatments	Ear height (m)								Mean
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Crop row 5	Crop row 6	Crop row 7	Crop row 8	
DT	1.20[abcd]	1.22[abcde]	1.29[ce]	1.23[abcde]	1.23[abcde]	1.28[bcde]	1.21[abcde]	1.22[abcde]	1.24[b]
ST	1.20[abc]	1.20[ab]	1.22[abcde]	1.19[ab]	1.19[ab]	1.21[abcde]	1.19[ab]	1.17[a]	1.20[a]
NT	1.22[abcde]	1.20[abcde]	1.17[a]	1.21[abcde]	1.22[abcde]	1.20[ab]	1.22[abcde]	1.23[abcde]	1.21[a]
Mean	1.21[a]	1.21[a]	1.23[a]	1.21[a]	1.21[a]	1.23[a]	1.21[a]	1.21[a]	
20 and 168 DF	SEM	P value	LSD	CV (%)					
TS	0.009	0.02	0.03	2.30					
CR	0.009	0.32	0.03	4.10					
TS × CR	0.017	0.001	0.05						

†TIP- Tyre inflation pressure, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure, DT-deep tillage, ST-shallow tillage, and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 5.10. Effect of tyre inflation pressure, tillage system and crop row on the ear length of maize, in the North field in 2018

Treatments†	Ear length (m)			Mean
	DT	ST	NT	
STP	0.177[a]	0.178[a]	0.171[a]	0.175[a]
LTP	0.189[a]	0.183[a]	0.186[a]	0.186[b]
Mean*	0.183[a]	0.181[a]	0.179[a]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	0.002	<.001	0.006	4.20
TS	0.002	0.44	0.007	
TIP × TS	0.003	0.37	0.01	

†TIP- Tyre inflation pressure, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure, DT-deep tillage, ST-shallow tillage, and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

5.5.3.2. Yield Parameters and Grain Yield of Maize

The 2016 data in Table 5.11 shows that the subplot effect of crop row had a significant influence on both 1000 grain weight and hand harvested grain yield of maize (P = 0.005 and 0.038, respectively) with no significant main effect of tyre inflation pressure and interaction with crop row. Among crop rows, the highest 1000 grain weight of maize was recorded in CR1 (305 g) that was significantly different from the CR3 (291 g) (n = 30). Similarly, the highest hand harvested grain yield was recorded in CR1 (15.75 Mg ha^{-1}) followed by CR 4 (15.23 Mg ha^{-1}) but significantly different from CR3 (14.99 Mg ha^{-1}) and CR2 (14.97 Mg ha^{-1}). Highly trafficked areas might have a negative effect on the closest crop row 3, which in turns decreased 1000 grain weight and yield of maize in 2016.

Table 5.11. Effect of tyre inflation pressure and crop row on 1000 grain weight and hand harvest grain yield of maize, in the North field in 2016

Treatments	1000 grain weight (g)					Hand harvest grain yield (Mg ha^{-1})				
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Mean	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Mean
STP	303^{a}	293^{a}	291^{a}	291^{a}	295^{a}	15.4^{a}	15.2^{a}	15.3^{a}	15.3^{a}	15.3^{a}
LTP	306^{a}	298^{a}	291^{a}	299^{a}	298^{a}	16.1^{a}	14.6^{a}	14.6^{a}	15.1^{a}	15.1^{a}
Mean	305^{b}	296^{ab}	291^{a}	295^{ab}		15.7^{b}	14.9^{a}	14.9^{a}	15.2^{ab}	
24 and 80 DF	SEM	P value	LSD (0.05)	CV (%)		SEM	P value	LSD (0.05)	CV (%)	
TIP	4.64	0.46	12.87	2.70		0.229	0.31	0.63	4.30	
CR	3.52	0.005	7.26	5.40		0.294	0.03	0.60	8.20	
TIP × CR	6.33	0.73	13.75			0.427	0.09	0.88		

†TIP- Tyre inflation pressure, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, CR-crop row. Means with the same letter are not significantly different (P = 0.05) from each other.

The results given in Fig 5.10 reveal that there was no significant difference in combine harvested grain yield was observed between STP and LTP treatments with values of 14.36 Mg ha^{-1} and 14.27 Mg ha^{-1}, respectively with a CV of 1.70% (P = 0.32, n = 15).

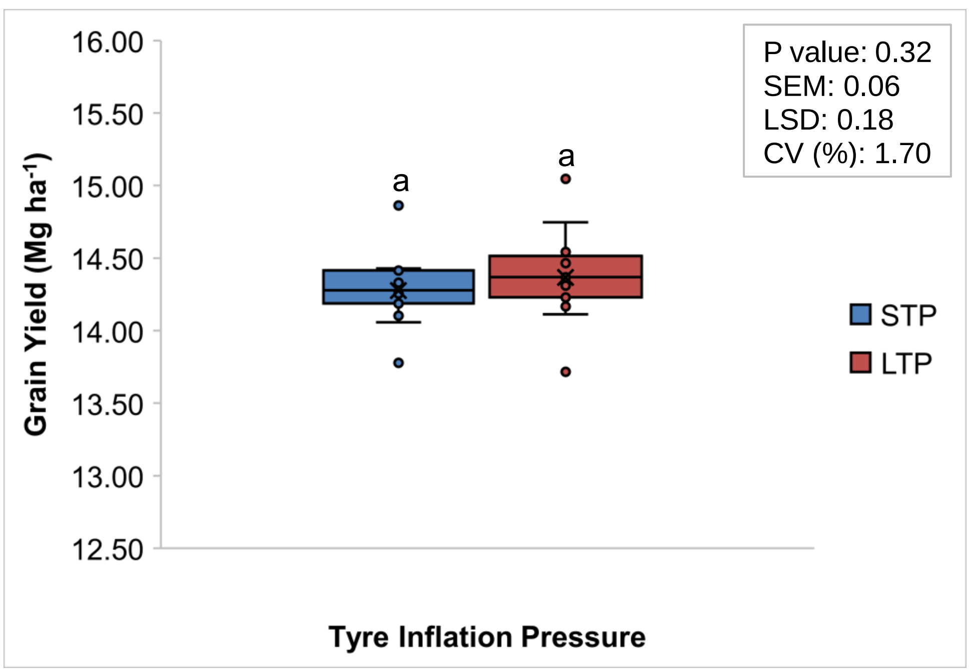


Figure 5.10. Effect of tyre inflation pressure on the combine harvested grain yield of maize, in the North field in 2016.

Note: The ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

In 2017, hand harvest of maize data showed that tyre inflation pressure, tillage system and their interaction had no significant effect on 1000 grain weight (P = 0.250, 0.414 and 0.312) or hand harvest yield of maize per ha (P = 0.769, 0.142 and 0.317, respectively) (Appendices 5.10 and 5.11). Mean hand harvested 1000 grain weights of maize were 336 and 340 g for the STP and LTP treatment, respectively. Results revealed that the subplot effect of crop row had a significant influence on the 1000 grain yield of maize (P = 0.04, n = 30; Table 5.12), however, its interactions with tyre inflation pressure and tillage system were not significant in terms of 1000 grain weight (P = 0.189, 0.702 and 0.908) or hand harvested grain yield of maize (P = 0.764, 0.283 and 0.881, respectively; Appendices 5.10 – 5.11). The highest 1000 grain weight of maize was recorded in the CR4 (342 g) which was significantly different from the CR2 (332 g) and CR1 (333 g). The mean hand harvested grain yields were recorded as 17.3 and 17.4 Mg ha^{-1} in STP and LTP treatment, respectively. The low quantity of hand-harvested sampling (5 ears/crop row) may not adequately represent the whole 180 m length of crop row and thus yield was similar. On the other hand, the mean hand harvested grain yields of DT, ST and NT systems were 17.4, 17.0 and 17.7 Mg ha^{-1}, respectively.

Table 5.12. Effect of tyre inflation pressure and crop row on 1000 grain weight of maize, in the South field in 2017

Treatments [†]	1000 grain weight (g)								Mean
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Crop row 5	Crop row 6	Crop row 7	Crop row 8	
STP	335[a]	328[a]	327[a]	339[a]	340[a]	341[a]	336[a]	339[a]	336[a]
LTP	331[a]	335[a]	344[a]	345[a]	339[a]	341[a]	339[a]	340[a]	339[a]
Mean	333[ab]	332[a]	336[abc]	342[c]	339[abc]	341[bc]	337[abc]	339[abc]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)					
TIP	2.19	0.25	6.47	2.50					
CR	2.62	0.04	7.32	4.20					
TIP × CR	4.10	0.18	11.4						

[†]TIP- Tyre inflation pressure, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure and CR – crop row. Means with the same letter are not significantly different (P = 0.05) from each other.

The 2017 results given in Figs. 5.11 - 5.13 showed that across all tillage treatments tyre inflation pressure had a significant effect on the combine harvested grain yield of maize ($P = 0.005$, $n = 15$), but tillage system and its interaction with tyre inflation pressure were not significant ($P = 0.32$ and 0.58, respectively). The grain yield was significantly 4.31% higher in LTP treatment (15.02 Mg ha^{-1}) as compared to STP treatments (14.40 Mg ha^{-1}) (Fig. 5.11). The mean combine harvested grain yield of maize in DT, ST and NT systems were 14.90, 14.70 and 14.52 Mg ha^{-1} ($n = 10$, Fig. 5.12). No significant interaction between tyre inflation pressure and tillage system showed that mean grain yields of the interaction between LTP×DT, LTP×ST and LTP×NT were recorded 15.27, 15.10 and 14.67 Mg ha^{-1} respectively ($n = 5$). Mean grain yields of the interaction between STP×DT, STP×ST and STP×NT were 14.53, 14.30 and 14.36 Mg ha^{-1}, respectfully (Fig. 5.13).

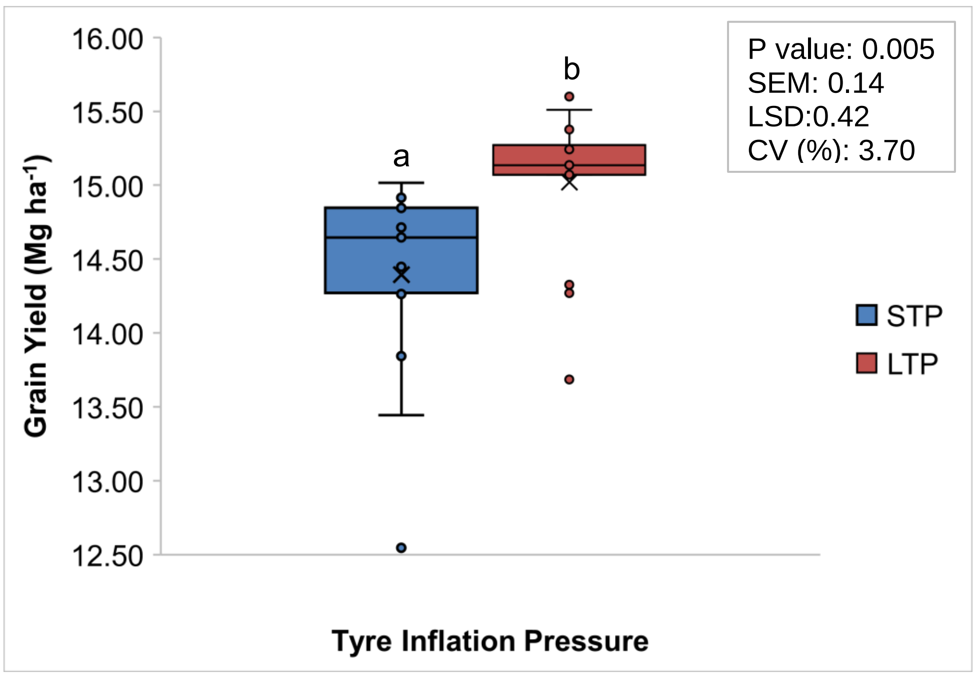


Figure 5.11. Effect of tyre inflation pressure on the combine harvested grain yield of maize, in the South field in 2017.

Note: The ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

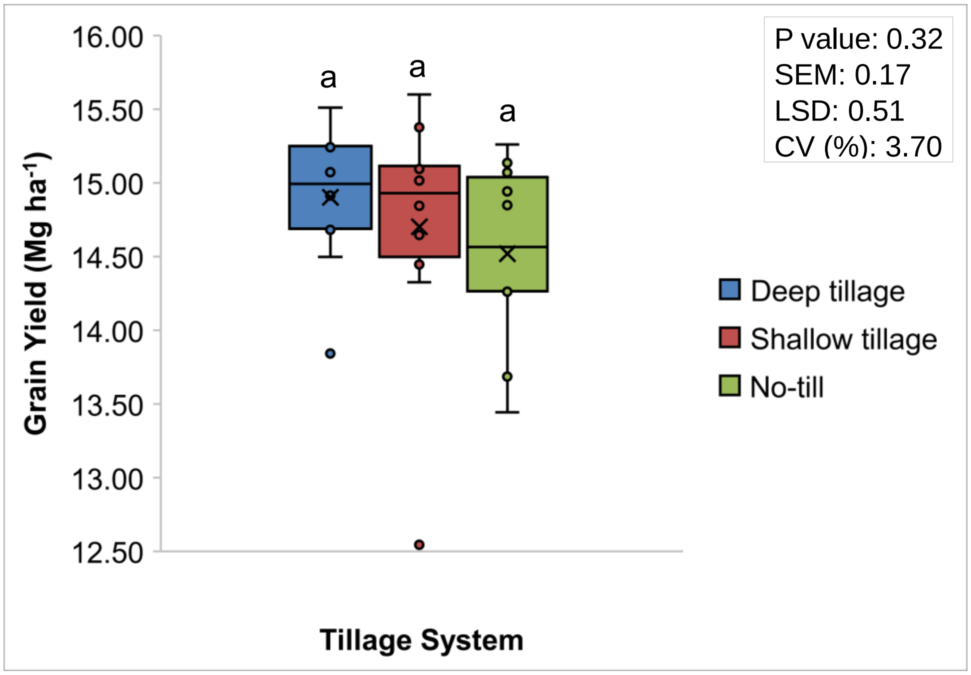


Figure 5.12. Effect of tillage system on the combine harvested grain yield of maize, in the South field in 2017.

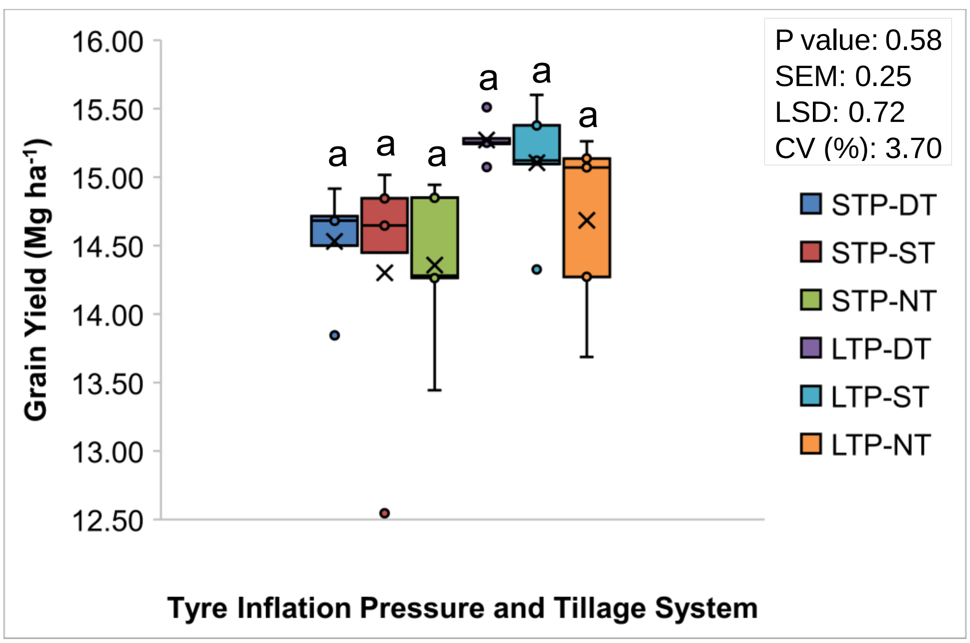


Figure 5.13. Effect of tyre inflation pressure and tillage system on the combine harvested grain yield of maize, in the South field in 2017.

Note: In Figs. 5.11-5.13, the ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

The crop yield results from 2018 demonstrate that the tillage system and crop row had a significant effect on the 1000 grain weight (P = 0.005 and <0.001, respectively) and hand harvested grain yield of maize (P = <0.001 and <0.001, respectively) while tyre inflation pressure (P = 0.478 and 0.125) and it's interaction with tillage system (P = 0.696 and 0.95) were not significant (Tables 5.13 - 5.14 and Appendix 5.12). Among the tillage system, the highest 1000 grain weight and hand harvested grain yield of maize was recorded in the DT treatment (309 g and 12.81 Mg ha^{-1}, respectively) that was significantly different from the ST (286 g and 11.49 Mg ha^{-1}, respectively) and NT treatments (285 g and 10.68 Mg ha^{-1}, respectively) (n = 80; Table 5.13). Among crops rows, the 1000 grain weight was recorded higher in the CR5 (308 g) than CR1 (283 g), CR8 (285 g) and CR2 (288 g). Higher 1000 grain weight in the crop row 5 in 2018, significantly increased the grain yield by 10.64% in the crop row 5 (12.37 Mg ha^{-1}, P = <0.001, n = 30) as compared to the trafficked crop row 1 (11.18 Mg ha^{-1}) and also significantly different from the CR3 (11.36 Mg ha^{-1}), CR8 (11.37 Mg ha^{-1}) and CR2 (11.59 Mg ha^{-1}) (Table 5.14b). The mean 1000 grain weight of maize showed that the LTP treatment led the STP treatment by 296 to 292 g. The mean hand harvested grain yields of maize were 11.41 and 11.91 Mg ha^{-1} in STP and LTP treatments respectively and were not significantly different (Table 5.14). These results are similar to the results recorded in 2017, where LTP was non-significantly higher than the STP treatment.

Table 5.13a. Effect of tyre inflation pressure and tillage system on 1000 grain weight of maize, in the North field in 2018

Treatments†	1000 grain weight (g)			Mean
	DT	ST	NT	
STP	305^a	287^a	283^a	292^a
LTP	314^a	285^a	288^a	296^a
Mean	309^a	286^b	285^b	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	4.18	0.47	12.3	5.50
TS	5.12	0.005	15.1	
TIP × TS	7.24	0.69	21.3	

†TIP- Tyre inflation pressure, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure, DT-deep tillage, ST-shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 5.13b. Effect of tyre inflation pressure and tillage system on hand harvest grain yield of maize, in the North field in 2018

Treatments[†]	Hand harvest grain yield (Mg ha^{-1})			Mean
	DT	ST	NT	
STP	12.5[a]	11.3[a]	10.4[a]	11.4[a]
LTP	13.1[a]	11.6[a]	10.9[a]	11.9[a]
Mean	12.8[b]	11.4[a]	10.6[a]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	0.21	0.12	0.64	7.20
TS	0.26	<.001	0.78	
TIP × TS	0.37	0.95	1.11	

[†]TIP- Tyre inflation pressure, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure, DT-deep tillage, ST-shallow tillage and NT-No- till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 5.14a. Effect of tyre inflation pressure and crop row on 1000 grain weight of maize, in the North field in 2018

Treatments[†]	1000 grain weight (g)								
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Crop row 5	Crop row 6	Crop row 7	Crop row 8	Mean
STP	277[a]	284[a]	290[a]	300[a]	307[a]	295[a]	292[a]	287[a]	292[a]
LTP	290[a]	292[a]	297[a]	301[a]	309[a]	295[a]	298[a]	284[a]	296[a]
Mean	283[a]	288[ab]	294[abc]	300[bc]	308[c]	295[abc]	295[abc]	285[ab]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)					
TIP	4.18	0.47	12.3	5.50					
CR	3.54	<.001	9.89	6.60					
TIP × CR	6.28	0.75	17.6						

[†]TIP- Tyre inflation pressure, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure, CR-crop row. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 5.14b. Effect of tyre inflation pressure and crop row on hand harvest grain yield of maize, in the North field in 2018

Treatments†	Hand harvest grain yield (Mg ha^{-1})								
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Crop row 5	Crop row 6	Crop row 7	Crop row 8	Mean
STP	10.9^{a}	11.2^{a}	10.7^{a}	11.7^{a}	12.3^{a}	11.3^{a}	11.6^{a}	11.3^{a}	11.4^{a}
LTP	11.4^{a}	11.9^{a}	12.0^{a}	12.2^{a}	12.3^{a}	12.0^{a}	11.8^{a}	11.3^{a}	11.9^{a}
Mean*	11.2^{a}	11.5^{ab}	11.3^{b}	12.0^{bc}	12.3^{c}	11.6^{abc}	11.7^{abc}	11.3^{ab}	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)					
TIP	0.218	0.125	0.642	7.20					
CR	0.178	<.001	0.498	8.40					
TIP × CR	0.321	0.184	0.903						

†TIP- Tyre inflation pressure, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure and CR-crop row. Means with the same letter are not significantly different (P = 0.05) from each other.

In 2018, the combine harvested yield results, given in Figs. 5.14-5.16 indicated that tyre inflation pressure and tillage system had a significant effect on the grain yield of maize (P = 0.019 and <0.001, respectively) while their combined effect was not significant (P = 0.85). Higher grain yield of maize was recorded in the LTP treatment (14.13 Mg ha^{-1}) as compared to STP (13.76 Mg ha^{-1}). The yield increment of maize in LTP plots was 2.70% compared to STP plots (n = 15; Fig. 5.14). Across both tyre inflation pressure treatments, the highest grain yield of maize was obtained in DT (15.11 Mg ha^{-1}) that was followed by ST (13.98 Mg ha^{-1}) and lowest yield was found in NT systems (12.73 Mg ha^{-1}) (Fig. 5.15, n = 10). The mean grain yield of STP×DT, STP×ST and STP×NT were recorded 14.87, 13.81 and 12.59 Mg ha$^{-1.}$ The mean grain yields of the interaction between LTP×DT, LTP×ST and LTP×NT were recorded as 15.35, 14.15 and 12.88 Mg ha^{-1} (n = 5, Fig. 5.16). This indicates that the yield benefit of low tyre inflation pressure tyres for maize production consistent for all tillage treatments.

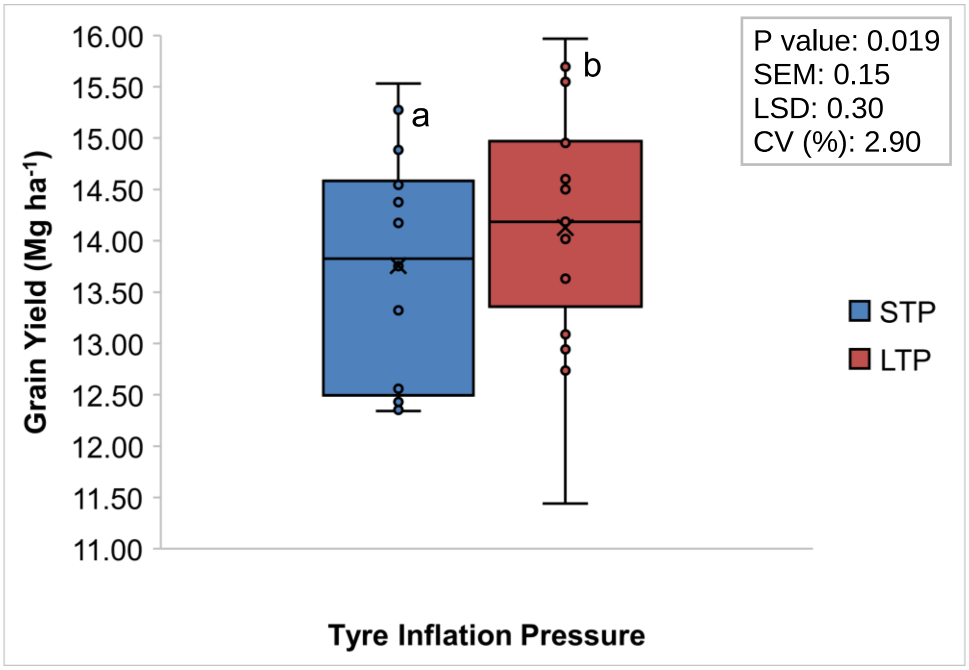


Figure 5.14. Effect of tyre inflation pressure on the combine harvested grain yield of maize, in the North field in 2018.

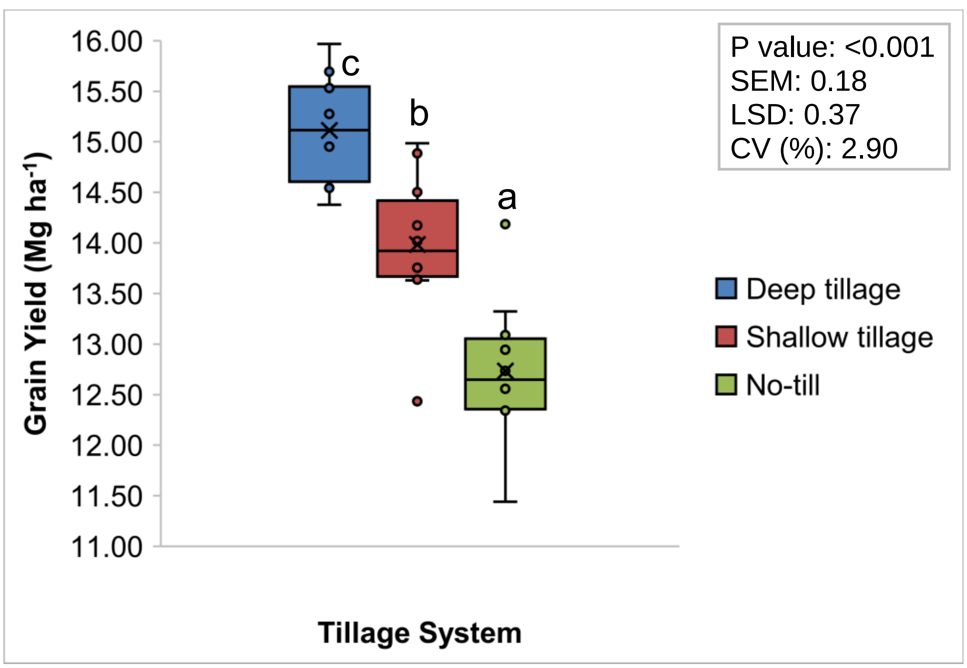


Figure 5.15. Effect of tillage system on the combine harvested grain yield of maize, in the North field in 2018.

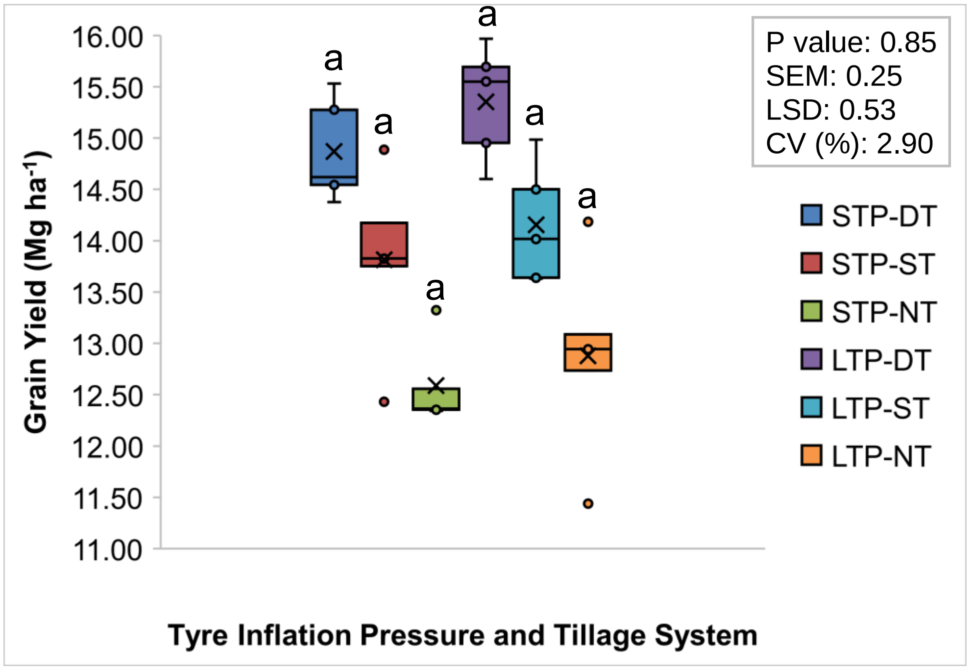


Figure 5.16. Effect of tyre inflation pressure and tillage system on the combine harvested grain yield of maize, in the North field in 2018.

Note: In figures 5.14 – 5.16, the ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

The three years field study showed that tyre inflation had had a significant effect in 2017 and 2018 with no significant effect on yield in the normalization year of 2016. Soane et al. (1982) reported that soil compaction increases with high tyre inflation pressure. Researchers showed that soils with a resistance greater than 2 MPa is considered to limit root growth (e.g. Hamza & Anderson, 2005). In the present study, soil penetrometer resistance data in 2016 was greater than 2 MPa in both STP and LTP treatments, however, there was no significant effect on yield while in 2017, PR was less than 2 MPa and in 2018 more than 2 MPa but higher in STP than LTP contributed to the negative effect on crop growth and grain yield to both years. The present findings are in agreement with the finding of others e.g. (Kulkarni et al., 2010) who reported that soil resistance on a loam soil as low as 1.6 MPa (measured range 1.6–2.9 MPa) affected crop growth but did not show any yield penalty. Another study showed that soils with a resistance of less than 2 MPa reduced crop yield (Carter and Tavernetti, 1968). The findings are in agreement with the findings that that field trafficking with low-pressure tyres can cause significantly less soil compaction and increase crop yield (Boguzas and Hakansson, 2001; Ridge, 2002). The higher PR and lower soil MC values in crop row 3 and crop row 1 as expected because of the additional wheel traffic on these rows before planting of crops and heavily trafficked region close to crop row 3 caused soil compaction which is in agreement that traffic frequency and tyre inflation pressure had strong effects on the soil condition, which increased bulk density and penetration resistance of soil (Solgi et al., 2016). Reduction in growth and yield of crops due to higher contact pressures and traffic intensity as explained in several findings (Raghavan et al., 1979c; Soane et al., 1980; Horn et al., 2003; Chyba, 2012) are in line with the present studies.

5.6. Conclusions

1) The results of the preliminary assessment of the field showed that despite a minor area of Thorp series in the North field, the selected experimental field (Drummer series) had a low BD (<1.30 Mg g^{-3}), an optimum total porosity (>50%) and low PR (>1.30 MPa) with no evidence of residual soil compaction. The uniformity of the site was further confirmed by the crop responses and crop yield for each of the tyre inflation pressures with a CV of 1.70%.

2) Tyre inflation pressure and across soil depth had a significant effect on PR of soil in 2016 (P = 0.006 and 0.004) where, lower values of PR were recorded in the LTP treatment as compared to the STP treatment with a peak PR of the soil of 3.35 MPa and 3.48 MPa at depths 275 and 300 mm, respectively. In 2017, tyre inflation pressure did not produce a significant difference in soil MC and PR of soil at 35-40 DAP of maize. However, in 2018, the results showed that across all tillage treatments, reduced tyre inflation pressure and its effect across soil depth had a significantly lower PR of soil than that of STP with a peak PR of the soil was of 3.16 MPa and 3.39 MPa, respectively (P = <0.001).

3) The effect of tillage in 2017 (P = 0.001) and across soil depth in 2017 and 2018 (P = 0.001 and <0.001) significantly affected the PR of soil in the maize field. The PR of soil in 2017 was overall in the order of NT>ST>DT while in 2018, initially, NT had a significantly higher PR of soil from soil depths of 25mm to 75mm than ST and DT. After that PR values were in the order of DT>ST>NT but significantly increased in DT from the

depths of 325mm to 450mm than ST and NT. There was no significant interaction between tyre inflation pressure and tillage system for soil MC and PR of soil.

4) The effect of crop row across all tyre inflation pressures and tillage systems had a significant effect on both soil MC and PR of soil in 2017 (P = <0.001 and <0.001) and 2018 (P = <0.001 and <0.001), where heavily trafficked crop row CR3 had the lowest soil MC than inter-row 4 & 5, CR8 and CR7 and the CR3 had the highest PR values of soil in varying depths with a peak PR of 1.77 MPa and 3.28 MPa at a depth of 75 mm and 275 mm in 2017 and 2018, respectively compared to other crop rows. Reducing tyre inflation pressure and field trafficked and non-trafficked crop row (P =004) resulted in reduced soil compaction in comparison to standard tyre inflation pressure.

5) Tyre inflation pressure had a significant effect on the plant establishment (P = 0.013) and the number of plants ha^{-1} (P = 0.012) but not significant on the plant heights at 30 and 45 DAP of maize, with the exception of plant height at 30 DAP (P = <0.001), where crop row due to field trafficking showed a significant variation in the year 2016. In 2017, both tyre inflation pressure and tillage system did not show any significant effect on plant establishment (%) in maize with the exception of plant height (P = 0.04) where tyre inflation pressure, and the number of plants per ha (P =<0.001), where tillage system had shown a significant influence. Crop row had a significant effect on the plant height of maize in 2017 (P = 0.002). In 2018, reducing tyre inflation pressure had a significant influence on the plant establishment (%) (P = 0.007), the number of plants per ha (P = 0.005), plant height (P = 0.004), ear height (P = 0.05) and ear length (P = <0.001) of maize. There was no significant effect of the main effect of tillage system and the interaction between tyre inflation pressure and tillage system on these growth parameters in 2018 with the exception of plant height (P = 0.04) and ear height (P = 0.02), where tillage system had shown a significant influence.

6) Tyre inflation pressure, tillage system and their interaction had no significant effect upon 1000 grain weight and hand harvested yield of maize with the exception in 2018, where deep tillage system had a significantly higher 1000 grain weight and hand harvested grain yield maize than ST and NT (P = 0.005 and <0.001). The subplot effect of crop row had a significant influence on the 1000 grain weight in 2017 and 2018 (P = 0.04 and <0.001) and hand harvest grain yield of maize in 2018 (P = <0.001) with no significant interaction between tyre inflation pressure, tillage system and crop row.

7) Reduced tyre inflation pressure had a significant effect on the combine harvested grain yield of maize in 2017 ($P = 0.005$) and 2018 ($P = 0.019$) but not in the pilot study in 2016 ($P = 0.32$). In 2017, the grain yield in the low tyre inflation pressure treatments across all tillage treatments (15.02 Mg ha^{-1}) was 4.31% higher than that of the standard tyre inflation pressure treatments (14.40 Mg ha^{-1}). In 2018, the grain yield of maize in the low tyre inflation pressure treatments (14.76 Mg ha^{-1}) was 2.70% greater than that of the standard tyre inflation pressure treatments (13.76 Mg ha^{-1}).

8) The main effect of tillage system had a significant ($P = <0.001$) influence on the combine harvested grain yield of maize in 2018, where the grain yield of maize was recorded 8.08% and 18.32% higher for the deep tillage treatment (15.11 Mg ha^{-1}) than shallow tillage (13.98 Mg ha^{-1}) and no-till (12.73 Mg ha^{-1}), respectively. There was no significant effect in 2017 or with the interaction between tyre inflation pressure and tillage system on the grain yield of maize in 2017 and 2018.

CHAPTER 6: SOIL PROPERTIES AND CROP DEVELOPMENT OF SOYBEAN

6.1. Introduction

To feed > 9.6 billion people by 2050, the two big challenges are to ensure sufficient and sustainable food production and secure food security. Farm machinery saves timeliness of field operations and labour and costs and helps to promote sustainable production (FAO, 2017b). Mechanization was one of the key components of the success of the Green Revolution. However, the use of heavy machinery and excessive field trafficking causes compaction of soil that changes soil structure and reduces soil and crop productivity. Soil compaction a physical form of soil degradation, changes the soil structure and influences soil productivity and causes damage to the environment (Raghavan et al., 1976; Mueller et al., 2011). The average tractor weight has increased threefold from 1950 to 2000 (Soane and van Ouwerkerk, 1998; Sidhu and Duiker, 2006) but the continuous increase in equipment size and weight of heavier machinery are significant threats to soil compaction (Chamen, 2011). Field traffic and heavy machinery passes create soil compaction by increasing BD, PR, and also result in reduced porosity, soil hydraulic properties, and stability index (Alakukku, 1996a; b; Hula et al., 2009). Increased in both dynamic load (vertical load) of the tractor and tyre inflation pressure increased the peak soil stresses and BD of soil (Bailey et al., 1996; Abu-Hamdeh et al., 2000). Subsoil compaction increased with loads to the soil, and is difficult to remove (Kroulík et al., 2009). Increased traffic frequency and high ground pressure had significant negative effects on soil physical properties as these increased higher BD and PR values (Solgi et al., 2016).

Compaction creates physical (e.g. soil structural damages, reduction in porosity), chemical (e.g. reduction of plant available water and nutrient) and biological changes (e.g. reduction of soil biota) in the soil that negatively impact on crop performance (Chyba, 2012; Horn et al., 2003). Cone index values in excess of 2 MPa have been shown to restrict, to varying degrees, crop root development (Taylor and Gardner, 1963; Aase et al., 2001). It restricts plant root growth and accessibility of nutrients due to an increase in BD and reduced pore size (Nawaz et al., 2013) and reduces plant growth as it limits root growth (Rosolem et al., 2002). High contact pressures and multiple vehicles pass caused 40–50% reduction of grain yield of maize (Raghavan et al. 1979b) while in soybean, a yield reduction ranging from 0.25 - 0.45 Mg ha^{-1}

under light to heavy equipment traffic (Botta et al., 2010). Farm equipment equipped with Ultraflex tyres run at low tyre inflation pressure and provide a longer footprint which aims at reduce soil compaction and improve crop yield (Michelin, 2017). Low ground pressure systems transmit reduced ground contact stress (Trautner and Arvidsson, 2003) and area suitable approach to minimise soil compaction (Smith et al., 2014b). They can have a significant positive effect in reducing soil compaction whilst increasing crop production (Millington, 2019). Currently, no research has been conducted on the effect of Ultraflex low ground pressure tyres with different tillage practices a silty clay loam soils in mid-west farming operations in the United States. Hence, the present field-scale studies were undertaken to improve the understanding of the effect of low inflation tyre inflation pressure systems on soil conditions and crop growth and yield of soybean in central Illinois, USA.

6.2. Hypothesis

It is possible to increase the yield of soybean by improving crop growth and development by reducing soil compaction using reduced tyre inflation pressure systems.

6.3. Aim and Objectives

The main aim of the study is to determine the effect of tyre inflation pressure on soil properties, and crop development and yield of soybean for three tillage systems. The overall objectives are as follows:

a) To determine the effects of tyre induced inflation pressure, by comparing ultra-flex high and low inflation tyre systems, on soil structure, crop development and yield of soybean for 2 tillage depths (deep tillage and shallow tillage) and no-till through field-scale studies in a silty clay loam soil in Illinois, the United States.

b) To correlate the effects of the different tyre inflation pressure and tillage systems on soil structure, whilst correlating to soil and crop parameters.

6.4. Materials and Methods

The experiment was established at the Agricultural Engineering farm of the Department of Agricultural and Biological Engineering, the University of Illinois at Urbana-Champaign, Champaign County, Illinois, the United States (lat/lon: 40.070965, -88.217538) from November

2015 to October 2018. Design and treatments of the experiment, plot layout and area, trafficked and un-trafficked crop rows (Table 3.5 and Appendices 3.5-3.7), variety of soybean, field operations, sampling, weather data, collection of data on soil and crop and approach, and statistical procedures of analyses of these data were described in Chapter 3: General Methodology.

6.5. Results and Discussion

6.5.1. Initial Soil Properties Assessment

Assessment of soil uniformity was conducted through analysis of BD, soil MC, PR and EC, and selected chemical properties of soil and presented in Tables 6.1 - 6.2, and Figs. 6.1 - 6.2. The result showed that the mean initial soil MC (%) at three depths of 0-100, 101-200 and 201-300 mm were 27, 26 and 28%, respectively (Table 6.1). The dry BD at 3 depths of 0-100, 101-200 and 201-300 mm was 1.19, 1.30 and 1.31 Mg m^{-3} at respectively. These data indicate that the BD of the soil in the experimental field was below the critical BD of a silty clay loam soil of 1.40 Mg m^{-3} which when exceeded can restrict water storage, root penetration and growth of the plant (USDA NRCS, 2019d). The mean particle density of this silty clay loam soil was recorded 2.62. The mean total porosity of the soil in the Drummer soil series was 52% with slightly higher porosities in the topsoil of 0-100 mm depth (54%).

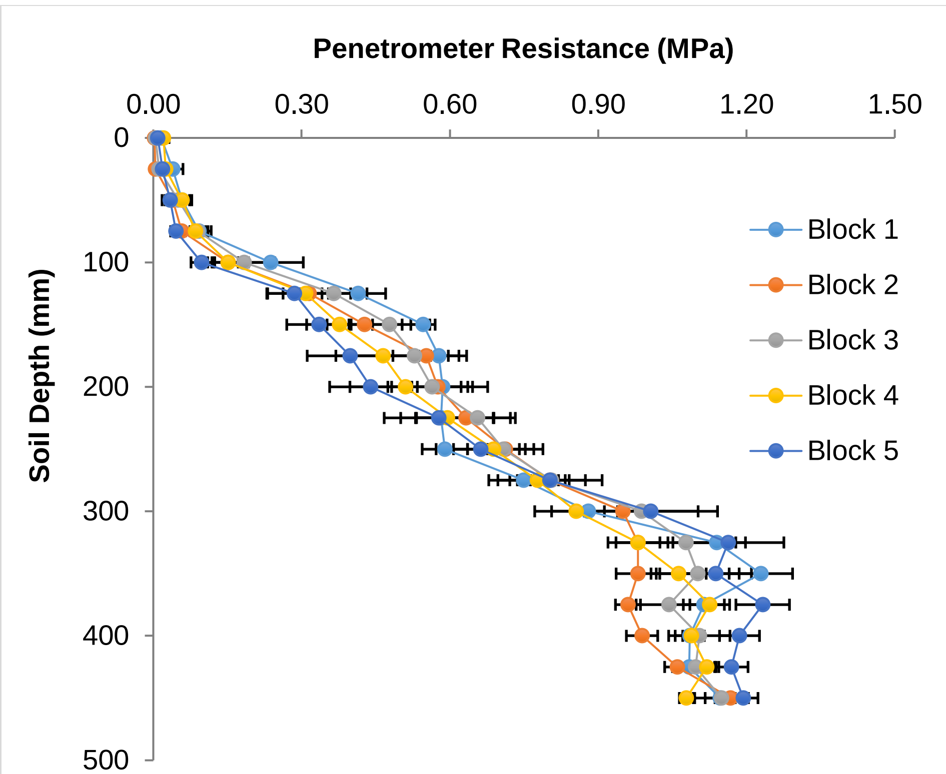
Table 6.1. Initial bulk density, particle density, porosity and soil MC at three different depths of soil in the South field in April 2016

Series	Soil properties	Unit	Soil depth[a]			Mean
			0-100 mm	101-200 mm	201-300 mm	
152A-Drummer	BD	Mg m^{-3}	1.19±0.02	1.30±0.02	1.31±0.02	1.27±0.02
	PD	Mg m^{-3}	2.62±0.01	2.62±0.01	2.62±0.01	2.62±0.01
	Porosity	%	54.3±0.67	50.2±0.63	50.1±0.61	51.5±0.64
	Soil MC	%	26.5±0.78	26.4±0.53	27.6±1.01	26.8±0.77

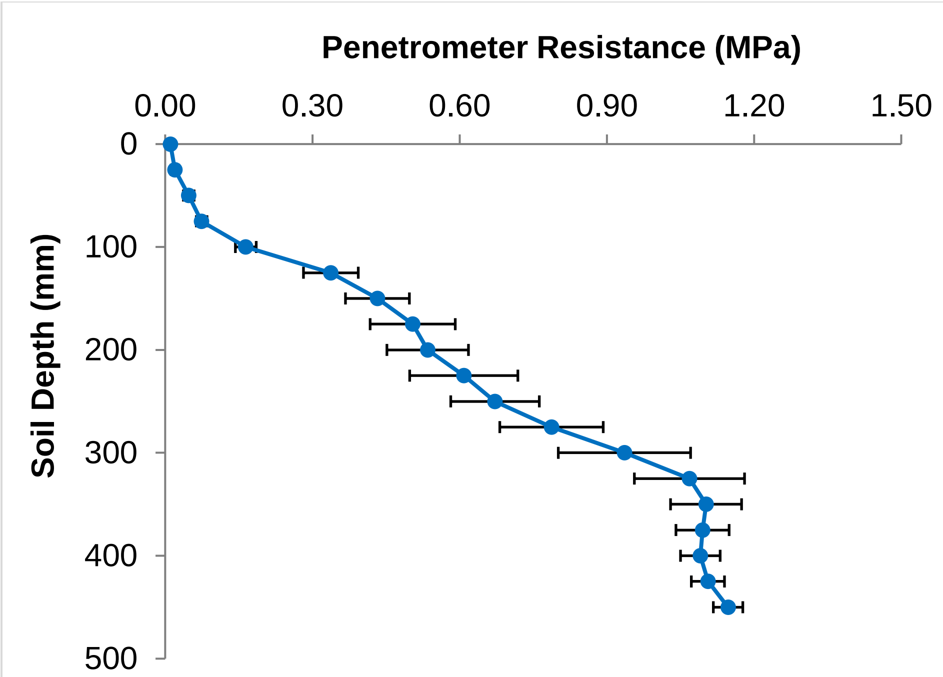
[a]Average of 25 samples at each depth (Mean ± SE)

The data in Fig 6.1a-b showed that experimental block (n = 15) and overall mean (n = 75) PR values in the south field gradually increased to values from zero at the soil surface to 1.23 MPa and 1.10 MPa at a depth of 350 mm, respectively then remained relatively consistent, with some fluctuations, to values of 0.96 - 1.23 MPa and 1.09 – 1.15 MPa, respectively. Lower bulk density and lower PR in the south field indicate that the field had no residual compaction from the previous year's cultivation or if there was, deep ripping operations at 450 mm soil depth had effectively removed the residual compaction.

Figure 6.2. shows that initial EC data in the South field recorded in April 2016 were in the range of 13.24 – 46.00 mS/m Although, a few data points indicated higher EC values of 46-55 mS/m at the western boundary of the field, however, the EC values were similar to the values of North field as described in Chapter 5.



a)



b)

Figure 6.1. Initial penetrometer resistance of soil for block (a) and overall mean (b) data in the South field in 2016. Error bar indicates the standard error of mean.

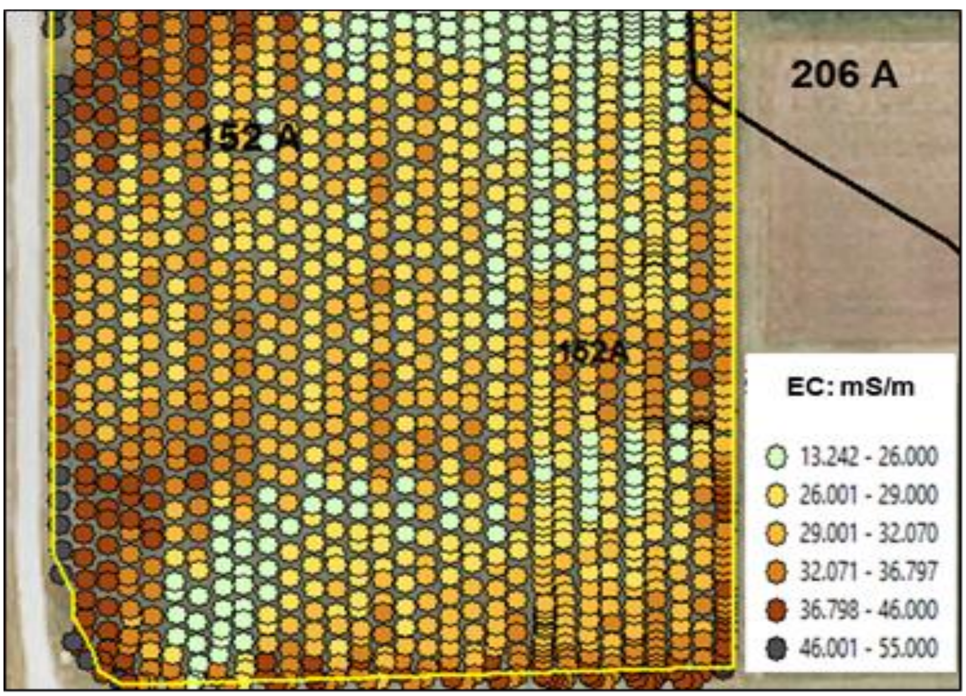


Figure 6.2. Electrical conductivity digital terrain map laid onto the NRCS soil survey map in the South field in 2016. 152A and 206 indicate the Drummer and Thorp soil series, respectively.

The results of the analysis of the chemical properties of soil are presented in Table 6.2. These results revealed that the soil pH at two depths 0-150 and 151-300 mm were 6.26 and 6.47. The OM of the soil was 3.41% and 3.37% at these two respective depths. The mean cation exchange capacity (CEC) was 28 meq/100g soils with a range of 26.88-28.56 meq/100g soils. The soil nutrient analysis data showed that Nitrate (NO_3-N) and Ammonium (NH_4^+N) in soils were higher (13.80 and 5.00 ppm) in the topsoil than the deeper depth of 151-300 mm (10.80 and 4.20 ppm) respectively. The mean values of primary nutrient such as P, K, Ca and Mg were 64, 254, 8465 and 1110 Kg ha^{-1}, respectively. Mean values of base saturation of Ca, Mg, K and H were 68, 14.9, 1.10 and 15.70 respectively. Results of other micronutrients showed that the mean values of S, Zn and B were 15.57, 4.73 and 1.57 Kg ha^{-1}, respectively. The pH and CEC are in agreement with the typical values of the Drummer soil series (USDA NRCS, 2019d) as between 5.6-7.8 and 24-35 (meq/100g of soils) respectively. However, OM values are lower than the typical values of 4.0-7.0%. The present assessment of the soil showed that values of these parameters are (with the exception of the OM levels) within or sometimes higher than their ranges which indicated that soil quality of the present experimental field was homogenous and favourable for plant establishment and growth. These results are in agreement with the findings of Fernández et al. (2012) who reported that P, K, Ca and Mg of Illinois soil were 71, 214, 2027 and 297 kg ha^{-1}, respectively, which are similar or in some cases lower than the values recorded in the present assessment of the South field.

Table 6.2. Chemical properties of soil in the South field in April 2016

Soil properties	Unit	Depth[a]	
		0-150 mm	150-300 mm
Soil pH	-	6.26±0.11	6.47±0.07
OM	%	3.41±0.03	3.37±0.05
CEC	meq/100g of soils	28.5±1.31	26.8±1.24
NO_3^- N	ppm	13.8±0.97	10.8±1.65
NH_4^+ N	ppm	5.00±0.318	4.20±0.20
P^{3-}	kg/ha	87.1±7.64	41.45±7.5
K^+	kg/ha	294.2±14.2	213.9±11.6
Ca^{2+}	kg/ha	8454.7±416.1	8477.3±463
Mg^{2+}	kg/ha	1105.6±68.7	1114.4±69.2
Ca^{2+} (Base saturation)	%	66.2±3.28	70.3±1.66
Mg^{2+} (Base saturation)	%	14.4±0.79	15.2±0.52
K^+ (Base saturation)	%	1.28±0.06	0.92±0.04
H^+ (Base saturation)	%	17.9±4.05	13.4±1.90
S^{2-}	kg/ha	17.2±0.45	13.8±0.45
Zn^{2+}	kg/ha	5.15±0.97	4.30±0.94
B^{3+}	kg/ha	1.48±0.21	1.65±0.15

[a]Average of 25 samples at each depth (Mean ± SE)

6.5.2. Effect of Tyre Inflation Pressure and Tillage System on Soil Properties

Penetrometer resistance data in the soybean field (South field) in the year 2016 are presented in Figs. 6.3a – 6.3c. The results revealed that tyre inflation pressure and the interaction effect with trafficked location had no significant effect on PR in the soybean field (P = 0.69 and 0.63, respectively). However, the subplot effect of trafficked location had a significant effect on PR in the soybean field (P = <0.001, n = 570). Fig 6.3c shows that the PR values in HT location were higher at all soil depths up to 450 mm in comparison to UT location with a peak PR of soil at depth 75 mm were 2.27 MPa and 1.66 MPa, respectively (n = 30) while at depth 250 mm, the peak PR values were of 2.18 MPa and 2.00 MPa, respectively. The differences of PR values between the trafficked locations were much higher at depths from 75 mm to 325 mm and then decreased slowly down to the 450 mm soil depth. The mean whole profile PR values in the HT location was 1.91 MPa while in the UT location it was 1.68 MPa.

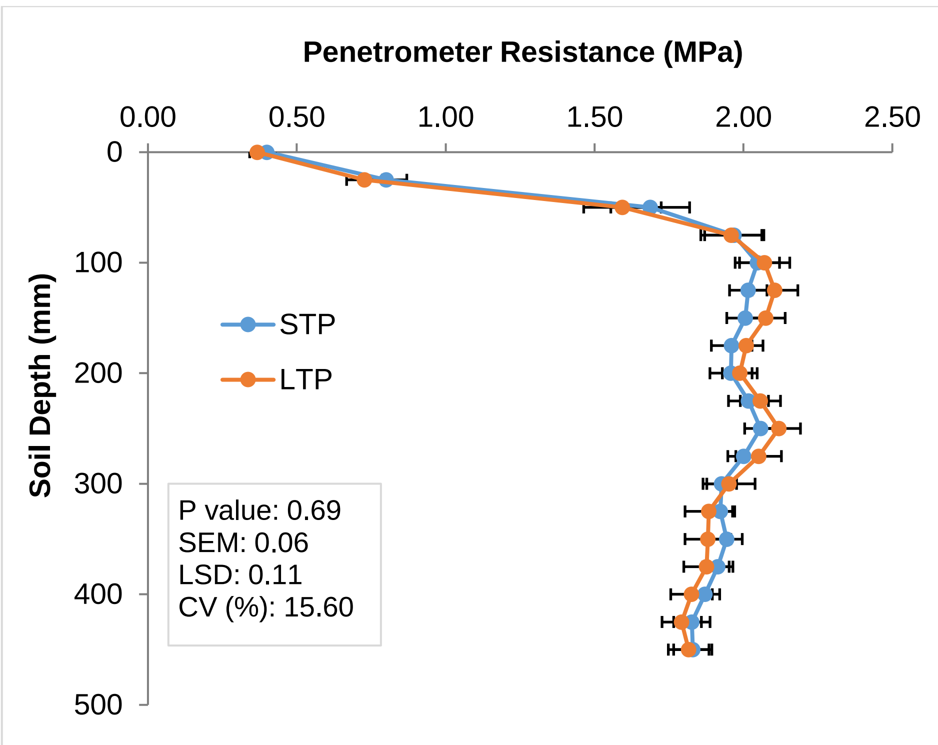


Figure 6.3a. Effect of tyre inflation pressure on the penetrometer resistance in the South field in 2016. Error bar indicates the standard error of mean.

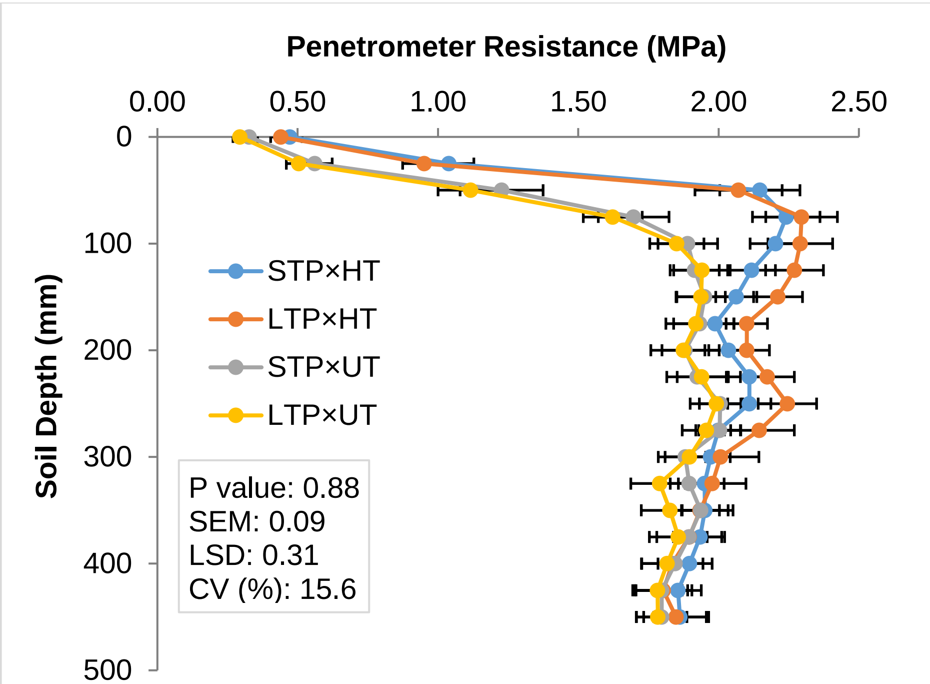


Figure 6.3b. Effect of tyre inflation pressure on the penetrometer resistance in the heavily trafficked and un-trafficked locations in the South field in 2016. Error bar indicates the standard error of mean.

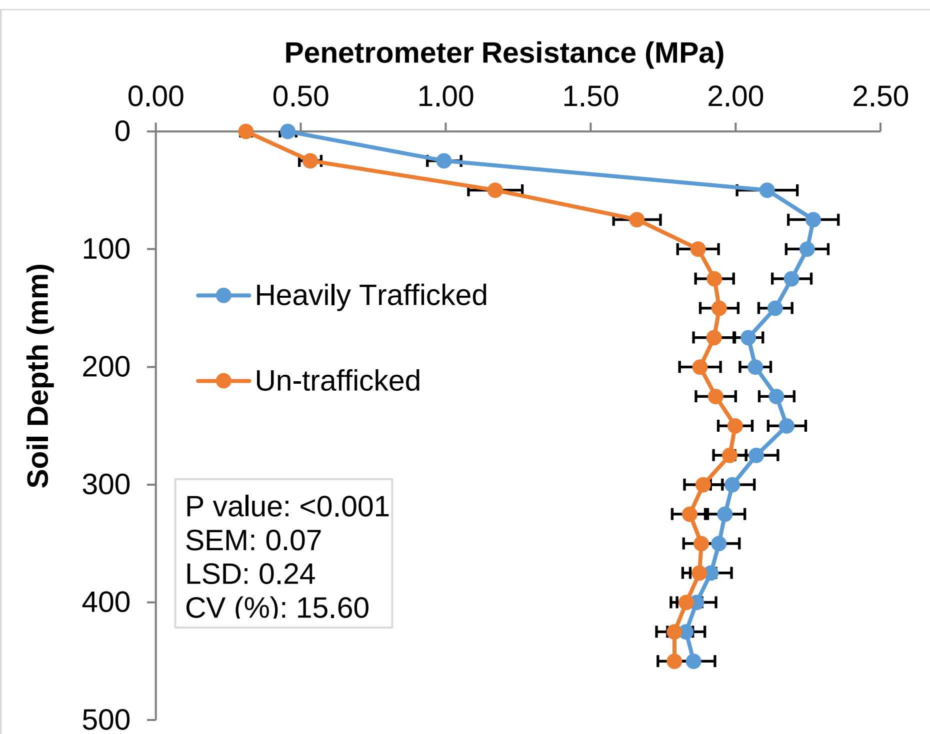


Figure 6.3c. Effect of heavily trafficked and un-trafficked locations on the penetrometer resistance in the South field in 2016. Error bar indicates the standard error of mean.

Soil physical data recorded during rooting depth study (un-replicated) are shown in Appendices 6.1 - 6.3. The result shows that the mean BD of soil in STP and LTP treatments was recorded as 1.52 Mg m^{-3} and 1.49 Mg m^{-3}, respectively. The mean gravimetric soil MC in the STP and LTP treatments was 16.85% and 15.08%, respectively. As expected, from the BD results, the mean total porosity of soil was increased in the LTP treatment (43%) than STP (42%). These data indicate that standard tyre inflation pressure plot especially soils of crop rows 3 and 4 near to wheel traffic had higher BD due to compaction in the STP plots.

Soil MC data in June 2017 presented in Figs. 6.4a-b show that the subplot effect of crop row had a significant influence on Soil MC in the North field (P = 0.001, n = 30). There was no significant effect of tyre inflation pressure, tillage system and the interaction between them and crop row on soil MC in the soybean field. Fig. 6.4a shows that the un-trafficked inter-row between CR4 & CR5 (centre line of the plot) had a significantly higher soil MC (43%) that was significantly different from other crop rows. The mean soil MC was marginally higher in LTP treatment (35%) than STP (34%) while in tillage system, mean values of soil MC in DT, ST and NT were recorded as 34, 35 and 33%, respectively (Fig. 6.4b).

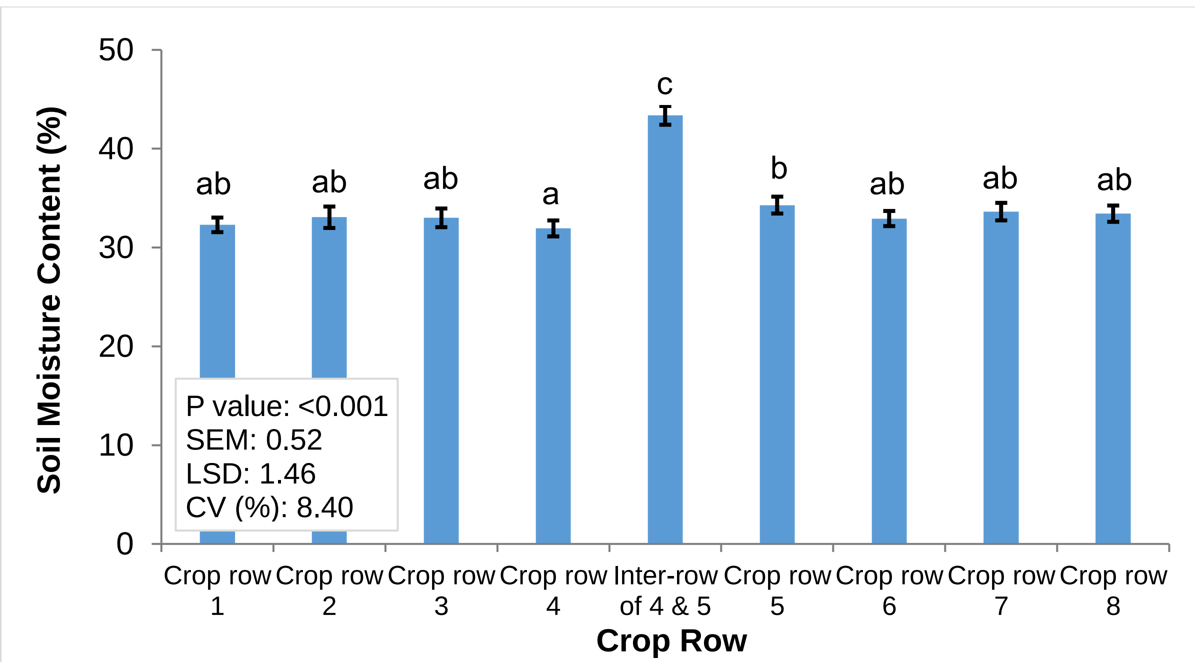


Figure 6.4a. Effect of crop row (CR) on soil moisture content in the North field in 2017. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

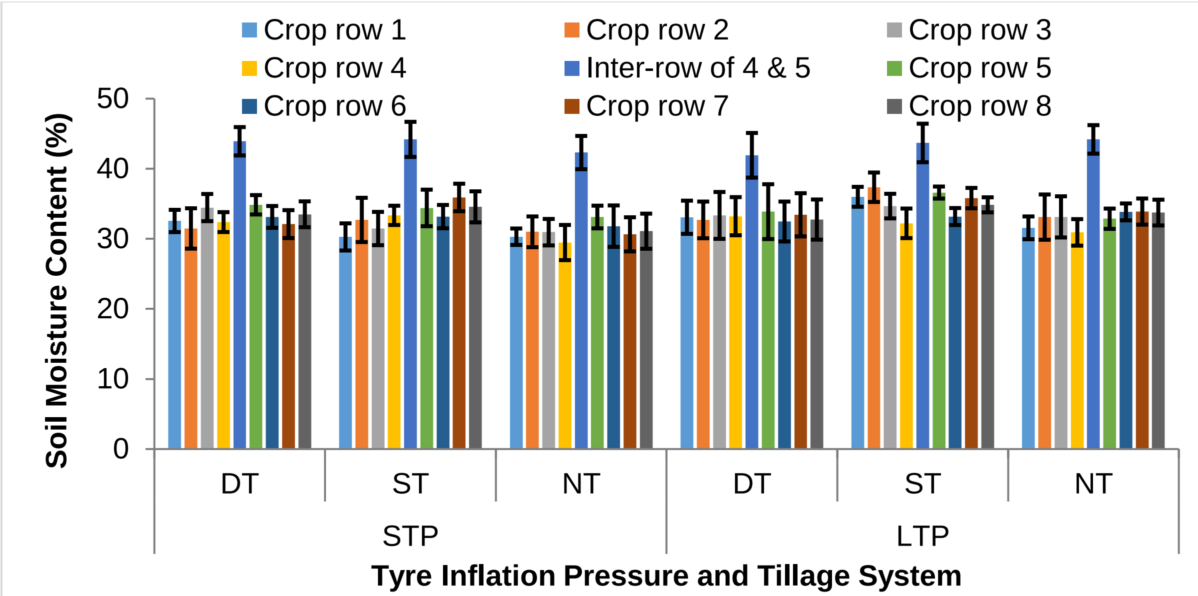


Figure 6.4b. Effect of tyre pressure, tillage system and crop row on soil moisture content in the North field in 2017. Error bar indicates the standard error of mean.

The PR data for 2017 are shown in Figs. 6.5a - 6.5e. The results indicate that irrespective of soil depth, tyre inflation pressure and tillage system and their interaction had no significant effect on the PR of soil in the soybean field. However, the effect of tillage system across depth, crop row and crop row across depth had a significant influence on the PR of soil (P = <0.001, <0.001 and <0.001, respectively) with no significant interaction. Among the tillage systems, initially, NT had significantly higher PR values to depths of 25 mm, however, values of PR were in the order of NT>ST & DT up to a depth 50 mm. After that, the PR values were significantly higher in DT from the depth 75 to 175 mm than NT and ST treatments where the trends of PR were in the order of DT>NT>ST to the depth of 450 mm with a few exceptions at depths from 250-300 mm (n = 90; Fig. 6.5a). The peak PR of soil was recorded higher in DT treatment (2.03 MPa) at soil depths 100-125 mm that was followed by ST and NT with the peak PR of 1.77 MPa and 1.72 MPa, respectively. Among crop rows, the highest PR of soil was recorded in the CR1 (1.79 MPa) that was significantly different from the inter-row between 4 & 5, CR4, CR5 and CR8. Un-trafficked inter-row CR4 and CR5 had the lowest PR of soil (1.10 MPa) than others (n = 570; Fig. 6.5b). Fig. 6.5c shows that the highest PR values were recorded in CR3 up to 75 mm depth (2.20 MPa) which was the region of HT areas and after that higher PR of soil was recorded in CR1 (2.05 MPa), which was also the region of extra compaction areas with some fluctuations to depths of 450 mm except between depths 125 – 150 mm depths where CR6 and CR7 had higher PR of soil (n = 30). These results indicate that field trafficking causes more soil compaction in the HT location than that of UT areas which are in align with reports of others that PR values exceeding 2 MPa restrict varying degrees to crop root developments (Hamza and Anderson, 2005; Aase et al., 2001) and matched with other similar results (Raper and Kirby, 2006; Hula et al., 2009; Hamza et al., 2011). The results are also in line with the findings that increasing traffic frequency and tyre inflation pressure contributes to the higher BD and PR of soil (Solgi et al., 2016).

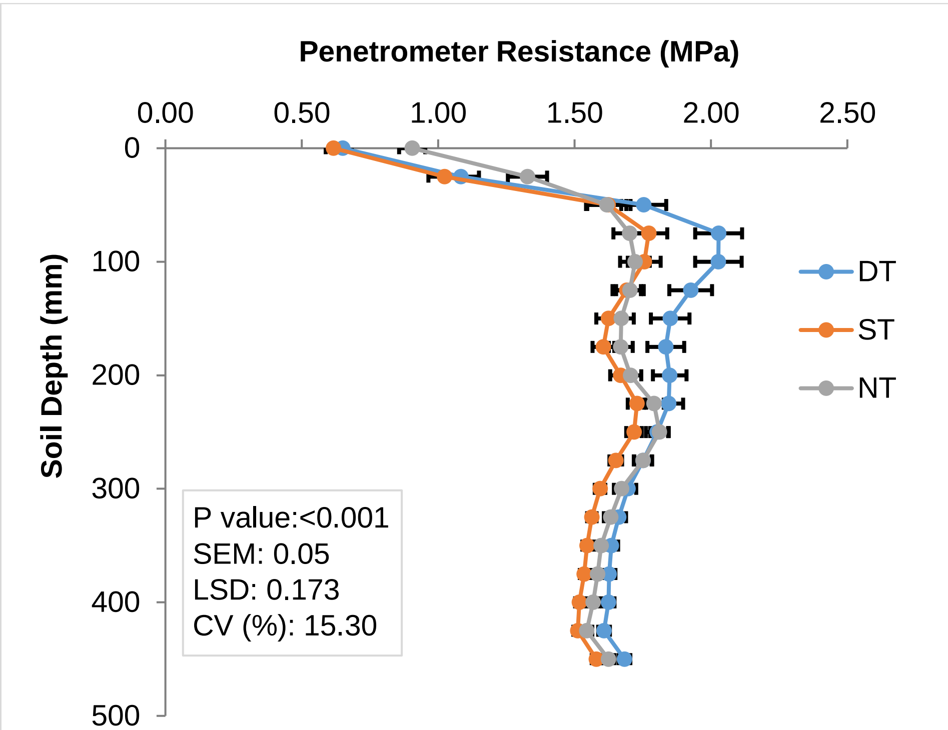


Figure 6.5a Effect of tillage system on the penetrometer resistance in the North field in 2017. Error bar indicates the standard error of mean.

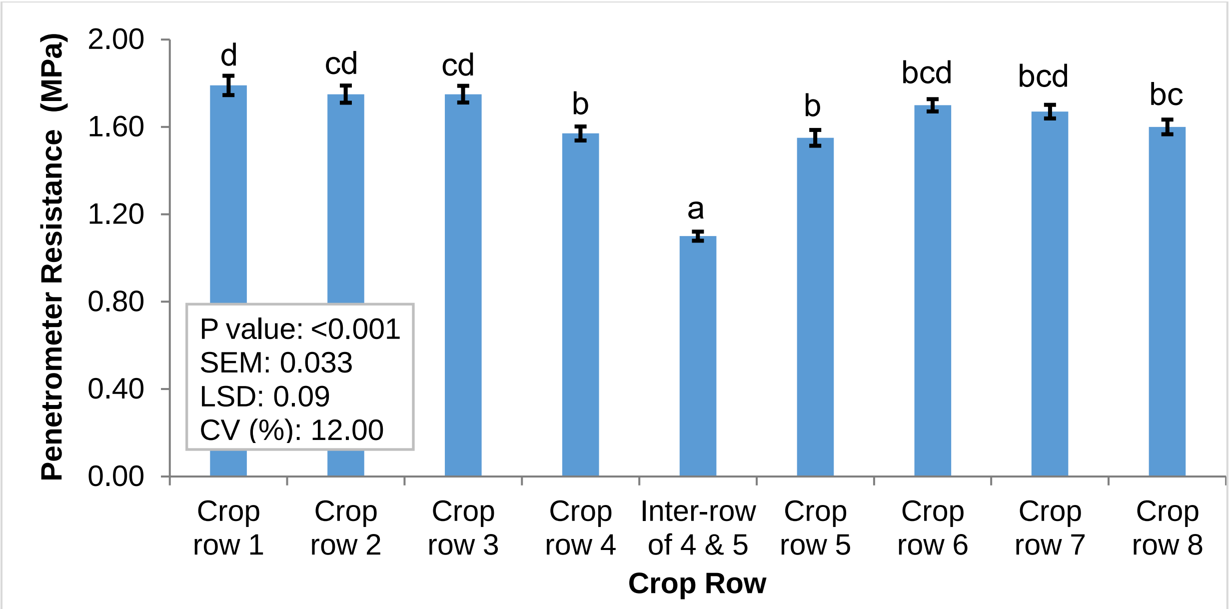


Figure 6.5b. Effect of crop row on the mean penetrometer resistance in the North field in 2017. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

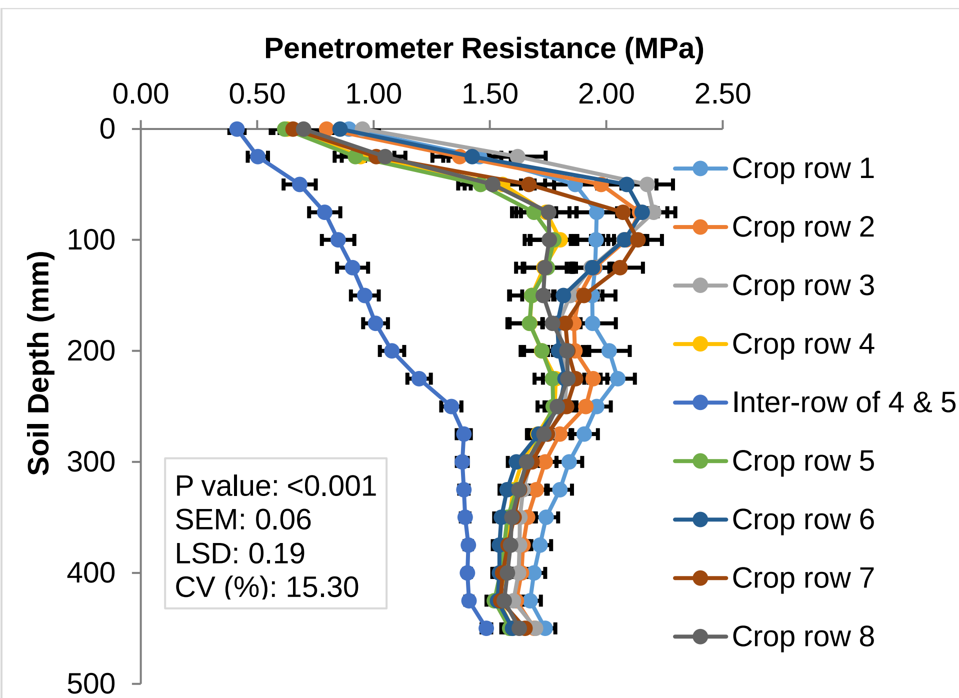


Figure 6.5c. Effect of crop row on the penetrometer resistance in the North field in 2017. Error bar indicates the standard error of mean.

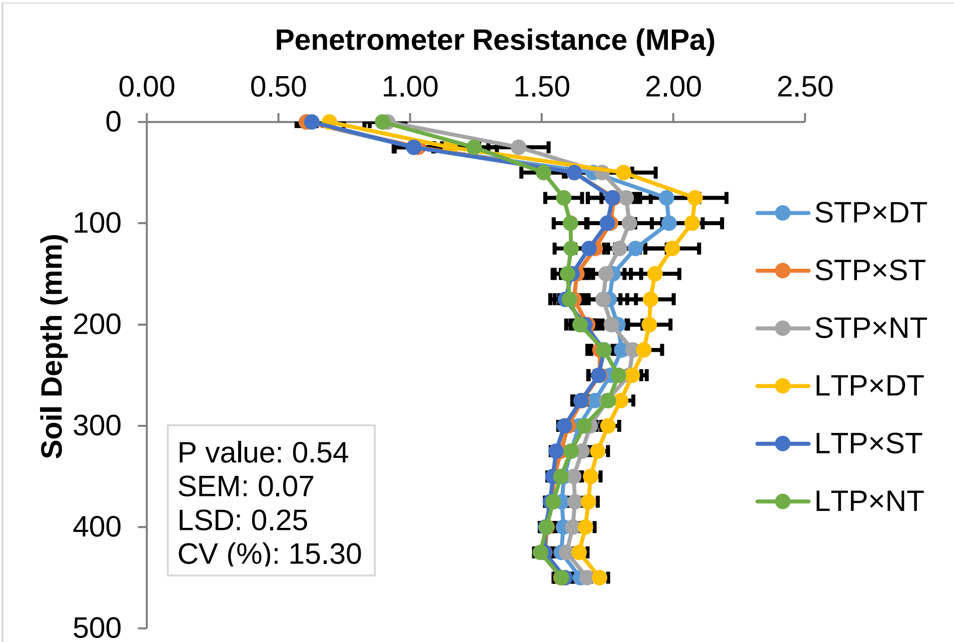


Figure 6.5d. Effect of tyre inflation pressure and tillage system on the penetrometer resistance in the North field in 2017. Error bar indicates the standard error of mean.

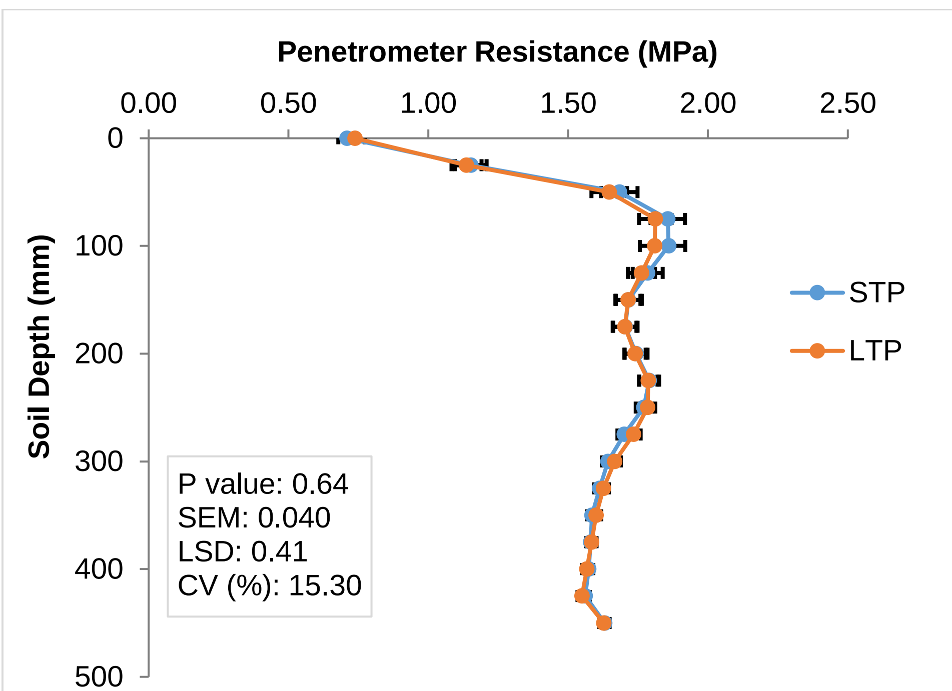


Figure 6.5e. Effect of tyre inflation pressure on the penetrometer resistance in the North field in 2017. Error bar indicates the standard error of mean.

On the contrary, in 2018, the results showed that crop row had a significant effect on soil MC in soybean field (P = 0.004, n = 30) but the main effect of tyre inflation pressure and tillage system and their interaction were not significant on soil MC at depths of 200 mm in the soybean field (n = 5; Fig. 6.6a-b). The highest soil MC was recorded in the CR4 (32.74%) which was significantly different from the CR3 (29.13%). The mean soil MC in the LTP and STP treatments were 35% and 34%, respectively.

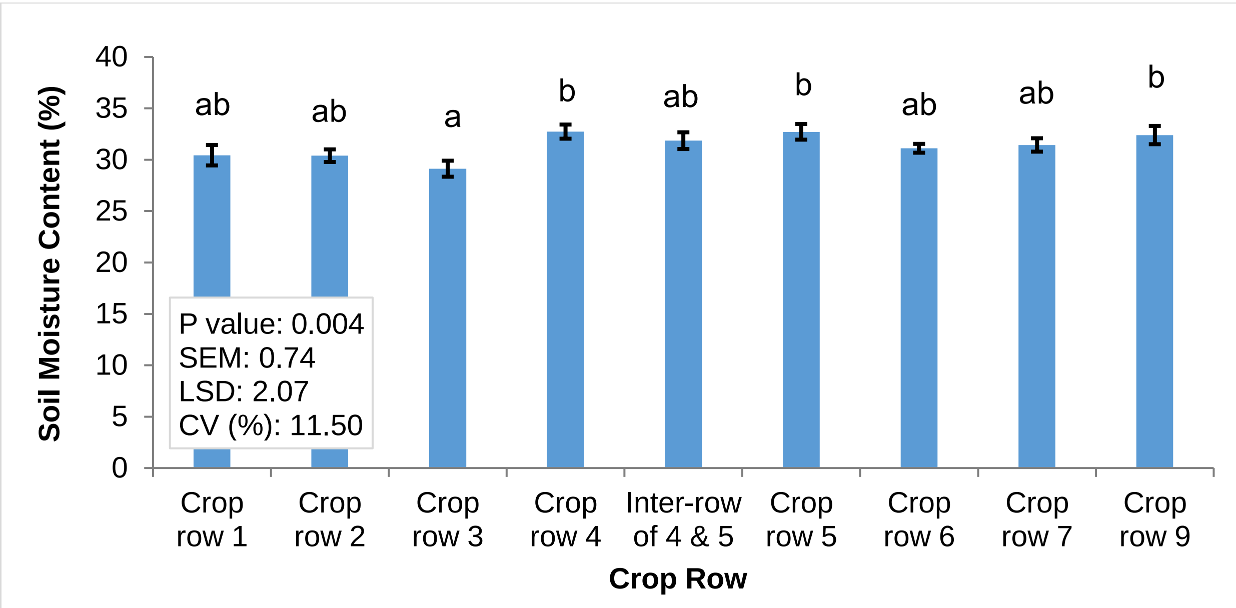


Figure 6.6a. Effect of crop row on soil moisture content at 200 mm depth at 55-60 DAP in the South field in 2018. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

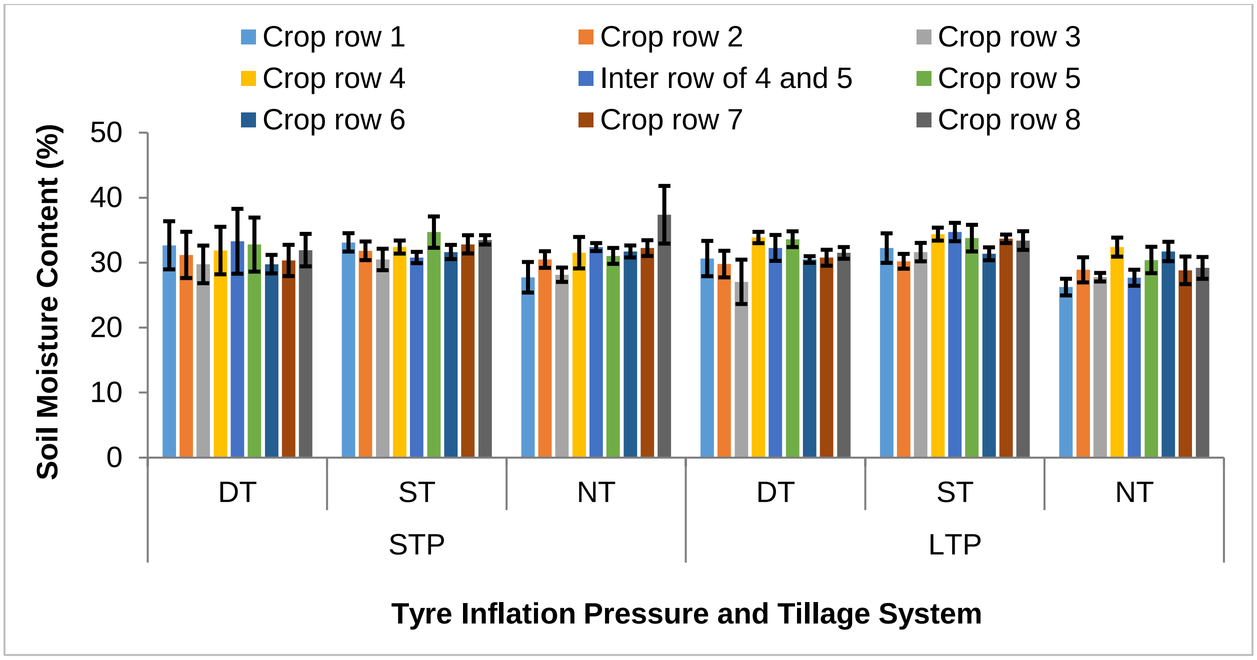


Figure 6.6b. Effect of tyre inflation pressure, tillage system and crop row on soil moisture content at 200 mm depth at 55-60 DAP in the South field in 2018. Error bar indicates the standard error of mean.

Results indicated that the tyre inflation pressure (P = 0.002) had a significant effect on the PR of soil in the soybean field in 2018 (Fig. 6.7a) but the tillage system and interaction of tyre inflation pressure and tillage system were not significant. Further, results observed that the effect of tyre inflation pressure across soil depth (P = <0.001) and tillage system across soil depth (P = <0.001) had a significant effect on the PR of soil in the soybean field (Fig. 6.7b-c). The mean PR value of soil was significantly lower in the LTP treatment (1.89 MPa) than the STP treatment (2.11 MPa) (n = 2565, Fig. 6.7a). Similarly, the PR values at different soil depths were recorded higher in the STP treatment as compared to the LTP treatment with an exception from the topsoil of 0-120 mm depth, where both treatments were not significant (n = 135; Fig. 6.7b). The peak PR values of STP and LTP treatments at soil depth 300 mm were 2.43 MPa and 2.27 MPa, respectively. With little fluctuations, the trends of PR values in the STP and LTP treatments remained the same to 250 mm depths with the PR values of 2.51 and 2.29 MPa, respectively and then gradually decreased to the 450 mm depth, where the PR value was still recorded higher in STP (2.05 MPa) in comparison to LTP (1.61 MPa). Among the tillage systems, the results revealed that the PR values at varying soil depths were initially the highest in NT treatment up to 225 mm soil depth with a peak PR of 2.43 MPa with an exception between the depths 100-150 mm, where ST had higher PR values with a peak PR of 2.46 MPa at depth 125 mm as compared to others tillage treatments (n = 90; Fig. 6.7c). The PR values from the depth 275 mm were recorded in the order of DT>ST &NT down to the depth of 450 mm with a peak PR of 2.46 MPa at depth 275 mm. The mean PR of soil in STP with NT, ST and DT treatment combinations was 2.22, 2.08 and 2.04 MPa, respectively while the PR values in LTP with DT, ST and NT treatment combinations were 1.89, 1.90 and 1.88 MPa respectively (n = 855; Fig. 6.7d),.

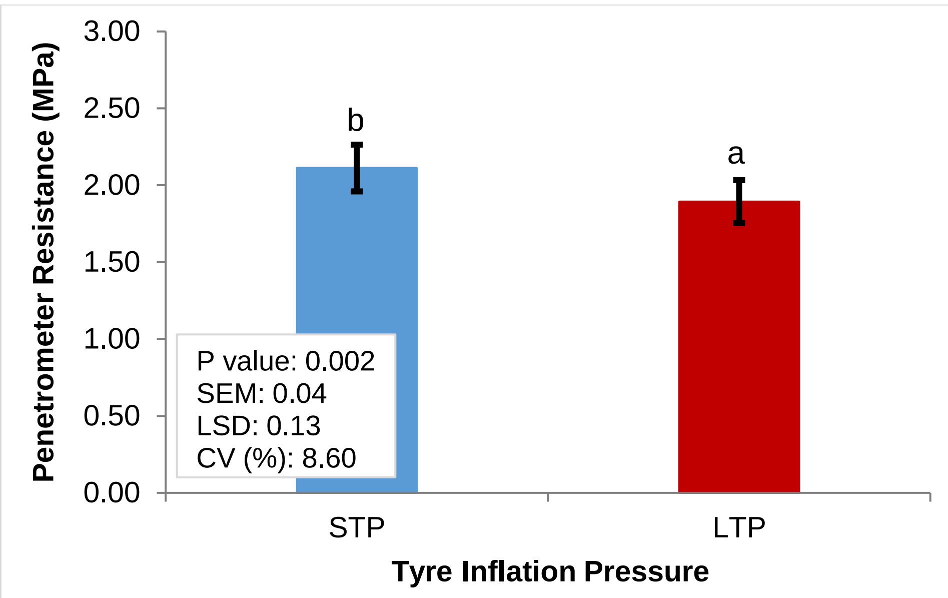


Figure 6.7a. Effect of tyre inflation pressure on mean penetrometer resistance in the South field in 2018. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

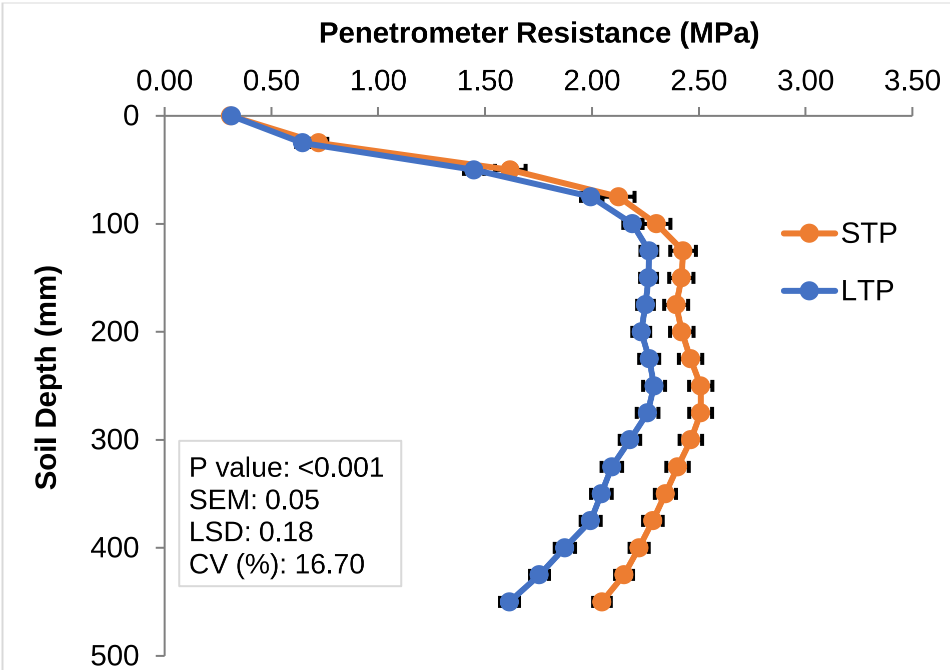


Figure 6.7b. Effect of tyre inflation pressure on penetrometer resistance in the South field in 2018. Error bar indicates the standard error of mean.

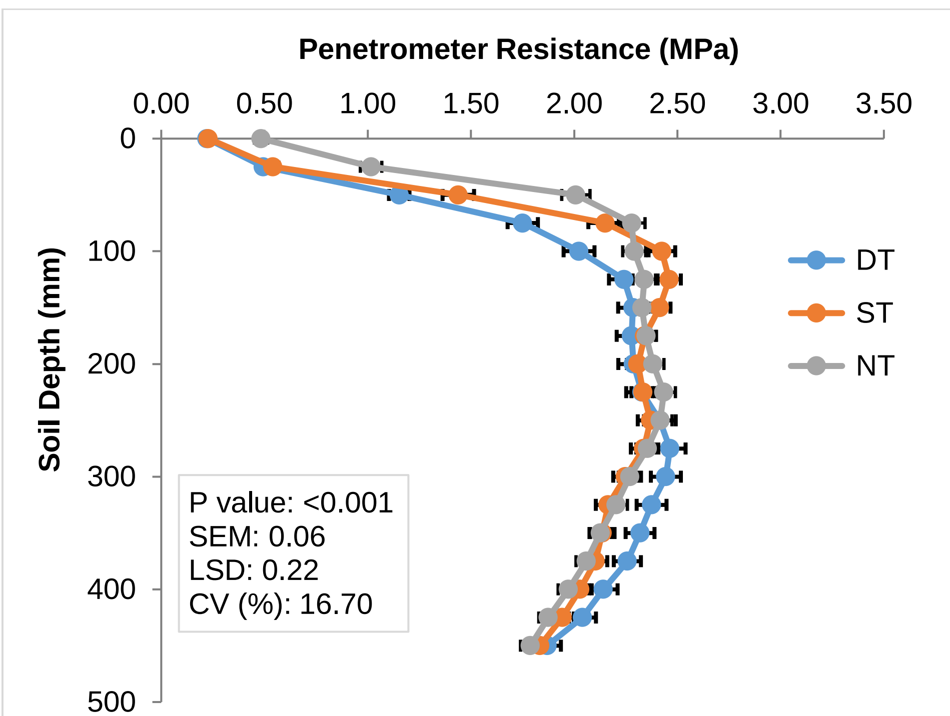


Figure 6.7c. Effect of tillage system on penetrometer resistance in the South field in 2018. Error bar indicates the standard error of mean.

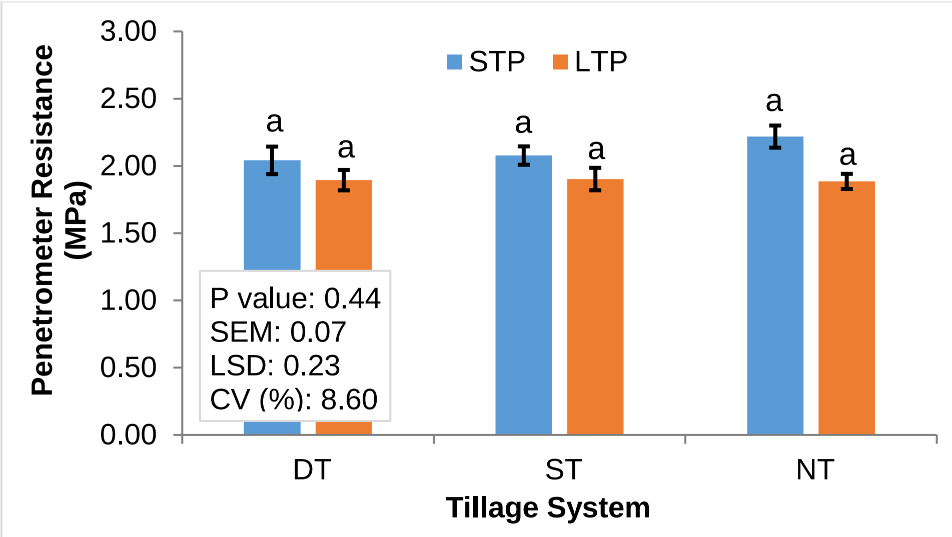


Figure 6.7d. Effect of tyre inflation pressure and tillage system on mean penetrometer resistance in the South field in 2018. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

Figure 6.7e-g showed that the subplot effect of crop row, crop row across soil depth and interaction effect of tyre inflation pressure and crop row had a significant influence on the PR of soil in the soybean field (P = <0.001, <0.001 and 0.002, respectively). Results revealed that the highest PR of soil was recorded in the crop row 3 (2.31 MPa) that was significantly different from other crop rows while the lowest PR of soil was observed in CR4 (1.80 MPa) and closely followed by the inter-row 4 & 5 (1.84 MPa) (n = 570; Fig. 6.7e). The PR of soil across depth showed that CR3 had higher PR values from the depths of 75 – 150 mm with a peak PR of 2.98 MPa at both depths of 75 and 100 mm, while CR8 and CR4 had the lowest PR values from 0 to 200 mm depths (n = 30; Fig. 6.7f). After that, the lower values were observed in the inter-row of CR4 and CR5 and CR7 to the depth of 450 mm. The PR of soil of all crop rows at depth 450 mm ranged from 1.75 to 2.07 MPa.

Likewise, the mean PR values of soil among the crop rows under tyre inflation pressure treatments was significantly the highest in CR3 of the STP treatment plot (2.55 MPa) that was significantly different from some but not all other crop rows of both tyre inflation pressure treatments. The lowest PR of soil was recorded in the inter-row of CR4 and CR5 of LTP treatment plots (1.71 MPa) (n = 285; Fig. 6.7g). Overall, the results showed that the PR values were higher in STP plots for all crop rows as compared to the LTP with all corresponding crop rows combinations.

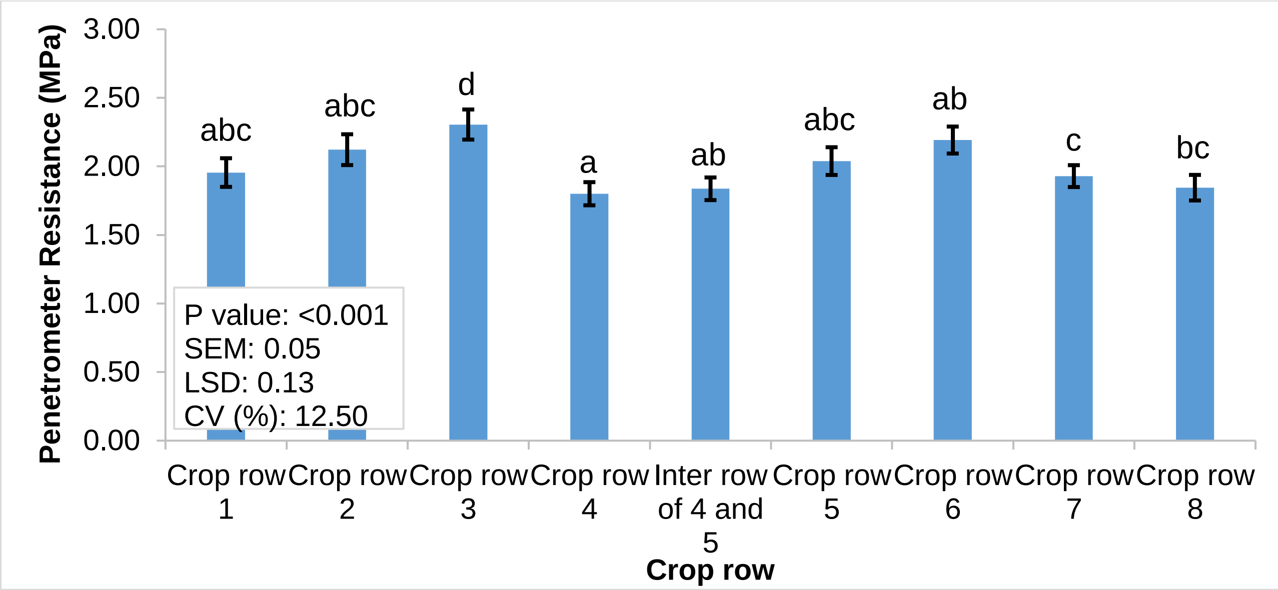


Figure 6.7e. Effect of crop row (CR) on mean penetrometer resistance in the South field in 2018. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

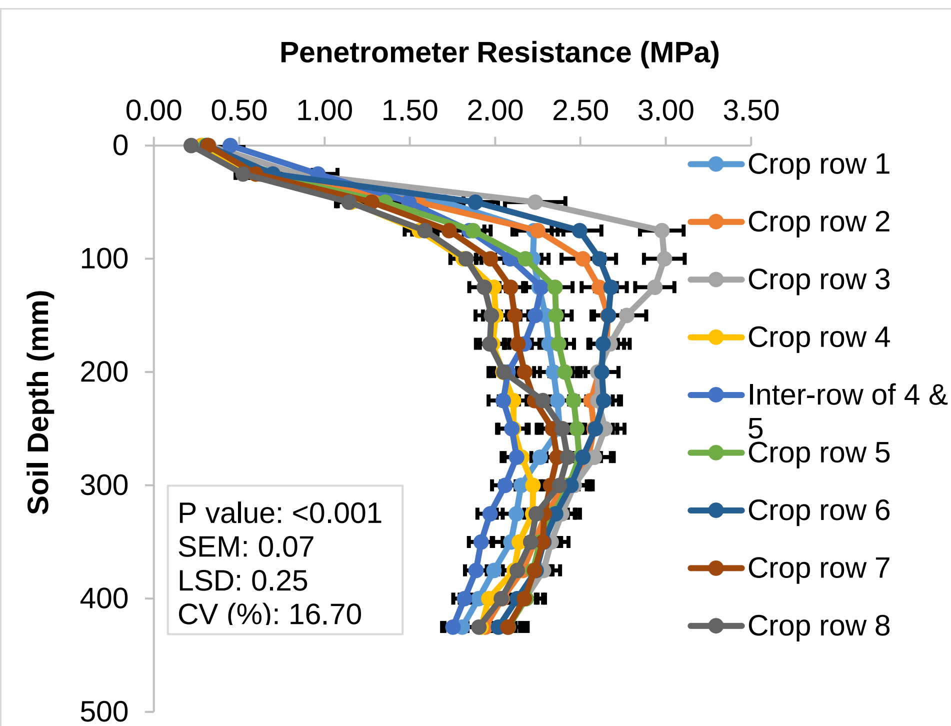


Figure 6.7f. Effect of crop row at different soil depths on mean penetrometer resistance in the South field in 2018. Error bar indicates the standard error of mean.

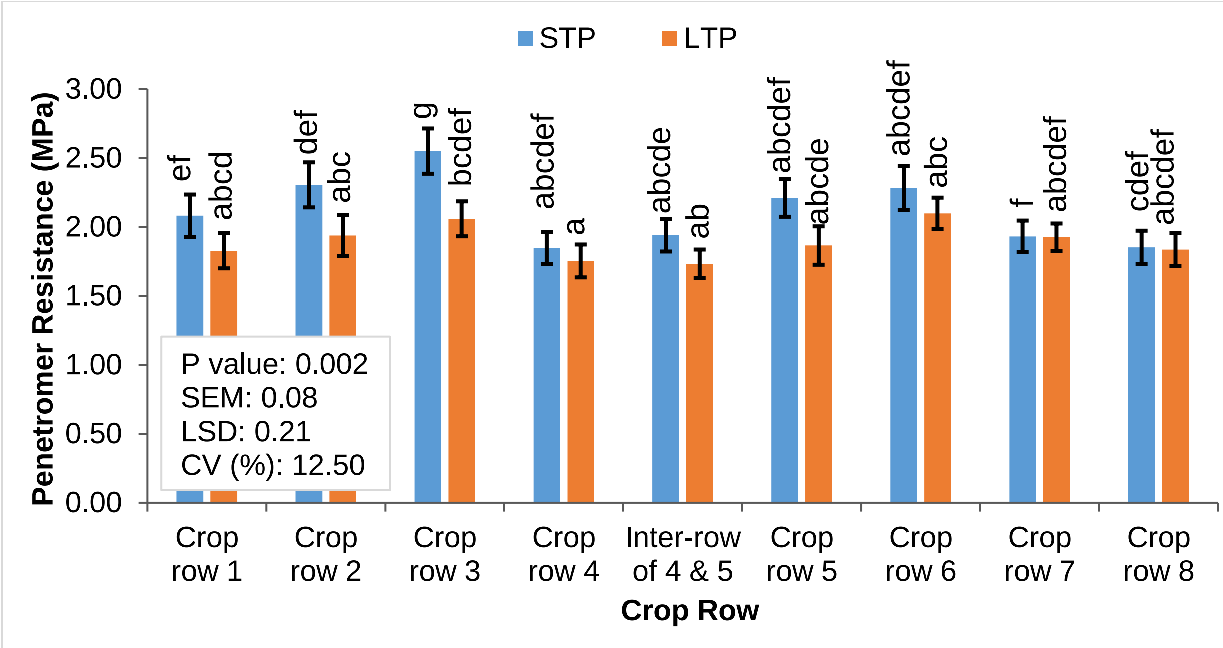


Figure 6.7g. Effect of tyre inflation pressure at different crop row on mean penetrometer resistance in the South field in 2018. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

Results of the three-year field-scale studies showed that there was no significant difference between the tyre inflation pressure treatments in the first two years for both soil MC and PR of soil but had a significant effect in 2018. However, PR values were observed more in STP than LTP treatment in 2018 is in line with the findings that high tyre inflation pressure increased compaction of soil (Soane et al., 1982). Soybean received a substantial amount of precipitation during the vegetative growth of stages in 2016 that may have allowed soils to preserve moisture that was eventually used by the crop for normal growth and development. In 2017, PR data in STP was narrowly higher than the LTP treatment but it was not significant, however, the PR at all depth was below 2.00 MPa. Thus, it can be assumed that less PR in 2017 and significantly lower PR in 2018 in LTP treatment in comparison to the STP treatment indicate that soils under low inflation tyre system cause less compaction than STP tyre system. The results are in agreement in part with the observation that field trafficking with low-pressure tyres can significantly decrease soil compaction and increase crop yield (Boguzas and Hakansson, 2001; Ridge, 2002). The higher PR values in CR3 and CR1 as expected because of the wheel trafficked areas, which were near to the CR3 and CR6, and the additional compaction applied on the crop row 1 and 3 before planting of crops. Hence, these crop rows had higher soil strength due to compaction by machinery trafficked under tyre inflation pressures which in turn had higher PR across 450 mm soil depths and lower soil MC at 200 mm soil depth.

6.5.3. Effect on Growth and Yield of Soybean

Crop growth and development and grain yield of soybean as influenced by the tyre inflation pressure and tillage system are presented in Tables 6.3 - 6.14.

6.5.3.1. Growth Parameters of Soybean

Plant establishment (%), the number of plants ha^{-1} and plant height of soybean for 2016 are shown in Tables 6.3 and 6.4. The results showed that tyre inflation pressure had no significant effect on plant establishment (%), the number of plants ha^{-1} and plant height at 30 DAP but had an effect on plant height at 45 DAP of soybean ($P = 0.003$, $n = 60$). Although not significantly different, the mean values of plant establishment for STP and LTP treatments were 92.8 and 92.5%, respectively while the number of plants ha^{-1} was 0.4% more in STP (293821) treatment than that of LTP treatment (292565) (Table 6.3). The results revealed that LTP treatment had a small (3.20% higher) but a significant effect on plant height of soybean at 45 DAP (0.354 m) than that of STP (0.343 m). Tables 6.3 and 6.4 show that crop row had a significant effect on the plant establishment (%) ($P = 0.03$, $n = 30$), the number of plants ha^{-1} ($P = 0.030$, $n = 30$) and plant height at 45 DAP ($P = <0.001$, $n = 30$) and had no significant effect on plant height of soybean at 30 DAP ($P = 0.581$). The results indicate that the highest plant establishment (%) (93.84%), the number of plants ha^{-1} (296961) and plant height of soybean (0.355 m) were recorded in crop row 2 which was significantly different from the crop row 1 for plant establishment and plants ha^{-1} (91.53% and 289677 respectively) and crop row 3 (0.340 m) for plant height of soybean. Non-replicated rooting depth study revealed that the rooting depth of all the LTP crop rows was more than that of the STP treatment plot, with mean depths of 0.97 m and 0.88 m, respectively (Appendix 6.4), which is comparable to typical soybean rooting depth of 0.99 m found in the Midwest soils in the USA (Merrill et al., 2002). Vegetative growth and harvesting of soybean are shown in Fig. 6.8.

Table 6.3. Effect of tyre inflation pressure and crop row on plant establishment and number of plants ha^{-1} of soybean, in the South field in 2016

Treatments†	Plant establishment (%)					Number of plants ha^{-1}				
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Mean	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Mean
STP	91.0[a]	93.7[a]	92.6[a]	93.9[a]	92.8[a]	288002[a]	296709[a]	293193[a]	297379[a]	293821[a]
LTP	92.0[a]	93.9[a]	91.3[a]	92.4[a]	92.4[a]	291351[a]	297212[a]	289174a	292523[a]	292565[a]
Mean	91.5[a]	93.8[b]	92.0[ab]	93.2[ab]		289677[a]	296961[b]	291184[ab]	294951[ab]	
24 and 80 DF	SEM	P value	LSD	CV (%)		SEM	P value	LSD	CV (%)	
TIP	0.40	0.52	1.57	1.00		127	0.52	4992	1.00	
CR	0.56	0.03	1.64	1.90		178	0.03	5200	1.90	
TIP × CR	0.79	0.33	2.32			252	0.33	7348		

†TIP- Tyre inflation pressure, CR-crop row, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure; CVs (%) are for the main effect and subplot effects, respectively. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 6.4. Effect of tyre inflation pressure and crop row on the plant height of soybean, in the South field in 2016

Treatments†	Plant height at 30 DAP (m)					Plant height at 45 DAP (m)				
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Mean	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Mean
STP	0.224[a]	0.222[a]	0.250[a]	0.221[a]	0.229[a]	0.348[a]	0.347[a]	0.335[a]	0.341[a]	0.343[a]
LTP	0.224[a]	0.222[a]	0.219[a]	0.224[a]	0.222[a]	0.357[a]	0.362[a]	0.344[a]	0.352[a]	0.354[b]
Mean	0.224[a]	0.222[a]	0.235[a]	0.222[a]		0.352[b]	0.355[b]	0.340[a]	0.347[ab]	
24 and 80 DF	SEM	P value	LSD	CV (%)		SEM	P value	LSD	CV (%)	
TIP	0.005	0.45	0.02	5.70		0.001	0.003	0.005	0.80	
CR	0.007	0.58	0.02	10.50		0.002	<0.001	0.007	2.20	
TIP × CR	0.01	0.34	0.03			0.003	0.73	0.009		

†TIP - Tyre inflation pressure, STP - standard tyre inflation pressure, LTP - low tyre inflation pressure, CR - crop row, DAP - Days after planting. Means with the same letter are not significantly different (P = 0.05) from each other.

a) Vegetative stage *b) Rooting depth study*

c) Combine harvester and weigh wagon *d) Harvesting of soybean*

Figure 6.8. Vegetative growth, rooting depth study and harvesting of soybean, in the South field in 2016.

In 2017, the results showed that the main effect of tillage system and subplot effect of crop row had a significant influence on plant establishment (%) (P = 0.009 and 0.001, respectively), plants ha^{-1} (P = 0.01 and 0.004, respectively) and plant height of soybean (P = 0.001 and 0.01, respectively) and other were not significant (Fig. 6.9a-c and Tables 6.5 - 6.6 and Appendix 6.5). The highest plant establishment (%) of soybean was recorded for the NT system (89.7%), which was significantly different from the DT (88.5%) and ST treatments (85.10%) (n = 80; Fig. 6.9a). The highest number of plants ha^{-1} was observed in DT (263526) and NT (257540) which was significantly higher than ST (248236) (Table 6.5a). Stress provided by the STP and low soil MC in NT plots could have contributed to sporadic crop drying and could explain the reduction in plant population for the NT treatments. Among crop rows, the highest plant establishment of soybean was recorded in crop row 8 (91%) that was significantly different from the crop row 3 (85.87%) and crop row 2 (86.63%) (n = 30; Fig. 6.9b). Correspondingly, the number of plants ha^{-1} was recorded 2% higher in the crop row 8 (264433) than and significantly varied from the crop row 3 (250188) and crop row 7 (252588) (Table 6.5b).

Table 6.6a shows that there was a small (4.04%) but significantly greater plant height was recorded in the DT treatment (1.03 m) as compared to the NT treatment (0.99 m) (n = 80). The effect of crop row 8 had the highest plant height that was 2.41% higher than some, but not all the remaining crops rows (Table 6.6b).

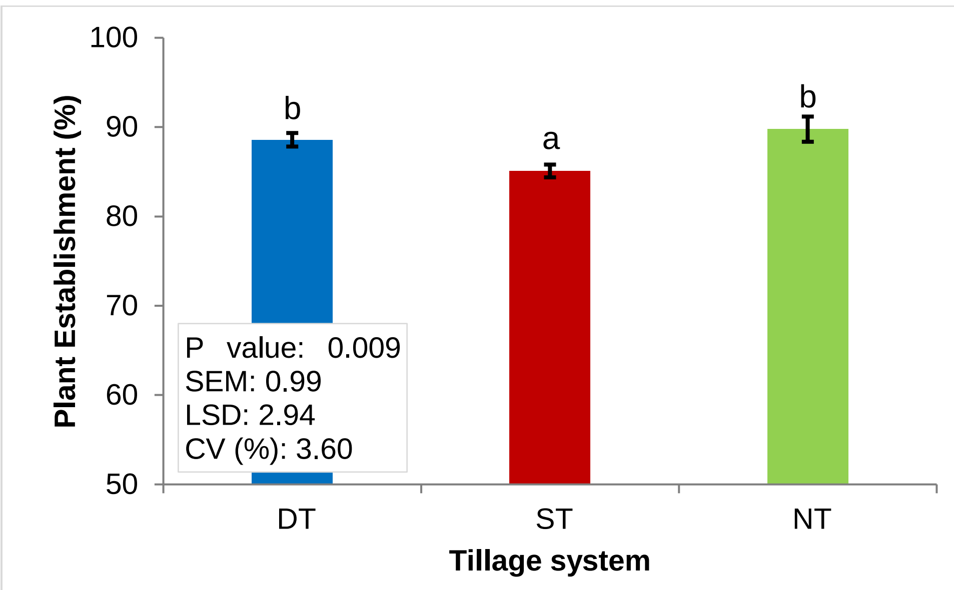


Figure 6.9a. Effect of tillage system on plant establishment of soybean in the North field in 2017. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

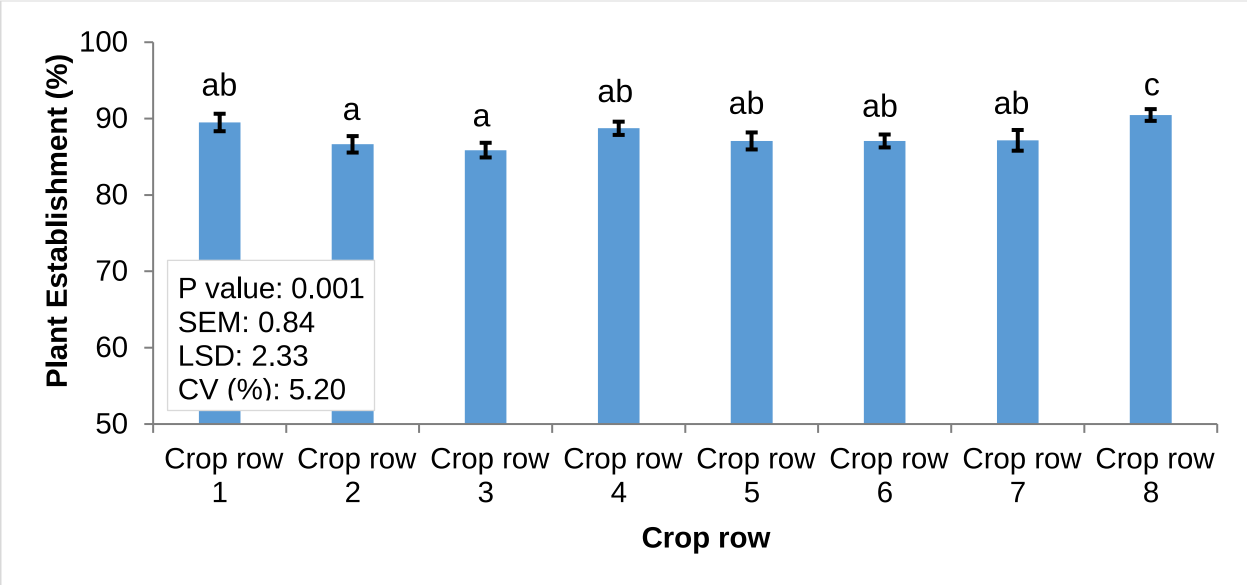


Figure 6.9b. Effect of crop row on plant establishment of soybean, in the North field in 2017. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

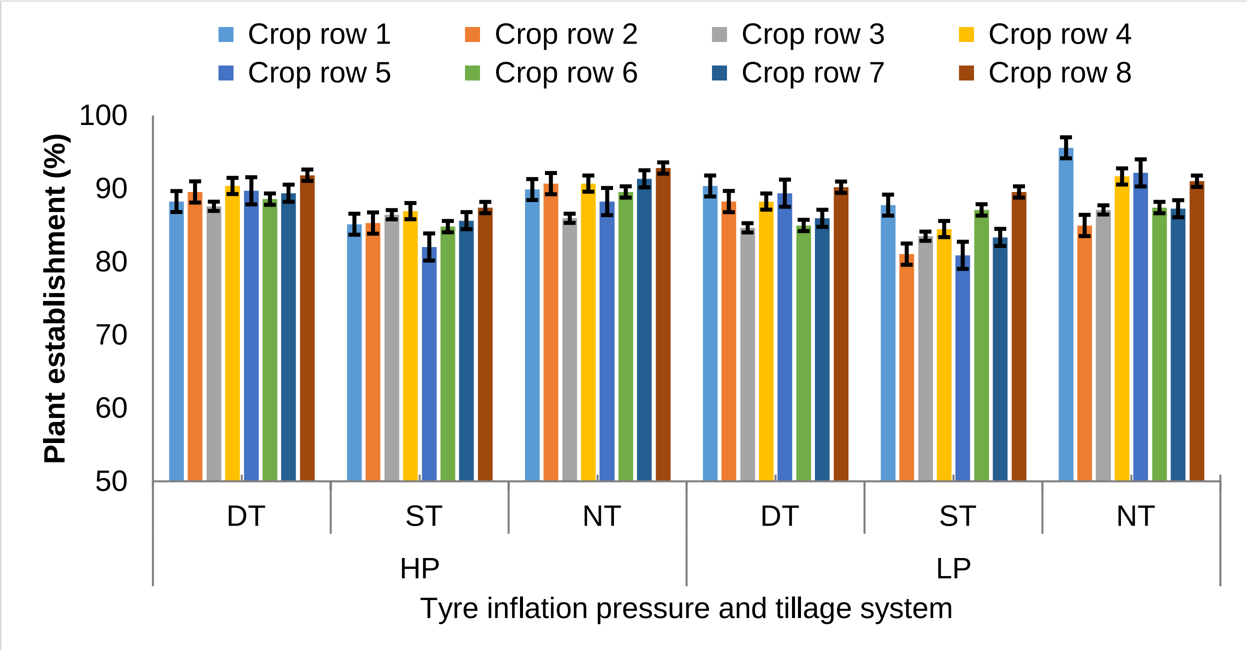


Figure 6.9c. Effect of tyre inflation pressure, tillage system and crop row on plant establishment of soybean, in the North field in 2017. Error bar indicates the standard deviation of mean.

Table 6.5a. Effect of tyre inflation pressure and tillage system on the number of plants ha^{-1} of soybean, in the North field in 2017

Treatments†	Number of plants ha^{-1}			Mean
	DT	ST	NT	
STP	266341[a]	247838[a]	261464[a]	258548[a]
LTP	260711[a]	248634[a]	253615[a]	254320[a]
Mean	263526[b]	248236[a]	257540[ab]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	2722.4	0.28	8031.1	4.10
TS	3334.3	0.01	9836.1	
TIP × TS	4715.4	0.64	13910.3	

†TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 6.5b. Effect of tyre inflation pressure and crop row on the number of plants ha^{-1} of soybean, in the North field in 2017

Treatments†	Number of plants ha^{-1}								Mean
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Crop row 5	Crop row 6	Crop row 7	Crop row 8	
STP	259035[a]	261602[a]	251165[a]	258421[a]	256858[a]	257639[a]	258477[a]	265186[a]	258548[a]
LTP	264505[a]	247481[a]	249211[a]	257193[a]	255798[a]	249993[a]	246700[a]	263679[a]	254320[a]
Mean	261770[ab]	254542[ab]	250188[a]	257807[ab]	256328[ab]	253816[ab]	252588[a]	264433[b]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)					
TIP	2722	0.28	8031	4.10					
CR	2710	0.004	7566	5.80					
TIP × CR	4501	0.20	12616						

†TIP- Tyre inflation pressure, CR-crop row, STP-standard tyre inflation pressure, LTP-low tyre inflation pressure. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 6.6a. Effect of tyre inflation pressure and tillage system on plant height of soybean at harvest, in the North field in 2017

Treatments†	Plant height (m)			Mean
	DT	ST	NT	
STP	1.01[a]	1.01[a]	0.99[a]	1.01[a]
LTP	1.04[a]	1.02[a]	0.98[a]	1.02[a]
Mean	1.03[b]	1.01[ab]	0.98[a]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	0.006	0.28	0.07	2.20
TS	0.007	0.001	0.02	
TIP × TS	0.01	0.04	0.03	

†TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 6.6b. Effect of tyre inflation pressure and crop row on plant height of soybean at harvest, in the North field in 2017

Treatments†	Plant height (m)								Mean
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Crop row 5	Crop row 6	Crop row 7	Crop row 8	
STP	1.008[a]	1.017[a]	0.991[a]	0.997[a]	1.000[a]	1.009[a]	1.003[a]	1.014[a]	1.005[a]
LTP	1.015[a]	1.015[a]	1.003[a]	1.002[a]	1.018[a]	1.016[a]	1.022[a]	1.028[a]	1.015[a]
Mean	1.012[ab]	1.016[ab]	0.997[a]	1.000[a]	1.009[ab]	1.013[ab]	1.013[ab]	1.021[b]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)					
TIP	0.006	0.24	0.02	2.20					
CR	0.005	0.01	0.01	2.60					
TIP × CR	0.011	0.09	0.03						

†TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

The plant establishment (%), the number of plants ha^{-1} and plant height of soybean in 2018 are shown in Tables 6.7 to 6.9, Figs 6.10 and 6.11, and Appendix 6.6. The results showed that tyre inflation pressure and crop row had a significant effect on plant establishment (P = <0.001 and <0.001, respectively), the number of plants ha^{-1} (P = 0.001 and 0.002, respectively) and plant height (P = <0.001 and <0.001, respectively) of soybean. The main effect of the tillage system was also significant on both plant establishment (P = 0.03) and plant height (P = 0.03) while its interaction with tyre inflation pressure had a significant influence on plant establishment (%) (P = 0.008) and the number of plants ha^{-1} (P = 0.022). There was no significant effect of tillage system on the number of plant ha^{-1} and the interaction with tyre inflation pressure on plant height of soybean. The results showed that LTP treatment had a 2.45% higher plant establishment (92.1%) and 2.13% higher number of plants ha^{-1} of soybean (289488) in comparison to the STP treatment plot where plant establishment (%) and the number of plants ha^{-1} were 89.9% and 283464 respectively (n = 120; Table 6.7 and 6.8a). Similarly, the mean values of plant height of soybean were higher (5.98%) in LTP treatment (0.833 m) than that of the STP treatment plot (0.786 m) (n = 120; Table 6.9). These results indicate that STP treatment might have an effect on plant growth by causing soil compaction, which can be correlated with the higher PR data recorded in the STP plots than that of LTP (Fig. 6.7a-b).

Among tillage systems, plant establishment (%) of soybean was recorded as marginally higher in DT (91.8%) that was significantly different from the NT system (90.1%) (n = 80; Table 6.7). A significantly 3.53% higher plant height of soybean was also found in the DT treatment (0.822 m) which was significantly different from the NT treatment (0.794 m). The effect of interaction between tyre inflation pressure and tillage systems showed that the higher plant establishment (92.9%) led the higher number of plants ha^{-1} of soybean (292031) in the treatment combination of LTP × DT that was significantly different from the treatment combination STP × NT with the lowest plant establishment of 88% and the number of plants ha^{-1} (278154) (n = 40; Tables 6.7 and 6.8a).

Data in Fig. 6.10 and Table 6.8b show that plant establishment (%) and the number of plants ha^{-1} of soybean among the crop rows were recorded significantly higher in the non-trafficked crop row CR 7 (92.64% and 290179, respectively) than the trafficked CR3 (89.20% and 282965, respectively) and CR1 (89.65% and 283802, respectively) (n = 30). Fig. 6.11 shows that plant height of soybean was obtained the highest in the non-trafficked CR8 (0.824 m) which was significantly varied from the CR3 (0.788 m) and CR5 (0.804 m). Reasons of the lowest plant establishment, plant populations and plant height of soybean in CR3 compared to the non-trafficked crop rows could be due to the vehicles wheeling run close to the CR3 and CR6 and a further application of additional compaction on the CR1 and CR3 possibly caused additional stressed in soils underneath of CR3 and CR1 which is explainable because the PR data recorded on the CR1 and CR3 had significantly higher compared to the UT crop rows (Figs. 6.7e and 6.7f).

Table 6.7. Effect of tyre inflation pressure and tillage system on plant establishment of soybean, in the South field in 2018

Treatments[†]	Plant establishment (%)			Mean
	DT	ST	NT	
STP	90.6[ab]	91.3[b]	88.1[a]	89.9[a]
LTP	92.9[b]	91.3[b]	92.1[b]	92.1[b]
Mean	91.8[b]	91.3[ab]	90.1[a]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	0.33	<.001	0.99	1.40
TS	0.41	0.03	1.21	
TIP × TS	0.58	0.008	1.71	

[†]TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

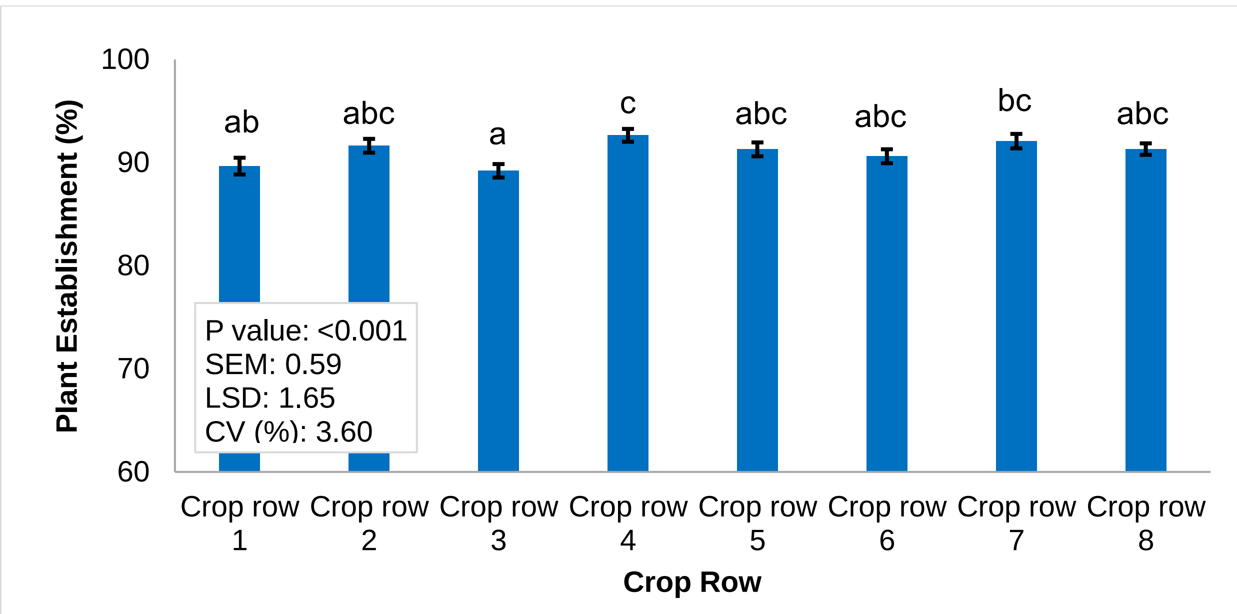


Figure 6.10. Effect of crop row (CR) on plant establishment of soybean, in the South field in 2018. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

Table 6.8a. Effect of tyre inflation pressure and tillage system on the number of plants ha^{-1} of soybean, in the South field in 2018

Treatments†	Number of plants ha^{-1}			Mean
	DT	ST	NT	
STP	285606[ab]	28663[1ab]	278154[a]	283464[a]
LTP	292031[b]	286537[ab]	289896[b]	289488[b]
Mean	288819[a]	286584[a]	284026[a]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	1120.7	0.001	3306.0	1.50
TS	1372.5	0.070	4049.0	
TIP × TS	1941.1	0.022	5726.1	

†TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 6.8b. Effect of tyre inflation pressure and crop row on the number of plants ha^{-1} of soybean, in the South field in 2018

Treatments†	Number of plants ha^{-1}								Mean
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Crop row 5	Crop row 6	Crop row 7	Crop row 8	
STP	281221[a]	282700[a]	281277[a]	287165[a]	282979[a]	281221[a]	287053[a]	284095[a]	283464[a]
LTP	286384[a]	290849[a]	284653[a]	293193[a]	290849[a]	289984[a]	293891[a]	286105[a]	289488b
Mean	283802[a]	286774[ab]	282965[a]	290179[b]	286914[ab]	285602[ab]	290472[b]	285100[ab]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)					
TIP	1120.7	0.001	3306.0	1.50					
CR	1463.9	0.002	4087.1	2.80					
TIP × CR	2237.4	0.701	6250.8						

†TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 6.9. Effect of tyre inflation pressure and tillage system on the plant height of soybean at harvest, in the South field in 2018

Treatments†	Plant height (m)			Mean
	DT	ST	NT	
STP	0.787[ab]	0.796[ab]	0.776[a]	0.786[a]
LTP	0.857[c]	0.831[bc]	0.813[ab]	0.833[b]
Mean	0.822[b]	0.813[ab]	0.794[a]	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	0.006	<.001	0.017	2.70
TS	0.007	0.03	0.021	
TIP × TS	0.010	0.157	0.029	

†TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

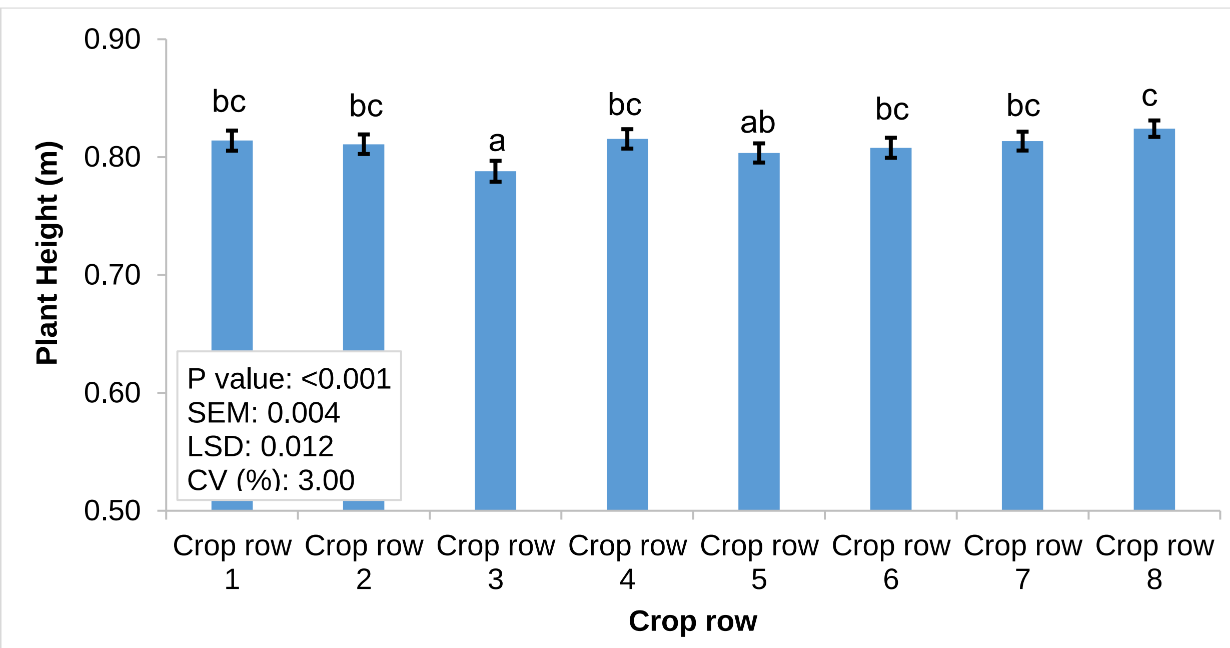


Figure 6.11. Effect of crop row (CR) on plants height of soybean at harvest, in the South field in 2018. Means with the same letter are not significantly different (P = 0.05) from each other. Error bar indicates the standard error of mean.

6.5.3.2. Yield Parameters and Grain Yield

In 2016, the results on yield parameters and yield data showed that tyre inflation pressure and crop row and their interaction had no significant effect on 1000 grain weight and hand harvested grain yield of soybean (Appendix 6.7). The mean hand harvest grain yields of soybean were 6.13 and 5.66 Mg ha^{-1} in STP and LTP, respectively (n = 60). Likewise, the results showed that tyre inflation pressure had no significant effect on the combine harvested grain yield of soybean with mean values for the STP and LTP treatments were of 4.93 and 4.91 Mg ha^{-1}, respectively (P = 0.55, n = 15; Fig. 6.12).

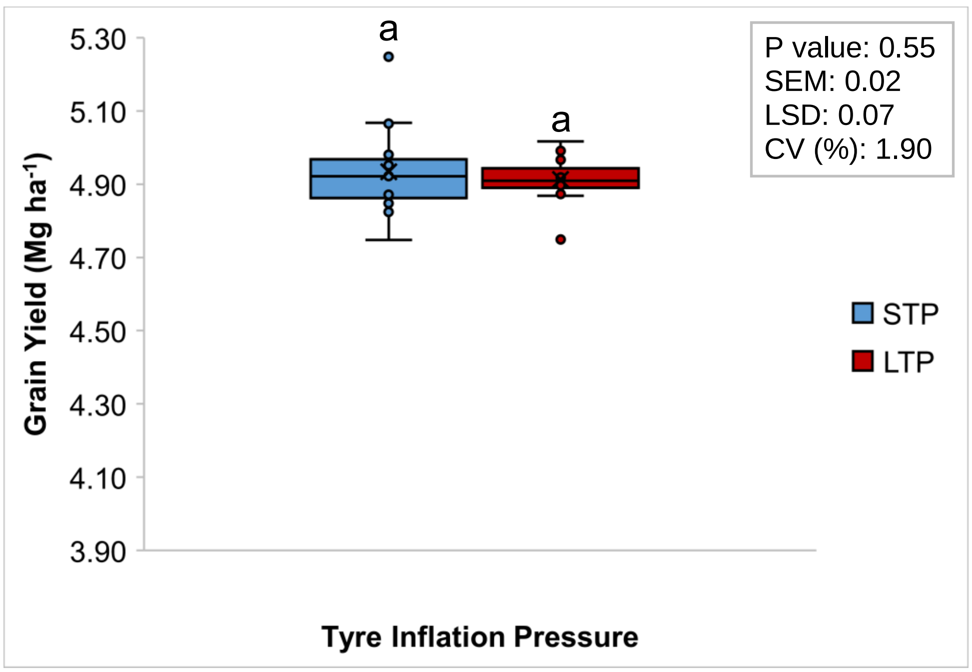


Figure 6.12. Effect of tyre inflation pressure on the combine harvested grain yield of soybean in the South field in 2016.

Note: The ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

The 2017 hand harvest data of soybean are given in Table 6.10 and Appendix 6.8. The results showed that tyre inflation pressure and interaction between tyre inflation pressure and crop row had a significant effect on the hand-harvested grain yield of soybean (P = 0.030 and 0.020, respectively) but had no significant effect on 1000 grain weight. However, the main effect of tillage system and the sub plot effect of crop row and their effects of interaction were significant neither on 1000 grain weight nor on hand harvested grain yield of soybean. The hand-harvested grain yield showed a small (+5.97%) but significantly higher yield in the LTP tyre system (5.96 Mg ha^{-1}) compared to the STP tyre system (5.63 Mg ha^{-1}) (n = 120; Table 6.10a). The mean hand harvested grain yields were not significantly different between DT, ST and NT systems with values of 5.67, 5.89 and 5.83 Mg ha^{-1}, respectively (n = 80). It is noteworthy to mention that the low quantity of hand-harvested sampling (5 plants/crop row) was possibly not adequately represent the whole 160 m length of a crop row and thus, the yield difference between tyre inflation pressure treatments was minimized. Hence, to observe the main effects of tyre inflation pressure and tillage system, it would be more meaningful to focus on combine harvested grain yield. Correspondingly, the interaction results between tyre inflation pressure and crop row showed that the highest hand harvested grain yield was recorded in the treatment combination of LTP × CR1 (6.23 Mg ha^{-1}) that was significantly different from the treatment combination of STP × crop row 3 with the lowest value of 4.99 Mg ha^{-1} (n = 15; Table 6.10b).

Table 6.10a. Effect of tyre inflation pressure and tillage system on hand harvest grain yield of soybean, in the North field in 2017

Treatments†	Hand harvest grain yield (Mg ha^{-1})			Mean
	DT	ST	NT	
STP	5.66^{a}	5.68^{a}	5.55^{a}	5.63^{a}
LTP	5.67^{a}	6.10^{a}	6.11^{a}	5.96^{b}
Mean	5.67^{a}	5.89^{a}	5.83^{a}	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	0.09	0.03	0.28	6.50
TS	0.120	0.41	0.35	
TIP × TS	0.16	0.25	0.49	

†TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 6.10b. Effect of tyre inflation pressure and crop row on hand harvest grain yield of soybean, in the North field in 2017

Treatments†	Hand harvest grain yield (Mg ha^{-1})								Mean
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Crop row 5	Crop row 6	Crop row 7	Crop row 8	
STP	5.63^{ab}	5.72^{ab}	4.99^{a}	5.55^{ab}	5.56^{ab}	5.45^{ab}	6.22^{b}	5.94^{ab}	5.63^{a}
LTP	6.23^{b}	5.66^{ab}	6.05^{ab}	5.84^{ab}	6.21^{b}	5.97^{ab}	5.98^{ab}	5.69^{ab}	5.96^{b}
Mean	5.93^{a}	5.69^{a}	5.52^{a}	5.70^{a}	5.89^{a}	5.71^{a}	6.10^{a}	5.82^{a}	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)					
TIP	0.09	0.03	0.28	6.50					
CR	0.15	0.19	0.41	14.2					
TIP × CR	0.22	0.02	0.61						

†TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Figure 6.13 – 6.15 shows that tillage system had a significant effect on the combine harvested grain yield of soybean (P = 0.001, n = 10), however, tyre inflation and interaction with tillage system were not significant in 2017 (P = 0.48 and 0.96, respectively). The combine harvested mean grain yields of soybean in STP and LTP were 4.76 and 4.73 Mg ha^{-1}, respectively (n = 15, Fig. 6.13). Among the tillage systems, the highest combine harvested grain yield was recorded in the DT treatment (4.86 Mg ha^{-1}) that was significantly different from the NT treatment with the lowest value of 4.65 Mg ha^{-1} (n = 10, Fig. 6.14). The grain yield in the DT treatment was increased by 2.75% and 4.52% as compared to the ST (4.73 Mg ha^{-1}) and NT treatments, respectively. The mean grain yields of the interaction between tyre inflation pressure and tillage systems in the treatment combinations of LTP × DT, LTP × ST and LTP × NT were 4.85, 4.72 and 4.63 Mg ha^{-1} while for the treatment combination of STP × DT, STP × ST and STP × NT, the yields were 4.87, 4.74 and 4.67 Mg ha$^{-1,}$ respectively (n = 5, Fig. 6.15). These results indicate that the yield benefit of LTP systems for soybean production in 2017 was consistent for all tillage treatments, although the combined effect was not significant.

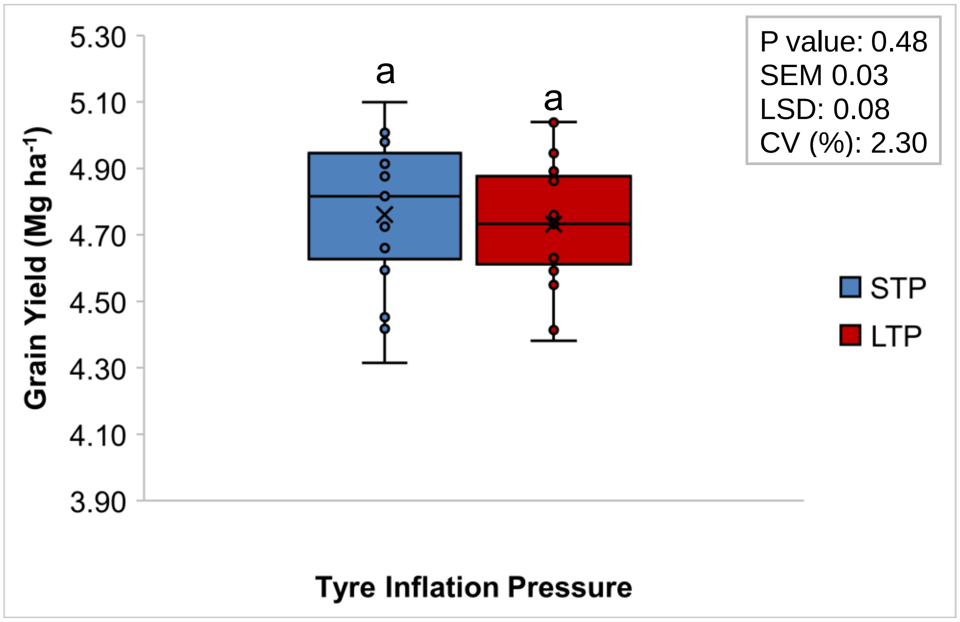


Figure 6.13. Effect of tyre inflation pressure on the combine harvested grain yield of soybean, in the North field in 2017.

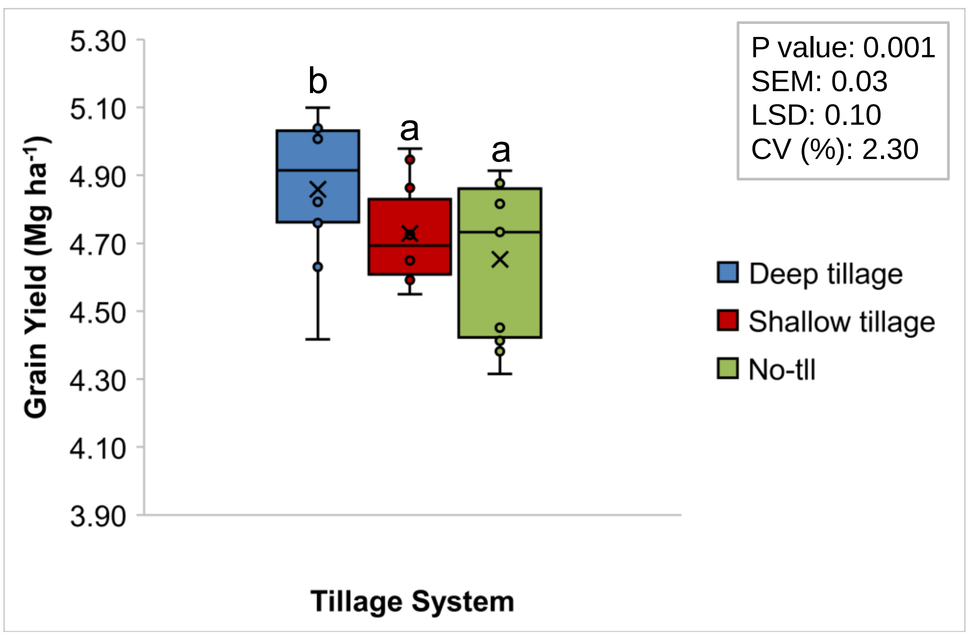


Figure 6.14. Effect of tillage system on the combine harvested grain yield of soybean, in the North field in 2017.

Note: In Figs. 6.13 - 6.14, the ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

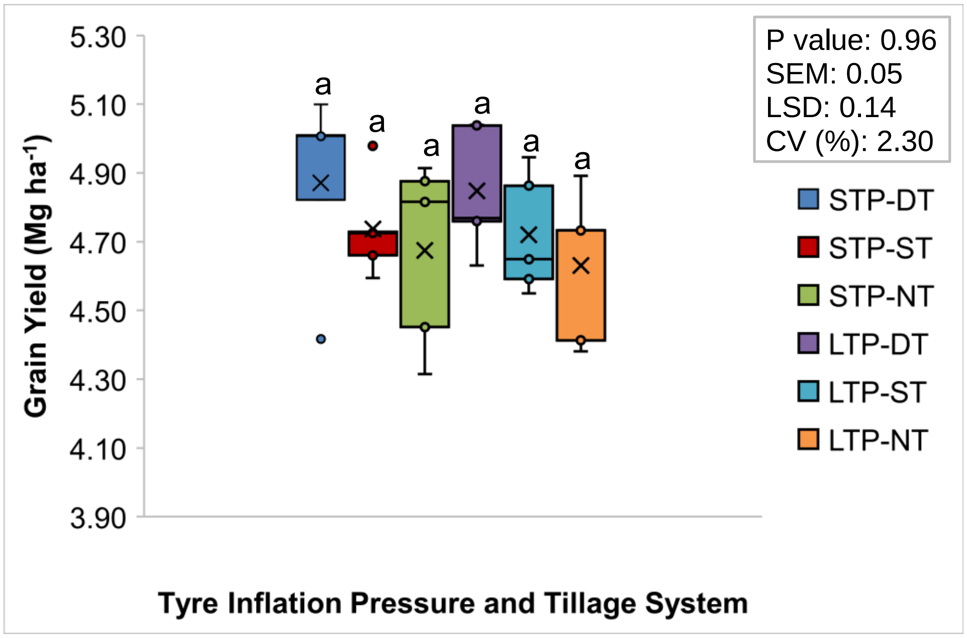


Figure 6.15. Effect of tyre inflation pressure and tillage system on the combine harvested grain yield of soybean, in the North field in 2017.

Note: The ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

Results in 2018 hand harvest data revealed that tyre inflation pressure, tillage system and their interaction had no significant effect on the 1000 grain weight of soybean (P = 0.339, 0.805 and 0.139). However, the subplot effect of crop row and the interaction effect of tyre inflation pressure and crop row was significant (P = 0.006 and 0.049, respectively) (Table 6.11 and Appendix 6.9). The 1000 grain weight was the highest in the crop row 1 (155 g) which was significantly different from crop row 3 and 7 (n = 30). Likewise, the highest 1000 grain weight was recorded in the treatment combination of LTP × crop row 8 (157 g) which was significantly different from the treatment combinations of STP × crop row 3 (149 g) and LTP × crop row 3 (149 g) (n = 15, Table 6.11). The results revealed that tyre inflation pressure had a significant effect on the biomass and hand harvested grain yields of soybean (P = 0.001 and 0.003; Tables 6.12 and 6.13). The biomass and hand harvested grain yields of soybean in the LTP treatment were recorded 8.41% (8.64 Mg ha^{-1}) and 8.35% (4.80 Mg ha^{-1}) higher compared to the STP treatment (7.97 Mg ha^{-1} and 4.43 Mg ha^{-1}, respectively) (n = 120). There was no significant difference between tillage systems, crop rows and their interaction with tyre inflation pressure on the biomass and hand harvested grain yields of soybean in 2018 (Tables 6.12 and 6.13).

Table 6.11. Effect of tyre inflation pressure and crop row on 1000 grain weight of soybean, in the South field in 2018

Treatments†	1000 grain weight of soybean (g)								
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Crop row 5	Crop row 6	Crop row 7	Crop row 8	Mean
STP	154^{ab}	153^{ab}	149^{a}	152^{ab}	152^{ab}	151^{ab}	151^{ab}	151^{ab}	151^{a}
LTP	156^{ab}	150^{ab}	152^{ab}	150^{ab}	153^{ab}	151^{ab}	149^{a}	15^{7b}	152^{a}
Mean	155^{b}	151^{ab}	151^{a}	151^{ab}	152^{ab}	151^{ab}	150^{a}	154^{ab}	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)					
TIP	0.67	0.33	1.98	1.70					
CR	1.01	0.006	2.84	3.70					
TIP × CR	1.50	0.04	4.20						

†TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 6.12. Effect of tyre inflation pressure and tillage system on the biomass yield of soybean, in the South field in 2018

Treatments†	Biomass yield (Mg ha^{-1})			Mean
	DT	ST	NT	
STP	8.06^{a}	8.03^{a}	7.82^{a}	7.97^{a}
LTP	8.86^{a}	8.67^{a}	8.37^{a}	8.64^{b}
Mean	8.46^{a}	8.35^{a}	8.10^{a}	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	0.12	0.001	0.36	5.80
TS	0.15	0.24	0.45	
TIP × TS	0.21	0.84	0.63	

†TIP- Tyre inflation pressure, TS-Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

Table 6.13. Effect of tyre inflation pressure and tillage system on the hand harvest grain yield of soybean, in the South field in 2018

Treatments†	Hand harvest grain yield (Mg ha^{-1})			Mean
	DT	ST	NT	
STP	4.37^{a}	4.42^{a}	4.50^{a}	4.43^{a}
LTP	4.87^{a}	4.87^{a}	4.66^{a}	4.80^{b}
Mean	4.62^{a}	4.65^{a}	4.58^{a}	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)
TIP	0.07	0.003	0.22	6.40
TS	0.09	0.86	0.27	
TIP × TS	0.13	0.40	0.39	

†TIP- Tyre inflation pressure, TS -Tillage systems, STP- standard tyre inflation pressure, LTP- low tyre inflation pressure, DT- deep tillage, ST- shallow tillage and NT- no-till. Means with the same letter are not significantly different (P = 0.05) from each other.

On the contrary, Figs. 6.16 - 6.18 show that tyre inflation pressure and interaction between tyre inflation pressure and tillage system had a significant effect on the combine harvested grain yield of soybean in 2018 (P = 0.024 and 0.040, respectively) while the main effect of tillage system (P = 0.295) was not significant. A significantly 3.70% higher combine harvested grain yield of soybean was obtained in the LTP treatment (4.25 Mg ha^{-1}) as compared to the STP treatment (4.10 Mg ha^{-1}) (n = 15; Fig. 6.16). The combine harvested mean grain yields of soybean in the DT, ST and NT systems were 4.13, 4.16 and 4.24 Mg ha^{-1}, respectively (n = 10; Fig. 6.17). The highest combine harvested grain yield of soybean was recorded in the treatment combination of LTP × NT (4.35 Mg ha^{-1}) which was significantly different from STP × ST treatment combination with the lowest yield of 3.97 Mg ha^{-1} (n = 5; Fig. 6.18). These data like 2017 indicate that LTP treatment had higher grain yields than STP in all three tillage systems in 2018, even though the combined effect was not significant in that year.

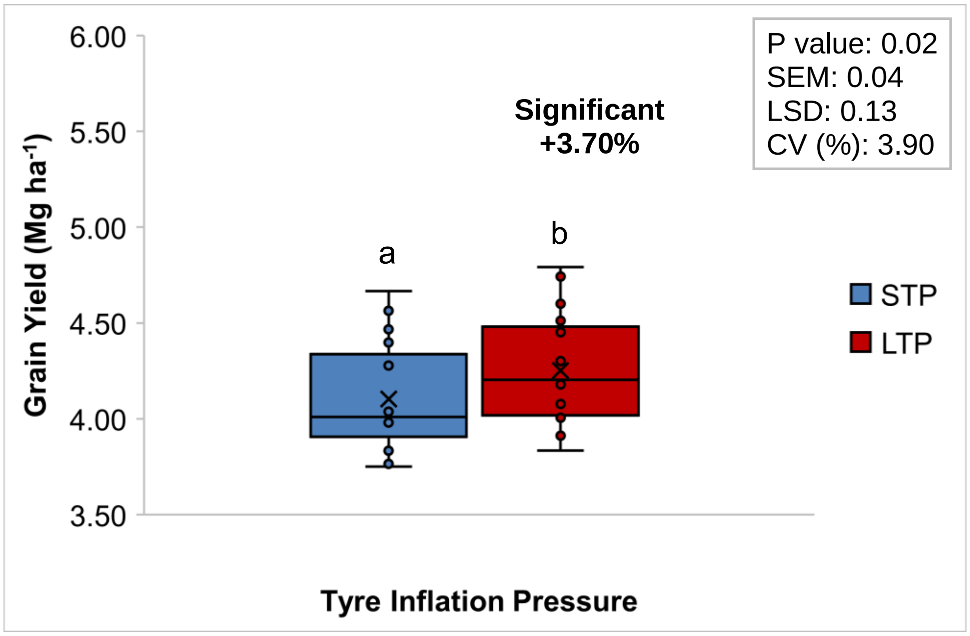


Figure 6.16. Effect of tyre inflation pressure on the combine harvested grain yield of soybean, in the South field in 2018.

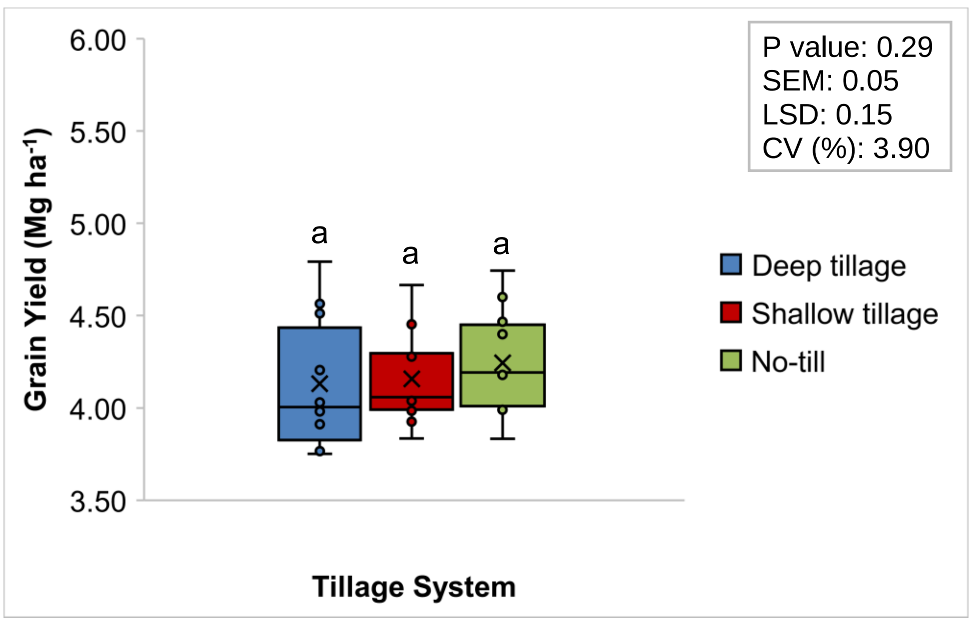


Figure 6.17. Effect of tillage system on the combine harvested grain yield of soybean, in the South field in 2018.

Note: The ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

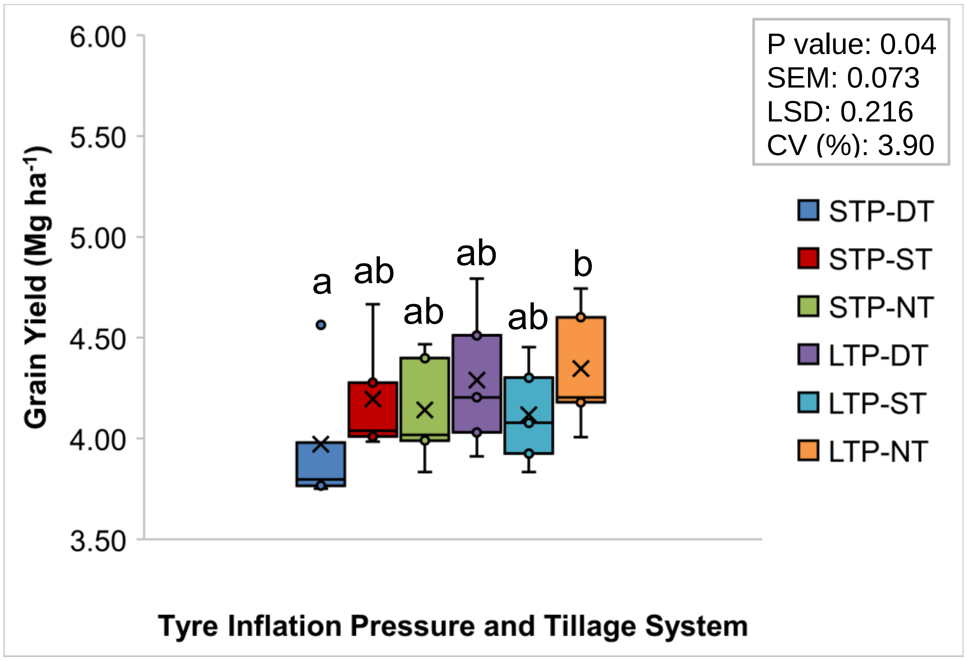


Figure 6.18. Effect of tyre inflation pressure and tillage system on the combine harvested grain yield of soybean, in the South field in 2018.

Note: In Fig 6.17b-c, the ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

The present field scale-study during the year 2017 to 2018 including a pilot study trial in 2016 indicate that the yield of soybean in 2016 and 2017 was not influenced by the tyre inflation pressure with an exception in plant height at 45 DAP in 2016. However, a positive effect due to the use of low tyre inflation pressure tyres was observed on soil properties and crop growth and yield of soybean in 2018. PR >2.00 MPa that affect soil structure and limit the growth and yield of crops (Hamza & Anderson, 2005). Higher PR of soil (>2 MPa) under both standard and low tyre inflation pressures in 2016 (even though PR in LTP<STP) might have affected the soil structure. However, higher plant establishment (%) (>92) and the higher number of plants ha^{-1} of soybean in both tyre inflation pressure treatments because of higher rainfall at 70-80 DAP in 2016 contributed to the non-significant yield difference between them. In 2017, neither plant establishment (%) and the number of plants ha^{-1} nor the combine harvested grain yields were significant between the tyre inflation pressures. The amount of precipitation, especially during the vegetative growth stage of soybean in 2017 was lower than in 2016 and 2018 and thus, the year 2017 was considered to be a partial dry weather year. Therefore, the lack of response in 2017 to reduced tyre inflation pressure with the soybean yield was possibly attributed to the negative effect of the moderately dry season which is in line with the report of Yang et al. (2003).

The present finding is also in agreement with the findings of Kulkarni et al. (2010) who reported that soil resistance on a loam soil as low as 1.6 MPa (measured range 1.6–2.9 MPa) affected crop growth but did not show any yield penalty. Conversely in 2018, higher grain yield of soybean in the LTP tyre system was attributed due to the higher plant establishment (%) and a higher number of plant ha^{-1} in comparison to STP tyre systems plot. Lower PR of soil in the LTP treatment in 2018, in turn, maintains soil porosity higher than the STP can be the main reason in increasing crop growth and grain yield higher than that of the STP treatment. These findings are in agreement with (Boguzas and Hakansson, 2001; Ridge, 2002). Restricted root growth and accessibility of nutrients due to an increase in soil strength (BD) and reduced pore size due to soil compaction (Nawaz et al., 2013; Kaspar et al., 2001) may be further reasons can be related to the present findings.

6.6. Conclusions

1) Initial assessment of the South field showed that the soil contains relatively high OM and had adequate plant nutrients. The low soil BD (<1.30 Mg g^{-3}), relatively high porosity (>50%) and low PR of soil (peak PR 1.23 MPa) indicate that the experimental field was relatively uniform with no underlying residual compaction.

2) Tyre inflation pressure had no significant effect on the PR of soil in 2016. The PR of the un-trafficked areas had a significantly lower than the heavily trafficked areas with a peak PR of soil at depth 75 mm (1.66 and 2.27 MPa, respectively) (P = <0.001). Low tyre inflation pressure had no significant effect on the soil MC in 2017 and 2018 and PR of soil in 2017 while in 2018, it had a significant effect on PR of soil with the peak value of 2.29 MPa at soil depth 250 mm, was lower than that of standard tyre inflation pressure (2.51 MPa) (P = <0.001).

3) The tillage system across soil depth had a significant effect on the PR of soil in both 2017 and 2018 (P = <0.001 and <0.001) with no significant effect on soil MC in both years, however, reducing tillage (ST, depth 100 mm) was shown to have a benefit of

reducing soil compaction in the soybean field. In 2017, values of PR were recorded in the order of NT>ST & DT up to a depth 50mm. After that the values were observed in the order of DT>NT>ST to a depth 450 mm, While in 2018, the PR of soil were recorded in the order of NT>ST>DT up to a depth of 225 mm, however, the values of PR were in the order of DT> ST & NT from the depth of 275 mm down to soil depth of 450 mm. No significant effects of the interaction between tyre inflation pressure and tillage system were found between PR and soil MC (%) in both 2017 and 2018. Regardless of tyre inflation pressure and tillage system, reducing field trafficked and UT crop row had shown a significant benefit over the HT crop rows by reducing soil compaction and creating an opportunity for soil to conserve more moisture in both 2017 and 2018.

4) In 2016, tyre inflation pressure had no significant effect on the plant establishment (%), the number of plants per ha and plant height at 30 DAP of soybean except plant height at 45 DAP (P = 0.003). Crop row had a significant effect on the plant establishment (%) (P = 0.03), number of plants per ha (P = 0.03) and plant height at 45 DAP (P = <0.001) and others were not significant. There was also no significant interaction effects of the tyre inflation pressure and crop row on the growth parameters of soybean in 2016.

5) There was no significant influence of tyre inflation pressure on crop development of soybean in 2017, but the effect of tillage system and crop row were significant on the plant establishment (%) (P = 0.009 and 0.001), the number of plants ha^{-1} (P =0 .01 and 0.004) and plant height (P = 0.001 and 0.01). In 2018, reduced tyre inflation pressure was shown to have a significant effect on the plant establishment (%) (P = <0.001), number of plants per ha (P = 0.001) and plant height (P = <0.001) of soybean while tillage system had a significant effect on the plant establishment (%) (P = 0.03) and plant height (P = 0.03) of soybean. The interaction between tyre inflation pressure and tillage system had also found a significant influence on plant establishment (%) (P = 0.008) and the number of plants per ha (P = 0.02). Results revealed that crop row had a significant influence on the plant establishment (%), the number of plants ha^{-1} and plant height of soybean in 2007 (P = 0.001, 0.01 and 0.004, respectively) and in 2018 (P = <0.001, 0.002 and <0.001, respectively) with no significant interaction neither with tyre inflation pressure nor with tillage systems on these growth parameters in both the year.

6) Tyre inflation pressure, tillage system and their interaction had no significant effect on the 1000 grain weight and hand harvested yield of soybean except for grain yield in the

year 2017 where tyre inflation pressure (P = 0.03), and the interaction of the tyre inflation pressure and crop row (P = 0.02) show a significant influence on the hand harvested yield of soybean. Reduced tyre inflation pressure had a significantly higher biomass yield than standard tyre inflation pressure in 2018 (P = 0.001).

7) Tyre inflation pressure had a significant influence on the combine harvested grain yield of soybean in 2018 (P = 0.021) but had no significant effects in 2016 and 2017 (P = 0.553 and 0.083). The grain yield in the low tyre inflation pressure treatments (4.25 Mg ha^{-1}) was 3.70% higher than that of the standard tyre inflation pressure treatment (4.10 Mg ha^{-1}).

8) The tillage system had no significant effect on the grain yield of soybean in the year 2018 (P = 0.295), however, this was significant in 2017 (P = 0.001) where higher grain yields of soybean were recorded for the deep tillage treatments (4.86 Mg ha^{-1}) than shallow tillage (4.73 Mg ha^{-1}) and no-till (4.65 Mg ha^{-1}). The yield benefits from deep tillage system were 2.75% and 4.52% greater than that of shallow tillage and no-till systems, respectively. Both tyre inflation pressure and tillage system had a significant effect on the grain yield of soybean in 2018 (P = 0.04) but they were not significant in the year 2017 (P = 0.96).

CHAPTER 7: ECONOMIC ANALYSIS OF ALTERNATE TYRE SYSTEMS IN MAIZE-SOYBEAN ROTATION

7.1. Introduction

The economic profitability of a given cropping system is crucial to make the system viable and sustainable. Farmers adopt technology based on the visible short as well as long-term economic benefits while protecting the environment. Results from the earlier studies at Harper Adams University, UK found that low tyre inflation pressure systems had a positive benefit in increasing yield of crops in sandy loam soil compared to the standard tyre inflation pressure systems, but these studies have not considered on economic analysis of the benefit (Smith et al., 2014b; Millington, 2019). In another study, (Smith et al., 2014a) showed that there was no significant difference in contact pressures in soil between the standard and Ultraflex tyres when running at low inflation pressures. Economic analysis of the farming systems using different tyres and field trafficking systems are also scarce and robust experimental results are not available. The present study has focused here on the level of the economic benefit that can be obtained by the use of Ultraflex tyres operating at the rated lower tyre inflation pressures in comparison to standard tyre inflation pressures for three tillage systems in a maize/soybean rotation in Central Illinois.

7.2. Hypothesis

Reduced tyre inflation pressure systems increase the economic profitability for a maize/soybean rotation for three tillage systems.

7.3. Objectives

To determine the potential economic benefit of Ultraflex tyres on low inflation pressures for a maize/soybean rotation for 3 tillage systems (conventional deep tillage, shallow tillage and no-till).

7.4. Assumptions

The present study was emphasized to determine the effects of the 2 tyre inflation pressures for 3 different soil conditions, provided by the 3 alternative tillage systems. Although the different tillage systems would have different costs and benefits due to cultivation and difference in fuel cost, these were not considered in the analysis. Standard pressure was used to simulate normal tyres without the need to change the tyres during the experiment as shown by Smith et al. (2014b). Studies showed that fuel consumption between standard and Ultraflex tyres operated at standard and low tyre inflation pressure systems in the UK were not significantly different (Arslan et al., 2014). Hence, it is assumed that fuel consumptions were same in both STP and LTP tyre inflation pressure systems. The assumptions are as follows:

1) All raw yield data for 2017 & 2018 for both maize and soybean (four crop seasons) were considered irrespective of the statistical significance. The data of 2016 has not included as this was a preliminary study where all plots were deep tilled (450 mm depth).

2) Two farm sizes of 200 and 809 ha were considered. The first is one third larger than the official quoted size of an average Illinois farm (c.150 ha, Illinois Department of Agriculture, 2019) and the second that of frequently found commercial farming operations (M. Pantaleo, Personal communication, 20 March 2019).

3) The retail prices for the standard and Ultraflex tyres for the equipment required for the two farm sizes were provided by Michelin, North America Inc., (M. Pantaleo, Personal communication, 20 March 2019) and Michelin, UK (G. Brooks, Personal communication, 12 March 2019). Tyre costs required for these two farms were given in Appendices 7.1 – 7.2.

4) Tyre life expectancy was considered as 5 years (M. Pantaleo, Personal communication, 20 March 2019). A recent report showed that the longevity of Michelin Ultraflex tyres in the farmers' field was 9,500 hours (Tillage & Soils, 2020). The news also highlighted that the tyre life may last even longer period with the benefits from a large footprint aiming at reducing soil compaction and rut formation.

5) The annual mean prices of grains i.e. maize and soybean in 2018 in Illinois of the United States were taken from the *farmdocdaily* news journal. The prices were @ US$ 142.00

Mg^{-1} ($US 3.60 $Bu.^{-1}$) and 323 Mg^{-1} ($US 8.80 $Bu.^{-1}$) for maize and soybean respectively (Schnitkey and Swanson, 2019).

6) Seed, fertilizer, herbicides, labour, tillage, fuel use, machinery depreciation, repair and overhead costs were assumed equal for both tyre inflation pressure treatments as these were applied equally to both tyre systems for each type of tillage. Straight-line method was used to measure depreciation cost for the two tyre systems.

7) The mean of each rotation years assuming, typically, equal areas of maize and soybean (50:50) as suggested by Melvin (S. W. Melvin, Personal communication, 20 December 2018)[4] was also calculated.

The economic component mainly total difference in tyre spend (Standard vs. Ultraflex tyres), the annual value of crops, yield increase/decrease, annual earnings increase over the tyre life and payback period were calculated for maize and soybean production using equations of 7.1 to 7.5.

Difference in tyre spend

$$\left(\text{US\$ha}^{-1}\right) = \text{Total cost for the Ultraflex tyres} - \text{Total cost for the standard tyre} \qquad [7.1]$$

$$\textbf{GVC for STP or LTP} = \left\{\frac{(\text{FS}\times\text{GYM}\times\text{PM})+(\text{FS}\times\text{GYS}\times\text{PS})}{2}\right\} \qquad [7.2]$$

$$\textbf{AE increase / decrease } \left(\textbf{US\$ ha}^{\mathbf{-1}}\right) = (\text{GVC in STP} \times \text{Percent yield (+/-) in LTP}) - \left\{\frac{\text{Difference in tyre spend } \left(\text{US\$ ha}^{-1}\right)}{\text{Tyre life (5 years)}}\right\} \qquad [7.3]$$

$$\textbf{Total income over the tyre life } \left(\textbf{US\$ ha}^{\mathbf{-1}}\right) = \text{AE increase} \times \text{Tyre life (5 years)} \qquad [7.4]$$

[4] Dr. Stewart W. Melvin, Farmer and Consultation, Currie-Wille & Associates, Ames, Iowa and Emeritus Professor of Agricultural Engineering, Iowa State University, Ames, IA.

$$\textbf{Payback period} = \frac{\text{Difference in GVC between LTP and STP } (\text{US\$ ha}^{-1})}{\text{Differences in tyre spend } (\text{US\$ ha}^{-1})} \qquad [7.5]$$

Where,

TC = Total cost ($US/farm)

GVC = Gross value of crops ($US/farm)

FS = Farm size (ha)

GYM = Grain yield of maize (Mg ha^{-1})

GYS = Grain yield of soybean (Mg ha^{-1})

PM = Unit price of maize ($US Mg^{-1})

PS = Unit price of soybean ($US Mg^{-1})

AE = Annual Earnings

The experimental data mainly grain yield was processed for the economic analysis in term of annual cost difference, annual earnings increase or decrease, the payback period for LTP treatment over STP treatment for the maize and soybean production systems. Grain yields of both crops were analysed using Genstat statistical software18th Edition (VSN International, 2015). Economic analysis was conducted by Microsoft Excel 2016 spreadsheet provided by Michelin, UK (G. Brooks, Personal communication, 12 March 2019) (Appendices 7.3 and 7.4).

7.5. Results and Discussion

7.5.1. Grain Yields of Crops in the Cropping Systems

Two years mean yield data showed that the grain yield of maize was 3.52% higher in low tyre inflation pressure systems (14.58 Mg ha^{-1}) as compared to standard tyre inflation tyre system (14.08 Mg ha^{-1}). Similar to maize, the two years mean grain yield of soybean was 1.35 % higher in low tyre inflation pressure system (4.49 Mg ha^{-1}) than standard tyre inflation tyre system (4.43 Mg ha^{-1}) (Table 7.1 and 7.2).

Table 7.1. Effect of standard (STP) and low (LTP) tyre inflation pressure on the grain yield of maize and soybean for 2 years cropping systems

Year	Crop/ Treatments*	Grain yield (Mg ha^{-1})		Yield difference (LTP-STP) (Mg ha^{-1})	Yield increase in LTP over STP (%)
		STP	LTP		
2017	Maize	14.40[a]	15.02[b]	0.62	4.31
2018	Maize	13.76[a]	14.13[b]	0.37	2.69
2017	Soybean	4.76[a]	4.73[a]	-0.03	-0.63
2018	Soybean	4.10[a]	4.25[b]	0.15	3.66
2-y mean	Maize	14.08	14.58	0.495	3.52
2-y mean	Soybean	4.43	4.49	0.06	1.35

Note: STP and LTP represent the standard and low tyre inflation pressure, respectively. Means with the same letter in a row are not significantly different (P = 0.05) from each other.

Table 7.2. Effect of tyre inflation pressure and tillage system on the grain yield of maize and soybean for 2 years cropping systems (% differences between LTP and STP)

Year	Crops†	Grain yield (Mg ha⁻¹)								Yield difference (Mg ha⁻¹)			Yield increase in LTP (%) over STP		
		STP				LTP									
		DT	ST	NT	Mean	DT	ST	NT	Mean	DT	ST	NT	DT	ST	NT
2017	Maize	14.53^{a}	14.30^{a}	14.36^{a}	14.40^{A}	15.27^{a}	15.10^{a}	14.67^{a}	15.02^{B}	0.74	0.80	0.31	5.09	5.59	2.16
2018	Maize	14.87^{a}	13.81^{a}	12.59^{a}	13.76^{A}	15.35^{a}	14.15^{a}	12.88^{a}	14.13^{B}	0.48	0.34	0.29	3.23	2.46	2.30
2017	Soybean	4.87^{a}	4.74^{a}	4.67^{a}	4.76^{a}	4.85^{a}	4.72^{a}	4.63^{a}	4.73^{a}	-0.02	-0.02	-0.04	-0.41	-0.42	-0.86
2018	Soybean	3.97^{a}	4.20^{ab}	4.14^{ab}	4.10^{a}	4.29^{ab}	4.12^{ab}	4.35^{b}	4.25^{b}	0.32	-0.08	0.21	8.06	-1.90	5.07
2-year mean	Maize	14.70	14.06	13.48	14.08	15.31	14.63	13.78	14.58	0.61	0.57	0.30	4.15	4.06	2.23
	Soybean	4.42	4.47	4.41	4.43	4.57	4.42	4.49	4.49	0.15	-0.05	0.09	3.39	-1.12	1.93

Note: STP, LTP, DT, ST and NT represent the standard and low tyre inflation pressure, deep tillage, shallow tillage and no–till, respectively. Means with the same letter (capital and small letters are for tyre inflation pressure and interaction with tillage system, respectively) in a row are not significantly different (P = 0.05) from each other.

7.5.2. Annual Cost of Different Tyre System for Typical Farms

The 5 year total and annual costs of LTP and STP systems and their differences for the 200 ha and 809 ha farms are given in Figs. 7.1 and 7.2 and Appendices 7.2 and 7.3. Fig. 7.1 shows that for a 200 ha of a farm, the total cost of using Ultraflex tyre was increased by 23.8% (US$ 8,200.00) than that of the standard tyre. Likewise, the total cost for an 809 ha of typical Illinois farm using Ultraflex tyre was 20.1% higher as compared to the cost of the standard tyre system. The annual costs increased due to the use of Ultraflex tyres were US$ 1640 and $3400 for the farm of 200 and 809 ha, respectively (Fig. 7.2a). Thus, the annual per ha cost was US$ 4.20 for the 809 ha farm which was almost 50% less than the annual cost per ha (US$8.10) required for 200 ha farm (Fig. 7.2b).

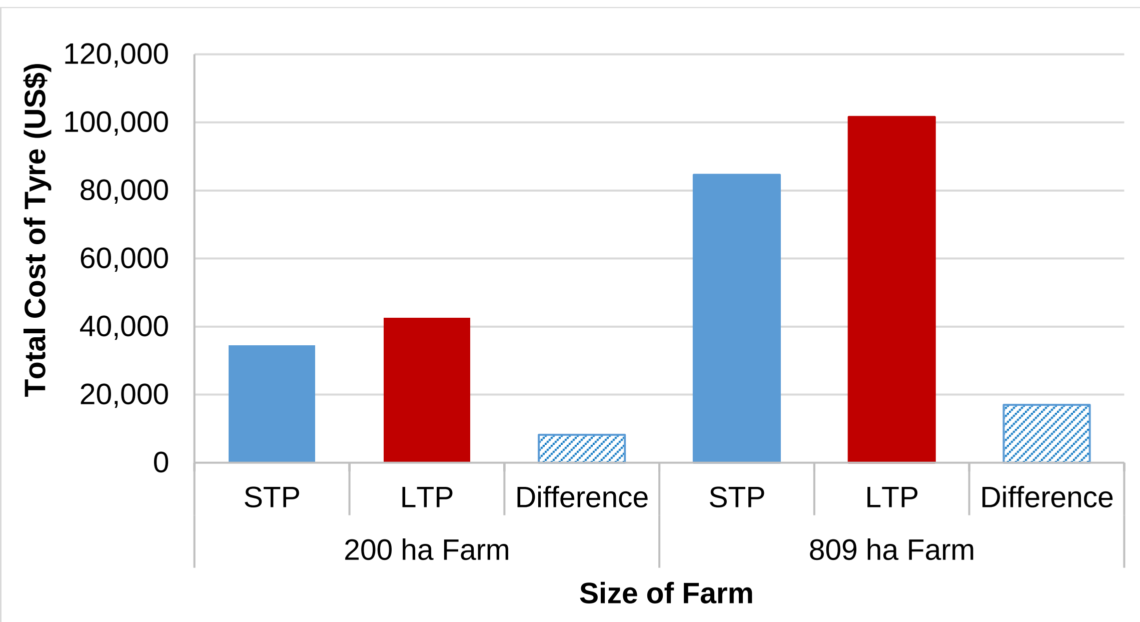


Figure 7.1. Total (5 years) cost involved for standard and Ultraflex tyre systems for 200 and 809 ha farms.

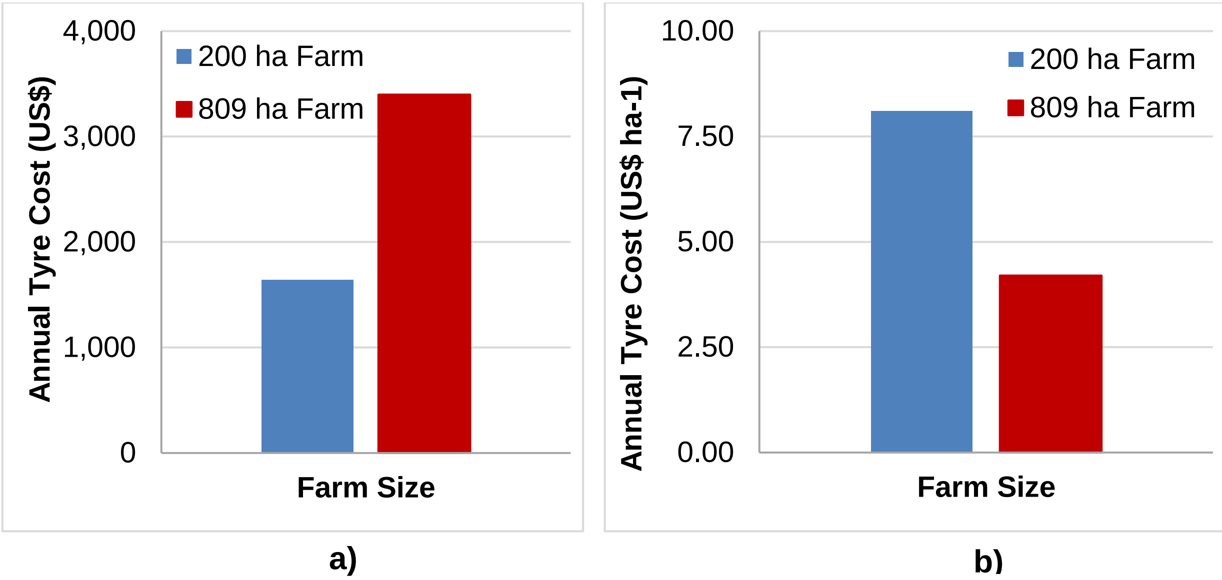


Figure 7.2. Annual (a) and per ha tyre (b) costs using Ultraflex tyre system for 200 and 809 ha of Illinois Farms.

7.5.3. Annual Increase

The results from the spreadsheet analysis (Appendix 7.1 and 7.2) for the annual earnings increase for 200 ha and 809 ha farms using LTP system over STP system are presented in Figs. 7.3 and 7.4. Also shown (hatched bar) is the mean value for the 2 years 2 crop rotation for each of the tillage systems and the grand mean. The grand mean is of little value to an individual farm, as few farms will have equal areas of maize and soybean split with equal areas of 3 tillage systems. It is of value when comparing the economics of the two different farm sizes and their machine systems.

The results show that the annual earnings of both farms were higher for maize than soybean, reflecting the current low soybean price. The annual and per ha earnings for the 200 ha farm were found to be more using Ultraflex tyre for deep tillage system. The mean annual earnings of maize and soybean rotation were recorded as highest in deep tillage system (US$ 11867) and the lowest earnings were obtained in shallow tillage (US$ 4839). However, irrespective of the tillage system, the mean total and per ha of annual earnings were found US$ 7357 and US$37, respectively (Fig. 7.3).

Total annual earnings and annual earnings per ha for the 809 ha farm, followed a similar trend as that of 200 ha farm. Mean of maize and soybean rotation using Utraflex tyre system showed that annual earnings were found to be highest in the deep tillage system (US$ 51163) while the lowest earnings were obtained in the shallow tillage system (US$ 22808), which was marginally lower than no-till system (US$ 24937). The mean total earnings for the three tillage practices using the Ultraflex tyre system increased by US$ 32969 (Fig. 7.4). The overall per ha mean annual earnings was of US$ 41, which was close to that of a 200 ha farm meaning that the per ha annual earnings vary with farm sizes. Thus, it can be said that the mean benefit ha^{-1} for both farm sizes is close; namely \$37 ha^{-1} and \$41 ha^{-1} for the 200 ha and 809 ha farms, respectively.

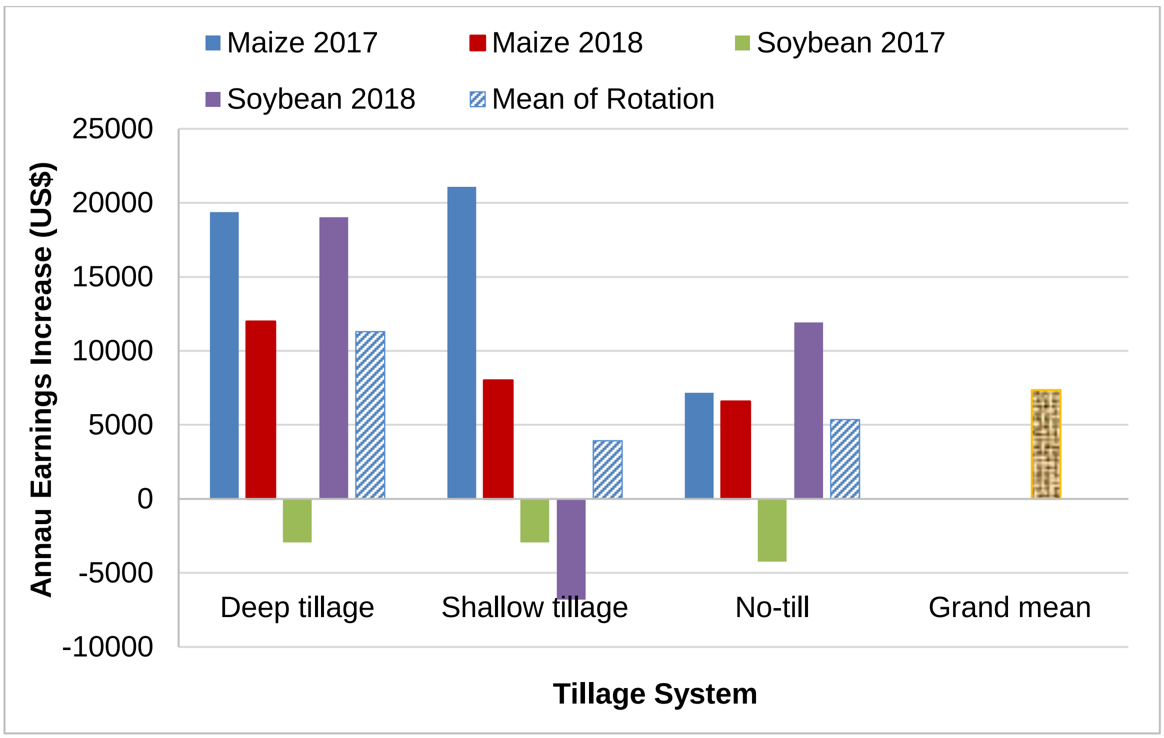


Figure 7.3. Annual earnings increase for a 200 ha farm.

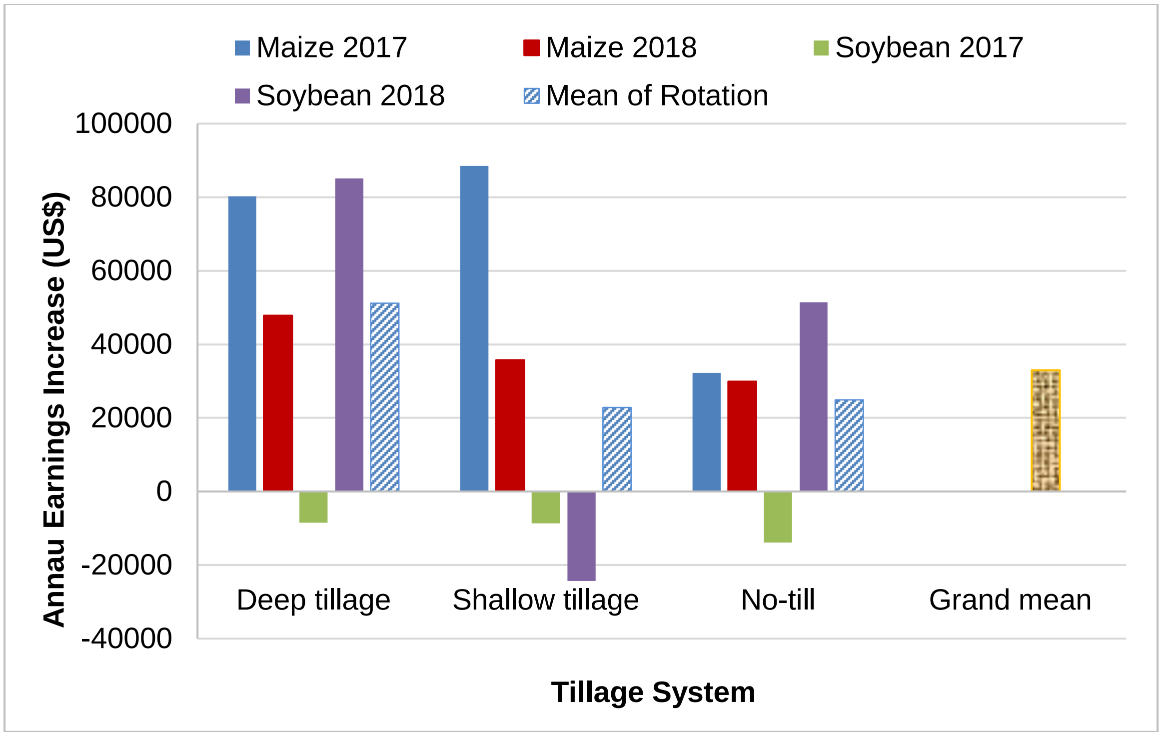


Figure 7.4. Annual earnings increase for an 809 ha farm.

7.5.4. Payback Period

The payback period for using Ultraflex tyres as compared to the standard tyres for the 200 and 809 ha farms are shown in Fig. 7.5. These results show that payback period for the three tillage systems and two farm sizes was less than two years, ranging from 0.31 years for the deep tillage system on the bigger farm to 1.27 years for the shallow tillage system on the smaller farm. Both farm sizes follow a similar trend for the different tillage systems, with the ratios for the 809 ha farm being in excess of twice the ratio of the smaller farm.

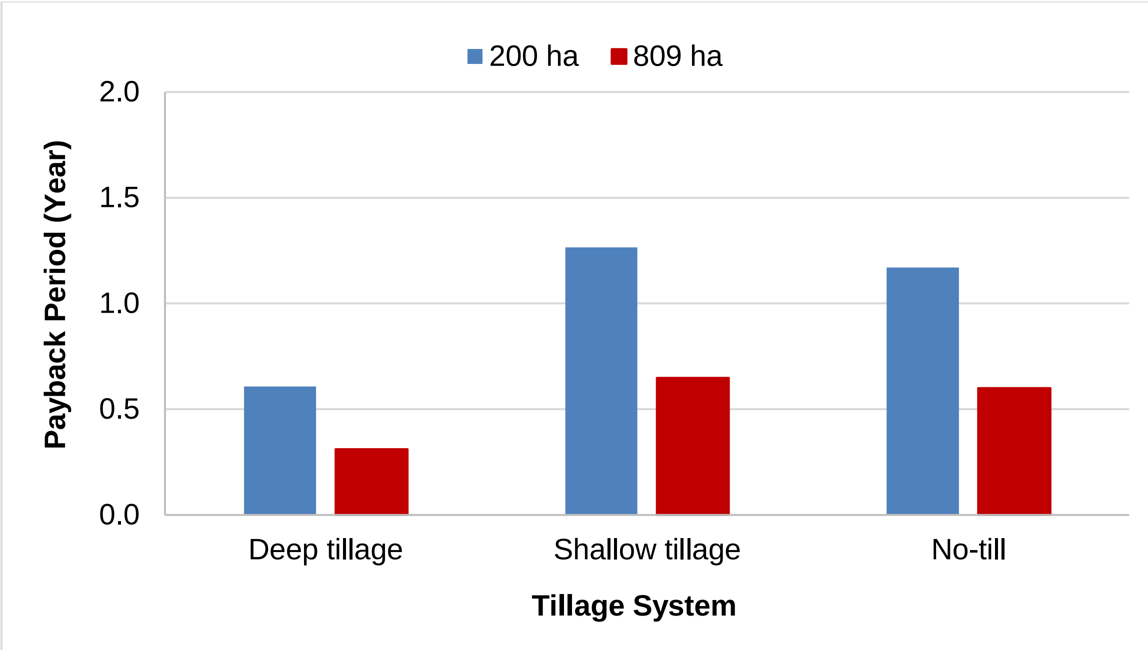


Figure 7.5. Payback period of using reduced tyre inflation pressure systems for two sizes of farms.

7.6. Conclusions

1) The total cost increase of using Ultraflex tyre system for the 200 and 809 ha farms was the US $ 8200 and $ 17000 respectively, hence assuming a 5 years tyre life, the annual costs increased by the US $ 1640 and $ 3400, respectively.

2) Despite the small reduction in soybean yield for all tillage systems in 2017 and the reduction in soybean yield for the shallow tillage system in 2018, there was an increase in the mean annual earnings of the maize and soybean cropping rotation for all tillage systems using Ultraflex as compared to standard tyre systems. The mean annual benefit using Ultraflex tyre systems for the 200 and 809 ha farms were US$ 7357 and US$ 32969, respectively.

3) The mean economic benefit for all tillage systems for the two farm sizes was similar close at $37 and $41 ha^{-1}. This is valuable as it means that with careful selection of equipment and tyres it is possible to achieve financial benefit from Ultraflex tyres, across farm size.

4) The payback period for the three tillage systems and two farm sizes were less than two years, ranging from 0.31 years for the deep tillage system on the bigger farm to 1.27 years for the shallow tillage system on the smaller farm. This indicates that investment in reduced tyre inflation pressure systems is economically profitable for many farmers.

CHAPTER 8: DISCUSSION

The present three-years (2016 – 2018) field-scale study was implemented to determine the effects of Ultraflex tyres operating at low and standard tyre inflation pressure modes on soil properties, crop growth and yield in a maize/soybean rotation for three tillage systems (DT, 450mm; ST, 100mm and NT) in Champaign County, Illinois, USA. A novel tool X-Ray Computed Tomography was used to investigate their effects on soil pore structural characteristics with high resolution (98 µm) of undisturbed soil core in 2017. Summary results of the effects of tyre inflation pressures and tillage systems on soil properties, growth and yield of crops are shown in Table 8.1 - 8.4.

8.1. Initial Soil Properties Assessment

Soils in good physical condition (e.g. loose, moist, and well-aerated with well-connected macropores) allows roots to grow unimpeded (Lal, 1996). Physical properties of soils have a definite deterministic effect on crop growth and yield (Cassel and Lal, 1992). These properties can be strongly influenced by management practices (Abawi and Widmer, 2000). Soil heterogeneity increases the chance of eliminating any positive effect of the applied treatments/managements if resources are limited. Given the current interest, the preliminary assessment of soils was conducted in the two experimental fields. The results showed that there was no such heterogeneity in the soil physical and chemical properties between the two fields. Soil moisture strongly affects the relationship between soil texture and the susceptibility of soils to compaction (Domżał et al., 1991). Initial soil MC (%) in 2016 in both fields indicates that the fields were at field capacity condition. The increased total porosity of soil (approximately 53%) and dry BD (<1.40 Mg m^{-3}) and PR of soil (<1.30 MPa) in both fields were lower than the threshold values of BD (> 1.40 Mg m^{-3}) (USDA NRCS, 2019d) and PR of soil (<2.0 MPa) (Hamza and Anderson, 2005). This indicates that the experimental fields were well-structured with no residual soil compaction. The organic matter status (3.39-3.41%), soil pH and CEC of soils in both fields were aligned with the findings of USDA (USDA NRCS, 2015b). Soil nutrients of both fields were also similar or slightly lower than the earlier results found for Illinois soils (Fernández et al., 2012). Overall, the preliminary studies indicate that the experimental sites were relatively uniform with no underlying compaction prevailing from the previous cropping season.

8.2. Effect of Tyre Inflation Pressure and Tillage Systems on Soil Pore Structural Properties: X-ray Computed Tomography

Soil pore structure changes with the induced soil management practices, e.g. land-use change, tillage, vehicle traffic, and fertilization (Schäffer et al., 2007; Lu et al., 2019). The changes of pore structure are likely to affect the soil aggregation, aeration, water retention, soil microbes and crop root growth (Papadopoulos et al., 2009; Ananyeva et al., 2013; Dal Ferro et al., 2014). X-ray computed tomography is a non-invasive technique that allows the study of morphological properties of the soil structure (Galdos et al., 2019; Pires et al., 2020). The X-ray CT scanned images of soil cores of this study showed a visible difference in the soil structure between the effects of the two tyre inflation pressure treatments, which is in agreement with the findings of Kooistra and Tovey (1994). However, the more compacted conditions for the HT location in STP system might be evidence of possible re-compaction after tillage, while the open structure with some cracks and pore spaces are more prominent in the LTP, which is in agreement with the results of the study by Millington (2019).

The results show that the pore system of the silty clay loam soil was influenced by the tyre inflation pressure (Table 8.1), where as expected, the LTP system maintained a higher CT measured macroporosity, number of pores and pore area than the STP treatment. This is mainly associated with the changes/damages in the soil structure especially at greater depths of soils under STP treatments and thus affects the larger pores and voids between soil particles and aggregates (Berisso et al., 2012). Schäffer et al. (2007) reported that compaction distinctly affects the macropore size and it's distribution in the soil that results in a decrease in porosity and connectivity of the macropores. Due to similar reasons, the heavily trafficked location/zone had a lower mean CTp and number of pores than un-trafficked location/zone. Millington (2019), assessing differences in STP and LTP in a sandy loam soil in the UK, observed a decrease in CTp and macropore in STP compared to the LTP. Conversely, the higher pore area in the LTP treatment than the STP, and UT location than the HT further demonstrate that soils in STP treatments and HT locations were highly compressed, especially in the lower strata of soils. Soane et al. (1986) reported that soil under deep tilled has less strength to support field trafficking, which increases susceptibility to re-compaction of soil. The greater differences at the deeper depths in this study may be due to the possibility of re-compaction or subsoil compaction caused by tillage with an STP tyre system (Millington, 2019).

Pore size distribution in soil affects the growth of the plant (Cary and Hayden, 1973). It helps to describe the complexity of soil structure between treatments over percentage porosity (Nimmo, 2013). Tyre inflation pressures and tillage systems were less likely to influence the pore size and cumulative frequency of pore size distribution. However, the average size of pores was higher in the lower strata of soil. A nonsignificant greater pore size distribution cumulative frequency in tilled soil as compared to NT are in agreement with the findings of both Mangalassery et al. (2014) and Millington (2019). The earlier, reported that the size of pores in tilled soil was higher (0.52 mm^2) compared to no-tilled soils (0.27 mm^2) (Mangalassery et al., 2014). The overall pore size, perimeter, circularity, and solidity of pores in the LTP treatments show no marked difference compared with the STP treatments. Higher pore perimeter and circularity of pores in un-trafficked zones/location could be due to better soil aggregation, root activity and soil fauna than the heavily trafficked zone as explained (Rachman et al., 2005). It is also seen that the average size of pores, pore perimeter and circularity were proportional to soil depth. The circularity and solidity of pore were greater in the lower layer of soils (180-300 mm). These results are partially in accordance with the findings of Li et al. (2016), who found that larger the pores, the smaller the tendency of the pores to be circular. Rachman et al. (2005) reported that circularity of pores tended to be more in the deeper soil compared to a shallow depth which is partially in agreement to the present study. Pore circularity is important because it facilitates water transport in the soils (Yang et al., 2018).

The classical soil physical properties of the soil from the data collected in 2017 showed that the lower dry BD and PR of soil at depths 50 - 325 mm, and greater total porosities of soil were associated in the LTP treatments as compared to the STP treatments of HT locations (Figs. 4.43-4.45 and Table 8.2). These results further indicate that higher stress on soils due to STP tyre system caused a prominent soil structural change than the LTP. The findings are confirmed with the report that field trafficking with low pressure tyres significantly decreased soil compaction (Boguzas and Hakansson, 2001; Ridge, 2002). Similar findings were also reported by Whalley et al. (2008). They found that the application of stress on soil caused compaction of soil that in turn, resulted in an increase in BD, PR, and shear strength of the soil. Therefore, the three key pore parameters: the number of pores, CT_P and pore area were substantially reduced in the STP system. The presence of higher CT measured macroporosity under LTP treatments could also reduce the stress from the entrapped air and volumetric change within the pore system (Lu et al., 2019).

X-ray CT scanned images due to its resolution (98 µm) provides macroporosities of soil which generally led to an underestimate of porosity. Vaz et al. (2011) reported that even though scanning of soil with high resolution of 3.7 µm, CT measured porosity vastly underestimated the physically measured porosity of the soil. Studies are scarce about the relationship or any link between CT_P to total porosity of the soil. The X-ray CT technique allowed determining the total porosity of soil by comparing CT_P of tyre inflation pressure treatment means to porosities derived from BD measurements. The difference between BD_P and CT_P is constant (39±2.87%). The constant could be added to the CT_P to provide the total porosity for a silty clay loam soil which partially corresponds to water-filled pore space for a silty clay loam soil as shown (Hall et al., 1977). The constant is in accordance with the report of Millington (2019), who found a value of 31% that was corresponded to the water-filled pore space for a sandy clay loam soils in the UK. However, the constant depends on soil type, the soil damage resulting from the collection of the so-called “undisturbed” soil cores, CT scanning resolution and the thresholding method. Nevertheless, the constant (39%) can be correlated and well fitted with the air-filled porosity at field capacity for silty clay loam soil as identified by others (Godwin and Dresser, 2003; Brady and Weil, 2008). The study would suggest that X-ray CT technique can be useful to determine macroporosity, pore connectivity, pore size distribution and other pore characteristics of the soil. These are valuable, particularly for soil aeration, nutrition exploration, nutrient cycling and distribution to plants, root growth, soil gas fluxes and water dynamics (Allaire-Leung et al., 2000; Mooney, 2006; Antille et al., 2015; Galdos et al., 2019). Further study is needed with higher CT resolution to harness the relationship between CT_P and field capacity porosity for other soil textures.

8.3. Effect of Tyre Inflation Pressure and Tillage Systems on Soil Physical Properties

The relationship between soil texture and susceptibility to compaction depends on soil moisture (Domżał et al., 1991). Volumetric soil MC data had shown a non-significant effect between the LTP and STP treatments in both 2017 and 2018. The soil MC ranged between 31% - 34% corresponds to the upper limit of the field capacity range for a silt loam to clay loam soil as indicated by Ward and Robinson (2000). The non-significant effect of traffic and tillage on soil MC during penetrometer data measurements also agree with the results of Botta et al. (2007) and Smith (2016).

Field trafficking under different tyre inflation pressures treatments increased the soil resistance in all years from 2016 - 2018 in comparison to the initial PR of soil (Table 8.2). However, the PR values of soil were found higher in the STP treatments as compared to the LTP treatments in 2016, 2007 and 2018 for the maize fields (Figs. 4.45a, 5.3a-b, 5.7a-b and Appendix 4.6) and in 2018 for the soybean field (Figs. 6.7a-b). These observations indicate that the soil density and soil penetrometer resistance was greater due to compaction of soil under STP treatments than in the LTP treatments, and is in agreement with the findings of Soane et al. (1982). The results confirm the research results that show that field trafficking with high tyre inflation pressure increases soil BD and PR of soil (Raper and Kirby, 2006; Hula et al., 2009; Hamza et al., 2011). The effect of compacting load increases the BD and thus reduces void ratio and porosity of soil (Keller, 2004), which is in agreement with the present results. However, the presence of higher soil moisture may be the reason for the lack of a significant difference between tyre inflation pressures on PR of soil at 35-40 DAP both in maize and soybean fields in 2017. Nonetheless, lower stress and decreased compaction of soil under LTP treatments may be the reasons of reduced dry BD and increased in total porosity of soil than in the STP systems after harvest of maize in 2017, which are in agreement with Soane et al. (1982), Boguzas and Hakansson (2001) and Ridge (2002). Similar to BD, lower PR values of soil from soil depths of 50 mm to 225 mm are mainly related to the more uniformly distributed contact stresses on soils under the LTP treatments and are in agreement with the findings of Koolen et. al. (1992). The application of load and high tyre inflation pressure by machinery traffic caused cracks and reduced voids on arable soils (Kooistra and Tovey, 1994) and increased BD in soil (Keller, 2004). Therefore, it is evident that LTP treatments able to maintain soil porosity by reducing soil PR than STP treatments. Similar findings were also found in the work of Hamza and Anderson (2005), who reported that compaction of soil causes degradation in soil structure that results in a reduction in pore size, pore area and percentage porosity of the soil.

Among tillage systems, higher PR values in the NT system throughout the soil depth in 2017 and up to 75 mm depth in 2018 as compared to ST and DT systems plots maybe because of these plots were not tilled. Consequently, soils in the NT treatment are more dense, especially 0 to 100 mm layer of soil ($P =< 0.001$), which is in agreement with the findings of Cantero-Martinez and Lampurlanes (2003). Yet, the trend of PR among the tillage systems in soybean fields was similar to the maize fields both in 2017 ($P = 0.04$) and 2018 ($P = 0.06$). Poor soil structure in the NT system without having diverse crop rotation as reported (Munkholm et al., 2013) may be one of the reasons for higher PR and BD in the NT soil. PR of soil in DT (depth, 150-200mm) and

ST (depth, 50-100 mm) was also reported to be lower than the traffic zone and NT (Etana et al., 2020). BD measurements of soil in the maize field in 2017 further confirmed that higher BD of soil adversely affected the total porosity in the NT system than DT and ST systems (Table 8.2). The increase in BD caused a reduction of soil aeration which might cause undesirable changes the pore size distribution in the NT system (Fageria, 1992). Galdos et al. (2019)**,** assessing differences between NT and DT (Conventional tillage) in a Rhodudalf clay soil, in Brazil, showed that soil under long-term NT had higher BD and lower porosity as compared to the DT.

Vehicle traffic and multiple passes caused compaction that resulted in increased soil strength and penetration resistance of soil (Soane et al., 1982; Raghavan et al., 1990; Hula et al., 2009; Hamza et al., 2011). Therefore, irrespective of tyre inflation pressure and tillage systems, as expected; the HT treatment had a significantly higher PR of soil at 35-40 DAP in both maize and soybean fields than the UT treatment in 2016. As can be seen, the PR of soil in HT locations was also increased after the harvest of maize in 2017 and a peaked strength indicated by PR was notably absent in UT locations. These findings are confirmed with the results of Chamen (2011) and Etana et al. (2020). Due to similar reasons heavily trafficked CR3 and CR1 had higher PR values of soil in 2017 and 2018 as compared to the UT zone/inter-row of 4 and 5 of both crops field. This is mainly because of the maximum amount of wheel traffic which was observed near to the CR3 and additional compaction that was applied to the CR3 and CR1. The results also showed that PR values of soil in heavily trafficked zones/locations/crop rows increased with a decrease in soil MC (Cassel and Lal, 1992). Etana et al. (2020), assessing the differences between trafficked and un-trafficked zones, observed higher soil strength in traffic zones as compared to the un-trafficked or less trafficked crop zones. The findings also match the data from Solgi et al. (2016) which showed that traffic frequency and tyre inflation pressure caused adverse effects on the soil condition, increasing soil strength, BD and PR of soil (Table 8.2).

In summary, it can arguably be said that field trafficking under standard tyre inflation pressure treatments markedly change the soil and pore structures and soil aggregates. The no-till system in general and heavily trafficked zones/crop rows deteriorate soil structure as measured by higher BD and PR of soil. The combination of tyre inflation pressure and tillage system is likely to have a less significant effect on soil properties. Overall, the above results are in line that soil compaction is demonstrated by a decrease in the total and air-filled porosity and soil volume and as a result, it causes deterioration of soil functions (Liebig et al., 1993; Li et al., 2001; Huber et al., 2008). Further work is required to explore the effect of soil compaction of each vehicle pass during the crop growing season and its relationship with weather conditions. The effects of compaction in early crop growth, flowering and fruiting stages and the corresponding effects on root growth, crop development and yield are worthy of further investigation in other soil textures.

8.4. Effect of Tyre Inflation Pressure and Tillage Systems on Growth and Yield of Crops

The agronomic results show that tyre inflation pressure influenced the growth and yield of maize. Comparing the STP treatments, the LTP treatments had increased the plant establishment (%) and the number of plant ha^{-1} in 2016 and 2018 and plant height in 2017 and 2018 (Table 8.3). The number of plants is a determining factor for the higher yield of maize that was consistently shown over the last 7 decades (Duvick and Cassman, 1999). Although, high population density adversely affect the yield of maize (Tokatlidis and Koutroubas, 2004), however, optimum plant population due to its contribution on yield is considered as one of the seven wonders of maize world (Below, 2008). Deformation and compression of soil (Berisso et al., 2013) may be one of the reasons under STP treatments that resulted in reduced porosity and hydraulic properties (Alakukku, 1996a; b), which in turn, caused an adverse effect on crop growth and yield of maize compared to the LTP treatments. Shreds of evidence of such situations in the STP treatments are higher dry BD in 2017 and PR of soil in 2017 and 2018 than LTP treatments. Thus, it is evident that the increased plant height in 2017 and 2018 and plant establishment (%) and the number of plants ha^{-1} in 2018 led to significant yield benefits for the LTP treatments of 4.31% and 2.70% over those of the STP treatments in 2017 and 2018, respectively. The results are in agreement with the findings that soil compaction causes negative impacts on soil properties and crop performance (Horn et al., 2003; Chyba, 2012) as it increases dry BD of soil and reduces pore size, restricts root growth and accessibility of nutrients (Nawaz et al., 2013). Larger macroporosity is beneficial to water transmission and substance exchange in soils (Lu et al., 2019), therefore, the higher CT derived macroporosity and total porosity of the soil, for an e.g. in 2017 in the LTP treatments should lead to improved air and water movement in the soils which in turn, should have an advantage to the growth and yield of maize. The results are in agreement with the findings that repeated traffic with high contact pressures caused 40–50% yield reductions of maize (Raghavan et al., 1979b). In Ohio, reductions in yield by 25% in maize due to compaction of soils was reported over seven years (Lal, 1996). These results are in agreement with McKyes et al. (1979 and Negi et al., 1981) who demonstrated that increases in BD and PR of the soil decreased the maize yield.

Among tillage systems, NT system in 2017 had a marginally higher number of plant ha^{-1} than others. However, with time, some plants were found dried up due to lower available soil moisture at times of low precipitation (Fig. 3.10). This was partially reflected by the slightly lower 1000 grain weight of maize in the NT treatment than ST and DT treatments. Lower BD and PR in the upper soil layers in DT treatment indicate that the soil in DT was well aerated and had a good structure, which might have a beneficial effect on maize both in 2017 and 2018, especially in later stages of maize growth in both years. However, increased plant height and ear height, and greater ear length (resulting in more kernels) and 1000 grain/kernel weight in DT as compared to ST and NT systems might be evidenced of positive crop response of maize and hence, increased grain yield in 2018. Yield is a function of kernel number and kernel weight while the number of kernels per ear is a function of ear length and kernel rows per ear (Subedi and Ma, 2005; Iowa State University, 2020). Thus, it is evident that greater ear length and 1000 grain weight enhanced the grain yield of maize in 2018. The results are supported by the findings that favourable structure of the soil in the upper layer had the greatest influence on yield (Seehusen et al., 2014). Soil compaction due to higher soil BD in the upper 0-50 mm soil strata caused a reduction in biomass, possibly through the increased impedance of root penetration (Wolkowski, 1990).

Irrespective of tyre inflation pressure and tillage systems, increased PR values of soil were associated with the heavily trafficked CR3 and CR1 in 2017 and 2018. This might be due to the increase in wheel traffic and additional compaction which in turn reduced soil MC and increased soil resistance (Kaspar et al., 2001; Etana et al., 2020). Consequently, plant height in 2017 and 1000 grain weight in 2017 and 2018, and grain yield in 2018 were decreased in highly trafficked CR1 and CR3 compared to some but not all un-trafficked and less trafficked crop rows. The results partially agree with Hamlett et al. (1990) who found that the trafficked crop row had a higher soil strength than the un-trafficked crop rows. However, Reeves et al. (1992) reported that the lack of yield response of maize to the wheel trafficked inter-rows could be compensated due to the positive effect of the un-trafficked crop rows.

Conversely, for soybean, responses of growth and yield varied across years (Table 8.4). Comparing with STP treatments, the LTP treatments had a higher plant establishment and the number of plant ha^{-1} in 2018. These determining factors might be led to an enhanced biomass and grain yield of soybean in 2018 (Van roekel and Purcell, 2016). Well structured soils characterised with low BD and low PR and well aeration disrupt due to compaction of soil (Chamen, 2011) and thus, the increased PR of soil under STP treatment may be the evidence of causing compaction which had an adverse effect on soil structure and soybean crop performance. The favourable structure of the soil as measured by decreased PR under LTP treatments resulted in a 3.70% yield increase of soybean compared to the STP treatments. These results confirmed with the findings of Busscher et al. (2000), who found that a 1 MPa PR decrease in the mean soil profile enhance the yield of soybean by 1.5 Mg ha^{-1}. Similar results on a fine clay soil were also reported by Botta et al. (2010). Farm equipment under LTP treatments may spread the weight on soil and increase the contact area, resulting in a larger footprint that reduces the compaction of soils (Raper, 2005; Michelin, 2017). Nonetheless, a reason for the lack of response of grain yield in 2017 in LTP treatments could be because of the partial dry season. Comparing 2016 and 2018, the year 2017 had decreased precipitation and increased temperatures (Fig. 3.10). Therefore, growth and yield of soybean possibly equally respond to both treatments due to moderately dry year (Yang et al., 2003). The effect of compaction was also reported to be lower in soybean in a dry year than maize, however, root growth of soybean reduced in the dry year (Buttery et al., 1998). Another reason could be that the soybean plant may be slightly more tolerant to compaction, agreeing with the report found in a Kentucky soil by Schwab et al. (2004). Therefore, the response of soybean to the soils under the STP treatments was observed in the 3rd year of this experiment.

Contrarily, the lower soil PR in the 0-50 mm depths in the DT in 2017 could be the reason for the enhanced number of plant ha^{-1} of soybean than ST and NT systems. As the number of plants is a determining factor, it played a significant role in increasing the grain yield of soybean in DT over that other tillage system (Van roekel and Purcell, 2016). The findings agree with the report that higher soil dry BD in the upper 0-50 mm soil strata caused a reduction in yield in the NT treatments, possibly through the increased impedance of root penetration (Wolkowski, 1990). The results are in agreement with the findings that deep tillage for high strength soil management led to 0.36 Mg ha^{-1} higher grain yield of soybean than non-deep tilled soil (Busscher et al., 2006). The results also align with the results of Seehusen et al. (2014) who found that a favourable soil structure at the upper strata of soil had a great influence on crop yield. Similar to maize increased soil strength as measured by PR of soil and reduced soil MC (%) in the trafficked crop rows compared to un-trafficked and less traffic rows (Kaspar et al., 2001; Etana et al., 2020)**,** in general, caused adverse effects on the growth of soybean in 2017 and 2018. However, the trafficked and less trafficked crop rows are less likely to have a significant effect on the yield of soybean in both years.

Soane et al. (1980b) suggested that soil compaction resulted from high tyre contact pressure and low soil strength which was confirmed by Hula et al. (2009) who demonstrated that soil compaction had an adverse effect on soil properties and crop growth and yield. Nawaz et al. (2013) outlined that increased soil strength as measured by BD restricted root growth and accessibility of nutrients to plants. Overall, the present study showed that field trafficking under STP system is likely to affect the soil properties and growth and yield of crops. However, its effect would vary with the season due to moisture differences in soils.

The literature showed that soils with a PR >2 MPa can limit root growth and causes a reduction in crop yield (e.g.Hamza & Anderson, 2005). In the present study, the profile mean PR of soil in 2016 and 2018 were >2 MPa in both the STP and LTP treatments. However, there were no significant effects between tyre inflation pressure treatments on crop growth and yield in 2016 while in 2018 it was evident. In 2017, the PR of soil in both STP and LTP treatment plots was < 2 MPa (STP>LTP). However, the STP treatments had shown an adverse effect on maize yield while it was less likely to affect the growth and yield of soybean. Since both tyre inflation pressure treatments received the equal amounts of seed, fertilizer (maize) and care, it can be assumed that not always in all environment circumstances soil resistance >2.0 MPa can affect crop growth and yield. Rather, PR of soil depends on soil texture, soil and weather conditions especially timing and amounts of precipitation, size and weight of machinery and tyre inflation pressure (Wolfe et al., 1995; Eliasson, 2005; Sakai et al., 2008). In the paper by Carter and Tavernetti (1968), it is shown that soils with a resistance of <2 MPa even reduce crop yield. It is also observed that soil resistance as low as 1.6 MPa (measured range 1.6–2.9 MPa) adversely affected the crop growth but did not show any yield penalty (Kulkarni et al., 2010).

In summary, the benefit of the use of low inflation pressure tyres over standard pressure tyres are in helping to maintain soil porosity and to reduce soil damage (Hamza and Anderson (2005), to reduce compaction of soils as it spread the weight of farm machinery and increases the contact area with a larger footprint (Raper, 2005; Ansorge and Godwin, 2007), and eventually enhances crop growth and yield (Hamza and Anderson, 2005; Godwin et al., 2015; Millington, 2019). The study helped to identify the possible reasons behind the soil structural changes and crop response under field trafficking under different tyre inflation pressure and tillage systems. However, further work is required to explore the effect of compaction on root growth, root architecture, and development and the changes in crop physiology that results from the effects of compaction.

8.5. Economic Analysis of the Maize - Soybean Rotation

The economic analysis of the present two-year (four crop seasons) maize/soybean rotation excluding the preliminary trial/pilot season showed that the total cost of using Ultraflex tyre was 20.10% and 23.84% more than the cost of the standard tyre system for the two typical 200 and 809 ha farms respectively. Nonetheless, the annual earnings of using low tyre inflation tyre increased approximately \$37 and \$41 ha^{-1} for the 200 and 809 ha of farms, respectively as compared to the cost of the standard tyre system. Focusing on the payback period for the three tillage systems and two farms sizes, the low inflation pressure tyre systems i.e. Ultraflex tyre was found to be economically profitable. The use of low pressure tyres was reported to be advantageous over standard inflation pressure tyres agreeing with the results of Vermeulen and Perdok (1994). The results are also in agreement with the findings that the use of low inflation pressure field traffic systems reduces the incidence of soil compaction and has potential positive effects on farm economic profitability (Tijink et al., 1995). Reducing soil compaction, rolling resistance (40%) and less fuel use, the low tyre inflation pressure system clearly showed a financial advantage (Stranks, 2006) by increasing crop yield (Smith et al., 2014b; Millington, 2019) and farm income.

Table 8.1. Summary table of the effect of different treatments on pore parameters at 5 different depths of soil in 2017

Treatments[a]	HT Location[b]							# Obs./ mean (n)[c]	HT and UT Locations[b]							# Obs/ mean (n)[c]
	NoP	CT_P	TA	APS	Perim.	Cir.	Sol.		NoP	CT_P	TA	APS	Perim.	Cir.	Sol.	
TIP	*	**	**	ns	ns	ns	ns	75	ns (P=0.10)	**	**	ns	ns	ns	ns	150
TIP*D	**	**	**	ns	ns	ns	ns	15	ns	ns	ns	ns (P=0.10)	ns	ns	ns	30
TS	ns	ns	ns	ns	ns	ns	ns	50	ns	ns	ns	ns	ns	ns	ns	100
TS*D	ns	ns	ns	ns	ns	ns	ns	10	ns	ns	ns	ns	ns	ns	ns	20
TIP*TS	*	ns	ns	ns	ns	ns	ns	25	ns	ns	ns	ns	ns	ns	ns	50
TIP*TS*D	*	ns	ns	ns	ns	ns	ns	5	ns (P=0.06)	ns	ns	ns	ns	ns	ns	10
D-Depth	***	***	***	***	**	***	***	30	***	***	***	***	***	***	***	60
TL	-	-	-	-	-	-	-	-	***	***	***	ns	ns	ns (P=0.10)	*	150
TL*D	-	-	-	-	-	-	-	-	***	***	***	ns (P=0.06)	**	ns (P=0.08)	ns (P=0.06)	30
TIP*TL	-	-	-	-	-	-	-	-	ns	ns	ns	ns	ns	ns	ns	75
TIP*TL*D	-	-	-	-	-	-	-		ns	ns	ns	ns	ns	ns	ns	15
TS*TL	-	-	-	-	-	-	-	-	ns	ns	ns	ns	ns	ns	ns	50
TS*TL*D	-	-	-	-	-	-	-	-	ns	ns	ns	ns	ns (P=0.10)	ns (P=0.09)	ns	10
TIP*TS*TL	-	-	-	-	-	-	-	-	ns	ns	ns	ns	ns	ns	ns	25
TIP*TS*TL*D	-	-	-	-	-	-	-	-	ns	ns	ns	ns	ns	ns	ns	5

Here, ns – not significant ($p>0.05$), * denotes $p\leq0.05$, ** denotes $p\leq0.01$ and *** denotes $p\leq0.001$.

[a]TIP, TS, TL and D represent tyre inflation pressure, tillage system, trafficked location and soil depth (0-60mm, 60-120mm, 120-180mm, 180-240mm and 24-300mm), respectively.

[b]NoP, CT_P, TA, APS, Perim. Cir., Sol. represent the number of pores, CT measured macroporosity, total area of pores, average pore size, pore perimeter, circularity, and solidity of pores, respectively

[c]Number of observations per mean (n).

Table 8.2. Summary table of the effect of different treatments on soil properties during 2016 - 2018

Treatments[a]	Maize field									Soybean field						Number of observations per mean (n)				
	2016		2017					2018		2016		2017		2018						
	Soil MC	PR_V	Soil MC	PR_v	PR_{ss}	BD	TP	Soil MC	PR	Soil MC	PR	Soil MC	PR_v	Soil MC	PR_v	Soil MC	PR_v/ 2016	PR_v	PR_{ss}	BD &TP
TIP (2)	-	**	ns	ns	ns (P=0.07)	***	***	ns	***	-	ns	ns	ns	ns	**	135	570	2565	570	150
TIP*D	-	**	-	ns	*	ns	ns	-	***	-	ns	-	ns	-	***	-	30	135	30	30
TS (3)	-	-	ns	***	***	*	*	ns	ns	-	-	ns	ns (P=0.10)	ns	ns	90	-	1710	380	100
TS*D	-	-	-	***	ns	ns	ns	-	***	-	-	-	***	-	***	-	-	90	20	20
TIP*TS	-	-	ns	ns	ns	ns	ns	ns	ns	-	-	ns	ns	ns	ns	45	-	855	190	50
TIP*TS*D	-	-	-	ns	ns	*	*	-	Ns (P=0.06)	-	-	-	ns	-	ns	-	-	45	10	10
Depth (D, 19)	-	***	-	***	***	ns	ns	-	***	-	***	-	***	-	***	-	60	270	60	60
CR (9, incl. inter-row 4 & 5)/TL (2)	-	**	***	***	***	***	***	***	***	-	***	***	***	***	***	30	570	570	570	150
CR/TL*D	-	***	-	***	***	ns	ns	-	***	-	***	-	***	-	***	-	30	30	30	30
TIP*CR/TL	-	ns	ns	ns	ns	***	***	ns	**	-	ns	ns	ns	ns	**	15	285	285	285	75
TIP*CR/TL*D	-	ns	-	ns	*	ns	ns	-	ns	-	ns	-	ns	-	ns	-	15	15	15	15
TS*CR/TL	-	-	ns	**	ns	ns	ns	ns	ns	-	-	ns	***	ns	ns	10	-	190	190	50
TS*CR/TL*D	-	-	-	ns	**	ns	ns	-	ns	-	-	-	ns (P=0.06)	-	ns	-	-	10	10	10
TIP*TS*CR/TL	-	-	ns	ns	ns	ns	ns	ns	ns	-	-	ns	ns	ns	ns	5	-	95	95	25
TIP*TS*CR/TL*D	-	-	-	ns	ns	ns	ns	-	ns	-	-	-	ns	-	ns	-	-	5	5	5

Here, ns – not significant ($p>0.05$), * denotes $p\leq0.05$, ** denotes $p\leq0.01$ and *** denotes $p\leq0.001$. The experimental block was 5.

Note: TIP, TS, D, CR and TL represent tyre inflation pressure, tillage systems, soil depth, crop row and trafficked location, respectively. MC, PR_v and PR_{ss}, represent the soil moisture content, penetrometer resistance at the vegetative stage of both crops and during soil sampling (after harvest of maize) for X-ray CT study, respectively. BD and TP represent the bulk density and total porosity of the soil, respectively.

Table 8.3. Summary table of the effect of different treatments on growth and yield of maize during 2016 - 2018

Treatments	Growth parameters												Yield parameters and yield									Number of observations per mean (n)			
	2016				2017			2018					2016			2017			2018						
	PE	P/H	PH (30 DAP)	PH (45 DAP)	PE	P/H	PH	PE	P/H	PH	EH	EL	TGW	HHY	CHY	TGW	HHY	CHY	TGW	HHY	CHY	HHD[a]	CHY[a]	HHD[b]	CHY[b]
TIP (2)	**	**	ns (P=0.08)	ns	ns	ns (P=0.09)	*	**	**	**	*	***	ns	ns	ns	ns	ns	**	ns	ns	*	60	15	120	15
TS (3)	-	-	-	-	ns	***	ns	ns	ns	*	*	ns	-	-	-	ns	ns	ns	**	***	***	-	-	80	10
TIP*TS	-	-			ns	ns	ns	ns	ns (P=0.08)	ns	ns	ns	-	-	-	ns	ns	ns	ns	ns	ns	-	-	40	5
CR (4/8)	ns	ns	***	ns	ns	ns	**	ns	ns	ns	ns	ns	**	*	-	*	ns	-	***	***	-	30	-	30	-
TIP*CR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns (P=0.09)	-	ns	ns	-	ns	ns	-	15	-	15	-
TS*CR	-	-	-	-	ns	ns	ns	ns	ns	ns	*	ns	-	-	-	ns	ns	-	ns	ns	-	-	-	10	-
TIP*TS*CR	-	-	-	-	ns	ns	ns	ns	ns	ns	ns	ns	-	-	-	ns	ns	-	ns	ns	-	-	-	5	-

Here, ns – not significant (p>0.05), * denotes p≤0.05, ** denotes p≤0.01 and *** denotes p≤0.001.

Table 8.4. Summary table of the effect of different treatments on growth and yield of soybean during 2016 - 2018

Treatments	Growth parameters										Yield parameters and yield									
	2016				2017			2018			2016			2017			2018			
	PE	P/H	PH (30 DAP)	PH (45 DAP)	PE	P/H	PH	PE	P/H	PH	TGW	HHY	CHY	TGW	HHY	CHY	TGW	HHY	BMY	CHY
TIP	ns	ns	ns	**	ns	ns	ns	***	***	***	ns	ns	ns	ns	*	ns	ns	**	***	*
TS	-	-	-	-	**	**	***	*	ns (p=0.07)	*	-	-	-	ns	ns	***	ns	ns	ns	ns
TIP*TS	-	-	-	-	ns	ns	ns (p=0.07)	**	*	ns	-	-	-	ns	ns	ns	ns	ns	ns	*
CR	*	*	ns	***	***	**	**	***	**	***	ns	ns	-	ns	ns	-	**	ns	ns	-
TIP*CR	ns	ns	ns	ns	ns	ns	ns (p=0.09)	ns	ns	ns	ns	ns	-	ns	*	-	*	ns	ns	-
TS*CR	-	-	-	-	ns	ns	ns	ns	ns	ns	-	-	-	ns	ns	-	ns	ns	ns	-
TIP*TS*CR	-	-	-	-	ns	ns	ns	ns	ns	ns	-	-	-	ns	ns	-	ns	ns	ns	-

Here, ns – not significant (p>0.05), * denote p≤0.05, ** denotes p≤0.01 and *** denotes p≤0.001.

Note: In table 8.3-8.4, the TIP, TS, D, TL and CR represent tyre inflation pressure, tillage systems, soil depth, trafficked location and crop row, respectively. PE, P/H, PH, EH, EL, TGW, HHY and CHY denote plant establishment, plants ha^{-1}, plant height, ear height, ear length, 1000 grain weight, hand harvest and combine harvest grain yield, respectively.

[a]HHD - hand harvest data and CHY – combine yield in 2016 and [b]2017 and 2018 for both crops.

CHAPTER 9: CONCLUSIONS

1) In comparison to standard tyre inflation pressures, the use of low inflation pressure tyre systems has shown significant benefits when managing soil physical conditions in a maize/soybean rotation in silty clay loam soils in Illinois. This has been achieved by maintaining greater total soil porosity following tillage, together with lower soil penetrometer resistance. The penetration resistance in the upper soil layers in the two experimental fields in 2017 and 2018 were in the order of no-till > shallow tillage > deep tillage. This trend was observed throughout the 450 mm depth in the maize field in 2017.

2) The non-trafficked inter-row 4 and 5 had significantly higher soil moisture content (P = <0.001) in maize fields in 2017 and 2018 and in the soybean field in 2017 (P = <0.001) and lower penetrometer resistance (P = <0.001) than the trafficked crop row 3 (P = <0.001) in maize and crop row 1 in soybean fields (P = <0.001), respectively. Crop row 4 had significantly higher soil moisture content (P = 0.004) and lower penetrometer resistance (P = <0.001) than the trafficked crop row 3 in soybean in 2018. In general, penetrometer resistance of soil was higher in the heavily trafficked zones (location)/crop rows than zero traffic. Penetrometer resistance of soil increases with a decrease in soil moisture content.

3) In comparison to standard tyre inflation pressures, reducing tyre inflation pressure increased: a) the plant height of maize in 2017 and 2018 (P = 0.04 and 0.004, respectively), b) plant establishment in 2016 and 2018 ((P = 0.01 and 0.007, respectively) and c) the number of plants ha^{-1} of maize in 2016 and 2018 ((P = 0.012 and 0.005, respectively). Similarly for soybean: a) the plant height in 2016 and 2018 (P = 0.003 and <0.001, respectively), b) plant establishment (P = <0.001) and c) the number of plants per ha in 2018 (P = 0.001) were increased in the low tyre inflation pressure tyre treatments.

4) The depth of tillage had a significant effect on the growth of maize and soybean in 2017 and 2018. Where the results for the maize crop showed that: no-till had a significantly greater number of plants per ha in 2017 (P = <0.001) and b) deep tillage had a significantly greater plant and ear heights in 2018 (P = 0.004 and 0.05, respectively). Similarly the soybean crop showed: a) the no-till and deep tillage systems increased the plant establishment in 2017 (P = 0.009), b) deep tillage had a significantly greater plant

establishment in 2018 (P = <0.001) and c) the number of plants ha^{-1} in 2017 (P = 0.01) and plant height in 2017 and 2018 (P = 0.001 and 0.03, respectively).

5) Reducing the tyre inflation pressure increased the grain yield of maize by 4.31% (15.02 Mg ha^{-1}) in 2017 and 2.70% (14.13 Mg ha^{-1}) in 2018 compared to the standard tyre pressure treatments (14.40 and 13.76 Mg ha^{-1}, respectively) (P = 0.005 and 0.019, respectively). While for soybean, low inflation pressure increased the grain yield by 3.70% in 2018 (4.25 Mg ha^{-1}) compared to the standard inflation pressure tyre treatment (4.10 Mg ha^{-1}) (P = 0.021). The lack of response of soybean yield in 2017 to reduced tyre inflation pressure was attributed to the negative effect of partial dry year to 2018, which is in agreement with research reported by Yang et al. (2003) and Buttery et al. (1998).

6) Deep tillage and shallow tillage systems resulted in significant yield advantages to no-till for soybean in 2017 and maize in 2018 (P = 0.001 and <0.001, respectively). The yield of maize for deep (15.11 Mg ha^{-1}) and shallow tillage systems (13.98 Mg ha^{-1}) was 18.69 % and 9.82 % greater than that of the no-till system (12.73 Mg ha^{-1}). The grain yield of soybean for both deep (4.86 Mg ha^{-1}) and shallow tillage systems (4.73 Mg ha^{-1}) was 4.52 % and 1.72 % greater than that of no-till (4.65 Mg ha^{-1}).

7) Compared to heavily trafficked crop rows, the less and non-trafficked crop rows of maize had a significantly greater: a) plant height in 2016 and 2017 (P = <0.001 and 0.002), b) 1000 grain weight in all years (P = 0.005, 0.04 and <0.001) and c) hand harvest yield in 2016 and 2018 (P = 0.03 and <0.001). Similarly for soybean: a) the plant establishment (P = 0.03, 0.001 and <0.001), b) number of plants per ha (P = 0.03, 0.004 and 0.002), c) plant height (P = <0.001, 0.01 and <0.001) in all three years, d) 1000 grain weight in 2017 and 2018 (P = 0.04 and <0.001) and e) hand harvest yield in 2018 (P = <0.001) were significantly higher.

8) X-ray Computed Tomography has proven to be a valuable tool by increasing the resolution, in comparison with classical soil physics to determine the macroporosity differences between the various traffic systems for different tillage practices. The low inflation pressure tyre systems resulted in a significant increase in the mean profile pore count (105.2) (P = 0.05) and CT measured macroporosity (4.66%) (P = 0.004) and total pore area (92.6 mm^2) (P = 0.004) compared to the standard inflation pressure tyre

systems with the pore count of 75.8, CT measured macroporosity of 2.87% and pore area of 56.8 mm^2.

9) Comparing the X-ray Computed Tomography data and that from the classical soil physical analysis confirm the hypothesis reported by Millington (2019) that the addition of the field capacity porosity of silty clay loam soil (39%) to the CT measured macroporosity (3.77%) gives the total porosity of the soil.

10) The cost-benefit analysis of the maize/soybean farming system showed that Ultraflex low inflation pressure tyres had greater economic benefits over standard inflation pressure tyres. The annual cost of using Ultraflex tyres was 23.8% and 20.1% more for the 200 ha and 809 ha of farm respectively when compared to the cost of a standard tyre system. However, the mean annual benefit of using Ultraflex tyre systems for the two farms were US$7357 (US$37 ha^{-1}) and US$32969 (US$41ha^{-1}), respectively. The payback period for the three tillage systems using Ultraflex low inflation tyres for the two farms sizes were less than two years. Ranging from 0.31 years for the DT systems on the 809 ha farm to 1.27 years for the shallow tillage system on the 200 ha farm.

This study for a typical maize and soybean rotation demonstrates that, following a pilot season with a uniform deep tillage treatment, to remove any underlying compaction, the use of low inflation pressure tyre systems had a positive effect on soil structure, crop yield and profitability. While the use of reduced tyre inflation pressures has been recommended for several decades, this is the first major field experiment to quantify these benefits for high flexion tyres by linking the resulting soil conditions to crop yield and the economic benefit in so doing. Hence, the present experiment confirms the hypothesis that reducing tyre inflation pressure field traffic system improves crop development and yield by reducing soil compaction in a maize and soybean rotation in silty clay soil in central Illinois.

To put this into context, the Drummer soil series is the most common soil in Illinois and covers more than 0.6 million ha with significant areas in Indiana, Ohio and Wisconsin. The Thorp series whilst less common than the Drummer series is a significant soil series in the north and central Illinois and in Iowa. It would be valuable for extension purposes to undertake a number (possibly 3) of simplified experiments at various locations in Illinois and neighbouring states to demonstrate the benefits to farmers.

This work has also extended the frontier of the X-Ray Computed Technology by introducing the technique to the University of Illinois. Where the Beckman Institute for Advanced Science and Technology is now collaborating with the Departments of Agricultural and Biological Engineering and Natural Resources and Environmental Sciences use the technique in a detailed study of the soils of the Morrow Plots, the oldest experimental field (since 1876) in the USA.

CHAPTER 10: RECOMMENDATIONS FOR FURTHER WORK

Based on the observations from the present study, there are a number of other areas that are worthy of further investigation. These are as follows:

1) Determine the effect of tyre inflation pressures and the number of traffic passes for the different tyre inflation pressures on tyre footprint area, soil structure, soil hydraulic properties and stability index at different soil moisture regimes.

2) Determine the effect of the magnitude and intensity of vehicle traffic compaction for different tyre inflation pressures and tillage systems on infiltration rate, porosity, aggregates stability, bulk density and penetrometer resistance, root development and maize ear characterization during the growing season.

3) Determine the long-term effect of traffic on potential changes in the chemical and biological properties of the soil.

4) Investigate the long-term weather effects for the different traffic and tillage systems on soil properties and crop development.

5) Determine the distribution of soil stresses for both the ultra-flex and standard tyre systems in both laboratory and field conditions.

6) Model the effects of tyre inflation pressure on soil behaviour and compaction.

7) Determine the percentage of compacted field areas and the number of repeatedly compacted areas for the different traffic systems for the three tillage practices.

8) Repeat the current study with larger plots to also include controlled traffic farming.

9) Increase the resolution of the X-ray CT scan, to improve the assessment of soil porosity, pore size distribution, and pore connectivity. Including further verification of the different threshold methods of segmentation and the adoption of algorithms for image stack processing, analysis and data visualisation using MATLAB software.

10) Determine the plant root and soil interactions under different compaction treatments using X-ray computed tomography (CT) to investigate soil macro-pore distribution and

connectivity with samples taken across a wheel track transect both vertically and horizontally.

11) Include variable and overhead costs in future economic studies for the three tillage practices with the alternative tyre systems.

12) Quantify the seasonal changes in soil structure to assist in the development of management strategies to minimize the risks of soil degradation by compaction-induced erosion.

13) Define the impact of soil compaction on whole farm economics and natural resource management through sustainable soil and crop management options.

REFERENCES

A

Aase, J.K., D.L. Bjorneberg, and R.E. Sojka. 2001. Zone-subsoiling relationships to bulk density and cone index on a furrow–irrigated soil. Trans. ASAE 44(3): 577–583.

Abawi, G.S., and T.L. Widmer. 2000. Impact of soil health management practices on soilborne pathogens, nematodes and root diseases of vegetable crops. Appl. Soil Ecol. 15: 37–47. doi: 10.1016/S0929-1393(00)00070-6.

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. PMR 1009, Iowa State University Extension, Ames, IA.

Abu-Hamdeh, N.H., J.S. Abu-Ashour, H.F. Al-Jalil, A.I. Khdair, and R.C. Reeder. 2000. Soil physical properties and infiltration rate as affected by tire dynamic load and inflation pressure. Trans. ASAE 43(4): 785–792.

Abu-Hamdeh, N.H., and M.I. Al-Widyan. 2000. Effect of axle load, tire inflation pressure, and tillage system on soil physical properties and crop yield of a Jordanian soil. Trans. ASAE 43(1): 13–21.

Alakukku, L. 1996a. Persistence of soil compaction due to high axle load traffic. I. Short-term effects on the properties of clay and organic soils. Soil Tillage Res. 37(4): 211–222. doi: 10.1016/0167-1987(96)01016-1.

Alakukku, L. 1996b. Persistence of soil compaction due to high axle load traffic. II. Long-term effects on the properties of fine-textured and organic soils. Soil Tillage Res. 37(4): 223–238. doi: 10.1016/0167-1987(96)01017-3.

Alakukku, L. 2000. Response of annual crops to subsoil compaction in a field experiment on clay soil lasting 17 years. Adv. Geoecology 32: 205–208. https://www.cabdirect.org/cabdirect/abstract/20013087588.

Alakukku, L., P. Weisskopf, W.C.T. Chamen, F.G.J. Tijink, J.P. van der Linden, et al. 2003. Prevention strategies for field traffic-induced subsoil compaction: a review: Part 1. Machine/soil interactions. Soil Tillage Res. 73(1): 145–160. doi: 10.1016/S0167-1987(03)00107-7.

Alexandratos, N., and J. Bruinsma. 2012. World agriculture towards 2030/2050: The 2012 Revision. Rome.

Allaire-Leung, S.., S.. Gupta, and J.. Moncrief. 2000. Water and solute movement in soil as influenced by macropore characteristics: 1. Macropore continuity. J. Contam. Hydrol. 41(3): 283–301. doi: 10.1016/S0169-7722(99)00079-0.

Ananyeva, K., W. Wang, A.J.M. Smucker, M.L. Rivers, and A.N. Kravchenko. 2013. Can intra-aggregate pore structures affect the aggregate's effectiveness in protecting carbon? Soil Biol. Biochem. 57: 868–875. doi: 10.1016/j.soilbio.2012.10.019.

Anderson, R.L. 2015. Integrating a complex rotation with no-till improves weed management in organic farming. A review. Agron. Sustain. Dev. 35(3): 967–974. doi: 10.1007/s13593-015-0292-3.

Ansorge, D., and R.J. Godwin. 2007. The effect of tyres and a rubber track at high axle loads on soil compaction, Part 1: Single axle-studies. Biosyst. Eng. 98(1): 115–126. doi: 10.1016/j.biosystemeng.2007.06.005.

Ansorge, D., and R.J. Godwin. 2008. The effect of tyres and a rubber track at high axle loads on soil compaction, Part 2: Multi-axle machine studies. Biosyst. Eng. 99: 338–347. doi: 10.1016/j.biosystemseng.2007.11.014.

Ansorge, D., and R.J. Godwin. 2009a. The effect of tyres and a rubber track at high axle loads on soil compaction: part 3: comparison of virgin compression line approaches. Biosyst. Eng. 104(2): 278–287. doi: 10.1016/j.biosystemseng.2009.06.024.

Ansorge, D., and R.J. Godwin. 2009b. The effect of tyres and a rubber track at high axle loads on

soil compaction: part 3: comparison of virgin compression line approaches. Biosyst. Eng. 104(2): 278–287. doi: 10.1016/j.biosystemseng.2009.06.024.
Antille., D.L., S. Peets., J. Galambošová., G.F. Botta., V. Rataj, et al. 2019. Review: Soil compaction and controlled traffic farming in arable and grass cropping systems. Agron. Res. XX(x): xx–xx.
Antille, D.L., J.M.L. Bennett, and T.A. Jensen. 2016. Soil compaction and controlled traffic considerations in Australian cotton-farming systems. Crop Pasture Sci. 67(1): 1–28. doi: 10.1071/CP15097.
Antille, D.L., T. Chamen, and R. Lal. 2015. The potential of controlled traffic farming to mitigate greenhouse gas emissions and enhance carbon sequestration in Arable land: a critical review. Trans. ASABE 58(June): 707–731. doi: 10.13031/trans.58.11049.
Arslan, S., P.A. Misiewicz, E.K. Smith, Z. Tsiropoulos, V.C. Girardello, et al. 2014. Fuel consumptions and draft power requirements of three soil tillage methods and three field traffic systems. ASABE and CSBE/SCGAB Annual International Meeting, Montreal, Canada, July 13-16, 2014, Paper no. 141912659
Arvidsson, J., and I. Håkansson. 1991. A model for estimating crop yield losses caused by soil compaction. Soil Tillage Res. 20(2): 319–332. doi: 10.1016/0167-1987(91)90046-Z.
Arvidsson, J., and I. Håkansson. 1996. Do effects of soil compaction persist after ploughing? Results from 21 long-term field experiments in Sweden. Soil Tillage Res. 39(3–4): 175–197. doi: 10.1016/S0167-1987(96)01060-4.
Arvidsson, J., and T. Keller. 2004. Soil precompression stress. Soil Tillage Res. 77(1): 85–95. doi: 10.1016/j.still.2004.01.003.
Arvidsson, J., and T. Keller. 2007. Soil stress as affected by wheel load and tyre inflation pressure. Soil Tillage Res. 96(1): 284–291. doi: 10.1016/j.still.2007.06.012.
ASAE. 1999a. Soil cone penetrometer. ASAE S313.3 Feb 1999 (R2018). Published by American Society of Agricultural and Biological Engineers (ASABE). St. Joseph (MI).
ASAE. 1999b. Procedures for using and reporting data obtained with the soil cone penetrometer. ASAE EP542 FEB1999 (R2009). Published by American Society of Agricultural and Biological Engineers (ASABE). St. Joseph (MI).
ASTM International. 2019. ASTM D2216-19 Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. West Conshohocken, PA.

B

Badalıkova, B. 2010. Influence of soil tillage on soil compaction. In: Dedousis, A. and Bartzanas, T., editors, Soil Engineering. Springer, Berlin, Heidelberg. p. 19–30
Bailey, A.C., R.L. Raper, T.R. Way, E.C. Burt, and C.E. Johnson. 1996. Soil stress state orientation beneath a tire at various loads and inflation pressures. J. Terramechanics 33(1): 1–11. doi: 10.1016/S0022-4898(97)00003-7.
Bakker, D.M., and R.J. Davis. 1995. Soil deformation observations in a Vertisol under field traffic. Aust. J. Soil Res. 33(5): 817–832. doi: 10.1071/SR9950817.
Ball, B.C., A. Scott, and J.P. Parker. 1999. Field N2O, CO2 and CH4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Tillage Res. 53(1): 29–39. doi: 10.1016/S0167-1987(99)00074-4.
Batey, T. 2009. Soil compaction and soil management – a review. Soil Use Manag. 25(4): 335–345. doi: 10.1111/j.1475-2743.2009.00236.x.
Batey, T., and D. McKenzie. 2006. Soil compaction: Identification directly in the field. Soil Use Manag. 22(2): 123–131. doi: 10.1111/j.1475-2743.2006.00017.x.
Baveye, P.C., M. Laba, W. Otten, L. Bouckaert, P. Dello Sterpaio, et al. 2010. Observer-dependent variability of the thresholding step in the quantitative analysis of soil images and X-ray microtomography data. Geoderma 157(1–2): 51–63. doi: 10.1016/J.GEODERMA.2010.03.015.

Baveye, P.C., W. Otten, A. Kravchenko, M. Balseiro-Romero, É. Beckers, et al. 2018. Emergent properties of microbial activity in heterogeneous soil microenvironments: Different research approaches are slowly converging, yet major challenges remain. Front. Microbiol. 9(AUG): 1–48. doi: 10.3389/fmicb.2018.01929.

Beckers, E., E. Plougonven, C. Roisin, S. Hapca, A. Léonard, et al. 2014. X-ray microtomography: A porosity-based thresholding method to improve soil pore network characterization? Geoderma 219–220: 145–154. doi: 10.1016/J.Geoderma.2014.01.004.

Below, F.E. 2008. The seven wonders of the corn yield world. 2008 Illinois Crop Protection Technology Conference: Serving agriculture and the environment for 60 years. University of Illinois Extension, Urbana IL. p. 86–91

Benites, J.R., R. Derpsch, and D. McGarry. 2003. The current status and future growth potential of conservation agriculture in the world context. Proceedings of the 256 International Soil Tillage Research Organisation 16th Triennial conference, Brisbane, 13–18 July 2003. p. 120–129

Berisso, F.E., P. Schjønning, T. Keller, M. Lamandé, A. Etana, et al. 2012. Persistent effects of subsoil compaction on pore size distribution and gas transport in a loamy soil. Soil Tillage Res. 122: 42–51. doi: 10.1016/J.still.2012.02.005.

Berisso, F.E., P. Schjønning, M. Lamandé, P. Weisskopf, M. Stettler, et al. 2013. Effects of the stress field induced by a running tyre on the soil pore system. Soil Tillage Res. 131: 36–46. doi: 10.1016/j.still.2013.03.005.

Berli, M., J.M. Kirby, S.M. Springman, and R. Schulin. 2003. Modelling compaction of agricultural subsoils by tracked heavy construction machinery under various moisture conditions in Switzerland. Soil Tillage Res. 73(1): 57–66. doi: 10.1016/S0167-1987(03)00099-0.

Beylich, A., H.-R. Oberholzer, S. Schrader, H. Höper, and B.-M. Wilke. 2010. Evaluation of Soil Compaction Effects on Soil Biota and Soil Biological Processes in Soils. Elsevier B.V.

Bicki, T.J., and J.C. Siemens. 1991. Crop response to wheel traffic soil compaction. Trans. ASABE 3(34): 909–913. file://z/Ref_Works/Reifen/.

Billman, R.W., S.K. Pitla, A.A. Klopfenstein, I. Kuenzli, and S.A. Shearer. 2012. Historical perspective on the growth in tractor power, vehicle weight, tire size and fuel efficiency. A lecture presented at the 2012 ASABE Annual International Meeting, Dallas, Texas

Blackmore, S. 1994. Precision Farming: An Introduction. Outlook Agric. 23(4): 275–280. doi: 10.1177/003072709402300407.

Blanco-Canqui, H., M.M. Claassen, and L.R. Stone. 2010. Controlled traffic impacts on physical and hydraulic properties in an intensively cropped no-till soil. Soil Sci. Soc. Am. J. 74(6): 2142. doi: 10.2136/sssaj2010.0061.

Blanco-Canqui, H., and R. Lal. 2008. No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Sci. Soc. Am. J. 72(3): 693–701. doi: 10.2136/sssaj2008.0275l.

Blanco-Canqui, H., B.J. Wienhold, V.L. Jin, M.R. Schmer, and L.C. Kibet. 2017. Long-term tillage impact on soil hydraulic properties. Soil Tillage Res. 170: 38–42. doi: 10.1016/j.still.2017.03.001.

Blanke, J.H., S. Olin, J. Stürck, U. Sahlin, M. Lindeskog, et al. 2017. Assessing the impact of changes in land-use intensity and climate on simulated trade-offs between crop yield and nitrogen leaching. "Agriculture, Ecosyst. Environ. 239: 385–398. doi: 10.1016/j.agee.2017.01.038.

Blum, W.E.H. 1993. Soil protection concept of the council of Europe and Integrated Soil Research. In: Eijsackers, H.J.P. and Hamers, T., editors, Integrated soil and sediment research: A basis for proper protection. Springer, Dordrecht. p. 763

Blunden, B., R. Mcbride, H. Daniel, and P. Blackwell. 1994. Compaction of an earthy sand by rubber tracked and tired vehicles. Aust. J. Soil Res. 32(5): 1095–1108. doi: 10.1071/SR9941095.

Boguzas, V., and I. Hakansson. 2001. Barley yield losses simulation under Lithuanian conditions using the Swedish soil compaction model. Soil Manag. Dep. Lith. Univ. Agric. Student 11, Akad. (Kaunas LT-4324, Lithuania): 24–28.

Bommarco, R., D. Kleijn, and S.G. Potts. 2013. Ecological intensification: Harnessing ecosystem services for food security. Trends Ecol. Evol. 28(4): 230–238. doi: 10.1016/j.tree.2012.10.012.

Botta, G.., D. Jorajuria, R. Balbuena, and H. Rosatto. 2004. Mechanical and cropping behavior of direct drilled soil under different traffic intensities: effect on soybean (Glycine max L.) yields. Soil Tillage Res. 78(1): 53–58. doi: 10.1016/J.STILL.2004.01.004.

Botta, G.F., O. Pozzolo, M. Bomben, H. Rosatto, D. Rivero, et al. 2007. Traffic alternatives for harvesting soybean (Glycine max L.): Effect on yields and soil under a direct sowing system. Soil Tillage Res. 96: 145–154. doi: 10.1016/j.still.2007.05.003.

Botta, G.F., D. Rivero, M. Tourn, F.B. Melcon, O. Pozzolo, et al. 2008. Soil compaction produced by tractor with radial and cross-ply tyres in two tillage regimes. Soil Tillage Res. 101(1–2): 44–51. doi: 10.1016/j.still.2008.06.001.

Botta, G.F., A. Tolon-Becerra, X. Lastra-Bravo, and M. Tourn. 2010. Tillage and traffic effects (planters and tractors) on soil compaction and soybean (Glycine max L.) yields in Argentinean pampas. Soil Tillage Res. 110(1): 167–174. doi: 10.1016/j.still.2010.07.001.

Botta, G.F., A. Tolon-Becerra, M. Tourn, X. Lastra-Bravo, and D. Rivero. 2012. Agricultural traffic: Motion resistance and soil compaction in relation to tractor design and different soil conditions. Soil Tillage Res. 120: 92–98. doi: 10.1016/j.still.2011.11.008.

Bouwman, L.A., and W.B.M. Arts. 2000. Effects of soil compaction on the relationships between nematodes, grass production and soil physical properties. Appl. Soil Ecol. 14(3): 213–222. doi: 10.1016/S0929-1393(00)00055-X.

Brady, N.C., and R.R. Weil. 1996. The nature and properties of soils (N.C. Brady and R.R. Weil, editors). 11th ed. Upper Saddle River, N.J. : Prentice Hall.

Brady, N.C., and R.R. Weil. 2008. Soil water: characteristics and behavior. In: Brady NC, Weil RR (eds) The nature and properties of soils (N.C. Brady and R.R. Weil, editors). 14th ed. Prentice Hall, New Jersey.

Bray, R.H., and L.T. Kurtz. 1945. Determination of total, organic, and available form of phosphorus in soil. Soil Sci. 59: 39–45. doi: 10.1097/00010694-194501000-00006.

Bremner, J.M. 1960. Determination of nitrogen in soil by the Kjeldahl method. J. Agric. Sci. 55(1): 11–33. doi: https://doi.org/10.1017/S0021859600021572.

Bronick, C.J., and R. Lal. 2005. Soil structure and management: a review. Geoderma 124(1–2): 3–22. doi: 10.1016/j.geoderma.2004.03.005.

Bunemann, E.K., G. Bongiorno, Z. Bai, R.E. Creamer, G. De Deyn, et al. 2018. Soil quality – A critical review. Soil Biol. Biochem. 120(September 2017): 105–125. doi: 10.1016/j.soilbio.2018.01.030.

Busscher, W.J., P.J. Bauer, and J.R. Frederick. 2006. Deep tillage management for high strength southeastern USA Coastal Plain soils. Soil Tillage Res. 85(1–2): 178–185. doi: 10.1016/j.still.2005.01.013.

Busscher, W.J., J.R. Frederick, and P.J. Bauer. 2000. Timing effects of deep tillage on penetration resistance and wheat and soybean yield. Soil Sci. Soc. Am. J. 64: 999–1003. doi: 10.2136/sssaj2000.643999x.

Buttery, B.R., C.S. Tan, C.F. Drury, S.J. Park, R.J. Armstrong, et al. 1998. The effects of soil compaction, soil moisture and soil type on growth and nodulation of soybean and common bean. Can. J. Plant Sci. 78: 571–576. doi: 10.4141/P97-132.

Bwembya, S., J. Martlew, P. Misiewicz, S. Woods, and M. Moore. 2017. Can traffic and tillage methods in Sub-Saharan Africa optimise soil health and food crop production? Current Postgraduate Research Note. Harper Adams University. Newport, UK.

C

Calistru, A.-E., and G. Jităreanu. 2015. Applications of X-Ray Computed Tomography for examining soil structure: a review. Bull. USAMV Ser. Agric. 72(1): 30–36. doi: 10.15835/buasvmcn-agr: 11145.

Camp, C.R., G.D. Christenbury, and C.W. Doty. 1984. Coastal Plain Soils. 27(6): 1729–1733. doi: doi: 10.13031/2013.33036.

CampbellL, D.J. 1994. Determination and use of soil bulk density in relation to soil compaction. In: Soane, B.D. and van Ouwerkerk, C., editors, Developments in Agricultural Engineering. Elsevier Science B.V. p. 113–139

Canillas, E.C., and V.M. Salokhe. 2002. Modeling compaction in agricultural soils. J. Terramechanics 39(2): 71–84. doi: 10.1016/S0022-4898(02)00007-1.

Cantero-Martinez, C., and J. Lampurlanes. 2003. Soil Bulk Density and Penetration Resistance under Different Tillage and Crop Management Systems and Their Relationship with Barley Root Growth. Agron. J. 95(3): 526. doi: 10.2134/agronj2003.0526.

Çarman, K. 1994. Tractor forward velocity and tire load effects on soil compaction. J. Terramechanics 31(1): 11–20. doi: 10.1016/0022-4898(94)90029-9.

Carter, L.M., B.D. Meek, and E.A. Rechel. 1991. Zone production system for cotton. Soil response. Trans. ASAE 34(2): 354–360. doi: 10.13031/2013.31668.

Carter, L.M., and J.R. Tavernetti. 1968. Influence of precision tillage and soil compaction on cotton yields. Trans. ASAE 11(1): 65–67.

Cary, J.W., and C.W. Hayden. 1973. An index for soil pore size distribution. Geoderma 9: 249–256.

Cassel, D.K., and R. Lal. 1992. Soil Physical Properties of the Tropics: Common Beliefs and Management Restraints. In: Lal, P.A. and Sanchez, R., editors, Myths and Science of Soils of the Tropics, Volume 29. Soil Science Society of America

Cavalieria, K.M.V., A.P. Silva, C.A. Tormena, T.P. Leao, A.R. Dewxter, et al. 2009. Long-term effects of no-tillage on dynamic soil physical properties in a Rhodic Ferrasol in Paraná, Brazil. Soil Tillage Res. 103(1): 158–164.

Cavallo, E., E. Ferrari, L. Bollani, and M. Coccia. 2014. Strategic management implications for the adoption of technological innovations in agricultural tractor: the role of scale factors and environmental attitude. Technol. Anal. Strateg. Manag. 26(7): 765–779. doi: 10.1080/09537325.2014.890706.

Chamen, T. 2006. 'Controlled traffic' farming : Literature review and appraisal of potential use in the U.K. Bedfordshire, UK.

Chamen, W. 2011. The effects of low and controlled traffic systems on soil physical properties, yields and the profitability of cereal crops on a range of soil types. Ph.D. thesis, Cranf. Univ. Silsoe, UK (April). http://dspace.lib.cranfield.ac.uk/handle/1826/7009.

Chamen, T. 2015. Controlled traffic farming - From worldwide research to adoption in Europe and its future prospects. Acta Technol. Agric. 3 18(3): 64–73. doi: 10.1515/ata-2015-0014.

Chamen, T., L. Alakukku, S. Pires, C. Sommer, G. Spoor, et al. 2003. Prevention strategies for field traffic-induced subsoil compaction: a review. Soil Tillage Res. 73(1–2): 161–174. doi: 10.1016/S0167-1987(03)00108-9.

Chamen, W.C.T., A.P. Moxey, W. Towers, B. Balana, and P.D. Hallett. 2015. Mitigating arable soil compaction: a review and analysis of available cost and benefit data. Soil Tillage Res. 146: 10–25. doi: 10.1016/J.STILL.2014.09.011.

Chamen, W., C.W. Watts, P.R. Leede, and D.J. Longstaff. 1992. Assessment of a wide span vehicle (gantry), and soil and cereal crop responses to its use in a zero traffic regime. Soil Tillage Res. 24(4): 359–380. doi: 10.1016/0167-1987(92)90119-V.

Chan, K.Y., D.P. Heenan, and H.B. So. 2003. Sequestration of carbon and changes in soil quality under conservation tillage on light-textured soils in Australia: A review. Aust. J. Exp. Agric. 43(4): 325–334. doi: 10.1071/EA02077.

Chan, K.Y., A. Oates, A.D. Swan, R.. Hayes, B.S. Dear, et al. 2006. Agronomic consequences of

tractor wheel compaction on a clay soil. Soil Tillage Res. 89(1): 13–21. doi: 10.1016/j.still.2005.06.007.
Chen, G., and R.R. Weil. 2010. Penetration of cover crop roots through compacted soils. Plant Soil 331(1): 31–43. doi: 10.1007/s11104-009-0223-7.
Chyba, J. 2012. The influence of traffic intensity and soil texture on soil water infiltration rate. MSc. Thesis. Harper Adams Univ. Newport, Shropshire, UK.
Chyba, J., M. Kroulík, K. Krištof, P.A. Misiewicz, and K. Chaney. 2014. Influence of soil compaction by farm machinery and livestock on water infiltration rate on grassland. Agron. Res. 12(1): 59–64.
Combs, S.M., and M.V. Nathan. 2015. Soil organic matter. Recommended chemical soil test procedures for the North Central Region (North Central Regional Research publication no. 221, revised). Missouri Agricultural Experiment Station SB 1001, Columbia, MO. p. 12.1-12.6
Copas, M.E., A.J. Bussan, M.J. Drilias, and R.P. Wolkowski. 2009. Potato yield and quality response to subsoil tillage and compaction. Agron. J. 101(1): 82–90. doi: 10.2134/agronj2007.0031.
Cresswell, H., and J. Kirkegaard. 1995. Subsoil amelioration by plant-roots - the process and the evidence. Aust. J. Soil Res. 33(2): 221–239. doi: https://doi.org/10.1071/SR9950221.
Crestana, S., S. Mascarenhas, and R.S. Pozzi-Mucelli. 1985. Static and dynamic three-dimensional studies of water in soil using computed tomographic scanning. Soil Sci. 140(5): 326–332.
Cunningham, S.A., S.J. Attwood, K.S. Bawa, T.G. Benton, L.M. Broadhurst, et al. 2013. To close the yield-gap while saving biodiversity will require multiple locally relevant strategies. Agric. Ecosyst. Environ. 173: 20–27. doi: 10.1016/j.agee.2013.04.007.
Czyż, E.A. 2004. Effects of traffic on soil aeration, bulk density and growth of spring barley. Soil Tillage Res. 79(2): 153–166. doi: 10.1016/j.still.2004.07.004.

D

Dahnke, W.C. 1971. Use of the nitrate specific ion electrode in soil testing. Comun. Soil Sci. Plant Anal. 2(2): 73–84. doi: 10.1080/00103627109366292.
Dal Ferro, N., L. Sartori, G. Simonetti, A. Berti, and F. Morari. 2014. Soil macro- and microstructure as affected by different tillage systems and their effects on maize root growth. Soil Tillage Res. 140: 55–65. doi: 10.1016/j.still.2014.02.003.
Defossez, P., and G. Richard. 2002. Models of soil compaction due to traffic and their evaluation. Soil Tillage Res. 67(1): 41–64. doi: 10.1016/S0167-1987(02)00030-2.
Dejong-hughes, J. 2018. Soil compaction. https://extension.umn.edu/soil-management-and-health/soil-compaction (accessed 12 December 2019).
Dejong-Hughes, J. 2009. Tires, traction and compaction. Twin Cities, Minnessota.
DeJong-Hughes, J., J.F. Moncrief, W.B. Voorhees, and J.B. Swan. 2001. Soil compaction: Causes, effects and control.
DEKALB. 2018. Corn and soybean growth stages guide. https://www.dekalb.ca/corn/215-corn-and-soybean-growth-stages-guide. https://www.dekalb.ca/corn/215-corn-and-soybean-growth-stages-guide (accessed 30 December 2018).
Dexter, A.R., and E.A. Czyż. 2000. Soil Physical Quality and the Effects of Management. Soil Quality, Sustainable Agriculture and Environmental Security in Central and Eastern Europe. Springer Netherlands, Dordrecht. p. 153–165
Dick, R. 1992. A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. Agric. Ecosyst. Environ. 40(1–4): 25–36. doi: 10.1016/0167-8809(92)90081-L.
Dickson, J., and R. Ritchie. 1993. Soil and crop responses to zero, reduced ground pressure and conventional traffic systems in an arable rotation on a clay loam, 1991. Departmental Note-

Scottish Centre of Agricultural Engineering (UK).
Dickson, J.W., and R.M. Ritchie. 1996. Zero and reduced ground pressure traffic systems in an arable rotation 2. Soil and crop responses. Soil Tillage Res. 38(1–2): 89–113. doi: 10.1016/0167-1987(96)01027-6.
Domżał, H., J. Gliński, and J. Lipiec. 1991. Soil compaction research in Poland. Soil Tillage Res. 19(2): 99–109. doi: 10.1016/0167-1987(91)90079-D.
Duiker, S. 2002. Diagnosing soil compaction using a Penetrometer. Agron. Facts 63: 1–4.
Duiker, S. 2004. Avoiding soil compaction. Coll. Agric. Sci. Agric. Res. Coop. Extension, Pennsylvania State Univ.: 1–7. https://extension.psu.edu/avoiding-soil-compaction (accessed 4 March 2019).
Duiker, S.W., F.E. Rhoton, J. Torrent, N.E. Smeck, and R. Lal. 2003. Iron (Hydr)oxide crystallinity effects on soil aggregation. Soil Sci. Soc. Am. J. 67(2): 606–611. doi: 10.2136/sssaj2003.6060.
Duvick, D.N., and K.G. Cassman. 1999. Post-green revolution trends in yield potential of temperate maize in the north-central United States. Crop Sci. 39(6): 1622–1630. doi: 10.2135/cropsci1999.3961622x.

E

Eliasson, L. 2005. Effects of forwarder tyre pressure on rut formation and soil compaction. Silva Fenn. Monogr. 39(4): 549–557. doi: 10.14214/sf.366.
Elkins, C.B. 1985. Plant roots as tillage tools. International Conference on Soil Dynamics. Auburn, AL. p. 519–523
Eswaran, H., R. Lal, and P.F. Reich. 2001. Land degradation: an overview. Bridg. E.M., I.D. Hannam, L.R. Oldeman, F.W.T. Pening Vries, S.J. Scherr, S. Sompatpanit (eds.). Responses to L. Degrad. Proc. 2nd. Int. Conf. L. Degrad. Desertif. Khon Kaen, Thailand. Oxford Press. Ne. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054028 (accessed 7 February 2019).
Etana, A., and I. Hakansson. 1994. Swedish experiments on the persistence of subsoil compaction caused by vehicles with high axle load. Soil Tillage Res. 29(2): 167–172. doi: 10.1016/0167-1987(94)90053-1.
Etana, A., L. Holm, T. Rydberg, and T. Keller. 2020. Soil and crop responses to controlled traffic farming in reduced tillage and no-till: some experiences from field experiments and on-farm studies in Sweden. Acta Agric. Scand. Sect. B Soil Plant Sci. 70(4): 333–340. doi: 10.1080/09064710.2020.1728372.
Etana, A., M. Larsbo, T. Keller, J. Arvidsson, P. Schjønning, et al. 2013. Persistent subsoil compaction and its effects on preferential flow patterns in a loamy till soil. Geoderma 192: 430–436. doi: 10.1016/J.GEODERMA.2012.08.015.
European Commission. 2002. Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions: Towards a thematic strategy for soil protection. [COM (2002) 179 final]. Commission of the European Communities. Brussels, Belgium. p. 35

F

Fageria, N.K. 1992. Maximizing crop yields. Books in soils, plants, and the environemnts. Marcel Dekker Inc., New York.
FAO. 2013. Climate-smart agriculture sourcebook. Food and Agriculture Organization of the United Nations, Rome, Italy.
FAO. 2017a. The future of food and agriculture - Trends and challenges, Food and Agriculture Organization of the United Nations.
FAO. 2017b. Sustainable agricultural mechanization. Food and Agriculture of the United Nations,

Rome Italy. http://www.fao.org/sustainable-agricultural-mechanization.
FAO. 2018. FAO statistical databases (FAOSAT), Food and Agriculture of the United Nations. http://apps.fao.org (accessed 20 October 2018).
FAO. 2019a. Integrated Pest Management. http://www.fao.org/agriculture/crops/core-themes/theme/pests/ipm (accessed 30 January 2019).
FAO. 2019b. FAO Statistical Databases (FAOSAT): Crops production, Food and Agriculture of the United Nations, Rome, Italy. http://www.fao.org/faostat/en/#data/QC/visualize (accessed 30 December 2019).
Fernández, F.G., B.S. Farmaha, and E.D. Nafziger. 2012. Soil fertility status of soils in Illinois. Commun. Soil Sci. Plant Anal. 43(22): 2897–2914. doi: 10.1080/00103624.2012.728268.
Ferreira, T., and W. Rasband. 2012. ImageJ user guide - IJ 1.46r. http://imagej.nih.gov/ij/docs/guide.
Flowers, M.D., and R. Lal. 1998. Axle load and tillage effects on soil physical properties and soybean grain yield on a mollic ochraqualf in northwest Ohio. Soil Tillage Res. 48(1–2): 21–35. doi: 10.1016/S0167-1987(98)00095-6.
Fonteyne, S., M.A. Martinez Gamiño, A.S. Tejeda, and N. Verhulst. 2019. Conservation agriculture improves long-term yield and soil quality in irrigated maize-oats rotation. Agronomy 9(12): 1–13. doi: 10.3390/agronomy9120845.
Franzen, D.W. 2015. Sulfate-Sulfur. Recommended chemical soil test procedures for the North Central Region (North Central Regional Research publication no. 221, revised). Missouri Agricultural Experiment Station SB 1001, Columbia, MO. p. 8.1-8.6

G

Galambošová, J., M. Macák, V. Rataj, D.L. Antille, R.J. Godwin, et al. 2017. Field evaluation of controlled traffic farming in central europe using commercially available machinery. Trans. ASABE 60(3): 657–669. http://10.0.50.231/trans.11833%0Ahttp://search.ebscohost.com/login.aspx?direct=true&db=a9h&AN=123824703&site=ehost-live.
Galdos, M. V., L.F. Pires, H. V. Cooper, J.C. Calonego, C.A. Rosolem, et al. 2019. Assessing the long-term effects of zero-tillage on the macroporosity of Brazilian soils using X-ray Computed Tomography. Geoderma 337: 1126–1135. doi: 10.1016/j.geoderma.2018.11.031.
Gameda, S., G.S.V. Raghavan, E. McKyes, A.K. Watson, and G. Mehuys. 1994. Long-term effects of a single incidence of high axle load compaction on a clay soil in Quebec. Soil Tillage Res. 29(2): 173–177. doi: 10.1016/0167-1987(94)90054-X.
García-Lara, S., and S.O. Serna-Saldivar. 2019. Corn history and culture. In: Serna-Saldivar, S.O., editor, Corn. Third. AACC International Press. p. 1–18
Garcia-Paredes, J.D., K.R. Olson, and J.M. Lang. 2000. Predicting corn and soybean productivity for Illinois soils. Agric. Syst. 64(3): 151–170. doi: 10.1016/S0308-521X(00)00020-2.
Garibaldi, L.A., B. Gemmill-Herren, R. D'Annolfo, B.E. Graeub, S.A. Cunningham, et al. 2017. Farming Approaches for Greater Biodiversity, Livelihoods, and Food Security. Trends Ecol. Evol. 32(1): 68–80. doi: 10.1016/j.tree.2016.10.001.
Gasso, V., F.W. Oudshoorn, C.A.G. Sørensen, and H.H. Pedersen. 2014. An environmental life cycle assessment of controlled traffic farming. J. Clean. Prod. 73: 175–182. doi: 10.1016/j.jclepro.2013.10.044.
Gaultney, L., G.W. Krutz, J.B. Steinhardt, and J.B. Liljedahl. 1982. Effects of subsoil compaction on corn yields. Trans. ASAE 25(3): 563–575.
Gelder, B.K., R.M. Cruse, and X.Y. Zhang. 2007. Comparison of track and tire effects of planter tractors on corn yield and soil properties. Trans. ASAE 50(2): 365–370. doi: 10.13031/2013.22627.
Gelderman, D., and R.H. Beegle. 2015. Nitrate-Nitrogen. Recommended chemical soil test procedures for the North Central Region (North Central Regional Research publication no.

221, revised). Missouri Agricultural Experiment Station SB 1001, Madison, WI. p. 5.1-5.4
Gerasimov, Y., and V. Katarov. 2010. Effect of boogie track and slash reinforcement on sinkage and soil compaction in soft terrains. Croat. J. For. Eng. 31: 35–45.
Godfray, H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, et al. 2010. Food security: The challenge of feeding 9 billion people. Science (80-.). 327(5967): 812–818. doi: 10.1126/science.1185383.
Godwin, R.J. 2014. Potential of "No-till" systems for arable farming. Newport.
Godwin, R., and M.L. Dresser. 2003. Review of soil management techniques for water retention and minimising diffuse water pollution in the River Parrett Catchment. Environment Agency R&D Technical Report P2-261/10. TR, Bristol.
Godwin, R.J., P.A. Misiewicz, E.K. Smith, W.A.Z. Millington, D.R. White, et al. 2017. Summary of the effects of three tillage and three traffic systems on cereal yields over a four-year rotation. ASABE Annu. Int. Meet. Spokane, 16 - 19 July 2017. Pap. no. 1701652: 1–8. doi: 10.13031/aim.201701652.
Godwin, R.J., P.A. Misiewicz, D. White, T. Chamen, J. Galambošová, et al. 2015. Results from recent traffic systems research and the implications for future work. Acta Technol. Agric. 18(3): 57–63. doi: 10.1515/ata-2015-0013.
Gold, M. V. 2007. Sustainable agriculture: Definitions and terms. Related terms. Natl. Agric. Libr. U.S. Dep. Agric. Beltsville, MD. https://www.nal.usda.gov/afsic/sustainable-agriculture-definitions-and-terms-related-terms (accessed 30 January 2019).
Grabski, A., H.B. So, and P.J. Desborough. 1995. A comparison of the impact of 14 years of conventional and no til cultivation on physical properties and crop yields of a loam soil at Grafton NSW. Proceedings of the National Controlled Traffic Conference,. p. 97–102
Grassini, P., J.E. Specht, M. Tollenaar, I. Ciampitti, and K.G. Cassman. 2015. High yield maize–soybean cropping systems in the US Corn Belt. Crop Physiology. Second Edi. Elsevier Inc. p. 17–41
Gregorich, E.G., D.R. Lapen, B.L. Ma, N.B. McLaughlin, and A.J. VandenBygaart. 2011. Soil and crop response to varying levels of compaction, nitrogen fertilization, and clay content. Soil Sci. Soc. Am. J. 75(4): 1483–1492. doi: 10.2136/sssaj2010.0395.
Gregory, P., D. Hutchison, D. Read, P. Jenneson, W. Gilboy, et al. 2003. Non-invasive imaging of roots with high resolution X-ray Micro-Tomography. Plant Soil 255(1): 351–359. doi: 10.1023/a:1026179919689.
Grzesiak, M.T. 2009. Impact of soil compaction on root architecture, leaf water status, gas exchange and growth of maize and triticale seedlings. Plant Root 3: 10–16. doi: 10.3117/plantroot.3.10.
Grzesiak, S., M.T. Grzesiak, T. Hura, I. Marcińska, and A. Rzepka. 2013. Changes in root system structure, leaf water potential and gas exchange of maize and triticale seedlings affected by soil compaction. Environ. Exp. Bot. 88: 2–10. doi: 10.1016/j.envexpbot.2012.01.010.
Gut, S., A. Chervet, M. Stettler, P. Weisskopf, W.G. Sturny, et al. 2015. Seasonal dynamics in wheel load-carrying capacity of a loam soil in the Swiss Plateau. Soil Use Manag. 31(1): 132–141. doi: 10.1111/sum.12148.
Gysi, M., A. Ott, and H. Flühler. 1999. Influence of single passes with high wheel load on a structured, unploughed sandy loam soil. Soil Tillage Res. 52(3–4): 141–151. doi: 10.1016/S0167-1987(99)00066-5.

H

Hainsworth, J.M., and L.A.G. Aylmore. 1983. The use of computer-assisted tomography to determine spatial distribution of soil water content. Aust. J. Soil Res. 21(4): 435–443. doi: 10.1071/SR9830435.
Hakansson, I. 1990. Soil compaction control — Objectives, possibilities and prospects. Soil Technol. 3(3): 231–239. doi: 10.1016/0933-3630(90)90003-L.

Hakansson, I. 1994. Subsoil compaction by high axle load traffic. Soil Tillage Res. 29(2–3): 105–306. https://www.sciencedirect.com/journal/soil-and-tillage-research/vol/29/issue/2.
Hakansson, I. 2005. Machinery induced compaction of arable soils. Incidence - Consequences - Countermeasures (I. Ha°kansson, editor). 1st ed. Swedish University of Agricultural Sciences Department of Soil Sciences, Uppsala.
Hakansson, I., and J. Lipiec. 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Tillage Res. 53(2): 71–85. doi: 10.1016/S0167-1987(99)00095-1.
Hakansson, I., and H. Petelkau. 1994. Benefits of limited axle load. In: Soane, B. and van den Akker, J.J.H., editors, Soil compaction in crop production. Elsevier, Amsterdam. p. 479–499
Hakansson, I., and R.C. Reeder. 1994. Subsoil compaction by vehicles with high axle load-extent, persistence and crop response. Soil Tillage Res. 29(2–3): 277–304. doi: 10.1016/0167-1987(94)90065-5.
Hakansson, I., W.B. Voorhees, and H. Riley. 1988. Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes. Soil Tillage Res. 11(3–4): 239–282. doi: 10.1016/0167-1987(88)90003-7.
Hall, D., M.J. Reeve, A.J. Thomasson, and V.F. Wright. 1977. Water retention, porosity and density of field soils. Harpenden, UK: Soil Survey of England and Wales.
Hallett, P., B. Balana, W. Towers, A. Moxey, and T. Chamen. 2012. Studies to inform policy development with regard to soil degradation. Subproject A : Cost curve for mitigation of soil compaction. Defra SP1305 (CTE 1024).
Hallett, P.D., and A.G. Bengough. 2013. Managing the soil physical environment for plants. In: Gregory, P.J. and Nortcliff, S., editors, Soil conditions and plant growth. 1st ed. Blackwell Publishing Ltd, Dundee, UK. p. 238–268
Hamlett, J.M., S.W. Melvin, and R. Horton. 1990. Traffic and soil amendment effects on infiltration and compaction. Trans. ASAE 33(3): 821–826.
Hamza, M.A., S.S. Al-Adawi, and K.A. Al-Hinai. 2011. Effect of combined soil water and external load on soil compaction. Soil Res. 49(2): 135–142. doi: http://dx.doi.org/10.1071/SR09144.
Hamza, M.A., and W.K. Anderson. 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Tillage Res. 82(2): 121–145. doi: 10.1016/j.still.2004.08.009.
Han, S.K., H.S. Han, D.S. Page-Dumroese, and L.R. Johnson. 2009. Soil compaction associated with cut-to-length and whole-tree harvesting of a coniferous forest. Can. J. For. Res. 39: 976–989. doi: 10.1139/X09-027.
Hatley, D., J. Wiltshire, B. Basford, S. Royale, D. Buckley, et al. 2005. Soil compaction and potato crops. Oxford, UK.
Hazell, P.B.R. 2009. The Asian Green Revolution. IFPRI Discussion Paper, No. 00911: 1-40.http://www.ifpri.org/publication/asian-green-revolution. Washington, D.C.
Heeraman, D., J. Hopkins, and V. Clausnitzer. 1997. Three dimensional imaging of plant roots in situ with X-Ray computed tomography. Plant Soil 189:167–179. Plant Soil 189: 167–179.
Heijs, A.W.J., J. de Lange, J.F.T. Schoute, and J. Bouma. 1995. Computed Tomography as a tool for non-destructive analysis of flow patterns in macroporous clay soils. Geoderma 64(3–4): 183–196. doi: 10.1016/0016-7061(94)00020-B.
Helliwell, J.R., C.J. Sturrock, K.M. Grayling, S.R. Tracy, R.J. Flavel, et al. 2013. Applications of X-ray Computed Tomography for examining biophysical interactions and structural development in soil systems: A review. Eur. J. Soil Sci. 64(3): 279–297. doi: 10.1111/ejss.12028.
Hillel, D. 1971. Soil and water: physical principles and processes. Physiological ecology, a series of monographs, texts and treatises. London: Academic Press.
Hillel, D. 1998. Environmental Soil Physics: Fundamentals, Applications, and Environmental Considerations. Academic Press, London, London.

Hoeft, R.G., E.D. Nafziger, R.R. Johnson, and S.R. Aldrich. 2000. Modern corn and soybean production. Champaign, IL: MCSP Publications. 1st ed. Champaign, IL.
Hoorman, J.J., and R. Islam. 2010. Understanding soil microbes and nutrient recycling. Fact Sheet Agric. Nat. Resour. doi: 10.1080/00220388.2016.1139696.
Horn, R., and H. Fleige. 2003. A method for assessing the impact of load on mechanical stability and on physical properties of soils. Soil Tillage Res. 73(1–2): 89–99. doi: 10.1016/S0167-1987(03)00102-8.
Horn, R., H. Fleige, S. Peth, and X. Peng. 2006. Soil management for sustainability. Catena, Reiskirchen.
Horn, R., and M. Lebert. 1994. Soil compatibility and compressibility. In: B.D. Soane and C. van Ouwerkerk, editor, Developments in Agricultural Engineering 11: Soil compaction in crop production. Elsevier. p. 45–70
Horn, R., T. Way, and J. Rostek. 2003. Effect of repeated tractor wheeling on stress/strain properties and consequences on physical properties in structured arable soils. Soil Tillage Res. 73(1–2): 101–106. doi: 10.1016/S0167-1987(03)00103-X.
Houšková, B., and L. Montanarella. 2008. The natural susceptibility of European soils to compaction. In: Gergely, T., Montanarella, L., and Rusco, E., editors, Threats to soil quality in Europe. European Commission Joint Research Centre Institute for Environment and Sustainability, Luxmbourg. p. 23–36
Huber, S., G. Prokop, D. Arrouays, G. Banko, A. Bispo, et al. 2008. Environmental assessment of soil for monitoring volume I: Indicators & Criteria (S. Huber, G. Prokop, D. Arrouays, G. Banko, A. Bispo, et al., editors). Luxembourg: Office for Official Publications of the European Communities.
Huggins, D.R., and J.P. Reganold. 2008. No-till : the quiet revolution. Sci. Am. 299(1): 70–77.
Hula, J., M. Kroulik, and P. Kovaricek. 2009. Effect of repeated passes over the soil on degree of soil compaction. (ČZU, In GPS autopiloty v zemědělstvi. CULS Prague): 39–44.
Hungria, M., J.C. Franchini, O. Brandao-Junior, G. Kaschuk, and R.A. Souza. 2009. Soil microbial activity and crop sustainability in a long-term experiment with three soil-tillage and two crop-rotation systems. Appl. Soil Ecol. 42(3): 288–296. doi: 10.1016/j.apsoil.2009.05.005.
Husnjak, S., D. Filipovic, and S. Kosutic. 2002. Influence of different tillage systems on soil physical properties and crop yield. Plant Soil Environ. (Rostlinna Vyroba) 48: 249–254. doi: https://doi.org/10.17221/4236-PSE.

I

Illinois Department of Agriculture. 2019. Facts about Illinois agriculture. https://www2.illinois.gov/sites/agr/About/History/Pages/default.aspx (accessed 8 January 2019).
Iowa State University. 2008. Soybean drying and storage. Iowa State Univ. Ext. Outreach: 1–2, Pm 1636. https://store.extension.iastate.edu/product/Soybean-Drying-and-Storage (accessed 12 October 2017).
Iowa State University. 2020. Kernels set early in season. Iowa State University Agronomy Extension Corn Production. https://crops.extension.iastate.edu/encyclopedia/kernels-set-early-season (accessed 5 May 2020).
IPCC. 1996. Climate change 1995: The science of climate change. Contribution of working group I to the second assessment report of the Intergovernmental Panel on Climate Change (IPCC). Intergovernmental Panel on Climate Change. 1996. Climate change: 1995. The science. Cambridge, UK.
Irmak, S., and D.R. Rudnick. 2014. Corn soil-water extraction and effective rooting depth in a silt-loam soil.
Ishaq, M., A. Hassan, M. Saeed, M. Ibrahim, and R. Lal. 2001a. Subsoil compaction effects on crops in Punjab, Pakistan: I. Soil physical properties and crop yield. Soil Tillage Res. 59(1–

2): 57–65. doi: 10.1016/S0167-1987(00)00189-6.
Ishaq, M., M. Ibrahim, A. Hassan, M. Saeed, and R. Lal. 2001b. Subsoil compaction effects on crops in Punjab, Pakistan: II. Root growth and nutrient uptake of wheat and sorghum. Soil Tillage Res. 60(3–4): 153–161. doi: 10.1016/S0167-1987(01)00177-5.
ISRIC. 2019. Why are soils important? About soils. https://www.isric.org/index.php/discover/about_soils/why-are-soils-important (accessed 15 February 2019).
ISWS. 2016. Monthly normals (1981-2010 avearges) and records for Champaign-Urbana, Illinois. Illinois Soil Water Survey (ISWS). https://www.isws.illinois.edu/statecli/cuweather/cu-averages.htm (accessed 30 June 2016).

J

James, I.., T.. Waine, R.. Bradley, J.. Taylor, and R.. Godwin. 2003. Determination of soil type boundaries using Electromagnetic induction scanning techniques. Biosyst. Eng. 86(4): 421–430. doi: 10.1016/j.biosystemseng.2003.09.001.
Janvier, C., F. Villeneuve, C. Alabouvette, V. Edel-Hermann, T. Mateille, et al. 2007. Soil health through soil disease suppression: Which strategy from descriptors to indicators? Soil Biol. Biochem. 39(1): 1–23. doi: 10.1016/j.soilbio.2006.07.001.
Jin, K., J. Shen, R.W. Ashton, R.P. White, I.C. Dodd, et al. 2015. The effect of impedance to root growth on plant architecture in wheat. Plant Soil 392(1–2): 323–332. doi: 10.1007/s11104-015-2462-0.
Jones, C., G. Basch, A. Baylis, D. Bazzoni, J. Biggs, et al. 2006. Conservation Agriculture in Europe: An approach to sustainable crop production by protecting soil and water? Jealott's Hill, Bracknell, RG42 6EY, UK.
Jones, R.J.A., G. Spoor, and A.J. Thomasson. 2003. Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Soil Tillage Res. 73(1–2): 131–143. doi: 10.1016/S0167-1987(03)00106-5.

K

Kaspar, T.C., H.J. Brown, and E.M. Kassmeyer. 1991. Corn root distribution as affected by tillage, wheel traffic, and tertilizer placement. Soil Sci. Soc. Am. J. 55(5): 1390–1394. doi: 10.2136/sssaj1991.03615995005500050031x.
Kaspar, T.C., J.K. Radke, and J.M. Laflen. 2001. Small grain cover crops and infiltration, runoff, and wheel traffic effects on infiltration, runoff, and erosion. J. Soil Water Conserv. 56(2): 160–164.
Katuwal, S., T. Norgaard, P. Moldrup, M. Lamandé, D. Wildenschild, et al. 2015. Linking air and water transport in intact soils to macropore characteristics inferred from X-ray Computed Tomography. Geoderma 237–238: 9–20. doi: 10.1016/J.GEODERMA.2014.08.006.
Kay, B.D., and A.J. Vandenbygaart. 2002. Conservation tillage and depth stratification of porosity and soil organic matter. Soil Tillage Res. 66: 107–118. doi: 10.1016/S0167-1987(02)00019-3.
Keller, T. 2004. Soil compaction and soil tillage – studies in Agricultural Soil Mechanics. Doctoral dissertation. Swedish University of Agricultural Sciences, Uppsala.
Keller, T., and J. Arvidsson. 2006. Prevention of traffic-induced subsoil compaction in Sweden: Experiences from wheeling experiments. Arch. Agron. Soil Sci. 52(2): 207–222.
Keller, T., J. Arvidsson, J.. Dawidowski, and A.. Koolen. 2004. Soil precompression stress. Soil Tillage Res. 77(1): 97–108. doi: 10.1016/j.still.2003.11.003.
Keller, T., T. Colombi, S. Ruiz, M.P. Manalili, J. Rek, et al. 2017. Long-term Soil Structure Observatory for Monitoring Post-compaction Evolution of Soil Structure: Observatory Desing and Characterization of Initial Compaction Effects. Vadose Zo. J.: 1–26. doi: 10.2136/vzj2016.11.0118.

Kibblewhite, M.G., K. Ritz, and M.J. Swift. 2008. Soil health in agricultural systems. Philos. Trans. R. Soc. B Biol. Sci. 363(1492): 685–701. doi: 10.1098/rstb.2007.2178.

Kim, H., S.H. Anderson, P.P. Motavalli, and C.J. Gantzer. 2010. Compaction effects on soil macropore geometry and related parameters for an arable field. Geoderma 160(2): 244–251. doi: 10.1016/J.Geoderma.2010.09.030.

Kirby, J.M. 1991. Strength and deformation of agricultural soil: measurement and practical significance. Soil Use Manag. 7(4): 223–229.

Kirby, M. 2007. Whither soil compaction research? Letter to the Editor. Soil Tillage Res. 93(2): 472–475. doi: 10.1016/j.still.2006.04.008.

Kirby, J.M., and G.B. Blunden. 1992. Avoiding compaction: soil strength more important than vehicle ground pressure. Aust. Cott. Grow. 13(2): 48–50.

Kladivko, E. 2001. Tillage systems and soil ecology. Soil Tillage Res. 61(1–2): 61–76. doi: 10.1016/S0167-1987(01)00179-9.

Koch, H.J., H. Heuer, O. Tomanová, and B. Märländer. 2008. Cumulative effect of annually repeated passes of heavy agricultural machinery on soil structural properties and sugar beet yield under two tillage systems. Soil Tillage Res. 101(1–2): 69–77. doi: 10.1016/j.still.2008.07.008.

Kodešová, R., V. Jirků, M. Vít Kodeš, A. Mühlhanselová, and A.Ž. Nikodem. 2011. Soil structure and soil hydraulic properties of Haplic Luvisol used as arable land and grassland. Soil Tillage Res. 111(2): 154–161. doi: https://doi.org/10.1016/j.still.2010.09.007.

Kohnke, H. 1968. Soil physics. McGraw-Hill Inc, New York, NY.

Komatsuzaki, M., and H. Ohta. 2007. Soil management practices for sustainable agro-ecosystems. Sustain. Sci. 2(1): 103–120.

Kooistra, M.J., and N.K. Tovey. 1994. Effects of compaction on soil microstructure. In: Soane, B.D. and van Ouwerkerk, C., editors, Developments in Agricultural Engineering. Elsevier Science B.V. p. 91–111

Koolen, A.J. 1974. A method for soil compactibility determination. J. Agric. Eng. Res. 19(3): 271–278. doi: 10.1016/0021-8634(74)90066-3.

Koolen, A.J. 1994. Mechanics of soil compaction. In: Soane, B.D. and van Ouwerkerk, C., editors, Developments in Agricultural Engineering. Elsevier B.V. p. 23–44

Koolen, A.J., and H. Kuipers. 1983. Agricultural Soil Mechanics. Advanced Series in Agricultural Sciences 13 (D.F.R. Bommer, B.R. Sabey, G.W. Thomas, Y. Vaadia, and L.D. Van Vleck, editors). Springer-Verlag.

Koolen, A.J., P. Lerink, D.A.G. Kurstjens, J.J.H. van den Akker, and W.B.M. Arts. 1992. Prediction of aspects of soil-wheel systems. Soil Tillage Res. 24(4): 381–396. doi: 10.1016/0167-1987(92)90120-Z.

Kragt, M.E., and M.J. Robertson. 2014. Quantifying ecosystem services trade-offs from agricultural practices. Ecol. Econ. 102: 147–157. doi: 10.1016/j.ecolecon.2014.04.001.

Kremen, C., A. Iles, and C. Bacon. 2012. Diversified farming systems: an agroecological, systems-based alternative to modern industrial agriculture. Ecol. Soc. 17(4): 44. doi: 10.5751/ES-05103-170444.

Kroulík, M., F. Kumhála, J. Hůla, and I. Honzík. 2009. The evaluation of agricultural machines field trafficking intensity for different soil tillage technologies. Soil Tillage Res. 105(1): 171–175. doi: 10.1016/J.STILL.2009.07.004.

Kroulík, M., Z. Kvíz, F. Kumhála, J. Hůla, and T. Loch. 2011. Procedures of soil farming allowing reduction of compaction. Precis. Agric. 12(3): 317–333. doi: 10.1007/s11119-010-9206-1.

Kulkarni, S.G., S.G. Bajwa, and G. Huitink. 2010. Investigation of the effects of soil compaction in cotton. Trans. ASABE 53(3): 667–674.

Kutilek, M., and D.R. Nielsen. 1994. Soil hydrology: texbook for students of soil science, agriculture, forestry, geoecology, hydrology, geomorphology and other related disciplines. Catena Verlag, Cremlingen-Destedt, Germany.

L

Labelle, E.R., and D. Jaeger. 2012. Quantifying the use of brush mats in reducing forwarder peak loads and surface contact pressures. Croat. J. For. Eng. 33(2): 249–274.

Laboski, C.A.M., R.H. Dowdy, R.R. Allmaras, and J.A. Lamb. 1998. Soil strength and water content influences on corn root distribution in a sandy soil. Plant Soil 203(2): 239–247. doi: 10.1023/A:1004391104778.

Lal, R. 1991. Soil structure and sustainability. J. Sustain. Agric. 1(4): 37–41. doi: 10.1300/J064v01n04_06.

Lal, R. 1993. Tillage effects on soil degradation, soil resilience, soil quality, and sustainability. Soil Tillage Res. 27(1–4): 1–8. doi: 10.1016/0167-1987(93)90059-X.

Lal, R. 1996. Axle load and tillage effects on crop yields on a Mollic Ochraqualf in Northwest Ohio. Soil Tillage Res. 37(2–3): 143–160. doi: 10.1016/0167-1987(95)01004-1.

Lal, R. 1997. Degradation and resilience of Soils. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 352(1356): 997–1010.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science (80-.). 304(June): 1623–1627. www.sciencemag.org.

Lal, R. 2008. Soils and sustainable agriculture . A review. Agrononmy Sustain. Dev. 28: 57–64. doi: 10.1051/agro2007025.

Lamandé, M., and P. Schjønning. 2010. Transmission of vertical stress in a real soil profile. Part II: Effect of tyre size, inflation pressure and wheel load. Soil Tillage Res. 114: 71–77. doi: 10.1016/j.still.2010.08.011.

Lamandé, M., and P. Schjønning. 2018. Soil mechanical stresses in high wheel load agricultural field traffic: A case study. Soil Res. 56(2): 129–135. doi: 10.1071/SR17117.

Lamandé, M., D. Wildenschild, F.E. Berisso, A. Garbout, M. Marsh, et al. 2013. X-ray CT and laboratory measurements on glacial till subsoil cores: Assessment of inherent and compaction-affected soil structure characteristics. Soil Sci. 178(7): 359–368. doi: 10.1097/SS.0b013e3182a79e1a.

Lançon, J., J. Wery, B. Rapidel, M. Angokaye, E. Gérardeaux, et al. 2007. An improved methodology for integrated crop management systems. Agron. Sustain. Dev. 27(2): 101–110. doi: 10.1051/agro:2006037.

Larson, W.E., A. Eynard, A. Hadas, and J. Lipiec. 1994. Control and avoidance of soil compaction in practice. In: Soane, B.D. and van Ouwerkerk, C., editors, Developments in Agricultural Engineering. Elsevier Science B.V. p. 597–625

Lauer, J. 2002. Methods for Calculating Corn Yield. F. Crop. 28(January): 47–33. http://corn.agronomy.wisc.edu/AA/pdfs/A033.pdf.

Leakey, R.R.B. 2014. The role of trees in agroecology and sustainable agriculture in the tropics. Annu. Rev. Phytopathol. 52(1): 113–133. doi: 10.1146/annurev-phyto-102313-045838.

Lebert, M., N. Burger, and R. Horn. 1989. Effects of dynamic and static loading on compaction of structured soils. In: Larson, W.E., Blake, G.R., Allmaras, R.R., Voorhees, W.B., and Gupta, S.C., editors, Mechanics and Related Processes in Structured Agricultural Soils. NATO ASI Series (Series E: Applied Sciences). Springer, Dordrecht. p. 73–80

Li, T.C., M.A. Shao, and Y.H. Jia. 2016. Application of X-ray Tomography to quantify macropore characteristics of loess soil under two perennial plants. Eur. J. Soil Sci. 67(3): 266–275. doi: 10.1111/ejss.12330.

Li, C.H., and P.K.S. Tam. 1998. An iterative algorithm for minimum cross entropy thresholding. Pattern Recognit. Lett. 19(8): 771–776. doi: 10.1016/S0167-8655(98)00057-9.

Li, Y., J.N. Tullberg, and D.M. Freebairn. 2001. Traffic and residue cover effects on infiltration. Aust. J. Soil Res. 39(2): 239–247. http://www.publish.csiro.au/sr/SR00017.

Licht, M. 2014. Soybean growth and development. Iowa State University of Science and Technology Cooperative Extension Services.

Lichtfouse, E., M. Navarrete, P. Debaeke, V. Ere, C. Alberola, et al. 2009. Agronomy for

sustainable agriculture. A review. Agron. Sustain. Dev 29: 1–6. doi: 10.1051/agro:2008054.
Liebig, M.A., A.J. Jones, L.N. Mielke, and J.W. Doran. 1993. Controlled wheel traffic effects on soil properties in ridge tillage. Soil Sci. Soc. Am. J. 57(4): 1061–1066. doi: 10.2136/sssaj1993.03615995005700040030x.
Lindsay, W.L., and W.A. Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. 42: 421–428. doi: https://doi.org/10.2136/sssaj1978.03615995004200030009x.
Lindstrom, M.J., and W.B. Voorhees. 1994. Responses of temperate crops in North America to soil compaction. In: Soane, B.D., van O., editor, Developments in Agricultural Engineering. Elsevier B.V. p. 265–286
Lipiec, J., and R. Hatano. 2003. Quantification of compaction effects on soil physical properties and crop growth. Geoderma 116(1): 107–136. doi: 10.1016/S0016-7061(03)00097-1.
Lipiec, J., R. Horn, J. Pietrusiewicz, and A. Siczek. 2012. Effects of soil compaction on root elongation and anatomy of different cereal plant species. Soil Tillage Res. 121: 74–81. doi: 10.1016/j.still.2012.01.013.
Lipiec, J., J. Kuś, A. Słowińska-Jurkiewicz, and A. Nosalewicz. 2006. Soil porosity and water infiltration as influenced by tillage methods. Soil Tillage Res. 89(2): 210–220. doi: 10.1016/j.still.2005.07.012.
Lipiec, J., V. V Medvedev, M. Birkas, E. Dumitru, T.E. Lyndina, et al. 2003. Effect of soil compaction on root growth and crop yield in Central and Eastern Europe. Int. Agrophysics 17: 61–69.
Lipiec, J., and C. Simota. 1994. Role of soil and climate factors in influencing crop responses to soil compaction in Central and Eastern Europe. In: Soane, B.D. and van Ouwerkerk, C., editors, Developments in Agricultural Engineering. Elsevier B.V. p. 365–390
Lipper, L., P. Thornton, B.M. Campbell, T. Baedeker, A. Braimoh, et al. 2014. Climate-smart agriculture for food security. Nat. Clim. Chang. 4(12): 1068–1072. doi: 10.1038/nclimate2437.
Lowery, B., and R.T. Schuler. 1991. Temporal effects of subsoil compaction on soil strength and plant growth. Soil Sci. Soc. Am. J. 55(1): 216–223. doi: 10.2136/sssaj1991.03615995005500010037x.
Lowery, B., and R.T. Schuler. 1994. Duration and effects of compaction on soil and plant growth in Wisconsin. Soil Tillage Res. 29(2–3): 205–210. doi: 10.1016/0167-1987(94)90058-2.
Lu, S., X. Yu, and Y. Zong. 2019. Nano-microscale porosity and pore size distribution in aggregates of paddy soil as affected by long-term mineral and organic fertilization under rice-wheat cropping system. Soil Tillage Res. 186: 191–199. doi: 10.1016/j.still.2018.10.008.

M

Mangalassery, S., S. Sjögersten, D.L. Sparkes, C.J. Sturrock, J. Craigon, et al. 2014. To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils? Sci. Rep. 4(4586): 1–8. doi: 10.1038/srep04586.
Marcelino, V., V. Cnudde, S. Vansteelandt, and F. Carò. 2007. An evaluation of 2D-image analysis techniques for measuring soil microporosity. Eur. J. Soil Sci. 58(1): 133–140. doi: 10.1111/j.1365-2389.2006.00819.x.
Martínez, E., J.P. Fuentes, P. Silva, S. Valle, and E. Acevedo. 2008. Soil physical properties and wheat root growth as affected by no-tillage and conventional tillage systems in a Mediterranean environment of Chile. Soil Tillage Res. 99(2): 232–244. doi: 10.1016/j.still.2008.02.001.
McGarry, D., and G. Sharp. 2003. A rapid, immediate, farmer-usable method of assessing soil structure condition to support conservation agriculture. In: Garcia-Torres, L., Benites, J., Martinez-Vilela, A., and Holgado-Cabrera, editors, Conservation Agriculture. 1st ed. Kluwer Academic Publishers. p. 375–380

McHugh, A., J. Tullberg, and D. Freebairn. 2003. Effects of field traffic removal on hydraulic conductivity, plant available water and water capacity. Proceedings of the International Soil Tillage Research Organisation 16th Triennial conference. Brisbane, Australia. p. 717–723

McHugh, A.D., J.N. Tullberg, and D.M. Freebairn. 2009. Controlled traffic farming restores soil structure. Soil Tillage Res. 104(1): 164–172. doi: 10.1016/j.still.2008.10.010.

McKenzie, R. 2010. Agricultural soil compaction : causes and management. Agrifacts (October): 1–10. www. agriculture.alberta.ca (accessed 10 January 2019).

McKenzie, F.C., and J. Williams. 2015. Sustainable food production: constraints, challenges and choices by 2050. Food Secur. 7(2): 221–233. doi: 10.1007/s12571-015-0441-1.

McKyes, E., S. Negi, E. Douglas, F. Taylor, and V. Raghavan. 1979. The effect of machinery traffic and tillage operations on the physical properties of a clay and on yield of silage corn. J. Agric. Eng. Res. 24(2): 143–148. doi: 10.1016/0021-8634(79)90048-9.

McLean, E.O. 1982. Soil pH and lime requirement. In: A.L. Page et al., editor, Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI

McPhee, J.E., M.V. Braunack, A.L. Garside, D.J. Reid, and D.J. Hilton. 1995. Controlled traffic for irrigated double cropping in a semi-arid tropical environment: Part 2, tillage operations and energy use. J. Agric. Eng. Res. 60(3): 183–189. doi: 10.1006/jaer.1995.1012.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15(12): 1409–1416. doi: 10.1080/00103628409367568.

Merrill, S.D., D.L. Tanaka, and J.D. Hanson. 2002. Root Length Growth of Eight Crop Species in Haplustoll Soils. Soil Sci. Soc. Am. J. 66(3): 913–923. doi: 10.2136/sssaj2002.9130.

Michelin. 2017. Michelin Agriculture, because the land is a series of challenges! Tire technical data book: Michelin Agriculture and Compact Line. Manufacture Française des Pneumatiques Michelin, Clermont-Ferrand, France.

Millham, P.J., A.S. Awad, R.E. Paul, and J.H. Bull. 1970. Analysis of plants, soils and waters for nitrate by using an ion-selective electrode. Analyst 95: 751–759.

Millington, W.A.J. 2019. The effect of low ground pressure and controlled traffic farming systems on soil properties and crop development for three tillage systems. Ph.D. thesis. Harper Adams University, Newport, Shropshire, UK.

Millington, W.A.J., P.A. Misiewicz, E.T. Dickin, D.R. White, and R.J. Godwin. 2016. An investigation into the effect of soil compaction and tillage on plant growth and yield of winter barley (Hordeum vulgare L.). ASABE Annu. Int. Meet. Orlando, 17-20 July 2016. Pap. no. 1901979: 1–12. doi: 10.13031/aim.20162461725.

Misiewicz, P.A. 2010. The evaluation of the soil pressure distribution and carcass stiffness resulting from pneumatic agricultural tyres. Ph.D. thesis. Cranfield University, UK.

Misiewicz, P.A. 2016. Effect of conventional and control traffic farming and tillage systems on soil and crop development. Pap. Present. to Can. Visit. Harper Adams Univ. UK under “Current Res. Precis. farming”, 21 January, 2016.

Misra, R.K., and A.K. Gibbons. 1996. Growth and morphology of eucalypt seedling-roots, in relation to soil strength arising from compaction. Plant Soil 182(1): 1–11. doi: 10.1007/BF00010990.

Mooney, S.J. 2006. Three-dimensional visualization and quantification of soil macroporosity and water flow patterns using computed tomography. Soil Use Manag. 18(2): 142–151. doi: 10.1111/j.1475-2743.2002.tb00232.x.

Mooney, S.J., T.P. Pridmore, J. Helliwell, and M.J. Bennett. 2012. Developing X-ray computed tomography to non-invasively image 3-D root systems architecture in soil. Plant Soil 352(1–2): 1–22. doi: 10.1007/s11104-011-1039-9.

Morris, N.L., P.C.H. Miller, J.H. Orson, and R.J. Froud-Williams. 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment-A review. Soil Tillage Res. 108(1–2): 1–15. doi: 10.1016/j.still.2010.03.004.

Mueller, L., U. Schindler, N.R. Fausey, and R. Lal. 2003. Comparison of methods for estimating

maximum soil water content for optimum workability. Soil Tillage Res. 72(1): 9–20. doi: 10.1016/S0167-1987(03)00046-1.
Mueller, L., U. Schindler, W. Mirschel, T.G. Shepherd, B.C. Ball, et al. 2011. Assessing the productivity function of soils. In: Lichtfous, E., Hamelin, M., Navarrete, M., and Debaeke, P., editors, Sustainable Agriculture Volume 2. Springer, Dordrecht, Germany. p. 743–760
Munkholm, L.J., R.J. Heck, and B. Deen. 2013. Long-term rotation and tillage effects on soil structure and crop yield. Soil Tillage Res. 127: 85–91. doi: 10.1016/j.still.2012.02.007.
Munkholm, L.J., P. Schjønning, K.J. Rasmussen, and K. Tanderup. 2003. Spatial and temporal effects of direct drilling on soil structure in the seedling environment. Soil Tillage Res. 71(2): 163–173. doi: 10.1016/S0167-1987(03)00062-X.

N

Naeve, S.L. 2018. Soybean growth stages. Grow. Soybean, Univ. Minnesota Ext. https://extension.umn.edu/growing-soybean/soybean-growth-stages (accessed 26 February 2019).
Nafziger, E. 2009. Corn. Illinois Agronomy Handbook. College of Agricultural, Consumer, and Environmental Sciences University of Illinois at Urbana Champaign, Urbana IL. p. 13–26
Naghdi, R., and A. Solgi. 2014. Effects of skidder passes and slope on soil disturbance in two soil water contents. Croat. J. For. Eng. 35(1): 73–80.
Nawaz, M.F., G. Bourrié, and F. Trolard. 2013. Soil compaction impact and modelling. A review. Agron. Sustain. Dev. 33(2): 291–309. doi: 10.1007/s13593-011-0071-8.
Nazrul, M.I., M.R. Shaheb, A.H. Khan, M, and A.S.M.R. Khan. 2013. On-Farm evaluation of production potential and economic returns of potato-rice based improved cropping system. Bangladesh Agron. J. 16(2): 41–50.
Negi, S.C., E. Mckyes, G. Raghavan, and F. Taylor. 1981. Relationships of field traffic and tillage to corn yields and soil properties. J. ofTerramechanics 18(2): 81–90.
Nimmo, J.R. 2013. Porosity and pore size distribution, Reference Module in Earth Systems and Environmental Sciences. Encycl. Soils Environ. Elsevier: 295–303. doi: 10.1016/B978-0-12-409548-9.05265-9.
Nkonya, E., N. Gerber, P. Baumgartner, A. De Pinto, V. Graw, et al. 2011. The economics of desertification, land degradation, and drought.

O

O'Sullivan, M.F., and C. Simota. 1995. Modelling the environmental impacts of soil compaction: a review. Soil Tillage Res. 35(1–2): 69–84. doi: 10.1016/0167-1987(95)00478-B.
Oldeman, L.R. 1992. Global extent of soil degradation. Wageningen, The Netherlands.
Oldeman, L.R., R.T.A. Hakkeling, and W.G. Sombroek. 1991. World map of the status of human-induced soil degradation: an explanatory note. Global assessment of soil degradation (GLASOD). Wageningen, The Netherlands.

P

Pagliai, M., A. Marsili, P. Servadio, N. Vignozzi, and S. Pellegrini. 2003. Changes in some physical properties of a clay soil in Central Italy following the passage of rubber tracked and wheeled tractors of medium power. Soil Tillage Res. 73(1–2): 119–129. doi: 10.1016/S0167-1987(03)00105-3.
Pagliai, M., and N. Vignozzi. 2002. The soil pore system as an indicator of soil quality. Sustainable Land Management—Environmental Protection—A Soil Physical Approach, Advances in GeoEcology. Catena Verlag, Reiskirchen. p. 69–80
Papadopoulos, A., N.R.A. Bird, A.P. Whitmore, and S.J. Mooney. 2009. Investigating the effects of organic and conventional management on soil aggregate stability using X-ray computed tomography. Eur. J. Soil Sci. 60(3): 360–368. doi: 10.1111/j.1365-2389.2009.01126.x.

Parikh, S.J., and B.R. James. 2012. Soil: The Foundation of Agriculture. Nat. Educ. Knowl. 3(10): 2. https://www.nature.com/scitable/knowledge/library/soil-the-foundation-of-agriculture-84224268.

Peng, S., Q. Hu, S. Dultz, and M. Zhang. 2012. Using X-ray computed tomography in pore structure characterization for a Berea sandstone: Resolution effect. J. Hydrol. 472–473: 254–261. doi: 10.1016/j.jhydrol.2012.09.034.

Pereira, P., I. Bogunovic, M. Munoz-Rojas, and E.C. Brevik. 2018. Soil ecosystem services, sustainability, valuation and management. Curr. Opin. Environ. Sci. Heal. 5: 7–13. doi: 10.1016/j.coesh.2017.12.003.

Peters, J.B., M. V. Nathan, and C.A.M. Laboski. 2015. pH and Lime Requirement. Recommended chemical soil test procedures for the North Central Region (North Central Regional Research publication no. 221, revised). Missouri Agricultural Experiment Station SB 1001, Columbia, MO. p. 4.1-4.7

Petrovic, A.M., J.E. Siebert, and P.E. Rieke. 1982. Soil bulk density analysis in three dimensions by computed tomographic scanning. Soil Sci. Soc. Am. J. 46(3): 445–450. doi: 10.2136/sssaj1982.03615995004600030001x.

Pires, L.F., A.C. Auler, W.L. Roque, and S.J. Mooney. 2020. X-ray Microtomography analysis of soil pore structure dynamics under wetting and drying cycles. Geoderma 362(January): 114103. doi: 10.1016/j.geoderma.2019.114103.

Pires, L.F., O.O.S. Bacchi, K. Reichardt, and L.C. Timm. 2005. Application of gamma ray computed tomography to analysis of soil structure before density evaluations. Appl. Radiat. Isot. 63: 505–511. doi: 10.1016/j.apradiso.2005.03.019.

Pires, L.F., J.A. Borges, O.O. Bacchi, and K. Reichardt. 2010. Twenty-five years of computed tomography in soil physics: A literature review of the Brazilian contribution. Soil Tillage Res. 110: 197–210. doi: 10.1016/j.still.2010.07.013.

Pires, L.F., J.A.R. Borges, J.A. Rosa, M. Cooper, R.J. Heck, et al. 2017. Soil structure changes induced by tillage systems. Soil Tillage Res. 165: 66–79. doi: 10.1016/j.still.2016.07.010.

Pretty, J.N. 1997. The sustainable intensification of agriculture. Nat. Resour. Forum 21(4): 247–256. doi: 10.1111/j.1477-8947.1997.tb00699.x.

Pretty, J. 2008. Agricultural sustainability: Concepts, principles and evidence. Philos. Trans. R. Soc. B 363(1491): 447–465. doi: 10.1098/rstb.2007.2163.

Pulido-Moncada, M., L.J. Munkholm, and P. Schjønning. 2019. Wheel load, repeated wheeling, and traction effects on subsoil compaction in northern Europe. Soil Tillage Res. 186: 300–309. doi: 10.1016/j.still.2018.11.005.

R

Rab, M.A., R.E. Haling, S.R. Aarons, M. Hannah, I.M. Young, et al. 2014. Evaluation of X-ray Computed Tomography for quantifying macroporosity of loamy pasture soils. Geoderma 213: 460–470. doi: 10.1016/J.Geoderma.2013.08.037.

Rachman, A., S.H. Anderson, and C.J. Gantzer. 2005. Computed-Tomographic measurement of soil macroporosity parameters as affected by stiff-stemmed grass hedges. Soil Sci. Soc. Am. J. 69(5): 1609–1616. doi: 10.2136/sssaj2004.0312.

Radford, B.J., D.F. Yule, D. McGarry, and C. Playford. 2001. Crop responses to applied soil compaction and to compaction repair treatments. Soil Tillage Res. 61(3–4): 157–166. doi: 10.1016/S0167-1987(01)00194-5.

Radford, B.J., D.F. Yule, D. McGarry, and C. Playford. 2007. Amelioration of soil compaction can take 5 years on a Vertisol under no till in the semi-arid subtropics. Soil Tillage Res. 97(2): 249–255. doi: 10.1016/j.still.2006.01.005.

Raghavan, G.S.V., P. Alvo, and E. McKyes. 1990. Soil compaction in agriculture: a view toward managing the problem (R. Lal and B.A. Stewart, editors). Springer, New York, NY.

Raghavan, G.S.V., E. McKyes, I. Amir, M. Chasse, and R.S. Broughton. 1976. Prediction of soil

compaction due to off-road vehicle traffic. Trans. ASAE 19(4): 610–613.
Raghavan, G.S.V., E. McKyes, R. Baxter, and G. Gendron. 1979a. Traffic-soil-plant (maize) relations. J. Terramechanics 16(4): 181–189. doi: 10.1016/0022-4898(79)90027-2.
Raghavan, G.S.V., E. McKyes, F. Taylor, P. Richard, and A. Watson. 1979b. The relationship between machinery traffic and corn yield reductions in successive years. Trans. ASAE [American Soc. Agric. Eng. 22(6): 1256–1259.
Raghavan, G.S.V., E. McKyes, F. Taylor, P. Richard, and A. Watson. 1979c. Vehicular traffic effects on development and yield of corn (maize). J. Terramechanics 16(2): 69–76. doi: 10.1016/0022-4898(79)90002-8.
Rahman, S. 2015. Green Revolution in India: Environmental degradation and impact onlLivestock. Asian J. Water, Environ. Pollut. 12(1): 75–80. https://content.iospress.com/articles/asian-journal-of-water-environment-and-pollution/ajw12-1-11.
Raper, R.L. 2005. Agricultural traffic impacts on soil. Journal of Terramechanics. p. 259–280
Raper, R.L., and J. Mac Kirby. 2006. Soil compaction: how to do it, undo it, or avoid doing it. Agric. Equip. Technol. Conf. (913): 1–15.
Reeves, D.W., H.H. Rogers, J.A. Droppers, S.A. Prior, and J.B. Powell. 1992. Wheel-traffic effects on corn as influenced by tillage system. Soil Tillage Res. 23(1–2): 177–192. doi: 10.1016/0167-1987(92)90013-2.
Reganold, J.P., and J.M. Wachter. 2016. Organic agriculture in the twenty-first century. Nat. plants 2(February): 1–8. doi: 10.1038/nplants.2015.221.
Renius, K.T. 1994. Trends in tractor design with particular reference to Europe. J. Agric. Eng. Res. 57: 3–22. https://eurekamag.com/pdf/002/002536241.pdf.
Rickson, R.J., L.K. Deeks, R. Corstanje, P. Newell-Price, M.G. Kibblewhite, et al. 2012. Indicators of soil quality - physical properties (SP1611). Final report to DEFRA. Cranfield University and ADAS, UK. Cranfield, UK, 1-45. http://randd.defra.gov.uk.
Ridge, R. 2002. Trends in sugarcane mechanization. Int. sugar J. 104(1240): 164–166.
Riley, H. 1994. The effect of traffic at high axle load on crop yields on a loam soil in Norway. Soil Tillage Res. 29(2): 211–214. doi: 10.1016/0167-1987(94)90059-0.
Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1993. How a corn plant develops. Special Re. Iowa State University of Science and Technology Cooperative Extension Services, Ames, IW.
Rose, D.C., W.J. Sutherland, A.P. Barnes, F. Borthwick, C. Ffoulkes, et al. 2019. Integrated farm management for sustainable agriculture : Lessons for knowledge exchange and policy Land Use Policy Integrated farm management for sustainable agriculture : Lessons for knowledge exchange and policy. Land use policy 81(December 2018): 834–842. doi: 10.1016/j.landusepol.2018.11.001.
Rosolem, C.., J.S.. Foloni, and C.. Tiritan. 2002. Root growth and nutrient accumulation in cover crops as affected by soil compaction. Soil Tillage Res. 65(1): 109–115. doi: 10.1016/S0167-1987(01)00286-0.
Rosolem, C.A., and M. Takahashi. 1998. Soil compaction and soybean root growth. In: Box, J.E., editor, Root Demographics and their Efficiencies in Sustainable Agriculture, Grasslands and Forest Ecosystems. Proceedings of the 5th Symposium of the Interna- tional Society of Root Research. Springer, Clemson, South Carolina. p. 295–304
Rusanov, V.A. 1991. Effects of wheel and track traffic on the soil and on crop growth and yield. Soil Tillage Res. 19(2–3): 131–143. doi: 10.1016/0167-1987(91)90082-9.
Russell, E.W. 1988. Russell's soil conditions and plant growth. 11th ed. Longman Scientific & Technical, Harlow, England.

S

Sadras, V.O., F.J. Villalobos, and F. Fereres. 2016. Crop development and growth. In: Villalobos, F. and Fereres, E., editors, Principles of Agronomy for Sustainable Agriculture. Springer,

Cham. p. 141–158
Sakai, H., T. Nordfjell, K. Suadicani, B. Talbot, and E. Bøllehuus. 2008. Soil compaction on forest soils from different kinds of tires and tracks and possibility of accurate estimate. Croat. J. For. Eng. 29(1): 15–27.
Salokhe, V.M., and N.T. Ninh. 1993. Modelling soil compaction under pneumatic tyres in clay soil. J. Terramechanics 30(2): 63–75. doi: 10.1016/0022-4898(93)90020-X.
Sanjai, B., and W. Resources. 2014. Soil : The Foundation of Agriculture Agriculture and Human Society. Nat. Educ. Knowl. Proj. (Trigger 2003): 1–12.
Sassenrath, G.F., P. Heilman, E. Luschei, G.L. Bennett, G. Fitzgerald, et al. 2008. Technology, complexity and change in agricultural production systems. Renew. Agric. Food Syst. 23(4): 285–295. doi: 10.1017/S174217050700213X.
Schäfer-Landefeld, L., R. Brandhuber, S. Fenner, H.-J. Koch, and N. Stockfisch. 2004. Effects of agricultural machinery with high axle load on soil properties of normally managed fields. Soil Tillage Res. 75(1): 75–86. doi: 10.1016/S0167-1987(03)00154-5.
Schafer, R.L., C.E. Johnson, A.J. Koolen, S.C. Gupta, and R. Horn. 1992. Future research needs in soil compaction. 35(December): 1761–1770.
Schäffer, B., M. Stauber, R. Müller, and R. Schulin. 2007. Changes in the macro-pore structure of restored soil caused by compaction beneath heavy agricultural machinery: A morphometric study. Eur. J. Soil Sci. 58(5): 1062–1073. doi: 10.1111/j.1365-2389.2007.00886.x.
Schindelin, J., I. Arganda-Carreras, E. Frise, V. Kaynig, M. Longair, et al. 2012. Fiji: an open-source platform for biological-image analysis. Nat. Methods 9(7): 676–82. doi: 10.1038/nmeth.2019.
Schjønning, P., J.J.H. van den Akker, T. Keller, M.H. Greve, M. Lamandé, et al. 2015. Driver-Pressure-State-Impact-Response (DPSIR) analysis and risk assessment for soil compaction-A European perspective. Advances in Agronomy. Elsevier Inc. p. 183–237
Schnitkey, G.D., and K. Swanson. 2019. Weekly farm economics: Release of 2020 crop budgets, revised 2019 Budgets, and up-dated revenues and costs. Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, July 16, 2019. farmdocDaily 9(130): 1–5. https://farmdocdaily.illinois.edu/2019/07/release-of-2020-crop-budgets-revised-2019-budgets- and-up-dated-revenues-and-costs.html.
Schoonover, J.E., and J.F. Crim. 2015. An introduction to soil concepts and the role of soils in watershed management. J. Contemp. Water Res. Educ. 154(1): 21–47. doi: 10.1111/j.1936-704x.2015.03186.x.
Schuler, R.T., W.W. Casady, and R.L. Raper. 2000. Soil compaction. In: Reeder, R., editor, Conservation tillage systems and management : crop residue management with no-till, ridge-till, mulch-till, and strip-till. MidWest Plan Services, Iowa State University, Ames, IA. p. 69–75
Schulte, E.E., and B.G. Hopkins. 1996. Estimation of soil organic matter by weight loss-on-ignition. In: Magdoff, F.R., Tabatasbai, M.A., and Hanlon Jr., E.A., editors, Soil organic matter: Analysis and interpretation (Special Publication No. 46). ASA, CSSA and SSSA, Madison, WI. p. 21–31
Schwab, G.J., L.W. Murdock, and L.G. Wells. 2004. Assessing and Preventing Soil Compaction in Kentucky. Univ. Kentuky Coop. Ext. Serv. ID-153.: 1–4.
Scialabba, N.E.H., and M. Mller-Lindenlauf. 2010. Organic agriculture and climate change. Renew. Agric. Food Syst. 25(2): 158–169. doi: 10.1017/S1742170510000116.
Scott, H.D. 2000. Soil physics: agricultural and environmental applications (H.D. Scott, editor). 1st ed. Iowa State University Press, Ames, IW.
Searchinger, T., C. Hanson, B. Lipinski, R. Waite, R. Winterbottom, et al. 2013. Creating a sustainable food future, a menu of solutions to sustainably feed more than 9 billion people by 2050.

Seehusen, T., T. Børresen, B.I. Rostad, H. Fleige, H. Zink, et al. 2014. Verification of traffic-induced soil compaction after long-term ploughing and 10 years minimum tillage on clay loam soil in South-East Norway. Acta Agric. Scand. Sect. B — Soil Plant Sci. 64(4): 312–328. doi: https://doi.org/10.1080/09064710.2014.907582.

Shaheb, M., M. Nazrul, and M. Sarker. 2014. Production potentials and economics of chickpea-rice based cropping system in Sylhet area (AEZ 20). Bangladesh J. Agric. Res. 39(3): 479–490.

Shaheb, M., M. Nazrul, and A. Sarker. 2016. Improvement of livelihood, food and nutrition security through homestead vegetables production and fruit tree management in Bangladesh. J. Bangladesh Agric. Univ. 12(2): 377–387. doi: 10.3329/jbau.v12i2.28698.

Sharifi, A., R.J. Godwin, M.J. O'Dogherty, and M.L. Dresser. 2007. Evaluating the performance of a soil compaction sensor. Soil Use Manag. 23(2): 171–177. doi: 10.1111/j.1475-2743.2007.00087.x.

Shen, J., Z. Cui, Y. Miao, G. Mi, H. Zhang, et al. 2013. Transforming agriculture in China: From solely high yield to both high yield and high resource use efficiency. Glob. Food Sec. 2(1): 1–8. doi: 10.1016/j.gfs.2012.12.004.

Sidhu, D., and S.W. Duiker. 2006. Soil compaction in conservation tillage: crop impacts. Agron. J. 98(5): 1257–1264. doi: 10.2134/agronj2006.0070.

Silva, A.P. da, L.C. Babujia, J.C. Franchini, R. Ralisch, M. Hungria, et al. 2014. Soil structure and its influence on microbial biomass in different soil and crop management systems. Soil Tillage Res. 142: 42–53. doi: 10.1016/j.still.2014.04.006.

Simmons, F.W., and E.D. Nafziger. 2009. Soil management and tillage. In: Nafziger, E.D., editor, Illinois Agronomy Handbook. 24th ed. University of Illinois at Urbana-Champaign, College of Agriculture, Cooperative Extension Service, Urbana IL. p. 133–142

Sindelar, M. 2015. Soils Support Agriculture-Soil Science Society of Amerial. (March): 1–2. https://www.soils.org/files/sssa/iys/march-soils-overview.pdf (accessed 5 February 2019).

Six, J., E.T. Elliott, and K. Paustian. 2000. Soil structure and soil organic matter II. A normalized stability index and the effect of mineralogy. Soil Sci. Soc. Am. J. 64(3): 1042–1049. doi: 10.2136/sssaj2000.6431042x.

Smith, D.L.O. 1987. Measurement, interpretation and modelling. 3(3): 87–93.

Smith, V.L. 2016. The effect of tillage depth and compaction level on earthworm density. B.Sc. thesis. Harper Adams University, Newport, UK.

Smith, E.K., P.A. Misiewicz, K. Chaney, D.R. White, and R.J. Godwin. 2014a. Effect of tracks and tyres on soil physical properties in a sandy loam soil. ASABE and CSBE/SCGAB Annual International Meeting, Montreal, Canada, July 13-16, 2014, Paper no. 141912659. American Society of Agricultural and Biological Engineers. p. 1–7

Smith, E.K., P.A. Misiewicz, V. Girardello, S. Arslan, K. Chaney, et al. 2014b. Effects of traffic and tillage on crop yield (winter wheat Triticum aestivum) and the physical properties of a sandy loam soil. ASABE and CSBE/SCGAB Annual International Meeting, Montreal, Canada, July 13-16, 2014, Paper no. 141912652. American Society of Agricultural and Biological Engineers. p. 1–14

Soane, B.D., B.C. Ball, J. Arvidsson, G. Basch, F. Moreno, et al. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil Tillage Res. 118: 66–87. doi: 10.1016/j.still.2011.10.015.

Soane, B.D., P.S. Blackwell, J.W. Dickson, and D.J. Painter. 1980. Compaction by agricultural vehicles: A review I. Soil and wheel characteristics. Soil Tillage Res. 1: 207–237. doi: 10.1016/0167-1987(80)90026-4.

Soane, B.D., P.S. Blackwell, J.W. Dickson, and D.J. Painter. 1981. Compaction by agricultural vehicles: A review II. Compaction under tyres and other running gear. Soil Tillage Res. 1(C): 373–400. doi: 10.1016/0167-1987(80)90039-2.

Soane, B.D., J.W. Dickson, and D.J. Campbell. 1982. Compaction by agricultural vehicles: A

review III. Incidence and control of compaction in crop production. Soil Tillage Res. 2(1): 3–36. doi: 10.1016/0167-1987(82)90030-7.
Soane, G., R. Godwin, M. Marks, and G. Spoor. 1987. Crop and soil response to subsoil loosening, deep incorporation of phosphorus and potassium fertilizer and subsequent soil management on a range of soil types.: Part 1: Response of arable crops. Soil Use Manag. 3(3): 123–130. doi: 10.1111/j.1475-2743.1987.tb00720.x.
Soane, G.C., R.J. Godwin, and G. Spoor. 1986. Influence of deep loosening techniques and subsequent wheel traffic on soil structure. Soil Tillage Res. 8: 231–237. doi: 10.1016/0167-1987(86)90336-3.
Soane, B.D., and C. van Ouwerkerk. 1994a. Soil compaction in crop production. Dev. Agric. Eng. 11: 1–662. https://www.sciencedirect.com/bookseries/developments-in-agricultural-engineering/vol/11/suppl/C (accessed 2 March 2018).
Soane, B.D., and C. van Ouwerkerk. 1994b. Soil compaction problems in world agriculture. In: Soane, B.D. and Ouwerkerk, C. van, editors, Soil compaction in crop production. Developments in Agricultural Engineering. Elsevier Science B.V. p. 1–21
Soane, B.D., and C. van Ouwerkerk. 1995a. Implications of soil compaction in crop production for the quality of the environment. Soil Tillage Res. 35(1–2): 5–22. doi: 10.1016/0167-1987(95)00475-8.
Soane, B.D., and C. van Ouwerkerk. 1995b. Implications of soil compaction in crop production for the quality of the environment. Soil Tillage Res. 35(1–2): 5–22. doi: 10.1016/0167-1987(95)00475-8.
Soane, B.D., and C. van Ouwerkerk. 1998. Soil compaction: A global threat to sustainable land use. Adv. Geoecology 31(1): 517–526.
Söchtig, W., and O. Larink. 1992. Effect of soil compaction on activity and biomass of endogeic lumbricids in arable soils. Soil Biol. Biochem. 24(12): 1595–1599. doi: 10.1016/0038-0717(92)90156-R.
Sohne, W. 1958. Fundamentals of pressure distribution and soil compaction under tractor tires. Agric. Eng. 39(5): 276–290.
Solgi, A., R. Naghdi, E.R. Labelle, P.A. Tsioras, and M. Nikooy. 2016. Effect of varying machine ground pressure and traffic frequency on the physical properties of clay loam soils located in mountainous forests. Int. J. For. Eng. 27(3): 161–168.
Sommer, C., and M. Zach. 1992. Managing traffic-induced soil compaction by using conservation tillage. Soil Tillage Res. 24(4): 319–336. doi: 10.1016/0167-1987(92)90117-T.
Spoor, G. 2006. Alleviation of soil compaction: Requirements, equipment and techniques. Soil Use Manag. 22(2): 113–122. doi: 10.1111/j.1475-2743.2006.00015.x.
Spoor, G., and R.J. Godwin. 1978. An experimental investigation into the deep loosening of soil by rigid tines. J. Agric. Eng. Res. 23(3): 243–258. doi: 10.1016/0021-8634(78)90099-9.
Spoor, G., and R.J. Godwin. 1981. Overcoming compaction. Soil Water 9: 11–13.
Spoor, G., F.G.J. Tijink, and P. Weisskopf. 2003. Subsoil compaction: Risk, avoidance, identification and alleviation. Soil and Tillage Research. p. 175–182
SSSA. 2008. Glossary of Soil Science Terms 2008. Soil Science Society of America Journal. Soil Science Society of America, Madison, Wisconsin. p. 1–82
Stavi, I., and R. Lal. 2015. Achieving zero net land degradation: Challenges and opportunities. J. Arid Environ. 112: 44–51. doi: 10.1016/j.jaridenv.2014.01.016.
Stranks, S.N. 2006. The effects of tyre systems on the depth and severity of compaction. MSc. thesis, Cranfield University, UK.
Subedi, K.D., and B.L. Ma. 2005. Nitrogen uptake and partitioning in stay-green and leafy maize hybrids. Crop Sci. 45(2): 740–747. doi: 10.2135/cropsci2005.0740.
Sudibyo, A. 2011. Soil compaction. : 1–29. ftp://ftp.fao.org/agl/emailconf/soilmoisture/docs/Soil_compaction_DEF.pdf.

T

Taina, I.A., R.J. Heck, and T.R. Elliot. 2008. Application of X-ray Computed Tomography to soil science: a literature review. Can. J. Soil Sci. 88: 1–20. doi: 10.4141/cjss06027.

Taud, H., R. Martinez-Angeles, J.F. Parrot, and L. Hernandez-Escobedo. 2005. Porosity estimation method by X-ray Computed Tomography. J. Pet. Sci. Eng. 47(3–4): 209–217. doi: 10.1016/J.Petrol.2005.03.009.

Taylor, H.M., and H.R. Gardner. 1963. Penetration of cotton seedlings taproots as influenced by bulk density, moisture content, and strength of soil. Soil Sci. 96(3): 153–156.

Taylor, H.M., G.M. Roberson, and J.J.J.R. Parker. 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Sci. 102(1): 18–22.

Tebrugge, F., and R.A. During. 1999. Reducing tillage intensity — a review of results from a long-term study in Germany. Soil Tillage Res. 53(1): 15–28. doi: 10.1016/S0167-1987(99)00073-2.

Tijink, F.G.J., H. Döll, and G.D. Vermeulen. 1995. Technical and economic feasibility of low ground pressure running gear. Soil Tillage Res. 35(1–2): 99–110. doi: 10.1016/0167-1987(95)00477-A.

Tillage & Soils. 2020. Michelin XeoBib tyres clocking up the hours for RM Simpson. Tillage Soils Mag. Farm Smart Publ. Limited, Kill. Hall Farm, UK. http://tillagemagazine.net/michelin-xeobib-tyres-clocking-hours-rm-simpson/ (accessed 11 January 2020).

Tokatlidis, I.S., and S.D. Koutroubas. 2004. A review of maize hybrids' dependence on high plant populations and its implications for crop yield stability. F. Crop. Res. 88(2–3): 103–114. doi: 10.1016/j.fcr.2003.11.013.

Towers, W., I.C. Grieve, G. Hudson, C.D. Campbell, A.Lilly, et al. 2006. Scotland's soil resource – current state and threats. Edinburgh.

Tracy, S.R., C.R. Black, J.A. Roberts, C. Sturrock, S. Mairhofer, et al. 2012. Quantifying the impact of soil compaction on root system architecture in tomato (Solanum lycopersicum) by X-ray micro-computed tomography. Ann. Bot. 110(2): 511–519. doi: 10.1093/aob/mcs031.

Tranter, G., B. Minasny, A.B. Mcbratney, B. Murphy, N.J. Mckenzie, et al. 2007. Building and testing conceptual and empirical models for predicting soil bulk density. Soil Use Manag. 23(4): 437–443. doi: 10.1111/j.1475-2743.2007.00092.x.

Trautner, A., and J. Arvidsson. 2003. Subsoil compaction caused by machinery traffic on a Swedish Eutric Cambisol at different soil water contents. Soil Tillage Res. 73(1–2): 107–118. doi: 10.1016/S0167-1987(03)00104-1.

Trükmann, K., E. Reintam, J. Kuht, E. Nugis, and L. Edesi. 2008. Effect of soil compaction on growth of narrow – leafed lupine , oilseed rape and spring barley on sandy loam soil. Agron. Res. 6(1): 101–108. http://www.eau.ee/~agronomy/vol061/p6110.pdf.

Tullberg, J.N. 2000. Wheel traffic effects on tillage draught. J. Agric. Eng. Res. 75(4): 375–382. doi: http://dx.doi.org/10.1006/jaer.1999.0516.

Tullberg, J. 2010. Tillage, traffic and sustainability-A challenge for ISTRO. Soil Tillage Res. 111(1): 26–32. doi: 10.1016/j.still.2010.08.008.

Tullberg, J.N., D.F. Yule, and D. McGarry. 2007. Controlled traffic farming-From research to adoption in Australia. Soil Tillage Res. 97(2): 272–281. doi: 10.1016/j.still.2007.09.007.

U

Udawatta, R.P., and S.H. Anderson. 2008. CT-measured pore characteristics of surface and subsurface soils influenced by agroforestry and grass buffers. Geoderma 145(3–4): 381–389. doi: 10.1016/J.Geoderma.2008.04.004.

United Nations. 2018. The Sustainable Development Goals Report 2018. New York, NY.

University of Wisconsin. 2010. Taking a stand count in corn and soybeans. UW Discov. Farms Progr. (May 26). doi: .1037//0033-2909.I26.1.78.

USDA ERS. 2016. Corn production practices report for 2016. Agricultural Resource Management

Survey (ARMS). St. Louis, MO.
USDA ERS. 2017. Soil tillage and crop rotation. https://www.ers.usda.gov/topics/farm-practices-management/crop-livestock-practices/soil-tillage-and-crop-rotation/ (accessed 10 February 2019).
USDA NASS. 2018a. Illinois agricultural statistics 2017 annual bulletin. (September): 42. http://www.nass.usda.gov/Publications/Ag_Statistics/.
USDA NASS. 2018b. November crop production: Executive summary. National Agricultural Statistics Service, United States Department of Agriculture.
USDA NASS. 2019a. Soybean Production Up in 2018, USDA Reports. (08 February): 1–2. https://www.nass.usda.gov/Newsroom/2019/02-08-2019.php.
USDA NASS. 2019b. Soybean Production Up in 2018, USDA Reports. (08 February): 1–2.
USDA NRCS. 1996. Soil Quality Indicators: Aggregate Stability USDA Natural Resources Conservation Service What are soil aggregates? Washington.
USDA NRCS. 2004a. Understanding soil risks and hazards using soil survey to identify areas with risks and hazards to human life and property. Lincoln, Nebraska. Date assessed 2019-10-12.
USDA NRCS. 2004b. Soil biology and land management. Soil Quality - Soil Biology, Technical Note no. 4.
USDA NRCS. 2015a. Custom soil resource report for Champaign County, Illinois. United States Department of Agriculture. Natural Resources.
USDA NRCS. 2015b. Soil survey of Champaign County, Illinois.
USDA NRCS. 2018. Soil health: Role of soil organic matter. https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/health/mgnt/?cid=nrcs142p2_053859 (accessed 15 October 2018).
USDA NRCS. 2019a. Soil health. Soils. https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/ (accessed 8 February 2019).
USDA NRCS. 2019b. Drummer - Illinois State Soil. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/il/soils/surveys/?cid=nrcs141p2_030689, Accss date 2019/10/12.
USDA NRCS. 2019c. Soil quality concepts overview. Soil Qual. https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/co/home/?cid=nrcs144p2_063020 (accessed 1 January 2019).
USDA NRCS. 2019d. Soil Health-Guides for Educators: Soil bulk density/moisture/aeration. United States Department of Agriculture - Natural Resources Conservation Service.

V

Van-camp, L., B. Bujarrabal, A.R. Gentile, R.J.A. Jones, L. Montanarella, et al. 2004. Reports of the technical working groups established under the thematic strategy for soil protection. EUR 21319 EN/1. Luxembourg.
Van den Akker, J.J.H. 1998. Prevention of subsoil compaction by defining a maximum wheel load bearing capacity. In: Märländer, B., Tijink, F., Hoffmann, C., and Beckers, R., editors, Soil compaction and compression in relation to sugar beet production. Advances in Sugar Beet Research, IIRB,. International Institute for Beet Research, Brussels, Belgium. p. 43–54
Van den Akker, J.J.H. 2006. Evaluation of soil physical quality of Dutch subsoils in two databases with some threshold values. In: Horn, R., Fleige, H., Peth, S., and Peng, X., editors, Soil Management for Sustainability (Advances in GeoEcology; No. 38). Catena Verlag, Reiskirchen, Germany. p. 490–497
Van den Akker, J.J.H., W.B.M. Arts, A.J. Koolen, and H.J. Stuiver. 1994. Comparison of stresses, compactions and increase of penetration resistances caused by a low ground pressure tyre and a normal tyre. Soil Tillage Res. 29(2–3): 125–134. doi: 10.1016/0167-1987(94)90048-5.
Van den Akker, J.J.H., and B. Soane. 2004. Compaction. In: Hillel, D., editor, Encyclopedia of

Soils in the Environment. p. 285–293
Van Ouwerkerk, C., and B.D. Soane. 1995. Soil compaction and the environment. Soil Tillage Res. 35(Special issue): 1–113.
Van roekel, R.J., and L.C. Purcell. 2016. Understanding and increasing soybean yields. Proceedings of the 28th Annual Integrated Crop Management Conference. p. 31–35
Vaz, C.M.P., I.C. de Maria, P.O. Lasso, and M. Tuller. 2011. Evaluation of an advanced benchtop micro-computed tomography system for quantifying porosities and pore-size distributions of two Brazilian Oxisols. Soil Sci. Soc. Am. J. 75(3): 832. doi: 10.2136/sssaj2010.0245.
Vermeulen, G.D., and U.D. Perdok. 1994. Benefits of low ground pressure tyre equipment. In: Soane, B.D. and van Ouwerkerk, C., editors, Developments in Agricultural Engineering. Elsevier B.V. p. 447–478
Voorhees, W.B. 1979. Energy aspects of controlled wheel traffic in the northern corn belt of the United States. 8th Conf. Int. Soil Tillage Research Organisation (ISTRO). Vol. 2. ISTRO, Stuttgart, Germany. p. 333–338
Voorhees, W.B. 2000. Long-term effects of subsoil compaction on yield of maize. Adv. GeoEcol. 32: 331–338.
Voorhees, W.B., S.D.E. And, and D.D. Warnes. 1985. Effect of preplant wheel traffic on soil compaction, water use, and growth of spring wheat. Soil Sci. Soc. Am. J. 49(1): 215–220.
VSN International. 2015. Genstat for Windows 18th Edition. VSN International, Hemel Hempstead. VSN International Ltd., Hertfordshire, UK.

W

Ward, R.C., and M. Robinson. 2000. Principles of hydrology. 4th ed. Maidenhead: McGraw- Hill.
Warncke, D., and J.R. Brown. 2015. Potassium and other basic cations. Recommended chemical soil test procedures for the North Central Region (North Central Regional Research publication no. 221, revised). Missouri Agricultural Experiment Station SB 1001, Columbia, MO. p. 7.1-7.3
Warner, D.J., R. Stobart, N. Morris, J. Tzilivakis, A. Green, et al. 2016. Crop specific implications of yield and energy use efficiency in non-inversion tillage systems. Proceedings Crop Protection in Northern Britain 2016. p. 17–22
Watson, M.E. 2015. Boron. Recommended chemical soil test procedures for the North Central Region (North Central Regional Research publication no. 221, revised). Missouri Agricultural Experiment Station SB 1001, Columbia, MO. p. 10.1-10.4
Whalley, W.R., C.W. Watts, A.S. Gregory, S.J. Mooney, L.J. Clark, et al. 2008. The effect of soil strength on the yield of wheat. Plant Soil 306(1–2): 237–247. doi: 10.1007/s11104-008-9577-5.
Whitney, D.A. 2015. Micronutrients: Zinc, Iron,Manganese and Copper. Recommended chemical soil test procedures for the North Central Region (North Central Regional Research publication no. 221, revised). Missouri Agricultural Experiment Station SB 1001, Columbia, MO. p. 9.1-9.4
Wiermann, C., D. Werner, R. Horn, J. Rostek, and B. Werner. 2000. Stress/strain processes in a structured unsaturated silty loam Luvisol under different tillage treatments in Germany. Soil Tillage Res. 53(2): 117–128. doi: 10.1016/S0167-1987(99)00090-2.
Wildenschild, D., and A.P. Sheppard. 2013. X-ray imaging and analysis techniques for quantifying pore-scale structure and processes in subsurface porous medium systems. Adv. Water Resour. 51: 217–246. doi: 10.1016/J.ADVWATRES.2012.07.018.
Wolf, D., T.H. Garner, and J.W. Davis. 1981. Tillage mechanical energy input and soil-crop response. Trans. ASAE 24(6): 1412–1419, 1425. doi: 10.13031/2013.34463.
Wolfe, D.W., D.T. Topoleski, N. a. Gundersheim, and B. a. Ingall. 1995. Growth and yield sensitivity of four vegetable crops to soil compaction. J. Amer. Soc. Hort. Sci. 120(6): 956–963.

http://journal.ashspublications.org/cgi/content/abstract/120/6/956%5Cnhttp://journal.ashspublications.org.ezproxy.library.wisc.edu/cgi/reprint/120/6/956.pdf.

Wolkowski, R.P. 1990. Relationship between wheel-traffic-induced soil compaction, nutrient availability, and crop growth: a review. J. Prod. Agric. 3(4): 460–469.

Y

Yang, J., R.D. Hammer, A.L. Thompson, and R.W. Blanchar. 2003. Predicting soybean yield in a dry and wet year using a soil productivity index. Plant Soil 250(2): 175–182. doi: 10.1023/A:1022801322245.

Yang, Y., J. Wu, S. Zhao, Q. Han, X. Pan, et al. 2018. Assessment of the responses of soil pore properties to combined soil structure amendments using X-ray Computed Tomography. Sci. Rep. 8(1): 1–10. doi: 10.1038/s41598-017-18997-1.

Yen, J., F. Chang, and S. Chang. 1995. A new criterion for automatic multilevel thresholding. IEEE Trans. Image Process. 4(3): 370–378. https://ieeexplore.ieee.org/abstract/document/366472.

Young, I.M., K. Montagu, J. Conroy, and A.G. Bengough. 1997. Mechanical impedance of root growth directly reduces leaf elongation rates of cereals. New Phytol. 135(4): 613–619. doi: 10.1046/j.1469-8137.1997.00693.x.

Young, I.M., C.E. Mullins, P.A. Costigan, and A.G. Bengough. 1991. Hardsetting and structural regeneration in two unstable British sandy loams and their influence on crop growth. Soil Tillage Res. 19(4): 383–394. doi: 10.1016/0167-1987(91)90114-D.

Z

Zulauf, C., and B. Brown. 2019. Tillage practices, 2017 US Census of Agriculture. farmdoc daily, Dep. Agric. Consum. Econ. Univ. Illinois Urbana-Champaign 9(136): 1–5. https://farmdocdaily.illinois.edu/2019/07/tillage-practices-2017-us-census-of-agriculture.html%0A.

APPENDICES

Appendix A: General

Appendix 1: Examples of farm equipment currently available in the farmers field of the US and other region.

Agricultural machinery	John Deere		CNH Industrial		AGCO	
	Model	Weight (Mg)	Model	Weight (Mg)	Model	Weight (Mg)
Tractor	JD 7930 Tractor	10.3	Steiger 270 wheeled	17.5	Challenger MT585D	7.7
	JD 7700 Tractor	9.0	Case IH 470 Steiger	18.1	Challenger MT645E	10.8
	JD 8335R Tractor	12.3	Csae IH 580 Steiger	22.8	MF 8730	10.8
	JD 9740R Tractor	9.10	AFS Connect Steiger370	17.5	MF 8737	11.0
	JD 8R280 Tractor	11.7	Magnum 220 MFD	9.8	MF 7726	14.0
Trac tractor	JD 9420 RX	24.5	Case IH, Steiger 580 Quadtrac	24.6	-	-
Combine	JD 4930 combine	18.4	Case IH Axial Flow 6150	16.8	MF ACTIVA 7344	12.8
	JD 9870 Combine	16.4	Case IH Axial Flow 7150	17.2	MF 9545	

[5]Source: T. Lecher, Personal communication, 15 October 2018

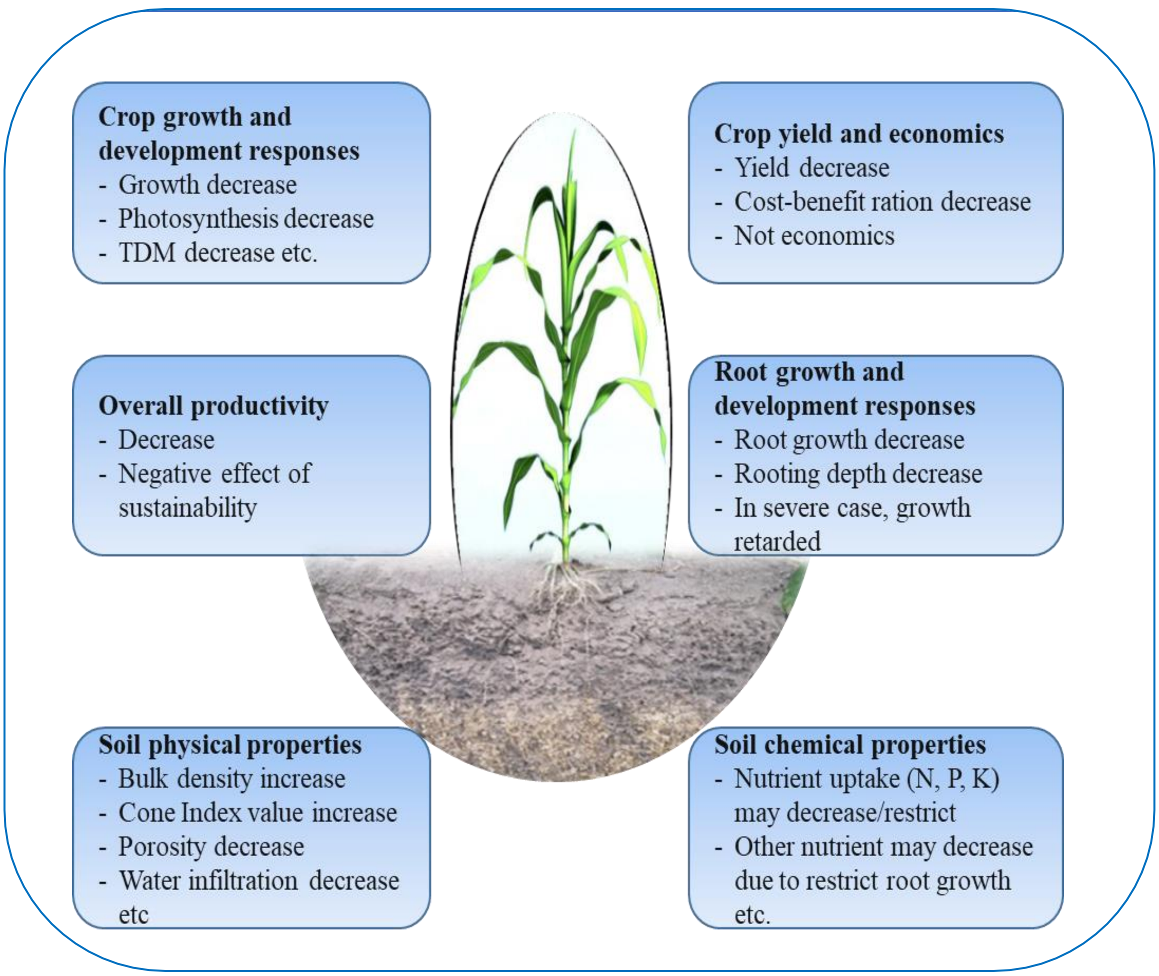
[5]Other sources: https://www.deere.com; https://www.agcocorp.com; https://www.caseih.com.

Appendix 2.1: US national and Illinois tillage practices (%), 2012 and 2017 US Census of Agriculture

Tillage practices[ǂ]	2012		2017		Percent change in 2017	
	US national	Illinois	US national	Illinois	US national	Illinois
No-till	35	37.50	37	28	2	-9.50
Reduced tillage	27	35.20	35	43	8	7.80
Conventional tillage	38	27.30	28	29	-10	1.70
Total (%)	100	100	100	100	0	0

Adapted from Zulauf and Brown (2019)

Appendix 2.2: A summary of the effect of compaction on soil and crop productivity (Example. Maize crop)

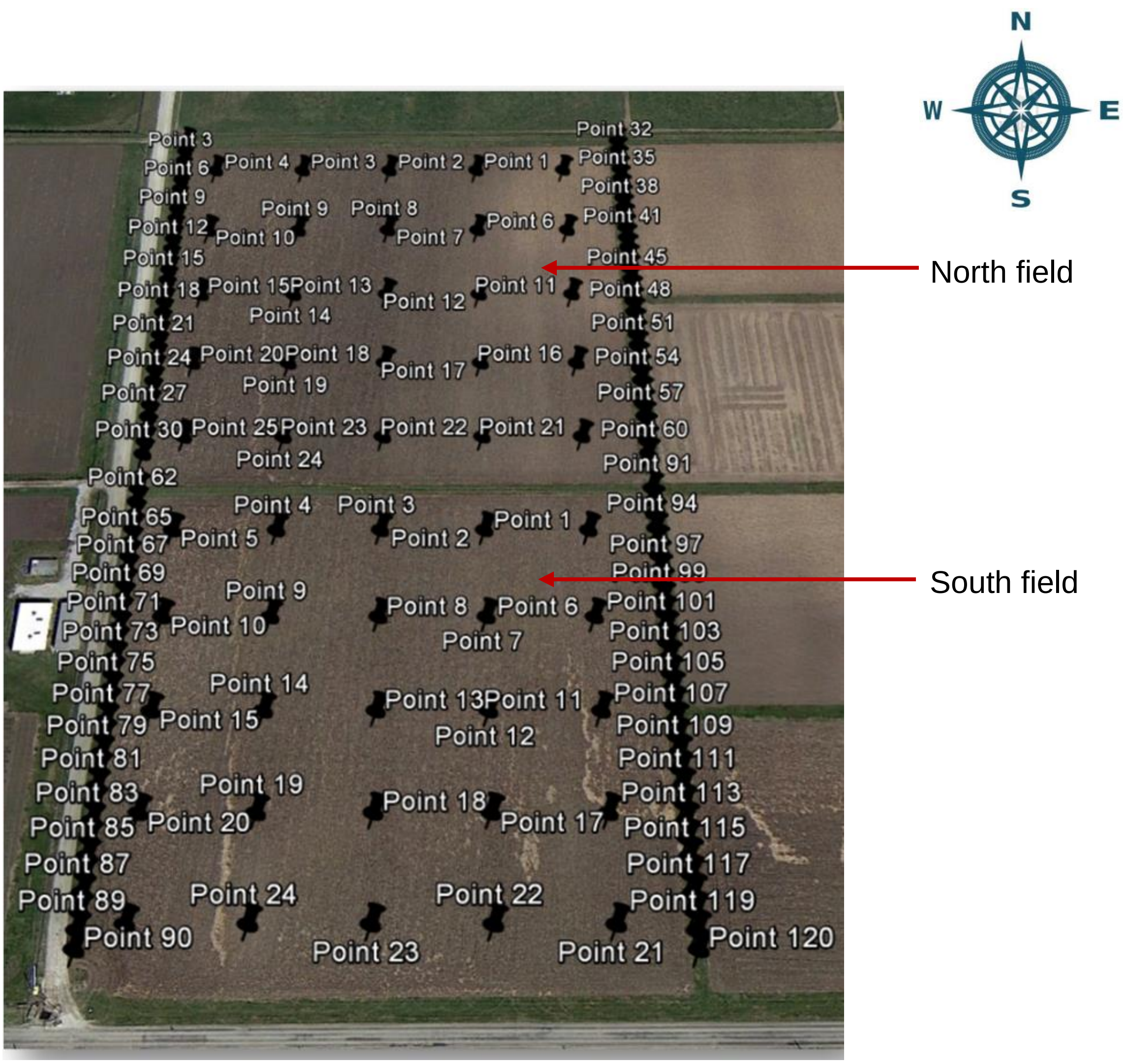


Appendix 3

Appendix 3.1. Typical tillage practices in Central Illinois

Tillage practices	Fall Tillage (450 mm depth)	Spring Tillage (100mm depth)	Planting
Deep Tillage	×	×	×
Shallow tillage		×	×
No-till			×

Appendix 3.2. Coordinate points for plot layout and soil sampling



Appendix 3.3. Specifications of tillage tools, disc ripper and planter used

Name	Manufacturer	Model	Spacing (m)	Working width (m)	Total Weight (Mg)
Spring tillage Tool (Disc gang/disc reel)	Sunflower /AGCO	6221-20	Disc blade - 0.2	6.20	4.23
Disc Ripper (Autumn tillage tool) – shanks-5	Case/IH	Ecolo-Tiger 527B	0.69m	3.43m	2.72
Planter	John Deere	7200 Max Emerge 2	0.75m	6m	

Appendix 3.4a. Crop production and data recording timeline of events in 2016

Field operations	Date of Field Operations		Remarks
	Maize (North field)	Soybean	
Deep tillage (450mm depth)	01 Nov. 2015	01 Nov. 2015	-
Layout of fields	10-12 April 2016	10-12 April 2016	
Soil sample collection	15 April 2016	15 April 2016	Initial soil sample analysis
Data recording-Penetrometer resistance	16-18 April 2016	16-18 April 2016	-
Shallow tillage (100mm depth)	25 April 2016	25 April 2016	Ultraflex tyres were fitted before tillage
Data recording-Electrical Conductivity	28 April 2016	28 April 2016	-
Pre-emergence spraying	16 May 2016	18 May 2016	Applied perpendicular to the plots (North-south direction)
Levelling	19 May 2016	19 May 2016	Chemical incorporation
Planting of crops	20 May 2016	20 May 2016	-
Data recording-Plant establishment	02-03 June 2016	03-04 June 2016	15 DAP
Post emergence spraying	17 June 2016	21 June 2016	Applied perpendicular to the plots (North-south direction)
Data recording-Plant counts	18-19 June 2016	22-23 June 2016	28-33 DAP
Data recording-Plant height	20 June 2016	23-24 June 2016	20 DAP and 33 DAP
Data recording-Penetration resistance	25 – 30 June 2016	30 June - 03 July 2016	35-40 DAP
Data recording-Plant height	06-07 July 2016	07-08 July 2016	45 DAP
Cutting of plant in the alleyways	10-11 July 2016	11-12 July 2016	-
Rooting depth study	26-27 July 2016	26-27 July 2016	-
Hand harvest sample collection	01-03 Oct. 2016	05-07 Oct. 2016	5 plants for maize and 0.5 m for soybean
Data recording-Combine harvest	07 Oct. 2016	01 Nov. 2016	Rainfall delayed the harvesting of soybean
Data recording-Hand harvest samples	01-06 Nov. 2016	07-09 Nov. 2016	Shelling (maize)/ threshing (soybean)

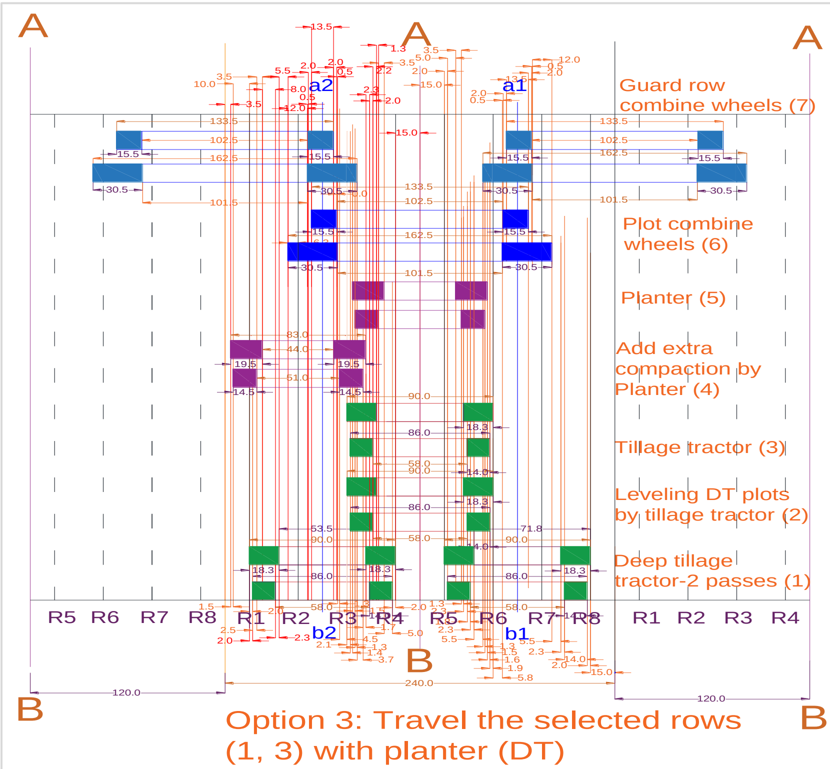
Appendix 3.4b. Crop production and data recording timeline of events in 2017

Field operations	Date of Field Operations		Remarks
	Maize (South field)	Soybean (North field)	
Deep tillage (450mm depth)	19 Feb. 2017	19 Feb. 2017	-
Shallow tillage (100mm depth)	29 Mar. 2017	29 Mar. 2017	-
Adding compaction (using planting tractor)	20 April 2018	20 April 2018	Applied on the crop row 1 and 3 to all plots
Pre-emergence spraying	25 April 2017	15 May 2017	Applied perpendicular to the plots (North-south direction)
Chemical incorporation/Levelling	26 April 2017	16 May 2017	-
Planting of crops	15 May 2017	18 May 2017	-
Data recording-Plant establishment	30-31 May 2017	01-02 June 2017	15-16 DAP
Data recording-Plant counts	15-16 June 2017	18-19 June 2017	30 and 32-33 DAP
Post emergence spraying (North-south direction)	21 June 2017	28 June 2017	Applied perpendicular to the plots
Cutting of plant in the alleyways	24-25 June 2017	26-27 June 2017	Headlands were 10m
Data recording-Penetration resistance	28 June – 01 July 2017	03-06 July 2017	Avoided sprayer wheel ways
Data recording-Soil moisture content (%)	28 June – 01 July 2017	03-06 July 2017	Avoided sprayer wheel ways
Collection of trial soil core samples for X-ray CT study	31 July 2017	-	-
Data recording-Plant height at harvest	01-05 Oct. 2017	10-15 Oct. 2017	Maize – from base to flag leaf; Soybean – from base to tip
Hand harvest	01-05 Oct. 2017	10-15 Oct. 2017	Maize- 5 plants Soybean – plants of 0.5 m
Combine harvest	10 October 2017	20 Oct. 2017	-
Deep tillage (450mm depth)	27 Oct. 2017	04 Nov. 2017	-
Data recording-Hand harvest samples shelling (maize)/ threshing (soybean)	12-17 Nov. 2017	05-08 Nov. 2017	-
Data recording-Penetrometer resistance	02-03 Nov. 2017	-	HT and UT locations
Collection of soil core samples	04 Nov. 2017	-	For X-ray CT study
Soil cores X-ray CT scanning	11-15 Dec and 18-20 Dec. 2017	-	MIL, Beckman Institute of UIUC

Appendix 3.4c. Crop production and data recording timeline of events in 2018

Field operations	Date of Field Operations		Remarks
	Maize (North field)	Soybean (South field)	
Soil cores X-ray CT scanning	03-05 and 22-26 Jan. 2018	-	MIL, Beckman Institute of UIUC
Soil cores X-ray CT scanning	06-08 and 12-13 Feb. 2018	-	-
Shallow tillage (100mm depth)	27 April 2018	13 May 2018	-
Adding compaction (using planting tractor)	26 April 2018	26 April 2018	Applied on the crop row 1 and 3 to all plots
Pre-emergence spraying (North-south direction)	28 April 2018	14 May 2018	Applied perpendicular to the plots
Chemical incorporation/Levelling	30 April 2018	05/15/2018	-
Planting of crops	01 May 2018	16 May 2018	-
Data recording-Plant establishment	17-18 May 2018	30-31 May 2018	17-18 DAP and 14-15 DAP
Data recording-Plant counts	01-03 and 08 June 2018	17-21 June 2018	30-33 DAP
Post emergence spraying (North-south direction to the plots)	04 June 2018	27 June 2018	Applied perpendicular to the plots
Cutting of plant in the alleyways	28-29 June 2018	01-02 July 2018	Headlands were 10m each side
Data recording-Penetration resistance	10-14 Aug. 2018	11-16 July 2018	95-100 DAP/55-60 DAP; Avoided sprayer wheel ways
Data recording-Soil moisture content (%)	10-14 Aug. 2018	11-16 July 2018	95-100 DAP/55-60 DAP; Avoided sprayer wheel ways
Data recording-Plant height at harvest	18-22 Sept. 2018	01-03 Oct. 2018	Maize – from base to flag leaf and soybean – from base to tip
Data recording-Ear height	18-22 Sept. 2018	-	From base to maize ear
Data recording-Hand harvest	18-22 Sept. 2018	06-08 Oct. 2018	5 plants for maize and plants of 0.5 m for soybean
Data recording-Combine harvest	Mid October 2018	22 Oct. 2018	160 DAP and 157 DAP; Rainfall events delayed the harvest
Data recording-Hand harvest samples shelling (maize)/ threshing (soybean)	01-06 Nov. 2018	07-09 Nov. 2018	-

Appendix: 3.5a. Summary of the % of width of trafficked and un-trafficked zones of deep tillage plot in 2017 and 2018



Appendix 3.5b. Width of trafficked and un-trafficked zones of deep tillage plot (from left to center line)

Width trafficked/ Passes (#)	Deep tillage plot (From left to centre line)																														
	0	1	2	3	4	3	2	1	0	1	2	3	4	4	3	2	3	5	7	8	9	8	7	7	8	6	4	3	2	1	0	Width
Width trafficked (inch)	3.5	1.5	10	2	2.5	3.5	8	2.3	5.5	12	0.5	2	13.5	2	0.5	1.3	4.5	2.1	1.4	1.5	1.3	3.7	1.7	2.3	2	2.2	1.3	3.5	5	2	15	120
Width trafficked (m)	0.09	0.04	0.25	0.05	0.06	0.09	0.20	0.06	0.14	0.30	0.01	0.05	0.34	0.05	0.01	0.03	0.11	0.05	0.04	0.04	0.03	0.09	0.04	0.06	0.05	0.06	0.03	0.09	0.13	0.05	0.38	3.00

Appendix 3.5c. Width of trafficked and un-trafficked zones of deep tillage plot (from right to center line)

Width trafficked/Passes (#)	Deep tillage plot (From right to centre line)																								
	0	1	2	1	0	1	2	3	4	3	2	1	2	5	6	6	6	7	8	6	4	3	2	1	0	Width
Width trafficked (inch)	15	2	14	2.3	5.5	12	0.5	2	13.5	2	0.5	5.8	1.9	1.6	1.5	1.3	5.5	2.3	1.8	2.2	1.3	3.5	5	2	15	120
Width trafficked (m)	0.38	0.05	0.35	0.06	0.14	0.30	0.01	0.05	0.34	0.05	0.01	0.15	0.05	0.04	0.04	0.03	0.14	0.06	0.05	0.06	0.03	0.09	0.13	0.05	0.38	3.00

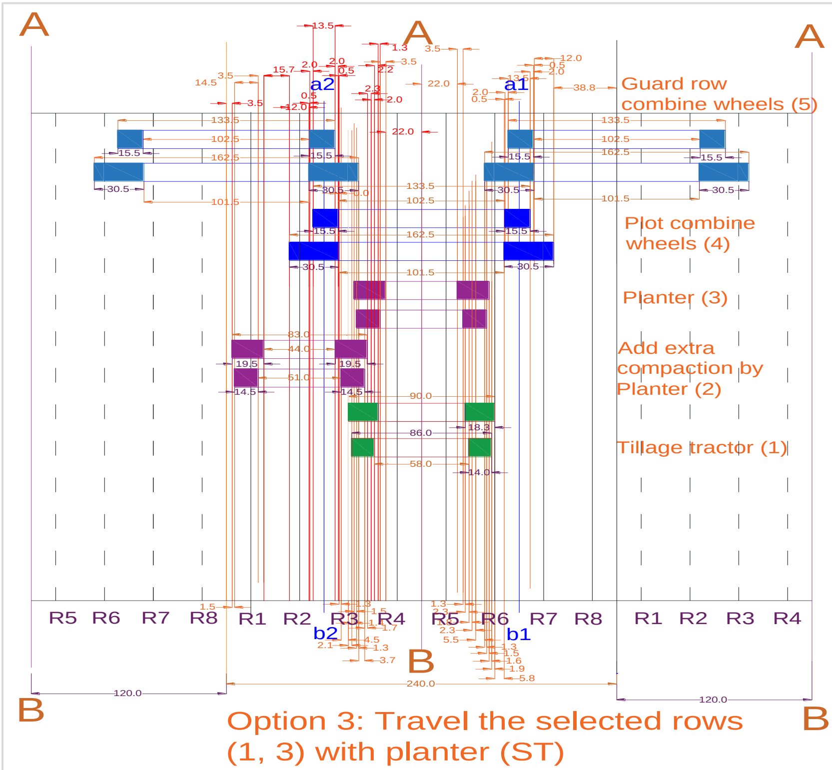
Appendix 3.5d. Total and % of width of trafficked and un-trafficked zones of deep tillage plot

From left to centre line (3m)				From right to centre line (3m)				% Width trafficked/ plot (6m)
Number of passes	Width trafficked			Number of passes	Width trafficked			
	Inches	m	%		Inches	m	%	
0	24.0	0.60	19.9	0	35.5	0.89	29.6	24.8
1	17.8	0.45	14.8	1	24.1	0.60	20.1	17.4
2	24.8	0.62	20.6	2	21.9	0.55	18.2	19.4
3	16.0	0.40	13.3	3	7.50	0.19	6.23	9.78
4	19.3	0.48	16.1	4	14.8	0.37	12.3	14.2
5	2.10	0.05	1.75	5	1.60	0.04	1.33	1.54
6	2.20	0.06	1.83	6	10.6	0.27	8.83	5.33
7	5.40	0.14	4.50	7	2.30	0.06	1.92	3.21
8	7.20	0.18	6.00	8	1.80	0.05	1.50	3.75
9	1.30	0.03	1.08	9	0.00	0.00	0.00	0.54
	120.1	3.00	100.0		120.1	3.00	100.0	100.0
	Total area trafficked		80.0	Total area trafficked			70.4	**75.2**
	Un-trafficked		19.9	Un-trafficked			29.6	**24.8**

Appendix 3.5e. Number of vehicle passes in deep tillage plot

Crop Row	Total number of vehicle passes (a+b+c)	Number of vehicle passes		
		On the crop row (a)	Edge of tyre at centre line of crop row (b)	Edge of tyre 60mm from centre line of crop row (c)
Crop row 1	2	1	1	0
Crop row 2	1	1	0	0
Crop row 3	5	2	1	2
Crop row 4	1	0	1	0
Crop row 5	1	0	1	0
Crop row 6	3	1	2	0
Crop row 7	1	1	0	0
Crop row 8	1	0	1	0

Appendix: 3.6a. Summary of the % of width of trafficked and un-trafficked zones of shallow tillage plot in 2017 and 2018



Appendix 3.6b. Width of trafficked and un-trafficked zones of shallow tillage plot (from left to center line)

Width trafficked/ Passes (#)	Shallow tillage plot (From left to centre line)																								
	0	1	2	1	0	1	1	3	4	4	3	2	3	4	5	6	7	6	5	4	4	3	2	1	0	Width
Width trafficked (inches)	3.5	1.5	14.5	3.5	15.7	12	0.5	2	13.5	2	0.5	1.3	4.5	2.1	1.4	1.5	1.3	3.7	1.7	2.3	2	2.2	1.3	3.5	22	**120**
Width trafficked (m)	0.09	0.04	0.36	0.09	0.39	0.30	0.01	0.05	0.34	0.05	0.01	0.03	0.11	0.05	0.04	0.04	0.03	0.09	0.04	0.06	0.05	0.06	0.03	0.09	0.55	3.00

Appendix 3.6c. Width of trafficked and un-trafficked zones of shallow tillage plot (from right to center line)

Width trafficked/ Passes (#)	Shallow tillage plot (From right to centre line)																			
	0	1	2	3	4	4	4	5	4	3	2	3	2	3	4	3	2	1	0	Width
Width trafficked (inches)	22.0	3.5	1.3	2.3	1.8	2.3	5.5	1.3	1.5	1.6	1.9	5.8	0.5	2.0	13.5	2.0	0.5	12.0	38.8	120.1
Width trafficked (m)	0.6	0.1	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.3	0.1	0.0	0.3	1.0	3.0

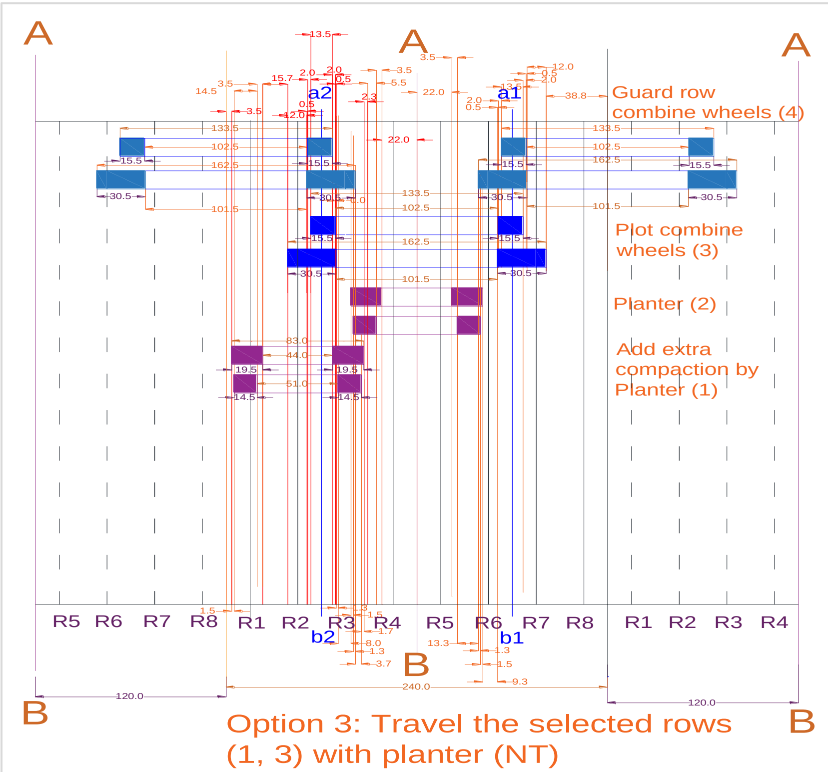
Appendix 3.6d. Total and % of width of trafficked and un-trafficked zones of shallow tillage plot

From left to centre line (3m)				From right to centre line (3m)				% Area trafficked/ plot (6m)
Number of passes	Width trafficked			Number of passes	Width trafficked			
	Inches	m	%		Inches	m	%	
0	41.2	1.03	34.3	0	60.8	1.52	50.6	42.5
1	21.0	0.53	17.5	1	15.5	0.39	12.9	15.2
2	17.1	0.43	14.2	2	4.20	0.11	3.50	8.87
3	9.20	0.23	7.67	3	13.7	0.34	11.4	9.54
4	21.9	0.55	18.3	4	24.6	0.62	20.5	19.4
5	3.10	0.08	2.58	5	1.30	0.03	1.08	1.83
6	5.20	0.13	4.33	6	0	0.00	0.00	2.17
7	1.30	0.03	1.08	7	0	0.00	0.00	0.54
	120.0	3.00	100.0		120.1	3.00	100	100.0
	Total area trafficked		**65.7**				**49.4**	**57.5**
	Un-trafficked		**34.3**				**50.6**	**42.5**

Appendix 3.6e. Number of vehicle passes in shallow tillage plot

Crop Row	Total number of vehicle passes (a+b+c)	Number of vehicle passes		
		On the crop row (a)	Edge of tyre at centre line of crop row (b)	Edge of tyre 60mm from centre line of crop row (c)
Crop row 1	1	1	0	0
Crop row 2	1	1	0	0
Crop row 3	4	2	1	1
Crop row 4	0	0	0	0
Crop row 5	0	0	0	0
Crop row 6	3	1	1	1
Crop row 7	1	1	0	0
Crop row 8	0	0	0	0

Appendix 3.7a: Summary of the % of width of trafficked and un-trafficked zones of no-till plot in 2017 and 2018



Appendix 3.7b. Width of trafficked and un-trafficked zones of no-till plot (from left to center line)

Width trafficked/ Passes (#)	No-Till Plot (From left to centre line)																				
	0	1	2	1	0	1	2	3	4	3	2	2	3	4	5	4	3	2	2	1	0	Width
Width trafficked (inches)	3.5	1.5	14.5	3.5	15.7	12	0.5	2	13.5	2	0.5	1.3	8	1.5	1.3	3.7	1.7	2.3	5.5	3.5	22	120
Width trafficked (m)	0.09	0.04	0.36	0.09	0.39	0.30	0.01	0.05	0.34	0.05	0.01	0.03	0.20	0.04	0.03	0.09	0.04	0.06	0.14	0.09	0.55	3.00

Appendix 3.7c. Width of trafficked and un-trafficked zones of no-till plot (from right to center line)

Width trafficked/ Passes (#)	No-Till Plot **(From right to centre line)**													
	0	1	2	3	2	1	2	3	4	3	2	1	0	Width
Width trafficked (inches)	22	3.5	13.3	1.3	1.5	9.3	0.5	2	13.5	2	0.5	12	38.8	120
Width trafficked (m)	0.55	0.09	0.33	0.03	0.04	0.23	0.01	0.05	0.34	0.05	0.01	0.30	0.97	3.00

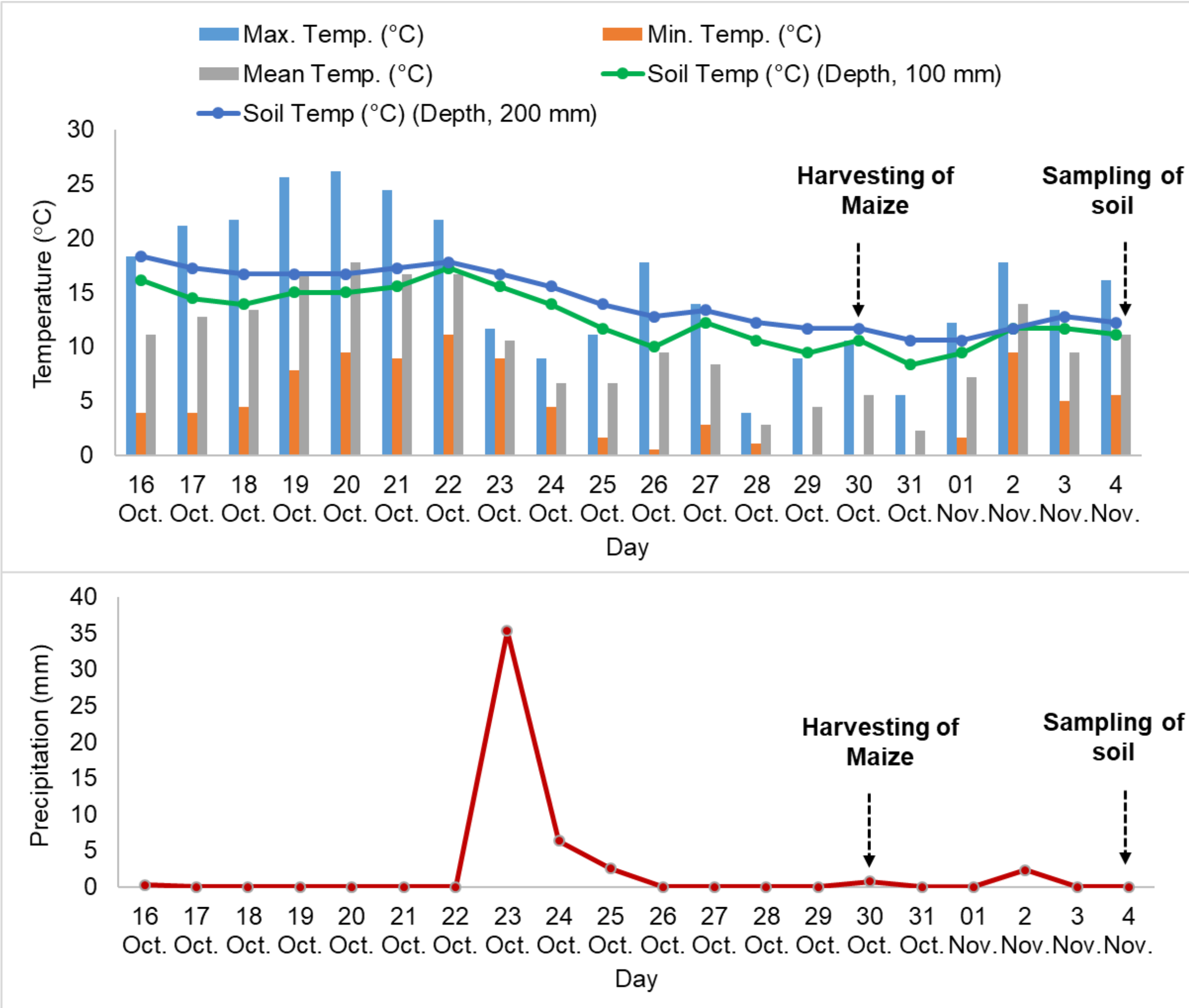
Appendix 3.7d. Total and % of width of trafficked and un-trafficked zones of no-till plot

From left to centre line (3m)				From right to centre line (3m)				% Area trafficked per plot (6m)
Number of passes	Width trafficked			Number of passes	Width trafficked			
	Inches	m	%		Inches	m	%	
0	41.2	1.03	34.3	0	60.8	1.52	50.6	42.5
1	20.5	0.51	17.1	1	24.8	0.62	20.6	18.9
2	24.6	0.62	20.5	2	15.8	0.40	13.1	16.8
3	13.7	0.34	11.4	3	5.3	0.13	4.41	7.91
4	18.7	0.47	15.6	4	13.5	0.34	11.2	13.4
5	1.3	0.03	1.08	5	0	0	0	0.54
	120	3.00	100.0		120.2	3.01	100.0	100.0
	Total area trafficked		65.67				49.4	**57.5**
	Un-trafficked		34.33				50.7	**42.5**

Appendix 3.7e. Number of vehicle passes in no-till plot

Crop Row	Total number of vehicle passes (a+b+c)	Number of vehicle passes		
		On the crop row (a)	Edge of tyre at centre line of crop row (b)	Edge of tyre 60mm from centre line of crop row (c)
Crop row 1	1	1	0	0
Crop row 2	1	1	0	0
Crop row 3	3	1	1	1
Crop row 4	0	0	0	0
Crop row 5	0	0	0	0
Crop row 6	2	1	0	1
Crop row 7	1	1	0	0
Crop row 8	0	0	0	0

Appendix 3.8. Air and soil temperatures and rainfall data during soil core collection for X-ray CT study from 16 October – November 04, 2017



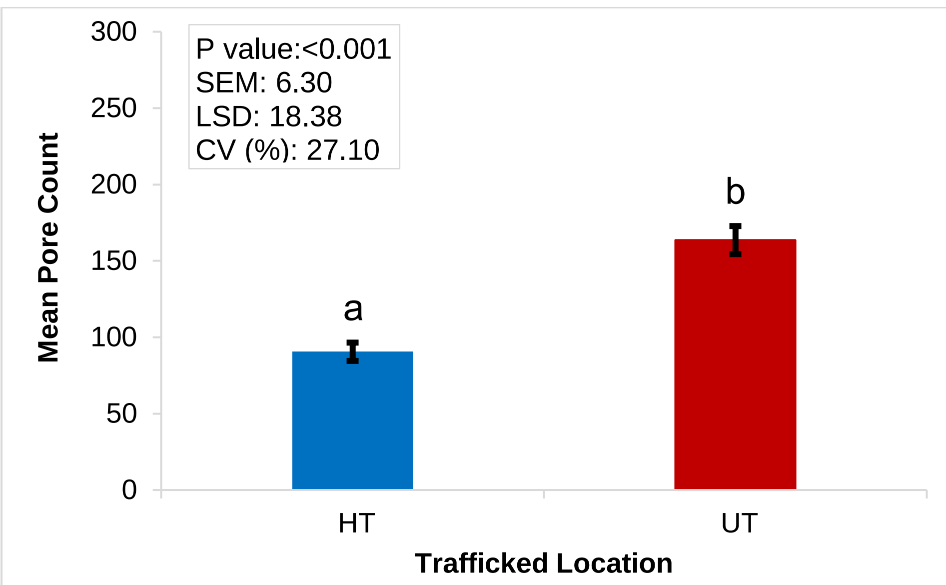
Appendix B: Additional Statistics

Appendix 4.1. Effect of tyre inflation pressure and tillage system on the number of pores, in the HT location in 2017

Statistics	Tyre inflation pressure					Tillage system					Tyre inflation pressure × tillage system				
	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5
P value	0.354	<0.001	0.006	0.28	0.13	0.328	0.336	0.208	0.43	0.58	0.122	0.006	0.058	0.08	0.19
SEM (df 2, 20)	15.11	8.83	11.2	6.61	10.4	18.5	10.8	13.7	8.09	12.7	26.1	15.3	19.4	11.4	18.0
LSD	44.5	20.0	23.3	19.4	30.7	54.5	31.9	28.6	23.8	37.6	77.2	45.1	40.4	33.7	53.2
CV (%)	37.0	40.1	43.9	44.8	49.0	37.0	40.1	43.9	44.8	49.0	37.0	40.1	43.9	44.8	49.0

Note: D1, D2, D3, D4 and D5 represent the soil depth of 0-60mm, 60-120mm, 120-180mm, 180-240mm and 240-300mm, respectively.

Appendix 4.2. Effect of heavily trafficked and un-trafficked locations on mean pore count of soil in 2017



Appendix 4.3. Effect of tyre inflation pressure and tillage system on CT Measured macroporosity (%), in the HT location in 2017

Statistics /Treatments	Tyre inflation pressure					Tillage system					Tyre inflation pressure × tillage system				
	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5
P value	0.18	0.013	0.012	0.47	0.05	0.51	0.789	0.522	0.58	0.66	0.69	0.254	0.265	0.37	0.59
SEM (df 2, 20)	0.54	0.66	0.624	0.61	0.76	0.66	0.81	0.77	0.75	0.94	0.94	1.15	1.08	1.06	1.33
LSD	1.60	1.96	1.84	1.81	2.26	1.96	2.37	2.26	2.22	2.77	2.77	3.39	3.19	3.14	3.92
CV (%)	52.9	61.8	62.7	76.8	79.1	52.9	61.8	62.7	76.8	79.1	52.90	61.8	62.7	76.80	79.1

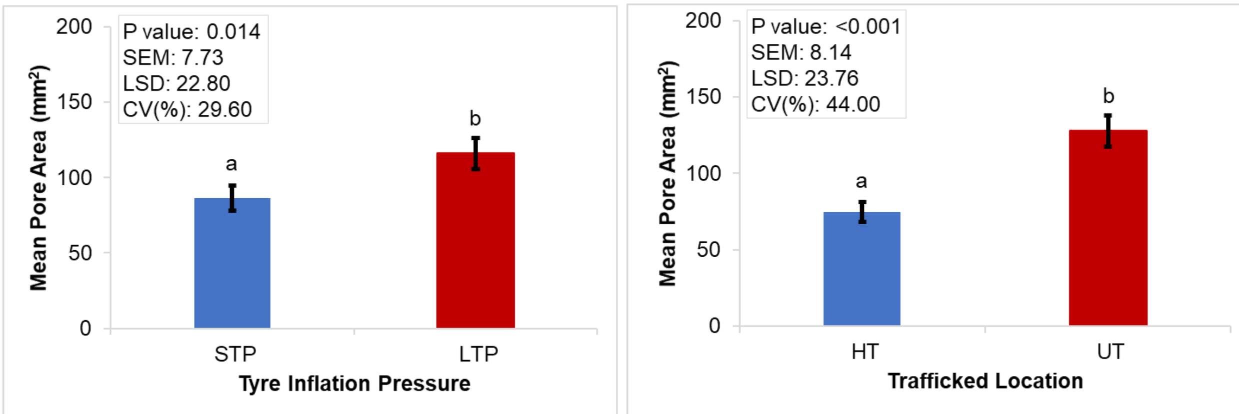
Note: D1, D2, D3, D4 and D5 represent the soil depth of 0-60mm, 60-120mm, 120-180mm, 180-240mm and 240-300mm, respectively.

Appendix 4.4. Effect of tyre inflation pressure and tillage system on Total Pore Area (mm^2), in the HT location in 2017

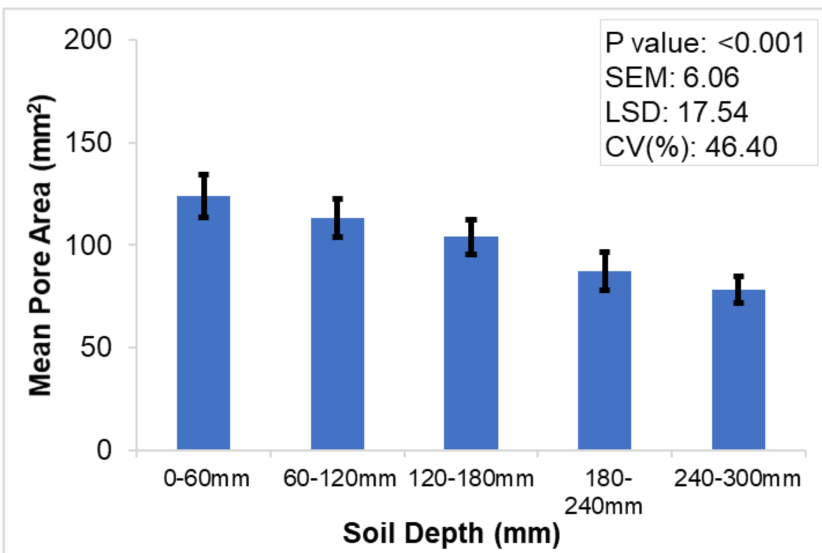
Statistics /Treatments	Tyre inflation pressure					Tillage system					Tyre inflation pressure × tillage system				
	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5
P value	0.17	0.012	0.012	0.46	0.05	0.52	0.79	0.52	0.57	0.66	0.68	0.25	0.26	0.34	0.59
SEM (df 2, 20)	10.7	13.1	12.4	12.2	15.2	13.1	16.1	15.2	14.9	18.6	18.6	22.8	21.5	21.1	26.4
LSD	31.7	38.8	36.6	36.0	44.9	38.8	47.6	44.8	4.11	55.1	54.9	67.1	63.4	62.3	77.9
CV (%)	53.0	61.9	62.8	77.1	79.2	53.0	61.9	62.8	77.1	79.2	53.0	61.9	62.8	77.1	79.2

Note: D1, D2, D3, D4 and D5 represent the soil depth of 0-60mm, 60-120mm, 120-180mm, 180-240mm and 240-300mm, respectively.

Appendix 4.5. Effect of tyre inflation pressure (a), trafficked location (b) and soil depth (c) on Total Pore Area (mm^2) of soil in 2017

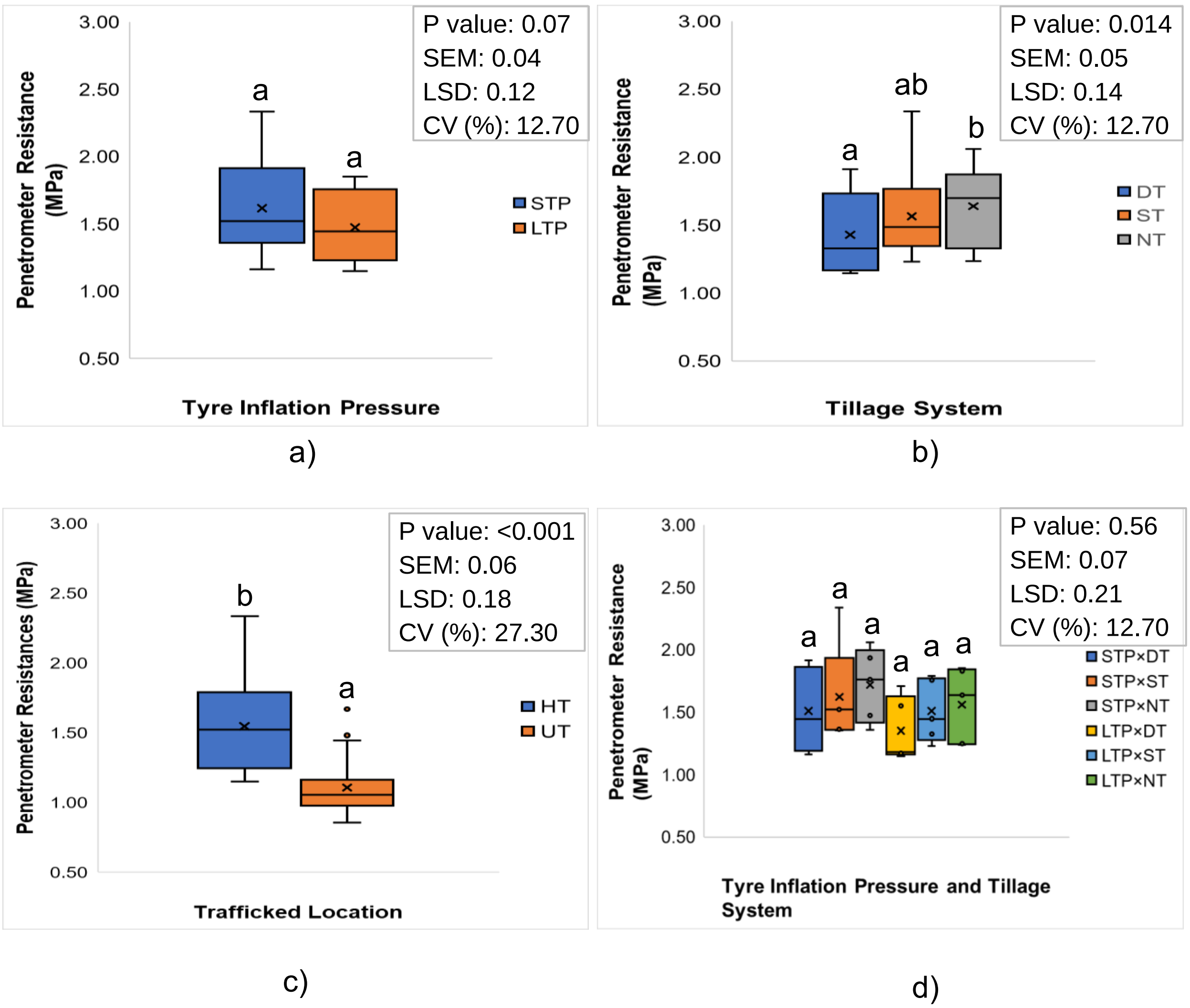


a) b)



c)

Appendix 4.6. Effect of tyre inflation pressure (a), tillage system (b), trafficked locations (c) and interaction of tyre inflation pressure and tillage system (d) on the mean penetrometer resistance of soil in 2017 (during soil sampling for X-ray CT study)

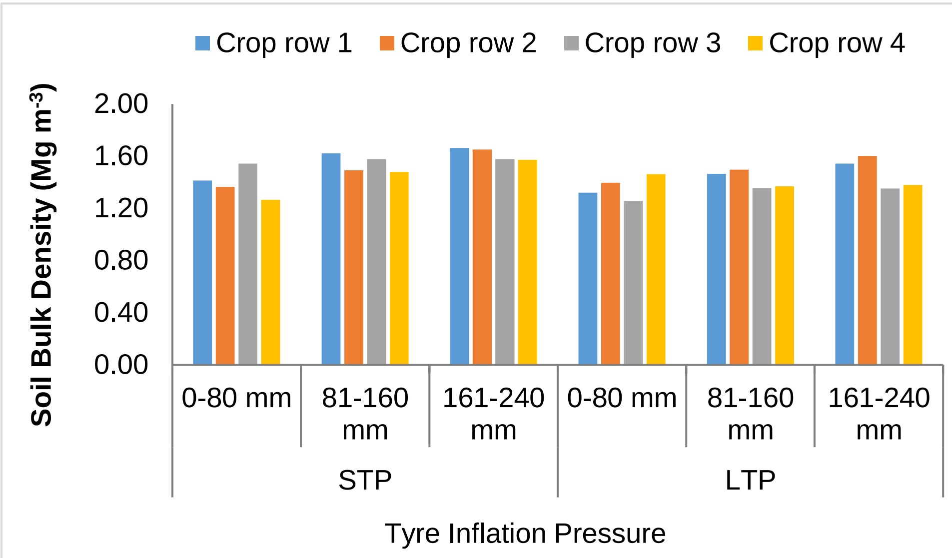


a) b) c) d)

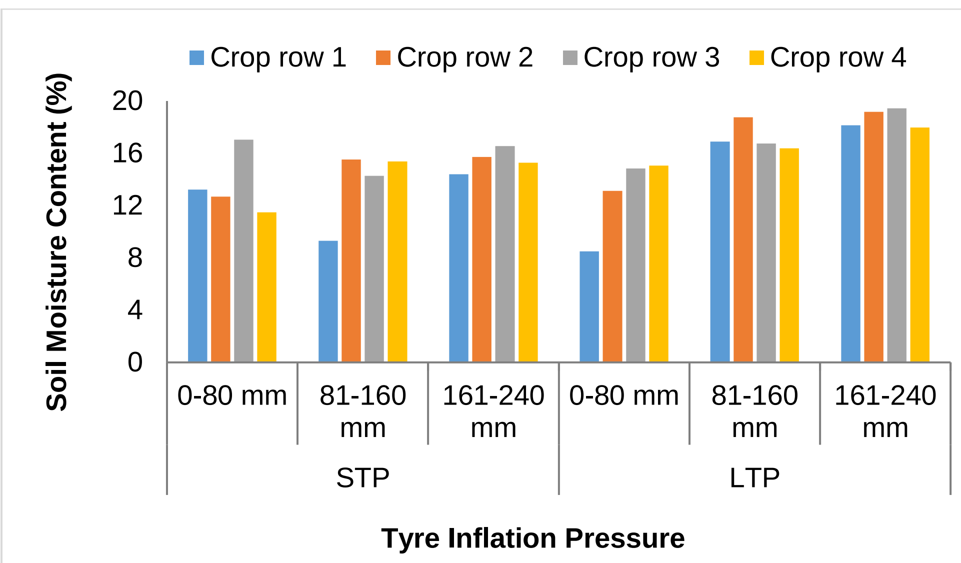
Means with the same letter are not significantly different (α =0.05) from each other.

Note: The ends of boxes are the upper and lower quartiles, the median is marked by a vertical line inside the box. The whiskers are the two lines outside the box that extends the highest and lowest observations.

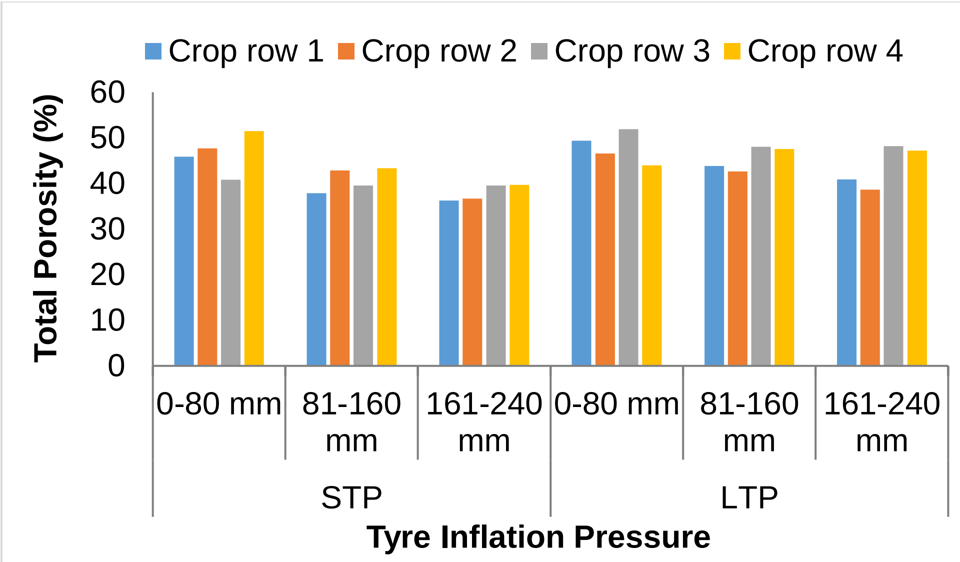
Appendix 5.1. Effect of tyre inflation pressure on bulk density of soil at different depths down to 240 mm in the North field in 2016.



Appendix 5.2. Effect of tyre inflation pressure on soil moisture content of soil at different depths down to 240 mm in the North field in 2016.



Appendix 5.3. Effect of tyre inflation pressure on total porosity of soil at different depths down to 240 mm in the North field in 2016.



Appendix 5.4. Effect of tyre inflation pressure and crop row on plant establishment and plants height of maize, in the North Field in 2016

Treatments†	Plant establishment (%)				Plant height at 45 DAP (base to tip, m)				Plant height at 45 (base to flag leaf, m)			
	SEM	P value	LSD	CV (%)	SEM	P value	LSD	CV (%)	SEM	P value	LSD	CV (%)
TIP	0.306	0.109		1.20	0.009	0.077	0.037	1.10	0.008	0.86	0.033	2.40
CR	0.463	0.573			0.006	0.090	0.018	2.40	0.009	0.44	0.029	4.10
TIP × CR	0.644	0.805		2.70	0.012	0.768	0.039		0.014	0.73	0.043	

Note:

DF – Degrees of freedom: 24 and 80. CV's are main effect and subplot effects, respectively.

TIP and CR represent tyre inflation pressure and crop row, respectively.

Appendix 5.5. Effect of tyre inflation pressure and crop row on plant height of maize at 45 DAP, in the North field in 2016

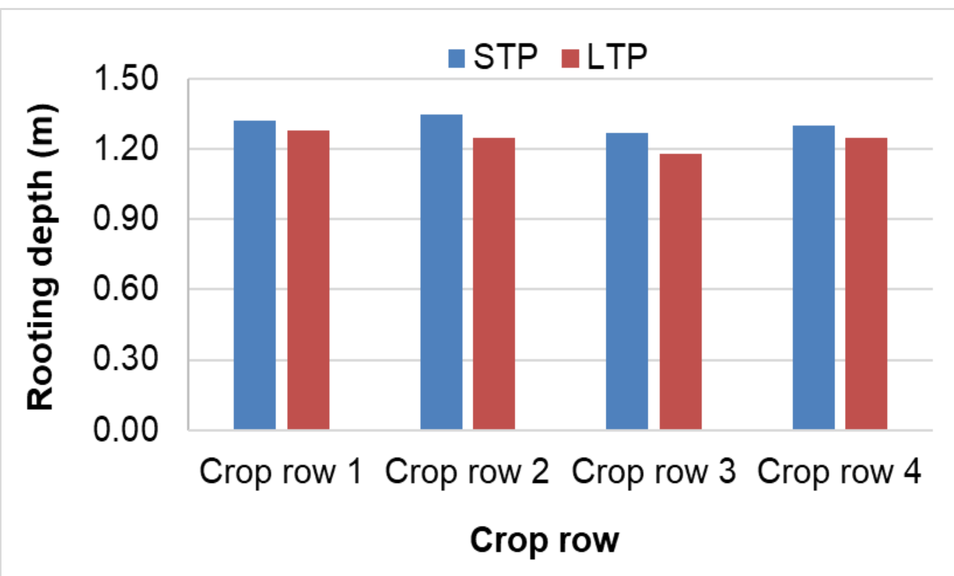
Treatments[†]	Plant height at 45 DAP (m) (Base to tip)					Plant height at 45 DAP (m) (Base to flag leaf)				
	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Mean	Crop row 1	Crop row 2	Crop row 3	Crop row 4	Mean
STP	1.89	1.88	1.88	1.90	1.89	1.29	1.30	1.29	1.30	1.30
LTP	1.91	1.89	1.88	1.90	1.89	1.30	1.29	1.28	1.32	1.29
Mean	1.90	1.88	1.88	1.90		1.29	1.29	1.29	1.31	
24 and 84 DF	SEM	P value	LSD	CV (%)		SEM	P value	LSD	CV (%)	
TIP	0.009	0.78		1.90		0.009	0.86		2.60	
CR	0.006	0.06		1.80		0.009	0.34		3.80	
TIP × CR	0.012	0.74				0.014	0.66			

Note:

DF – Degrees of freedom: 24 and 80. CV's are main effect and subplot effects, respectively.

TIP and CR represent tyre inflation pressure and crop row, respectively.

Appendix 5.6. Rooting depth of maize for STP and LTP tyre inflation pressures in the North field in 2016



Appendix 5.7. Effect of tyre inflation pressure, tillage system and crop row on number of plants ha^{-1} and plant height of maize, in the South Field in 2017

Treatments†	Number of plants ha^{-1}				Plant height (m)			
	SEM[a]	P value	LSD	CV (%)	SEM[a]	P value	LSD	CV (%)
TIP	100.0	0.099	294	0.40	0.007	0.045	0.019	1.20
TS	122.4	<0.001	361		0.008	0.446	0.023	
CR	279.8	0.386	781	1.70	0.007	0.002	0.018	1.70
TIP × TS	173.1	0.279	510		0.011	0.186	0.033	
TIP × CR	383.4	0.701	1069		0.011	0.110	0.030	
TS × CR	469.6	0.247	1310		0.013	0.336	0.037	
TIP × TS × CR	664.1	0.539	1.852		0.019	0.946	0.053	

Appendix 5.8. Effect of tyre inflation pressure, tillage system and crop row on plant establishment, plants ha^{-1} and plant height of maize, in the North Field in 2018

Treatments†	Plant establishment (%)				Number of plant ha^{-1}				Plant height			
	SEM[a]	P value	LSD	CV (%)	SEM	P value	LSD	CV (%)	SEM	P value	LSD	CV (%)
TIP	0.286	0.007	0.597	0.90	111	0.005	328	0.50	0.009	0.004	0.028	1.40
TS	0.350	0.269	0.731		136	0.473	402		0.012	0.047	0.034	
TIP × TS	0.496	0.955	1.03		193	0.085	569		0.016	0.329	0.048	
CR	0.695	0.282	1.37	3.00	209	0.370	582	1.40	0.008	0.423	0.022	1.70
TIP × CR	0.962	0.860	1.89		298	0.115	830		0.014	0.499	0.039	
TS × CR	1.18	0.771	2.32		364	0.766	1016		0.017	0.402	0.048	
TIP×TS×CR	1.66	0.851	3.28		515	0.516	1437		0.024	0.191	0.068	

Note: In appendices 5.7 and 5.8, TIP, TS, CR, STP, LTP, DT, ST and NT represent tyre inflation pressure, tillage system, crop row, standard tyre inflation pressure, low tyre inflation pressure, deep tillage, shallow tillage and no-till, respectively.

[a]DF represents degrees of freedom: 20 and 168. CV's are main effect and subplot effects, respectively.

Appendix 5.9. Effect of tyre inflation pressure, tillage system and crop row on ear height and ear length of maize, in the North Field in 2018

Treatments	Ear height (m)				Ear length (m)			
	SEM[a]	P value	LSD	CV (%)	SEM[a]	P value	LSD	CV (%)
TIP	0.007	0.05	0.021	2.30	0.002	<.001	0.006	4.20
TS	0.009	0.02	0.026		0.002	0.44	0.007	
TIP × TS	0.013	0.63	0.037		0.003	0.37	0.010	
CR	0.009	0.32	0.025	4.10	0.003	0.22	0.009	10.10
TIP × CR	0.014	0.32	0.039		0.005	0.37	0.013	
TS × CR	0.017	0.001	0.048		0.006	0.23	0.016	
TIP×TS×CR	0.024	0.18	0.067		0.008	0.69	0.023	

Appendix 5.10. Effect of tyre inflation pressure, tillage system and crop row on 1000 grain weight and hand harvest grain yield of maize, in the South field in 2017

Treatments	1000 grain weight (g)				Hand harvest grain yield (Mg ha^{-1})			
	SEM[a]	P value	LSD	CV (%)	SEM[a]	P value	LSD	CV (%)
TIP	2.19	0.250	6.47	2.50	0.181	0.796	0.535	4.00
TS	2.68	0.414	7.92		0.222	0.142	0.655	
TIP × TS	3.79	0.312	11.2		0.314	0.317	0.926	
CR	2.62	0.049	7.32	4.20	0.214	0.398	0.596	6.70
TIP × CR	4.10	0.189	11.4		0.336	0.764	0.939	
TS × CR	5.02	0.702	14.1		0.411	0.283	1.150	
TIP×TS×CR	7.10	0.908	19.8		0.582	0.881	1.626	

Note: In Appendices 5.9 and 5.10, TIP, TS, CR, STP, LTP, DT, ST and NT represent tyre inflation pressure, tillage system, crop row, standard tyre inflation pressure, low tyre inflation pressure, deep tillage, shallow tillage and no-till, respectively.

[a]DF – Degrees of freedom: 20 and 168. CV’s are main effect and subplot effects, respectively.

Appendix 5.11. Effect of tyre inflation pressure and tillage system on 1000 grain weight and hand harvest grain yield of maize, in the South field in 2017

Treatments†	1000 grain weight (g)				Hand harvested grain yield (Mg ha^{-1})			
	DT	ST	NT	Mean	DT	ST	NT	Mean
STP	335	335	337	336	17.12	17.16	17.72	17.33
LTP	345	335	338	339	17.74	16.87	17.59	17.40
Mean*	340	335	337		17.43	17.01	17.65	
20 and 168 DF	SEM	P value	LSD (0.05)	CV (%)	SEM	P value	LSD (0.05)	CV (%)
TIP	2.19	0.250	6.47	2.50	0.181	0.796	0.535	4.00
TS	2.68	0.414	7.92		0.222	0.142	0.655	
TIP × TS	3.79	0.312	11.2		0.314	0.317	0.926	

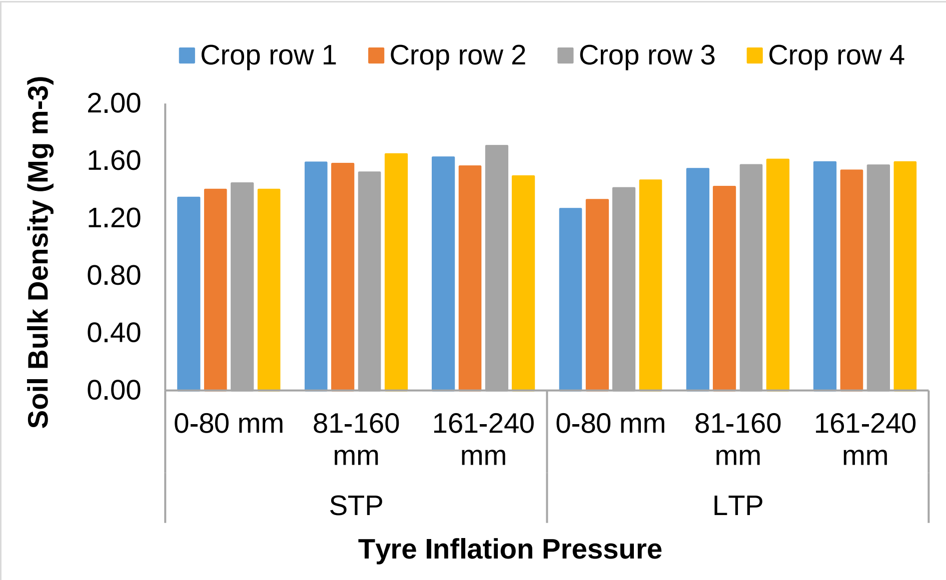
Appendix 5.12. Effect of tyre inflation pressure, tillage system and crop row on 1000 grain weight and hand harvest grain yield of maize, in the North field in 2018

Treatments	1000 grain weight (g)				Hand harvest grain yield (Mg ha^{-1})			
	SEM[a]	P value	LSD	CV (%)	SEM[a]	P value	LSD	CV (%)
TIP	4.18	0.478	12.33	5.50	0.218	0.125	0.642	7.20
TS	5.12	0.005	15.10		0.267	<.001	0.786	
TIP × TS	7.24	0.696	21.36		0.377	0.950	1.112	
CR	3.54	<.001	9.89	6.60	0.178	<.001	0.498	8.40
TIP × CR	6.28	0.759	17.66		0.321	0.184	0.903	
TS × CR	7.69	0.304	21.62		0.393	0.038	1.106	
TIP×TS×CR	10.88	0.331	30.58		0.556	0.611	1.565	

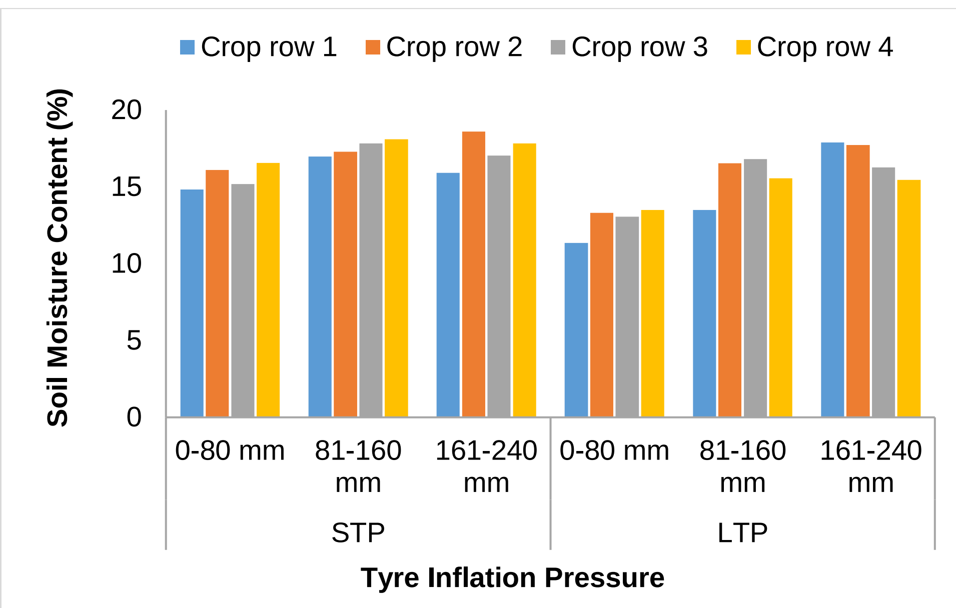
Note: TIP, TS, CR, STP, LTP, DT, ST and NT represent tyre inflation pressure, tillage system, crop row, standard tyre inflation pressure, low tyre inflation pressure, deep tillage, shallow tillage and no-till, respectively.

[a]DF – Degrees of freedom: 20 and 168. CV's are main effect and subplot effects, respectively.

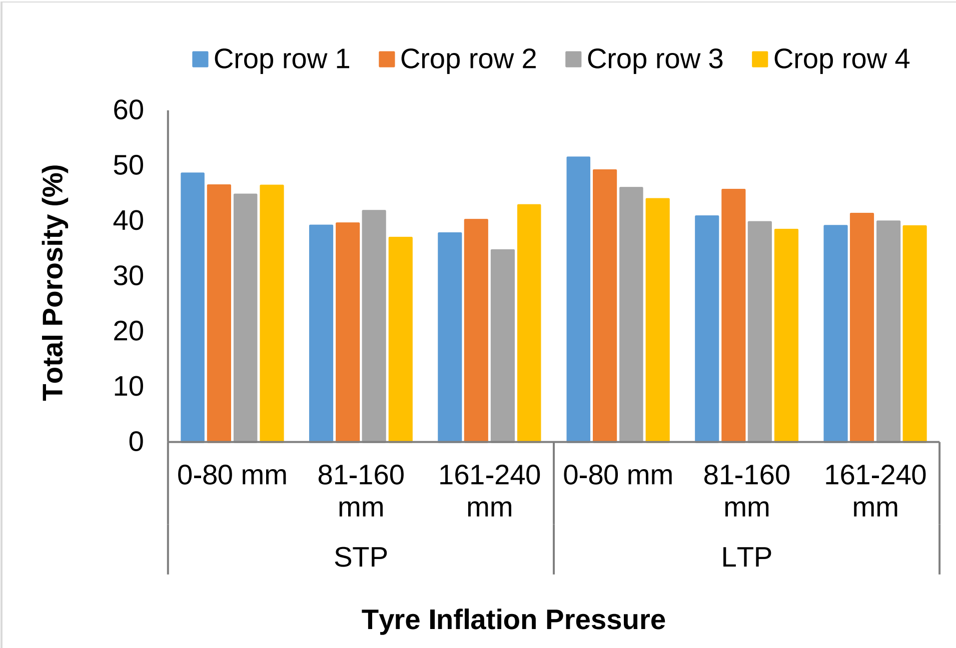
Appendix 6.1. Effect of tyre inflation pressure on the soil bulk density at different depths down to 240 mm in the South field in 2016.



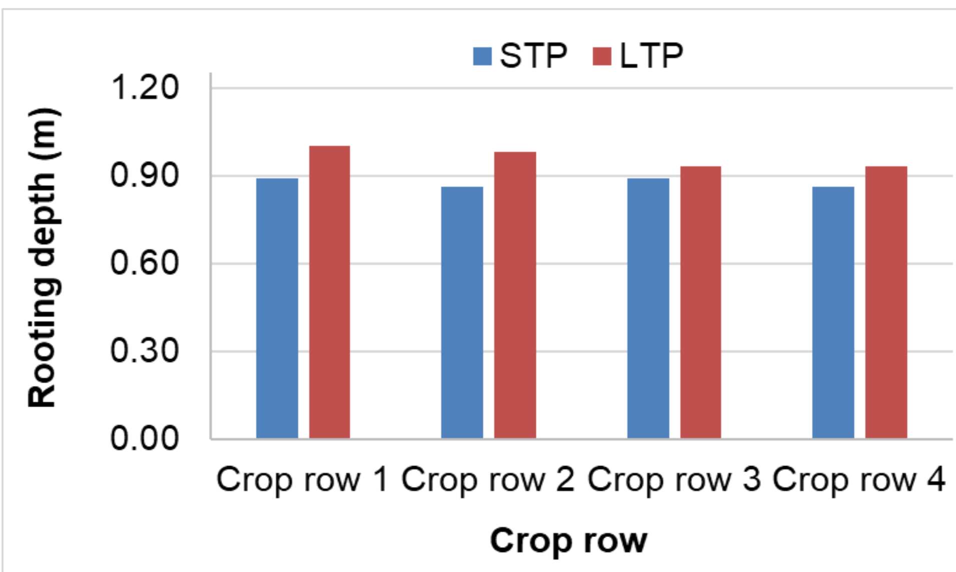
Appendix 6.2. Effect of tyre inflation pressure on soil moisture content at different depths down to 240 mm in the South field in 2016.



Appendix 6.3. Effect of tyre inflation pressure on total porosity of soil at different depths down to 240 mm in the South field 2016.



Appendix 6.4. Effect of tyre inflation pressure on the rooting depth of soybean in the South field in 2016



Appendix 6.5. Effect of tyre inflation pressure, tillage systems and crop row on number of plants ha^{-1} and plant height of soybean, in the North field in 2017

Treatments†	Number of plants ha^{-1}				Plant height (m)			
	SEM[a]	P value	LSD	CV (%)	SEM	P value	LSD	CV (%)
TIP	2722	0.285	8031	4.10	0.006	0.248	0.017	2.20
TS	3334	0.014	9836		0.007	0.001	0.021	
TIP × TS	4715	0.642	13910		0.010	0.074	0.029	
CR	2710	0.004	7566	5.80	0.005	0.010	0.014	2.60
TIP × CR	4501	0.200	12616		0.009	0.814	0.024	
TS × CR	5513	0.142	15451		0.011	0.099	0.029	
TIP×TS×CR	7796	0.709	21851		0.015	0.192	0.042	

Appendix 6.6. Effect of tyre inflation pressure, tillage system and crop row on plant establishment, number of plants ha^{-1} and plant height of soybean, in the South field in 2018

Treatments	Plant establishment (%)				Number of plants ha^{-1}				Plants height (m)			
	SEM[a]	P value	LSD	CV (%)	SEM[a]	P value	LSD	CV (%)	SEM[a]	P value	LSD	CV (%)
TIP	0.335	<.001	0.99	1.40	1120.7	0.001	3306.0	1.50	0.006	<.001	0.017	2.70
TS	0.411	0.027	1.21		1372.5	0.070	4049.0		0.007	0.032	0.021	
TIP × TS	0.581	0.008	1.71		1941.1	0.022	5726.1		0.010	0.157	0.029	
CR	0.591	<.001	1.65	3.60	1463.9	0.002	4087.1	2.80	0.004	<.001	0.012	3.00
TIP × CR	0.851	0.913	2.37		2237.4	0.701	6250.8		0.008	0.262	0.023	
TS × CR	1.042	0.226	2.91		2740.3	0.022	7655.7		0.010	0.052	0.028	
TIP×TS×CR	1.474	0.316	4.11		3875.4	0.743	10826.8		0.014	0.784	0.040	

Appendix 6.7. Effect of tyre inflation pressure and crop row on the 1000 grain weight and hand harvest grain yield of soybean, in the South field in 2016

Treatments†	1000 grain weight (g)				Hand harvest grain yield (Mg ha^{-1})			
	SEM[a]	P value	LSD	CV (%)	SEM[a]	P value	LSD	CV (%)
TIP	1.53	0.61	2.17	3.80	0.197	0.1645	0.775	7.50
CR	1.42	0.21	2.00	4.80	0.176	0.782	0.516	9.50
TIP × CR	2.31	0.78	3.27		0.293	0.797	0.880	

Note: In Appendices 6.5 - 6.7, TIP, TS, CR, STP, LTP, DT, ST and NT represent tyre inflation pressure, tillage system, crop row, standard tyre inflation pressure, low tyre inflation pressure, deep tillage, shallow tillage and no-till, respectively.

[a]DF – Degrees of freedom: 20 and 168. CV's are main effect and subplot effects, respectively.

Appendix 6.8. Effect of tyre inflation pressure, tillage systems and crop row on 1000 grain weight and hand harvest grain yield of soybean, in the North field in 2017

Treatments	1000 grain weight (g)				Hand harvest grain yield (Mg ha^{-1})			
	SEM[a]	P value	LSD	CV (%)	SEM[a]	P value	LSD	CV (%)
TIP	0.794	0.501	2.343	**1.70**	0.098	**0.030**	0.288	6.50
TS	0.973	0.188	2.870		0.120	0.411	0.353	
TIP × TS	1.376	0.764	4.059		0.169	0.256	0.499	
CR	0.898	0.706	2.506	2.70	0.150	0.197	0.419	14.20
TIP × CR	1.429	1.429	3.99		0.221	**0.020**	0.618	
TS × CR	1.750	0.412	4.89		0.271	0.326	0.757	
TIP×TS×CR	2.474	0.370	6.92		0.384	0.612	1.071	

Appendix 6.9. Effect of tyre inflation pressure, tillage system and crop row on 1000 grain weight, biomass and grain yields of soybean, in the South field in 2018

Treatments	1000 Grain weight (g)				Biomass yield (Mg ha^{-1})				Hand harvested grain yield (Mg ha^{-1})			
	SEM[a]	P value	LSD	CV (%)	SEM[a]	P value	LSD	CV (%)	SEM[a]	P value	LSD	CV (%)
TIP	0.674	0.339	1.987	1.70	0.125	0.001	0.368	5.80	0.076	0.003	0.225	6.40
TS	0.825	0.805	2.433		0.153	0.249	0.451		0.094	0.864	0.276	
TIP × TS	1.167	0.139	3.441		0.216	0.841	0.637		0.132	0.407	0.390	
CR	1.019	0.006	2.845	3.70	0.183	0.114	0.511	12.10	0.121	0.081	0.337	14.30
TIP × CR	1.507	0.049	4.207		0.227	0.778	0.761		0.177	0.759	0.494	
TS × CR	1.846	0.307	5.153		0.334	0.235	0.932		0.217	0.289	0.605	
TIP×TS×CR	2.610	0.619	7.287		0.472	0.446	1.318		0.307	0.51	0.856	

Note: In Appendices 6.5 - 6.6, TIP, TS, CR, STP, LTP, DT, ST and NT represent tyre inflation pressure, tillage system, crop row, standard tyre inflation pressure, low tyre inflation pressure, deep tillage, shallow tillage and no-till, respectively.

[a]DF – Degrees of freedom: 20 and 168. CV's are main effect and subplot effects, respectively.

Appendix C: Spreadsheet Analysis for Economic Assessment of the Use of Ultraflex Tyres

Appendix 7.1. Spreadsheet analysis of value to cost ratio for 200 ha farms under farm equipment with tyre systems (G. Brooks, Personal communication, 12 March 2019).

		Michelin Ultraflex Tyre Value to Cost Analysis				Example: For 200 ha farm			
Main Cultivation Tractor > 220HP		**General Duties Tractor > 126H**		**Combine Harvester**		**5000 lts Self-Propelled Sprayer**		**Chaser wagon**	
Number of machines	1	Number of machines	1	Number of machines	1	Number of machines	0	Number of machines	1
Cost of standard tyres / machine	$6,400	Cost of standard tyres / machine	$6,400	Cost of standard tyres / machine	$10,200	Cost of standard tyres / machine	$13,054	Cost of standard tyres / machine	$11,400
Cost of Ultraflex LGP tyres / machine	$7,600	Cost of Ultraflex LGP tyres / machine	$7,600	Cost of Ultraflex LGP tyres / machine	$14,400	Cost of standard tyres / machine	$18,075	Cost of standard tyres / machine	$13,000
Total Difference	$1,200	Total Difference	$1,200	Total Difference	$4,200	Total Difference	$0	Total Difference	$1,600
Total Difference in Tyre Spend	$8,200								
Crops area (ha)	200								
Tyre life (years)	5								
Standard Pressure yield / ha (Tonr	4.14								
Harvest value / Tonne	$323								
Annual value of crops	$267,444								
Yield increase/decrease from LGP	5.10%								
Annual Earnings increase	$12,000								
Over the tyre life	$59,998								
Value to Cost Ratio	50								

Appendix 7.2. Spreadsheet analysis of value to cost ratio for 809 ha farms under farm equipment with tyre systems (G. Brooks, Personal communication, 12 March 2019).

Michelin Ultraflex Tyre Value to Cost Analysis

Example: For 809 ha farm

Main Cultivation Tractor > 350HP			**General Duties Tractor > 300HP**		**Combine Harvester**		**elf-Propelled Sprayer**		**Chaser wagon**	
Number of machines	2		Number of machines	1	Number of machines	1	Number of machines	0	Number of machines	2
Cost of standard tyres / machine	$15,600		Cost of standard tyres / machine	$15,600	Cost of standard tyres / machine	$15,000	Cost of standard tyres / machine	$13,054	Cost of standard tyres / machine	$11,400
of Ultraflex LGP tyres / machine	$19,200		Cost of Ultraflex LGP tyres / machine	$19,200	Cost of Ultraflex LGP tyres / machine	$18,000	Cost of standard tyres / machine	$18,075	Cost of Ultraflex LGP/Machine	$13,000
Total Difference	$7,200		Total Difference	$3,600	Total Difference	$3,000	Total Difference	$0	Total Difference	$3,200
Total Difference in Tyre Spend	$17,000									
Crops area (ha)	809									
Tyre life (years)	5									
Historic yield / ha (Tonnes)	14.36									
Harvest value / Tonne	$142									
Annual value of crops	$1,649,648.08	Crop area*yield*price								
Yield increase from LGP	2.20%									
Annual Earnings increase	$32,892	$32,892.26	$36,292.26							
Over the tyre life	$164,461									
Value to Cost Ratio	23									

Appendix 7.3. Annual cost of using low tyre inflation tyre system over standard tyre inflation tyre system for a 200 ha farm at the University of Illinois.

Tyre systems	Equipment	Quantity	Axle tyre	Model	Brand name	Retail price (US$)†	Tyres needed	Cost/ Tyre #	Price total (US$)	% cost increase
STP	Tillage tractor (>220 HP)	1	Front tyre	380/85R34	Agribib	$1,100	2	$2,200	$6,400	-
			Rear tyre	480/80R46	Agribib	$2,100	2	$4,200		
	Planting tractor (>126 HP)	1	Front tyre	380/85R34	Agribib	$1,100	2	$2,200	$6,400	-
			Rear tyre	480/80R46	Agribib	$2,100	2	$4,200		
	Combine harvester	1	Front tyre	800/65R32	Megaxbib	$4,000	2	$8,000	$10,200	-
			Rear tyre	14.9R24	Agribib	$1,100	2	$2,200		
	Chaser wagon	1	Front tyre	900/60R32	Megaxbib	$5,700	2	$11,400	$11,400	-
	Total cost of STP tyres (A)							$34,400	$34,400	-
LTP	Tillage tractor (>220 HP)	2	Front tyre	VF380/85R34	Yieldbib	$1,300	2	$2,600	$7,600	18.75%
			Rear tyre	VF480/80R46	Yieldbib	$2,500	2	$5,000		
	Planting tractor (>126 HP)	1	Front tyre	VF380/85R34	Yieldbib	$1,300	2	$2,600	$7,600	18.75%
			Rear tyre	VF480/80R46	Yieldbib	$2,500	2	$5,000		
	Combine harvester	1	Front tyre	IF800/65R32	Cerexbib	$5,500	2	$11,000	$14,400	41.18%
			Rear tyre	480/65R24	Multibib	$1,700	2	$3,400		
	Chaser wagon	2	Front tyre	VF900/60R32	Cerexbib2	$6,500	2	$13,000	$13,000	14.04%
	Total cost of LTP tyres (B)							$42,600	$42,600	23.84%
	Difference (C) =(A-B)								$8,200	
	Annual cost for 5 years (US $) (D) = (C/5)								$1,640	
	Annual cost for 200 ha (US $/ha) (E) = (D/200)								$8.10	

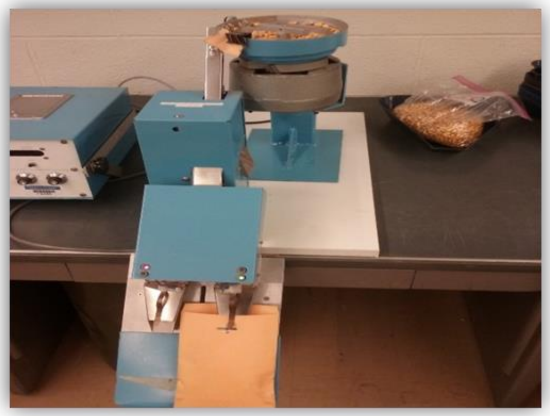
† Prices of tyres were collected from Michelin (G. Brooks, Personal communication, 12 March 2019; M. Pantaleo, Personal communication, 20 March 2019)

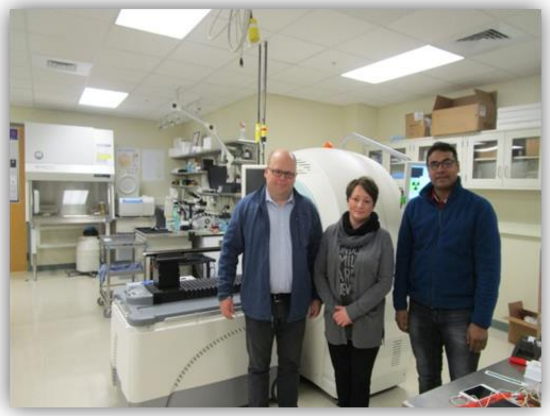
Appendix 7.4. Annual cost of using low tyre inflation tyre system over standard tyre inflation tyre system for an 809 ha hypothetical Illinois Farm

Tyre systems	Equipment	Quantity	Axle tyre	Model	Brand name	Retail price (US$)†	Tyres needed	Cost/ Tyre #	Price total (US$)	% cost increase
STP	Tillage tractor	2	Front tyre	420/85R34	Agribib2	$1,400	8	$11,200	$31,200	-
	(>350HP)		Rear tyre	480/80R50	Agribib2	$2,500	8	$20,000		
	Planting tractor	1	Front tyre	420/85R34	Agribib2	$1,400	4	$5,600	$15,600	-
	(>300 HP)		Rear tyre	480/80R50	Agribib2	$2,500	4	$10,000		
	Combine	1	Front tyre	520/85R42	Agribib2	$2,400	4	$9,600	$15,000	-
	harvester		Rear tyre	750/65R26	Megaxbib	$2,700	2	$5,400		
	Chaser wagon	2	Front tyre	900/60R32	Megaxbib	$5,700	4	$22,800	$22,800	-
	Total cost in STP (A)							$84,600	$84,600	-
LTP	Tillage tractor	2	Front tyre	VF420/85R34	Yieldbib	$1,700	8	$13,600	$38,400	23.08%
	(>350HP)		Rear tyre	VF480/80R50	Yieldbib	$3,100	8	$24,800		
	Planting tractor	1	Front tyre	VF420/85R34	Yieldbib	$1,700	4	$6,800	$19,200	23.08%
	(>300 HP)		Rear tyre	VF480/80R50	Yieldbib	$3,100	4	$12,400		
	Combine	1	Front tyre	VF520/85R42	Cerexbib	$2,900	4	$11,600	$18,000	20.00%
	harvester		Rear tyre	VF750/65R26	Cerexbib	$3,200	2	$6,400		
	Chaser wagon	2	Front tyre	VF900/60R32	Cerexbib2	$6,500	4	$26,000	$26,000	14.04%
	Total cost of LTP (B)							$101,600	$101,600	20.09%
	Difference (C) =(A-B)								$17,000	
	Annual cost for 5 years (US $) (D) = (C/5)								$3,400	
	Annual cost for 809 ha (US $/ha) (E) = (D/809)								$4.20	

†Prices of tyres were collected from Michelin (G. Brooks, Personal communication, 12 March 2019; M. Pantaleo, Personal communication, 20 March 2019)

Appendix D: Trial Photographs






ILLINOIS