THE EFFECTS OF SOIL STRUCTURAL FORMATION ON CROP DEVELOPMENT

BY:

MUSTAFA H. WAREOSH

(MSC. IRRIGATION SYSTEMS)

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ABSTRACT

Soil structure is a key element in determining the plant available water content and nutrient availability. Therefore, it is essential to study the effects of environmental factors on soil structure formation (especially the effect of weathering at after sowing), The soil surface was examined following different treatments of surface coverage (e.g. duration) to study the changes in soil structure and seed emergence timings simultaneously. The early stage soil surface coverage enhanced the soil structure formation so that the root system could be readily established and distributed consuming minimum plant energy which led to significantly higher ($P<0.05$) plant shoot and yield. While the soil surface treatments that were exposed to weathering (control) had the lowest yield. Additionally, the early stage soil surface coverage produced more circular pores which led to a significantly higher ($P<0.05$) soil water content. The results showed that the early stage soil coverage treatments for the growing seasons 2014/2015 and 2015/2016 had the significantly higher ($P<0.05$) soil pore circularity, water content, root, shoot and yield than the control treatments. A second experiment sought to quantify the effects and role of roots in soil structure formation using there the same soil cover treatments previously employed on a trial cultivated with winter wheat (cv. Rialto).The results showed that the presence of roots significantly ($P<0.05$) boosted the soil physical parameters such as porosity, water content, soil pore circularity and soil mean pore size in comparison with bare soil.

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DEDICATION

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Chapter 1: General Introduction

1.1. Rationale

The winter wheat growing season in the UK usually start in September-November of each year, at this time of the year the temperature can drop to -4 °C and rain can exceed 60mm. Hence, these environmental factors can affect soil structure formation and seed development. Soil structure can take a long time to form (e.g. decades) and it can influence plant root and shoot production. Intensive rainfall can cause soil erosion depending on its intensity and duration, which can severally affect the unprotected soil surface especially when the rain drops strike the soil surface with minimum plant coverage (Kelley 1990). This process can be affected by physical, biological and chemical factors which can form the final soil structure status and type. Additionally, other factors can assist the formation of the soil structure such as cultivation history and environmental conditions such as rainfall, soil and air temperature (Breure 2004).

Soil structure is dynamic and will continue to change long after a seed has been sowed. The soil structure at the soil surface will experience compaction due to rainfall. The plant at this stage can struggle to emerge if the surface has developed a crust. The plant will need considerable energy to overcome the soil structure which was already formed before the seed emergence. An artificial covering of the soil surface for certain period of time to protect the plant at early stages until emergence might benefit plant growth. The soil strength, if high, can cause the plant to produce

thicker roots to overcome the high penetration resistance of the soil which can cost the plant an extra consumed energy which could have been invested in shoot and yield formation.

Usually, the formation of soil structure can take place after the seed has been sowed and after rainfall, then soil structure can reform due to the soil surface compaction due to rainfall. The plant at this stage can struggle to emerge into the formed soil structure, by penetrating the strong formed soil aggregates to start the plant life cycle. Plants often need to consume energy to overcome the soil structure which was already formed before the seed emergence. The delaying process can be achieved by soil surface coverage for certain period of time to protect the plant at early stages until the soil penetration process will be achieved by the root system. The soil strength can represent a major obstacle that requires the plant to produce thicker roots to overcome the high penetration resistance of the soil, that can cost the plant an extra consumed energy which can be invested in shoot and yield formation.

To explore the exact effects of the root system into the soil structure it is important to compare the same soil texture but with contrasting crop cultivation history and thus soil structures.

1.2. Literature review

1.2.1. Soil physical effects on soil structure formation

1.2.1.1. Soil structure definition and background

Soil structure is important to the plant because of it will be the main receiver that determine the water and nutrients supply and availability, hence soil structure can

define as “arrangement of particles into aggregates, and the size, shape and distribution of pores both within and between aggregates” (Rowell, 1994). The arrangement of the soil particles with each other and can be achieved by the organic matter which will be activated by the soil microbial community activity, that can affect the root growth at future due to the control of water and nutrients flow through the soil (Hartge and Stewart, 2000).

Also, soil structure can be defined as “as the degree and type of aggregation and the nature and distribution of pores and pore space” where soil texture will form the structure by the developing and mixture of sand, silt and clay particles together and with the organic matter content (Fitzpatrick, 1986) as shown in Figure 1.1.

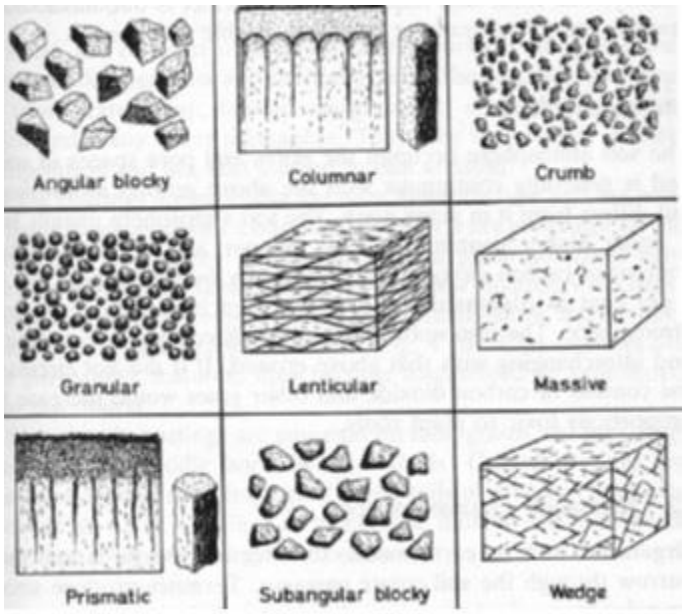


Figure 1.1 Representation of the main soil structure units / aggregates (Figure from Fitzpatrick, 1986).

Soil structure status can be essential for the whole crop cultivation process where it can affect by the adopted tillage system and then this process can change the stabilization, size and shape of soil seedbed aggregates (Soffe, 2003). Soil structure

also influences the root penetration ease into the soil structure which in turn affects the root's ability, water and nutrient exploration (White, 2006).

Soil structure classification can be considered according to the aggregate shape; such as granular, columnar, blocky, crumb, massive etc. (Fitzpatrick, 1986) or based on their size achieved on hierarchical order, where the soil microstructure aggregates (< 2 μm diameter), soil microaggregates (2-250 μm) and soil macroaggregates (> 250 μm) (Tisdall and Oades, 1982).

There are many physical, chemical and biological factors affecting the soil structure formation and development, which have their own impact on the soil structure (Dexter 1988). Soil wetting and drying cycles affect the soil structure development by igniting the interactions between different soil structures and this effect differ according to the soil texture and other factors Dexter (1988). Gerhardt (1997) successfully pointed a correlation between soil structural arrangement with the plant root's ease movement into the soil column and with the soil compaction and resistance ability for degradation. Hence, the preferred optimal soil physical conditions need to produce suitable aeration and soil available moisture for crop roots. Soil fertility is positively correlated to suitable porous soil structure and soil aggregates stability which are important to increase the crop yield and decrease erodibility (Bronick & Lal, 2005). The optimum soil structure in terms of mechanical and hydraulic properties that represent a preferred environment for maximum crop production, need to be stable against mechanical and water stresses and to have moderate soil strength (Dexter 1988).

1.2.1.2. Soil texture

Soil texture can be classified according to the ratio of clay, silt and sand into the soil content also called the soil particle analysis (White, 2006). However, soil contains other material such as soil organic matter content which is not considered into the soil texture classification. According to the soil texture classification there are twelve categories of soil texture based on the separation ratios of sand, silt and clay which will be derived on the soil texture triangle (Tan, 2000).

The importance of soil texture for the plant can be by determining the soil water capacity and that can affect the total soil porosity and water content, where soil textures with higher clay contents will have greater soil porosity and water content (White, 2006). However, plants sown in sandy soil are less likely suffer from anaerobic conditions caused by waterlogging due to free draining (Gregory, 2006).

Additionally, soil texture classification can be useful for root growth by acting as an indicator of soil temperature and nutrient retention (White, 2006). Sandy soils that hold less water and drain freely can modify the temperature of the soil and as a result can be affected by the air temperature faster than clay soil textures (White, 2006). Thus, soil biological activity can be influenced by the soil rapid temperature changes and that can affect the plant development (Wood, 1995).

Wakindiki & Ben-Hur (2002) successfully pointed out the role of soil texture in stabilization of soil structure where soil erosion and crusting processes were significantly different between different soil textures due to the different reaction of soil components with organic matter and microbial activity. Moreover soil texture can contribute in the stability of soil structure Blake et al. (2003).

1.2.1.3. Soil organic matter content

Soil organic matter content can have an important impact on soil structure formation, as it can assist in the aggregates formation and development of aggregates. Soil organic matter acts to bind the soil particles and can assist them in releasing the soil nutrient and increasing soil water content Watts et al. (2001). Additionally, plant nutrient requirements can be provided by the soil organic matter content after raising the soil fertility and enhancing soil structure (Soffe 2003).

1.2.1.4. Soil porosity

The crop yield could be mainly affected by the soil porosity where it can determine the soil water and nutrients content (Masle and Passioura, 1987). The soil porosity is directly correlated with soil bulk density and soil penetration resistance; hence the soil porosity range can influence the plant root development by determining the availability of oxygen and nutrients in the soil (Öpik et al., 2005; Gregory, 2006).

Maintaining soil structure that has enough porosity to contain moisture and nutrients without restricting the root to grow and distribute can produce in optimum environment for the plant to produce maximum yield (Dexter 1988). Therefore the soil microbial activity can be affected by oxygen deficiency (Kramer and Boyer 1995).

1.2.1.5. Soil water content

The soil water content can mainly affect the plant activity by determining the availability of nutrients to the plant, additionally; the root system will need to explore the soil structure deeply to find the required water and nutrients for plant

development (White, 2006). Each soil type has a maximum limit in holding water called the available soil water content after losing the gravitational water by the drainage (field capacity) and this water range is optimal to grow plants (Wood, 1995). There is a soil water level that the plant cannot take use of called permanent wilting point (Russell, 1977). The soil water content as well can be affected by the total size and shape of the pores and their connection with each other and that can increase the transmitted water and nutrients to the plant by the roots (Wood, 1995).

1.2.1.6. Soil strength

Soil strength can affect the root elongation when the soil penetration resistance exceeds 2 MPa even in relatively moist soils (-100 -200 kPa matric potential) Bengough et al. (2011). Although, the existence of the biopores and connected channels increases the roots elongation in undisturbed soil as seen in figure 1.2.

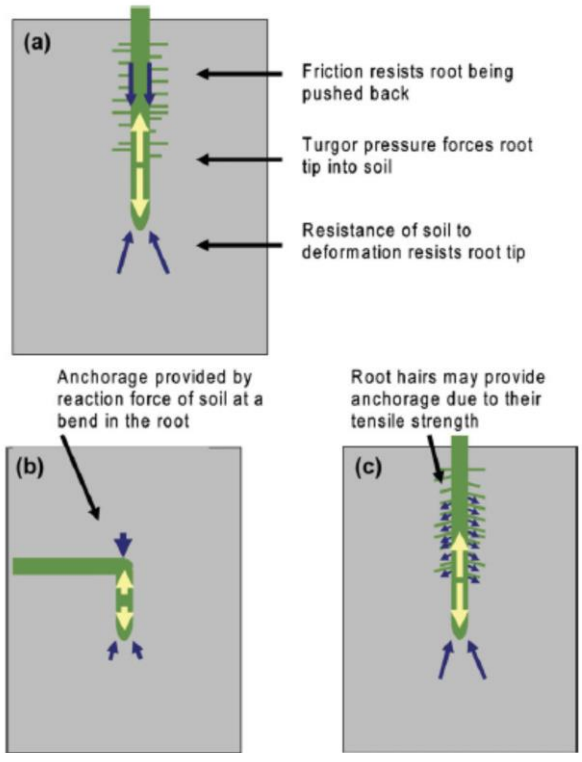


Figure 1.2 Schematic diagram illustrating (a) forces exerted by a penetrating root tip on the soil, (b) reaction force of soil at a bend in the root tip, and (c) anchorage of the root tip by root hairs (Bengough et al. 2011).

The crop yield can be affected by the soil that had lower soil porosity and higher soil penetration resistance, this impact was firstly affected plant root and shoot development then as a result on the crop final yield Gregory (2006). This crop yield reduction can be due to the requirement of the plant to consume an extra energy to enforce the root tips and system to penetrate the soil structure and that energy could be converted to yield if the soil strength was not high Whalley et al. (2008). In general, soil penetration resistance need to be in the range of<3.0MPa to germinate to permit the wheat seeds to germinate inside the soil structure Jakobsen and Dexter (1987). Roots were thicker in compacted soils in comparison with less compacted soils, the root diameter increment was to generate an axial stress on the root tip to enforce it to penetrate the soil compacted structure. The predicted mean stress at the root tip can be shown in figure 1.3 Kirby and Bengough (2002).



Figure 1.3 Predicted mean stresses near the tip of a thin root analogue penetrating soil. Kirby and Bengough (2002).

1.2.1.7. Soil repeated wetting and drying cycles

Soil natural wetting and drying cycles can assist compacted soil amelioration where plant root can be easily penetrating soil structure through cracks caused by the soil drying process. Then soil wetting process can secure the water and nutrients transportation after the root was already distributed in. The replicate of this natural process can increase soil water content due to root and microbial interaction with the soil aggregates over time. The existence of biopores that created by earth worm can secure suitable passes for the root system into the soil structure with minimum soil penetration resistance, that can save the plant energy to be invested by the plant in shoot and yield production at crop maturity stage Dexter (1991).

Soil repeated wetting and drying cycles is a natural phenomenon that influence soil structure formation and development. O'Keefe (2009) had referred to the role of the soil repeated wetting and drying cycles to improve soil undisturbed structure where bulk density was improved significantly after the third soil wet/dry cycle. Additionally, she referred to the importance of the wet session of the soil to increase the soil cracks which had been made by the drying session (in many instances). Therefore, the soil wetting and drying repeated cycle could give better results if the soil drying will be near soil wilting point and that will be followed in sequence by soil wetting session near the soil saturation point.

Carminati et alet al. (2009) had highlighted that the plant's root can affect the soil structure formation through soil repeated wetting and drying cycles where the roots itself will shrinkage after soil drying and this will results in gaps around the tap and lateral roots. This will create more pores into the soil and from that it can be

concluded the soil wetting and drying cycles will interact with both the soil and the plant.

Murray and Grant (2007) had referred to the soil natural amelioration processes by swelling and shrinkage where they claimed that the wet/dry cycle can affect only the surface layer of the soil and to reach the subsoil layer it is required to add a physical disturbance agent such as deep tillage. Gill (2012) had mentioned that the intensity of rain can affect the soil physical situation more than the single soil wet/dry cycle.

1.2.1.9. Soil compaction

Soil compaction can be caused by many natural and management sources such as soil surface compaction by rainfall and machinery passes. All these will lead to the same impact of decreasing soil porosity which will lead to decreasing of the available water content and nutrients and that can directly affect the plant establishment and growth Keller et al. (2013).

Soil compaction can affect the plant growth permanently, as it breaks down the soil structure and decreases the water holding capacity (Cook et al., 1996). Lindberg and Pettersson (1985) examined the effects of soil compaction on roots and found that the nutrients uptake was lower in soils that do not have compaction. Although, Mulholland (1994) mentioned that Masle and Passioura (1987) showed that wheat and sunflower impeded roots had no limitation of nutrients uptake. Soil compaction can decrease the root storage production Maduakor (1993) and lead to leaf area reduction (Masle and Passioura 1987).

Horn et al. (2003) determined the cause of the soil compaction to be when external forces applied on the soil surface rearrange the soil particles, which will realign

themselves to form a new soil structure. In the case of agriculture soils, soil compaction is caused artificially by heavy machinery driven on the land such as tractors and harvesters and naturally by rainfall drops. Two tractor's tyres next to each other on both side of the tractor can significantly reduce the extent soil compaction, due to the tractor's applied axle load on the soil surface is spread over several wheels and hence greater surface area for soil depth of 300 mm. (Keller and Arvidsson, 2004). Similarly, Arvidsson and Ristic (1996) found that tractor's tyre inflation pressure was the main reason for increasing the rut depth.

Wheat yield can be highly affected by soil strength regardless the soil type, structure and water status. Where soil compaction had increased the soil bulk density (as seen in figure 1.4) and that had affected the soil porosity and in return crop production Watts et al. (2008).

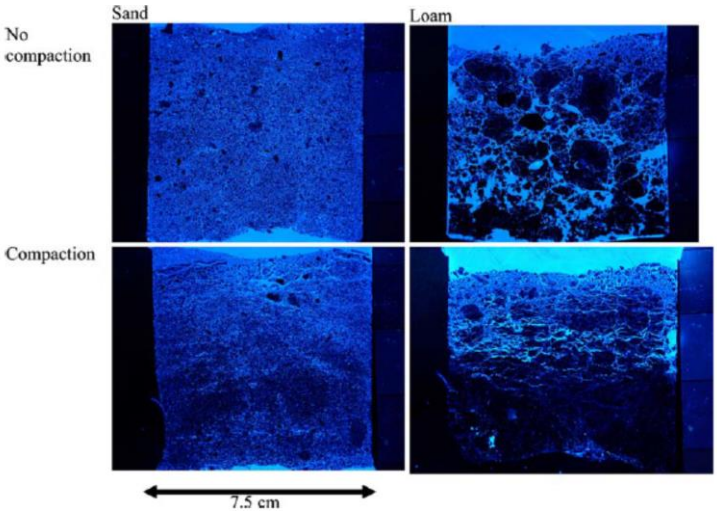


Figure 1.4 Resin-impregnated sections of soil from the fallow plots. Watts et al. (2008).

There is a direct correlation between soil compaction and the increment of soil penetration resistance, where the soil compaction can be caused by the traffic of heavy machinery or heavy rainfall (Jones et al. 2003). When the soil strength is higher that will require the root to enforce harder which can lead to producing thicker diameter (Alakukku 1996). Hence soil compaction can decrease crop establishment and final yield (Hamza and Anderson 2003).

1.2.2. Soil and plant interactions

Chapman et al. (2012) demonstrated the soil physical properties effects on roots formation and their effects on nutrients acquisition which resulted in controlling the growing and yield of the entire plant or crop. Figure 1.5 illustrates the nutrients flow and acquisition through the plant root system. They had described the roots path into the soil structure as two areas; the first one (root proliferation) represent the first third of root depth will be responsible about root architecture formation, nutrients distribution and soil strength. While the second area (mass flow and diffusion) which represent two thirds of the roots depth will take charge of water potential and uptake, hydraulic conductivity, net nutrients uptake, and Ion mobility.

Maintaining soil structure that has enough porosity to contain moisture and nutrients without restricting the root to grow and distribute can produce optimum environment to the plant to produce maximum yield (Dexter 1988). Angers and Caron (1998) described the interaction between the soil, roots and microbial activity as a three way relationship, where soil structure can initially influence root architecture especially at seed emergence stage. Then the roots can penetrate the soil structure reforming the soil aggregates and porosity by forming macropores which enhance the soil porosity, moisture and nutrients capacity. The soil microbes will

take advantage of the carbon source and plant residue as a food to contribute forming and developing of the soil structure. Plant root can increase the total soil porosity by 30% (Bonder et al. 2014).

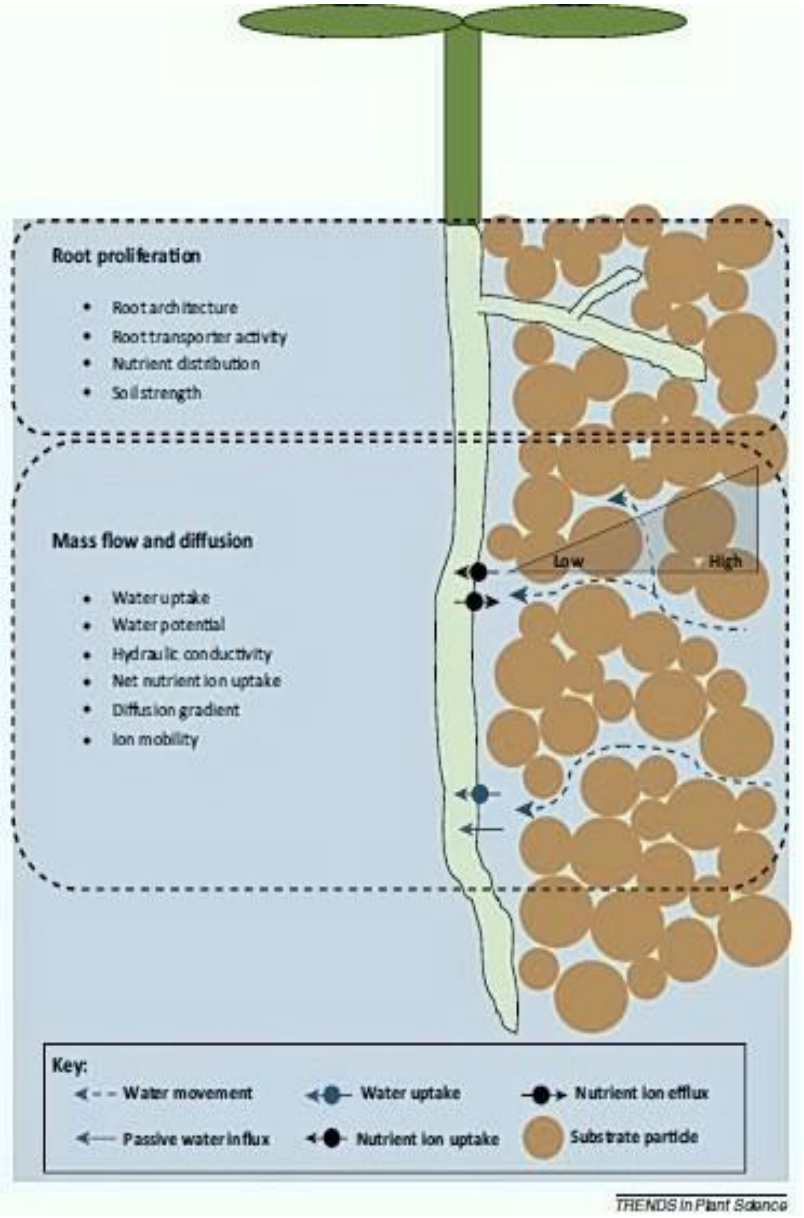


Figure 1.5 Nutrient acquisition depends on root proliferation and transporter function, exudation, symbioses, and diffusion of nutrient ions and mass flow of water to the root surface. These processes can be facilitated by root exudates to mobilise sparingly soluble nutrients and symbiotic associations with other organisms such as bacteria. Note that for root proliferation, soil strength is a biophysical factor while the other three listed are all biotic. These components are regulated by plant physiology and the physical properties of the substrate. Chapman et al. (2012).

1.2.3. Environmental effects on soil structure formation

1.2.3.1. Rainfall effects on soil surface compaction

Winter wheat can be affected by the excessive rainfall especially where the sow date is between September to November each year. Where this period of the year will have temperature decrease and heavy rainfall at the same time of seed sowing and that can decrease seed establishment which was directly linked to the decreasing of soil and air temperature (Blake et al. 2003).

1.2.3.2. Soil temperature effects on soil structure

The seedbed optimal temperature range is about 20-25^{o}C for cereals (Blake et al., 2003). The soil temperature can be mainly affected by the air temperature and the soil texture; hence this temperature is important to the plant development especially at the seedbed area at early seed emergence stages (McWilliam, 1998). However, depending on seed genetics, the seed can be germinated as low as 5^{o}C (Fitzpatrick, 1986).

1.2.4. Effects of biopores on soil structure and root formation

Pankhurst et al. (2002) stated high soil strength can minimise the soil exploration and distribution by the roots, 80% of the roots where found in macropores paths and those zones were higher in microbial activity in comparison with the other soil zones as shown in Figure 1.6.

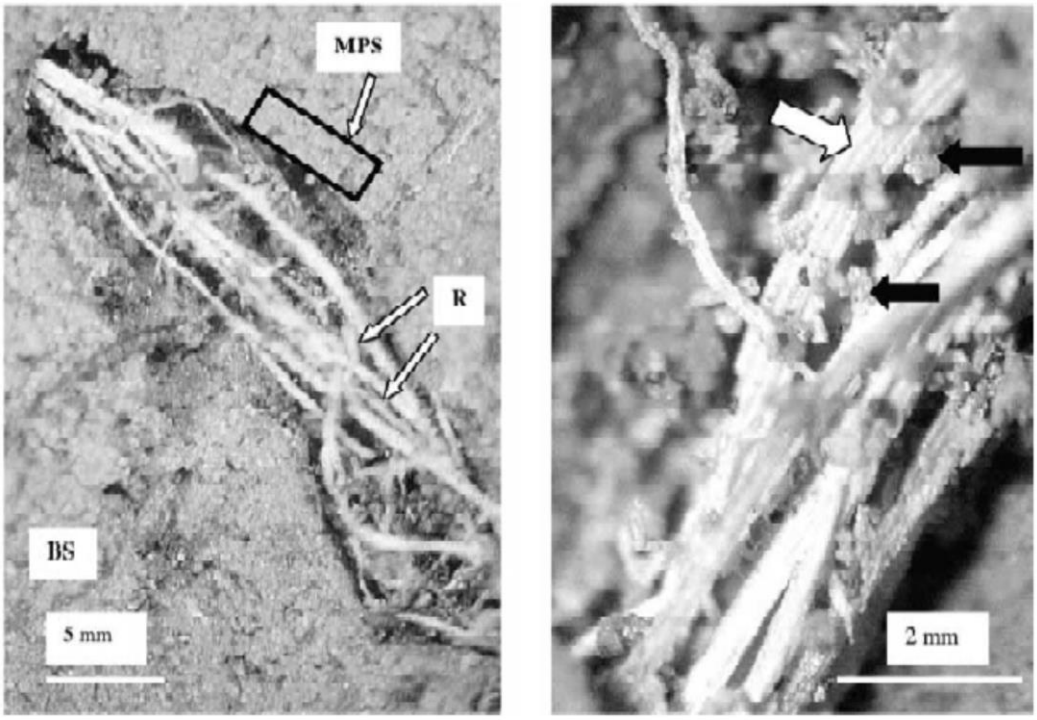


Figure 1.6 (1) Photograph showing several roots (R) within a macropore at 40–60 cm. Macropore sheath (MPS) soil includes the inside of the macropore wall and soil extending 1–3 mm into the soil matrix. Bulk soil (BS) was collected >10 mm from the macropore. (2) Photograph showing the clumping of roots (white arrow) within a macropore at 40–60 cm. The black arrows show small soil aggregates that are associated with the roots within the macropore. These aggregates are referred to as macropore root (MR) soil Pankhurst et al.. (2002).

Roots established contact with the biopores inside the soil structure and that was essential to increased nutrient transportation from the soil to the plant as seen in figure 1.7 (Athmann et al. 2013).



Figure 1.7 Fresh earthworm cast lining (left) and macropore root soil (right) in biopores. Left picture:75 cm soil depth, with barley root. Right picture: 65 cm soil depth, with barley roots.

1.2.5. Measuring techniques of soil physical parameters

1.2.5.1. X-ray µCT scan technology for soil physical and root measurement.

Mooney et al. (2012) highlighted the application of X-ray µ CT technology development for measuring undisturbed soil and root systems and how can the image processing techniques assist in obtaining measurement of 3D root architecture. Lontoc-Roy et al. (2006) showed the importance of root isolation inside the soil volume after scanning it with high resolution X-ray µ CT technology (500 CT image of 0.1mm) where they sowed Maize (Zea mays L.).

X-ray µCT technology enables exploration of soil structure and root architecture in situ, which can explain the relationship between soil structure and root formation (Dowine et al. 2015). The 3D insight gained from X-ray CT was important for understanding the soil deformation caused by internal and external hydraulic and mechanical stresses. Hence, this technology could measure the soil macropores before and after exposing the soil to hydraulic and mechanical stresses (Peth et al. 2010).

Non-invasive and non-destructive X-ray µ CT technology can measure the soil structure in 3D form; this provides accurate information on the soil structure especially pore size distribution and structure which are essential to understand the soil development (Taina et al. 2008). This technology can also examine the soil structural quality by measuring the stability of the aggregates for conventional and organically management, where organic management created aggregates which were much more stable than the conventional ones (Papadopoulos et al. 2009)

Kuka et al. (2013) mentioned X-ray µ CT can be useful in examining the relationship between the soil-root relationships in grassland soils, they had analysed

undisturbed soil (40 µm resolution) where they could measure the root volume and area and founded that there was a strong correlation between them. Koebernick et al. (2014) referred to using the X-ray CT non-destructive technology to measure the three dimensional structure of soil and the roots inside, this approach can be useful to determine the roots parameters and their temporal dynamics in situ. Aravena et al. (2011) mentioned that the adopting of X-ray µ CT technology was effective to measure the soil compaction and its effect on soil, roots and rhizosphere. They used a numerical modelling to obtain accurate measurements of soil aggregates and root in natural soil.

Metzner et al. (2015) did a comparison between using X-ray CT and MRI technologies for examining soil and root parameters and they had concluded that both methods were similar in results but the X-ray CT technology was higher in resolution. That can be useful for the project's goals examine the effects of soil structure variation on the plant's shoot and root development and correlate them together.

1.3. Research aim and objective

The overall research aim was to investigate the effects of soil structure formation on the plant root architecture development and to what extent can this impact the crop yield through the crop lifespan. That was achieved by conducting three main experiments on undisturbed soil structure to find that impact on plant root and shoot. The overarching hypothesis is "to what extent do environmental factors such as weathering affect soil structure development? And to what extent that will affect the crop development and yield". The following specific hypotheses will be tested:

1. Different soil structures developed from the same soil texture will have contrasting effects on plant root and shoot development.
2. Direct and partial exposure to rainfall on the soil surface will affect the soil structure and plant parameters differently and subsequently influence the crop yield. .
3. Coverage of the soil surface during the first month following establishment will significantly affect soil structure formation, plant root, shoot and crop yield.
4. The formation and development of root architecture in soil structure will significantly affect soil physical characteristics such as soil porosity, soil water content, soil mean pore size, soil pore circularity and soil penetration resistance.

1.4. Thesis Structure

An outline of the three experimental chapters within this thesis is submitted in table 1.1 where each experiment is presented with the various methodologies used. Chapter 2 describes the methods that have been used to take these measurements, while Chapter 6 goes on to discuss the overall findings of this thesis.

Table 1.1 Thesis structure explaining each chapter title, tested hypothesis, and the used methods.

Chapter Number	Experiment Title	Sub-aims tested	Methods used
3	Exploring undisturbed soil structure formation and development and its interaction with the plant using X-ray µCT technology	1,4	1. Soil size particle analysis. 2. X-ray µCT soil structure scan. 3. Non Invasive root segmenting (Manual and RooTrak). 4. WinRhizo root segmenting 5. Soil penetration test.
4	Increasing wheat crop yield by manipulating environmental factors involved in the formation of soil structure	1,2,3,4	6. X-ray µCT soil structure scan. 7. Non Invasive root segmenting (Manual and RooTrak). 8. WinRhizo root segmenting 9. NDVI 10. Theta probe soil moisture sensor 11. Soil penetration test.
5	Quantifying the effects of soil pore structure on wheat root and shoot formation and development using episodic X-ray µCT scans.	1,2,3,4	12. X-ray µCT soil structure scan. 13. Non Invasive root segmenting (Manual and RooTrak). 14. WinRhizo root segmenting 15. NDVI 16. Soil moisture sensor. 17. Soil penetration test.

Chapter 2:

General Methods

This chapter describes the general methods that were adopted to measure soil, plant and environmental parameters for the experimental chapters.

2.1. Soil Analysis

2.1.1. Soil particle size analysis (PSA)

PSA was conducted in all three experiments to define the soil texture type by analyzing the soil particle contents (soil, silt and clay percentages as shown in figures 2.1 and 2.2) from a representative soil sample. These percentages were calculated by taking 50g of loose soil in bags from the field from 0-17 cm depth randomly from each plot, three 150-300g soil samples were taken from 0-17cm depth from each plot. Secondly recording the reading of a mechanical analysis hydrometer of the soil sample after calibration of the hydrometer with distilled water was undertaken; the soil was sieved < 2mm and dried overnight and then hydrogen peroxide 6%, sodium hexa meta phosphate 5% and sodium carbonate in 1 liter of distilled water were added. Then, shaking the soil suspension by plunger these hydrometer readings and room temperature were recorded. Finally, the percentages of sand, silt and clay were recorded according to the time and particle diameter (sampling was at 32 seconds for silt and clay then at 8 hours after mixing the content using the plunger for silt; then the sand percentage was calculated by subtracting the clay and silt percentages from 100%). Then the hydrometer readings correction process was applied depending on the room temperature (adding 0.2 unit to the

readings of the samples for every 1°C above 20°C and subtract 0.2 unit for every 1oC below 20°C). These percentages were applied to the Soil Survey of England and Wales soil triangle to determine the soil texture type (Rowell 1994, Laker and Dupreez, 1982 and Day 1965).

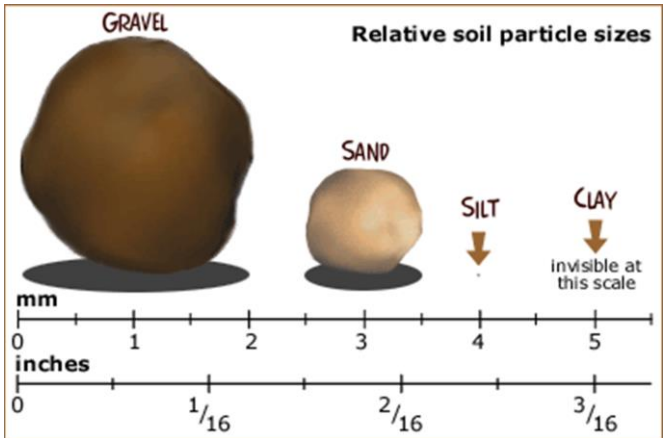
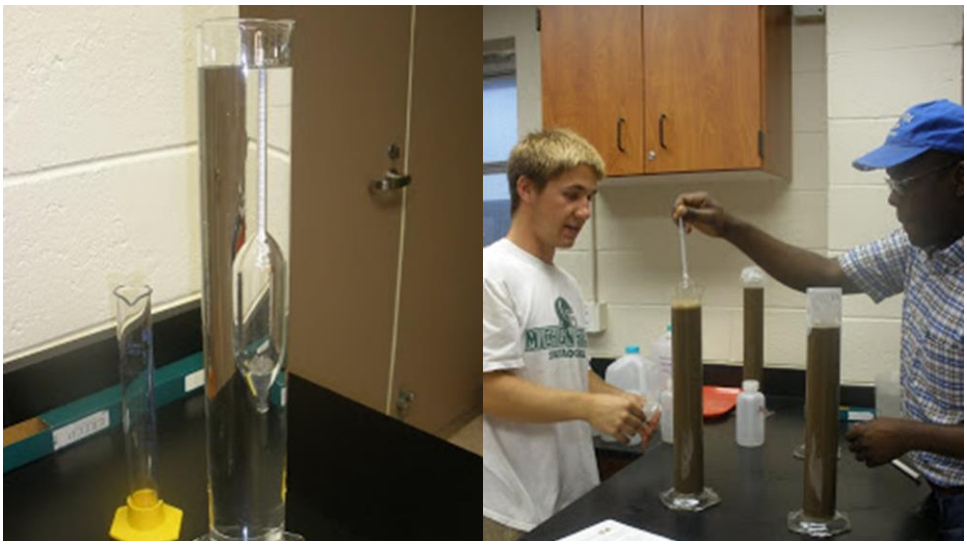


Figure 2.1 Soil particle sizes (gravel, sand, silt and clay) https://kosthilaire8162.wordpress.com



2.2 Soil particle analysis laboratory procedure (right and left). Photos source at http://abewaterfountain.blogspot.co.uk

2.1.2. Soil organic matter content analysis

The goal of soil organic matter sampling and analysis procedures was to derive the organic matter content percentage to the soil total weight. And to achieve that, firstly three 150-250g samples of loose soil were taken from 0-17cm depth from each experimental plot. Secondly, weighing a 50g of sieved soil sample to made the primary drying overnight in the oven at 105 °C to remove the soil moisture. Thirdly, was finding the percentage of the organic matter content in the soil sample by drying the soil again in another oven for another 72 hours at 500 °C to burn the soil organic matter content inside the soil sample, after weighing the soil sample before and after each process. Finally, the weight difference will be the soil organic matter weight, this weight was calculated as a percentage of the total soil sample weight to represent the soil organic matter content percentage of that replicate as shown in figure 2.3.

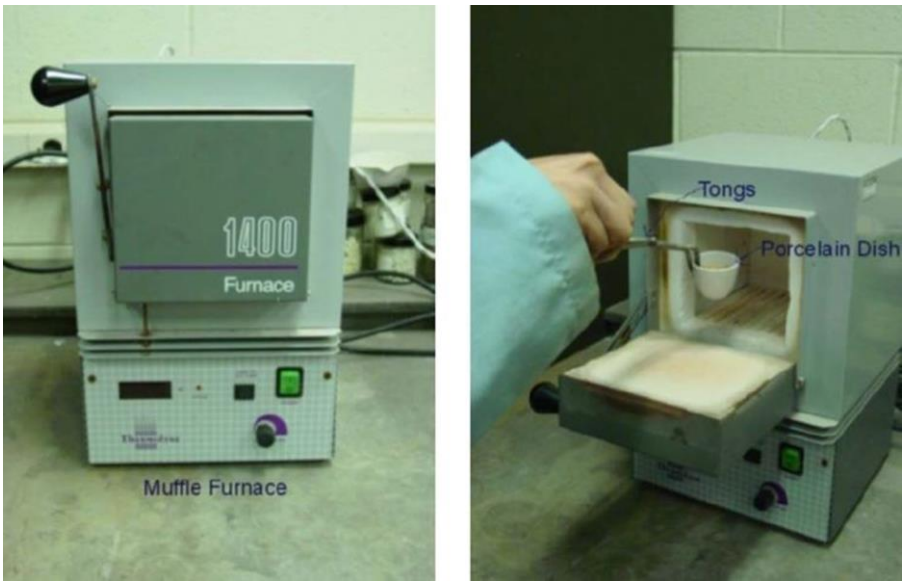


Figure 2.3 Soil sample analysis organic matter content by leaving the soil sample in the oven over night at 500 °C, the photo was taken from http://civilblog.org.

2.1.3. Soil moisture measurement

The soil moisture measurement was conducted by two methods; the first was indirectly by using the soil gravimetric method by weighing a soil sample before and after drying it in the oven overnight at 105 °C. The difference in sample weight represents the soil moisture percentage.

The second direct method was using the Theta probe soil moisture sensor model ML3, Delta-T Devices Ltd. Burwell, Camridgeshire, UK (www.delta.co.uk) as shown in Figure 2.4. This handheld soil moisture sensor provides the soil moisture content based on soil volumetric content percentage. Readings were recorded weekly for the average of three readings per plot for the whole wheat growing season.



Figure 2.4 Measuring the soil water content by the Theta probe soil moisture sensor, the photo was taken from https://www.delta-t.co.uk.

2.1.4. Soil penetration resistance

Soil penetration resistance was measured using the soil cone penetrometer Rimik model CP40II (Rimik, Toowamba, Queensland, Australia; http:wwwrimik.com) as shown in Figure 2.5. This measure was conducted on an approximatley monthly basis; then soil penetration readings were recorded for each plot to the maximum depth available for all experiment replicates. This was due to the field soil variation whereby the penetration rod did not reach the same depth for all treatments. The soil penetration resistance value was calculated as an average for the first 30 cm depth of field soil. The obtained readings of the soil penetration resistance were the average value of the top 40 cm of soil.



Figure 2.5 Soil cone penetrometer Rimik model CP40II, the photo was taken from http:wwwrimik.com.

2.1.5. Soil undisturbed sampling

The undisturbed soil sampling was conducted (on 15th December 15, 15th February 16, 15th June 16 and 29th July 16), by randomly choosing the soil sample location in the plot avoiding the plot edges and gently knocking a wooden block fixed on the top of the PVC pipe core firmly into the soil to the end as shown in figure 2.6 the core size was 170 mm x 84 mm. Then soil core was extracted by digging to the core's bottom, wrapped in cling film and stored at 5 °C until it scanned. Each PVC pipe core sample was weighted before taking the measurement of soil structure. The soil samples transportation process need to be vibration free and carful to guarantee the same field soil structure, where the vibration and cautiously hand them from place to another to avoid any soil structure deformation.



Figure 2.6 Soil undisturbed field core sampling,

2.1.6. X-ray µCT image scans

All the X-ray µ CT scans was achieved using scanner model (v ׀ tomex ׀ M) manufactured by GE© (https://www.gemeasurement.com). All the scans durations were 30 minutes for both samples bare soil and samples with roots for 58 µm resolutions, energy 180 kV 160 µA, and 3600 projections were collected for two sections per sample in the fast multi scan mode. The numbers of scans for each experiment are in Table 2.1 below.

Table 2.1 Experiment scan numbers for undisturbed soil samples with and without roots conducted at Hounsfield facility, The University of Nottingham.

Experiment	Soil scan	Root scan	Total scans
First	48	144	192
Second	160	96	256
Third	224	32	256
Total numbers of undisturbed soil scans samples			704

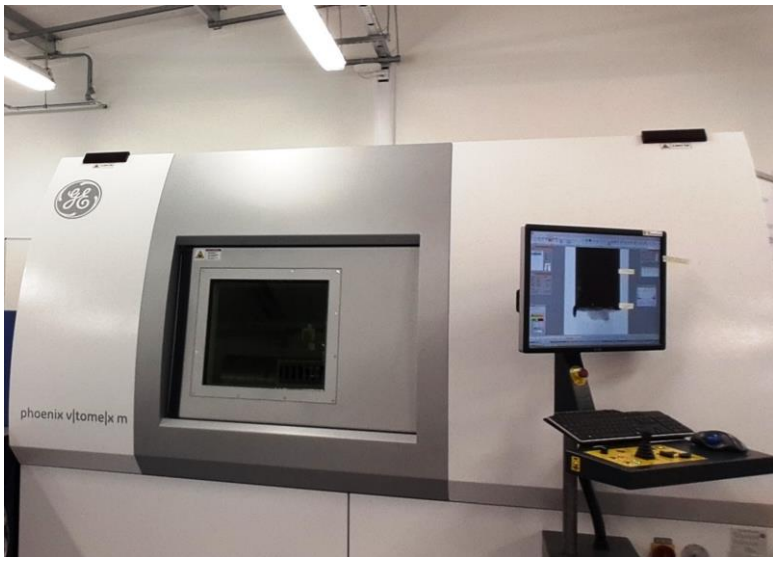


Figure 2.7 X-ray µCT Scanner at Hounsfield Facility, The University of Nottingham, Sutton Bonington Campus.

2.2. Root analysis

Root segmentation was conducted by both noninvasive and destructive methods as described below:

2.2.1. Non Invasive root segmentation from the X-ray µ CT image scans

2.2.1.1. Semi-automated Root segmenting by VG Studio Max ™

This procedure was achieved by using the semi-automatic method of region growing tool in VG Studio MAX™ to segmenting the root architecture inside the soil sample and thus determining the root area as a region of interest starting from the top of the soil core sample to the bottom selecting each area manually. This method was conducted on the chapter 4 root samples. In this method the root diameter was measured by taking the average of three root reading at the top, middle and bottom of the whole main root, while the root length was measured by tracking and calculating the longest root length in the soil sample core.

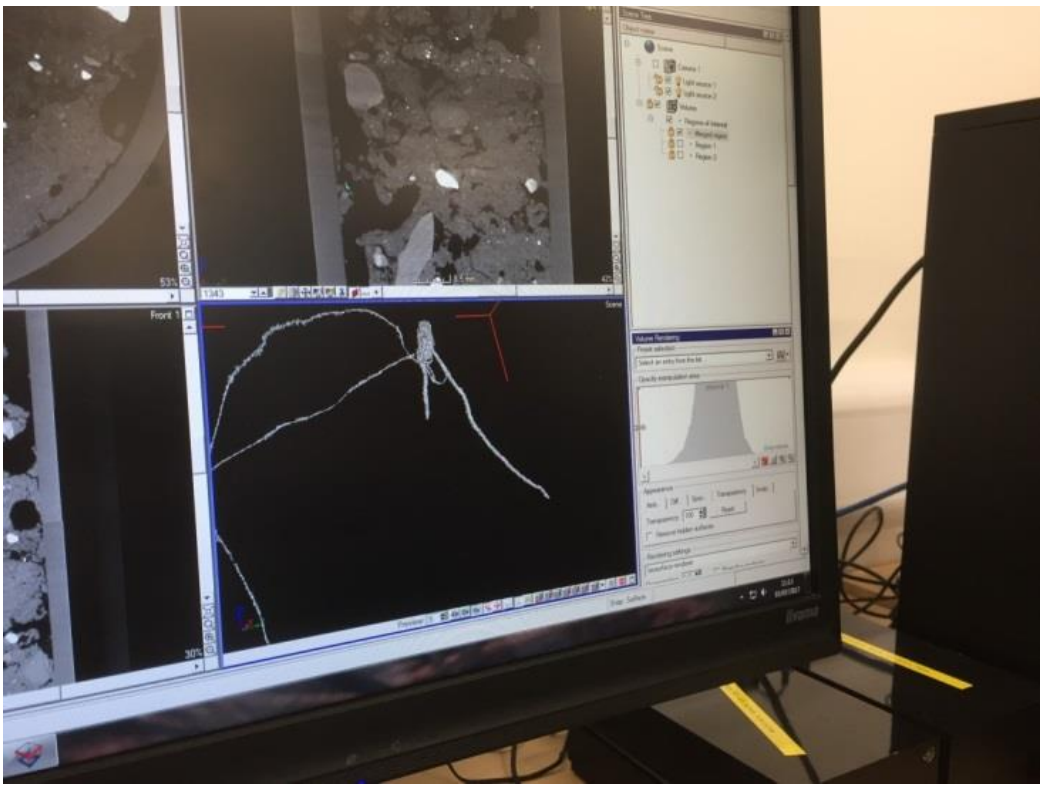


Figure 2.8 Wheat's root manual segmenting using software on computer that has special specifications. The computer specification was 40GB RAM and 64-bit operating system.

The process of subtracting the root volume calculated by VG Studio Max® from the calculated soil porosity volume will give an accurate estimation of the soil porosity calculated by Image J, where in this case this software will not differentiate between the soil particles and the root volume.

2.2.1.2. Autonomous root segmentation by RooTrak

This procedure was achieved by using RooTrak (Mairhofer et al. 2012) software to track the root architecture semi-automatically after adjusting the sample lighting as shown below in figure 2.9 and then seeding tracking points on the top of the root system, then these seeds tracked the root system inside the soil core sample image after another to the bottom. This method required less labor to achieve the root tracking, although many accurate settings were needed to achieve that. This procedure was conducted on the first experiment (Chapter 3 and 5) for tracking roots.

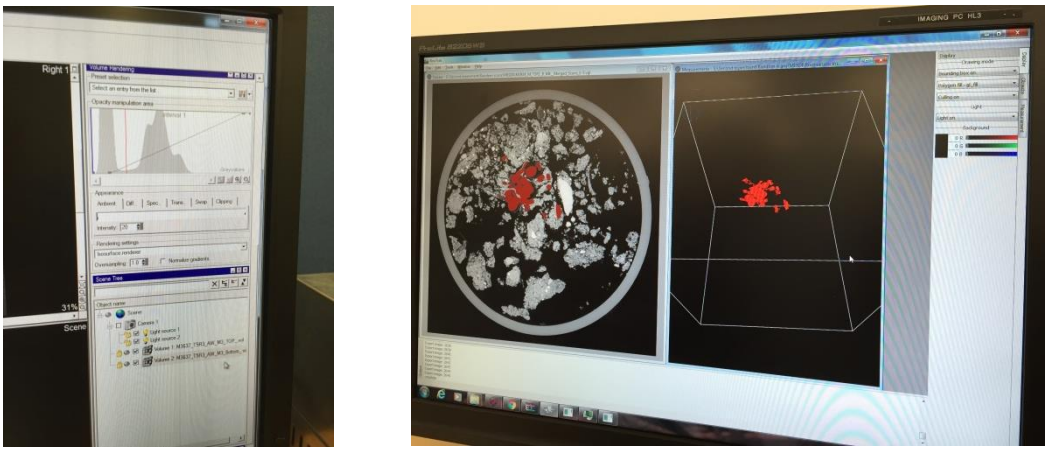


Figure 2.9 Wheat root autonomous segmenting using RooTrak software,(left) adjusting the sample contrast and (right) the autonomous root selecting procedure.

2.2.2. WinRhizo™ root scanning

The WinRhizo root scanning system is a destructive root scanning method that can measure the root parameters such as root volume, root surface area, root diameter and root length after washing the soil core undisturbed samples and extracting the root volume from the soil. Then the extracted root was kept frozen until they were scanned into a water sump on the WinRhizo scanner on specific setting and resolution to suit each type and kind of root system. Then the software showed the results and calculations of each root sample. This procedure was conducted for each root sample for all experiments. The scan image resolution was 600 DPI and BMP image was collected. Each root sample was divided into 3 sections to obtain accurate readings due to high root volume within the soil sample.

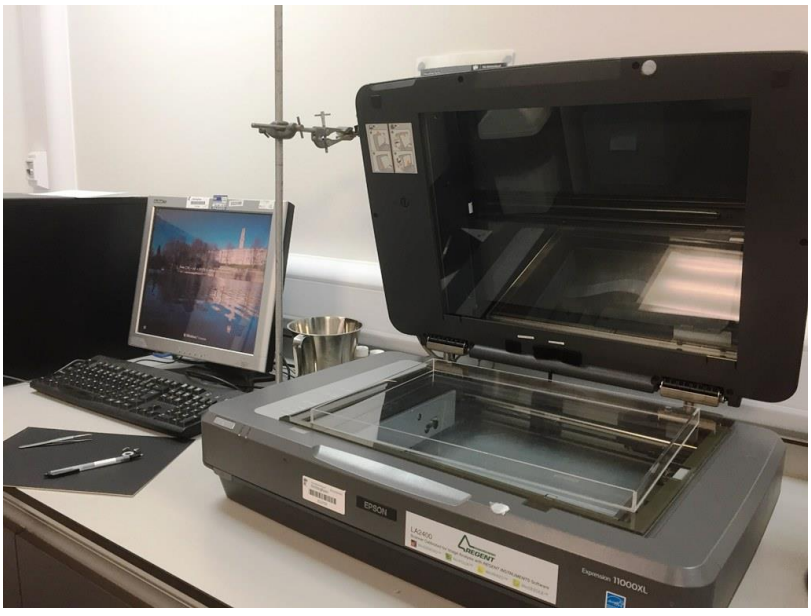


Figure 2.10 Destructive root scanning by WinRhizo™ root scanning technique

2.3. Plant analysis

2.3.1. Plant height

Plant height measurement was conducted on daily basis and then the average of each month was calculated. Each experimental plot was measured from the middle, beginning and the end to have one average reading as shown below in Figure 2.11 and 2.12.



Figure 2.11 Plant height measuring for the second experiment (left and right) for wheat growing season 2014/2015.



Figure 2.12 Plant height measuring for the third experiment (left and right) for wheat growing season 2015/2016.

2.3.2. Normalised Difference Vegetation Index (NDVI)

The Normalised Difference Vegetation Index (NDVI) was measured using a handheld spectroradiometer model GreenSeeker© manufactured by Trimble (www.trimble.com). This measurement was conducted for the second and third experiments (Chapter 4 and 5) where each experimental plot was examined by the average of 5 readings for the measurement date.

The measurements were taken between 10.00 and 15.00 on clear sunny days, which was achieved by tracking the national and local weather forecast. The Normalised Difference Vegetation Index sensor was held on height of 50 cm above the top of crop. Then the Normalised Difference Vegetation Index was calculated from the reflectance of light in the red and near infra-red (NIR) regions of the spectrum according to the below equation:

Normalised Difference Vegetation Index =(R900-R680)/(R900+R680) .Equation 1

where R680 and R900 are the reflectance at 680 and 900 nm, respectively.



Figure 2.13 Hand held GreenSeeker© used for measuring the wheat Normalised Difference Vegetation Index for the second and third experiments, the photo was taken from https://www.wnif.co.uk.

2.3.3. Crop yield and Harvest index

The harvest was conducted at end of July of 2015 and 2016 for each growing season for the second and third experiments (Chapter 4 and 5). This process required a manual harvesting for each experimental plot after removing the root system (undisturbed soil sampling for the same sample) and each plot area was two adjacent rows each and 50 cm length (0.13m^2). Then the wheat (cv. Rialto) sample was weighed before and after drying at 80°C for 72 hours in the oven. After the whole plant was separated to stem and attached leaf sheath, leaf lamina, ear, grains, and chaff, then each component was dried for 48 hours at 80 °C to calculate the dry weight of each component. Then the weight of 1000 grains was recorded to calculate the grain yield per unit area to finally converted it to Mg/ha. To calculate the harvest index percentage it required to divide the grain dry matter by the above ground dry matter as shown in Figure 2.14.



Figure 2.14 Wheat crop (cv. Rialto) at harvesting stage at the end of July for (left) the second experiment season 2014/2015 and (right) the third experiment 2015/2016.

2.4. Crop cultivation

2.4.1. Laboratory environment

The first experiment was conducted in a growth room chamber where it had 16 hours of day light from 08:00 till 18:00 at 20°C, the night period 21:00 till 05:00 at 16 °C. The rest of the time contained 3 hours dawn and dusk intervals, the humidity was 70% and the experiment lasted for 3 weeks. There were no added fertilisers or any chemicals to the soil core samples through the growing period and the pests were controlled by using special sticky pads to avoid using any pesticides that might affect the plant growing activity as shown in Figures 2.15a and 2.15b. The cores were manually irrigated by adding the same water quantity at the same time for each core to maintain them at a notional field capacity. This water quantity was calculated from the average weight of soil sample cores after saturation.



Figure 2.15a Soil undisturbed sowed samples for the first experiment 2016 (left) at week 0, (right) at week 3.



Figure 2.15b Soil undisturbed sowed samples for the first experiment 2014 (left) at week 0, (right) at week 3.

2.4.2. Field environment

The wheat (cv. Rialto) crop cultivation was conducted for two seasons (2014/2015 and 2015/2016) in fields of The University of Nottingham-Sutton Bonington Campus. For the first growing season 2014/2015 the second experiment last for 289 days and for the second season 2015/2016 the third experiment last for 298 days, where the first day was seed sowing and the last was crop harvesting. All the measured sample parameters type, time and numbers are shown in tables 2.2 for the second experiment and table 2.3 for the third experiment. The cloche dimensions were 150 cm height, 110 cm width and 55 cm in depth. The sunlight and temperature were monthly measured inside and outside the cloches then the data were tested for ANOVA test to check if there was any significant difference due to the cloche coverage, the results showed that there was no significant difference for sunlight and temperature due to soil coverage. The experimental plot size dimensions were (12 m length x 1.5 m width) in the Second experiment (Chapter 4) and (6 m length x 1.5 m width) in the third experiment (Chapter 5).

The soil coverage treatments were executed by fixing open sides cloches that have no heat difference with the environment as shown in figure 2.16 and 2.17. However keeping those cloches standing in the field was the main challenge where the weather conditions were hard to achieve that especially with wind storms that sometimes exceed 50 m/hr in speed. Therefore, that required a daily maintenance and supervision to rehabilitate any damages or issues that was occurred due to this hard weather as shown in figure 2.18.

Table 2.2 Second experiments conducted parameters type, time and location at The University of Nottingham-Sutton Bonington Campus for the wheat (cv. Rialto) season 2014/2015. Values represent number of measurements.

Sample type	First experiment sampling type, dates and numbers 2014/2015									Total
	Nov.	Dec.	Jan.	Feb.	Mar.	April	May.	Jun.	July	
Undisturbed soil structure	16	48	48	48			48		48	256
Soil particle size analysis	48									48
Soil organic matter content	48									48
Soil Water content %	16	48	48	48			48		48	256
Soil penetration resistance							48		48	96
Plant height	144	144	144	144	144	144	144	144	144	1296
Normalised Difference Vegetation Index						48	48			96
Crop harvesting									48	48

Table 2.3 Third experiments conducted parameters type, time and location at The University of Nottingham-Sutton Bonington Campus for the wheat (cv. Rialto) season 2015/2016. Values represent number of measurements.

Sample type	First experiment sampling type, dates and numbers 2015/2016									Total
	Nov.	Dec.	Jan.	Feb.	Mar.	April	May.	Jun.	July	
Undisturbed soil structure		64		64				64	64	256
Soil particle size analysis	64									64
Soil organic matter content	64									64
Soil Water content %	64	64	64	64	64	64	64	64	64	576
Soil penetration resistance	64	64		64		64	64	64	64	488
Plant height	96	96	96	96	96	96	96	96	96	864
Normalised Difference Vegetation Index					32	32	32	32		128
Crop harvesting									32	32




Figure 2.16 Second experiment field for wheat (cv. Rialto) growing season2014/2015.




Figure 2.17 Third experiment field for wheat (cv. Rialto) growing season 2015/2016.




Figure 2.18 Cloches damages due to wind storms that exceed 50 mph that represented a challenge at the field experiments and required daily supervision and maintenance.

Chapter 3:

The effect of different soil structure formed on the same soil texture on root growth

This chapter assesses the effects of soil cultivation derived soil structural differences using episodic X-ray CT scanning of undisturbed soil core samples from four farm locations/treatments that had the same soil texture, but different soil structure. These samples were sown with winter wheat (cv. Rialto) seeds and grown under lab conditions to explore the mutual effects between the plant's shoot and root with the soil structure over a four week period.

3.1. Abstract

Soil structure properties can affect the establishment and development of plant roots and subsequently shoots. These properties are in turn affected by the soil cultivation history and the plant itself can induce modifications that feedback back into the soil structure. Undisturbed soil samples were taken from different field locations that had a contrasting soil cultivation history hence a different soil structure but on the same soil texture classification to reveal the true effects of structure. The soils were episodically scanned by X-ray µCT before and after being sowed with wheat (cv. Rialto) seeds and grown for three weeks to explore the soil structure and plant interactions over this time. The different cultivations created very different soil structures as measured by image analysis. The results showed soil structure affected the formation and development of the plant root and shoot system. Additionally, the

root system architecture modified the soil structure characteristics to contrasting effects based on root activity. The soils with higher organic matter content were associated with enhanced plant growth with higher plant height, root volume and root surface areas. Whilst, the effects of soil texture on plant growth are well known, the impact of the precise pore geometry of the soil structure is less understood but clearly very important.

Keywords: Soil structure; Soil physical characteristics; plant root and shoot parameters; X-ray µCT scans.

3.2. Introduction

Soil cultivation history can play a major role in formation and development of the soil structure (Dexter 1991). Soil structure can influence plant root growth by determining the available water and soluble nutrients and the required strength to penetrate this media (the soil penetration resistance) by the root system (Carminati et al. 2009). As such a soil's structure can affect the shape of final root architecture. Aiken and Smucker (1996) found root tips can send signals to the entire plant root and shoot system regarding the soil environment; these signals can control the root architecture, distribution and penetration into the soil profile. Also these signals can affect the shoot formation where they are thought to reflect the soil moisture, nutrients status and mechanical attributes. Likewise, Amato and Ritchie (2000) found that the roots are continuously providing the plant with signals to assist with soil structure exploration. These signals have a significantly different impact on the plant shoot when they explore it in different soil structures (Dexter 1991).

Soil cultivation and its historical effects have an important influence on developing soil structure. Soil structure can affect the soil and plant growth by determining the soil porosity, water content and soil strength. Soil structure can be affected over time by annual conventional ploughing which can result in a significant reduction in the readily available water (Dexter, 1991). The addition of organic matter to the soil content can help create more stable aggregates and higher density and biomass of earthworms (Riley et al. 2008). Pulleman et al. (2003) concluded that adding organic matter can maintain the soil structure and increase the earthworm biomass and populations. Mangalassary et al. (2012) showed reduced porosity when soils were managed by zero tillage.

Reeve (1997) stated that soil organic matter is the most important indicator for soil physical quality because of the natural soil structure degradation process through the long term plant cultivation. In most cultivation systems the main soil organic matter content is from adding manure to the soil; however, the rate of the available C depends on the cropping and tillage systems, climate and the soil initial status. There is a direct impact between soil physical properties and root formation and distribution due to plant desire to maximise the acquisition of nutrients and available soil water (Chapman et al., 2012). Therefore, maintaining a good soil optimum structure can improve the plant growth, due to the natural availability and distribution of nutrients within the root zone.

The interaction between soil structure and the root system can be a sequential process, where the soil structure can firstly control the formation of root architecture and as a result of that the root system will have its own impact on the soil structure. The extent of this impact depends initially on the soil primary structure. Angers and

Caron (1998) concluded root penetration resistance, water availability and aeration can control the plant growth and the root system development can modify the soil porosity as roots form continuous macropores after penetrating and exploring soil. Amato and Ritchie (2002) suggested that reduced plant growth was a consequence rather than a cause in the case of incomplete soil exploration by the roots due to hard soil structure. A more efficient root exploration of the soil structure can increase the water and nutrient uptake and result in significant yield increase (Lilley and Kirkegaard 2011).

X-ray µ CT is a common tool employed to visualise soil structure dynamics via time series scanning. By scanning of soil column with a sown plant it is possible to explore the reaction of the plant root system to the initial status of the soil structure and quantify the feedbacks of the plant on soil structure characteristics such as porosity. While soil pore macroporosity can be quantified readily, the process of root segmenting can be time consuming (Mooney et al. 2012). Dal Ferro et al., (2014) highlighted that X-ray µ CT was effective to quantify the soil structure differences between two tillage systems on a short term experiment. The root segmenting process can be time consuming due to the similarity in X-ray attenuation between the soil matrix and root material. New solutions such as RooTrak show promising results in making this procedure less time consuming depending via automatous root determination whilst object tracking approaches (Mairhofer et al. 2012). No previous studies here explored the effects of the different soil structure developed by various soil cultivation history for the same soil texture type. In this chapter it is hypothesised that the same soil texture will develop different soil structures when exposed to contrasting soil cultivations and land use and that in turn it will significantly affect the plant shoot/root development.

The hypotheses of this paper were that (i) different soil cultivation can produce significantly different soil structure types even for the same soil texture classification, (ii) the initial soil structure status significantly effects the development of plant shoot and root and (iii) root system formation can significantly affect the soil structural development.

3.3. Materials and Methods

3.3.1. Experimental treatments and design

Soil sampling was conducted in July 2014 and July 2016 at the University of Nottingham, Sutton Bonington, Leicestershire UK (52.5°N, 1.3°W). Figure (3.1) shows the locations for each sample position which had a separate soil cultivation history. The locations were selected based on a previous reconnaissance survey that showed their similar soil texture but different structure caused by contrasting soil management.



Figure 3.1 Figure 3.1 The satellite image of the four sample locations at The University of Nottingham, Sutton Bonington, Leicestershire UK (52.5°N, 1.3°W) where samples were collected from the field in 2014 and 2016).

Table 3.1 Soil cultivation histories of soil sampling locations between the years 2013-2016 in The University of Nottingham- Sutton Bonington, Leicestershire UK (52.5°N, 1.3°W).

Treatment/ Location	Soil Cultivation History			
	2013	2014	2015	2016
T1/A	Disc-aerator Drill Grass then Roll	no cultivations	Plough, Carrier, drill and roll for Triticale	Plough and press, power harrow combination drill w wheat and roll (Trials)
T2/B	Disc-aerator Drill Grass then Roll	no cultivations	Plough, Carrier, drill and roll for Triticale	no plough, sumo drill and roll
T3/C	Sumo, drill roll w wheat	50 metric tonnes per ha farm yard manure then plough carrier drill forage maize and roll	Sumo, drill and roll w wheat	Flat lift to 280 mm drill OSR and roll
T4/D	Disc-aerator, drill w wheat roll	50 metric tonnes per ha farm yard manure then Disc-aerator drill Maize and roll	Disc-aerator, drill roll w wheat	Disc-aerator, drill triticale and roll

3.3.2. Undisturbed soil structure sampling

The soil structure sampling was conducted by collecting (17 cm in depth and 8.6 cm in diameter) depth PVC tube into the soil by force the tube into the soil by a hammer. The soil sample was dug out and wrapped with a cling film to maintain its initial moisture. Finally, the soil samples were transported carefully (trying to avoid any vibration) and kept in a cold store at 5°C until X-ray µ CT scanning. After scanning the samples were sowed with wheat (cv. Rialto) seeds and grown in the growth room at the conditions shown in table 3.2. The soil water content at field capacity was derived from a water release curve for this soil (Mooney and Morris 2008) and the samples were maintained at this by watering at two day intervals. The number of soil samples were 16 sample for 2014 and 32 for 2016 (48 in total). The experiment had four different treatments with four replicates for each treatment. The number of soil samples was 16 in 2014 and 32 for 2016 (48 in total for each sampling lot except the first time). The soil samples were stored in the cold store for minimum time that did not exceed 48 hours between soil sampling and X-ray µCT scanning. The time and weather conditions between 2014 and 2016 soil samples were almost the same where the weather was sunny to cloudy and the temperature was 23 °C in 2014 and 21 °C in 2016.

3.3.3. Soil texture sampling (soil particle size analysis)

The soil texture sampling was conducted briefly by taking 50g of loose soil was taken in bags from the field from 0-17 cm depth, three 150-300g soil samples was taken from 0-17cm depth from each plot. Secondly a mechanical analysis hydrometer reading was taken of the soil sample after calibration of the hydrometer; the soil was sieved < 2mm and dried overnight and then hydrogen peroxide 6%,

sodium hexa meta phosphate 5% and sodium carbonate in 1 litre of distilled water were added. Then, following shaking the soil suspension by plunger, the hydrometer readings were recorded and the time intervals and room temperature for the readings also recorded. Finally, the percentages of sand, silt and clay were recorded according to the time and particle diameter, and then applied to the soil triangle to determine the soil texture type according to the Soil Survey of England and Wales soil particle analysis triangle (Rowell 1994, Laker and Dupreez, 1982 and Day 1965).

3.3.4. Soil organic matter sampling

The soil organic matter sampling and analysis procedures were as described in Chapter 4.3.3.2, three 150-250g loose soil samples was taken from 0-17cm depth from each plot. The same that conducted in the previous chapters by weighing a 50gm sieved soil sample then primary drying overnight in the oven at 105 °C to remove the moisture inside the soil. Then the soil sample will be dried again in another oven for another 72 hours at 500 °C to burn the soil organic matter content inside the soil sample. Finally, after weighing the soil sample before and after each process, the weight difference will be the soil organic matter weight, and then this weight was calculated as a percentage of the total soil sample weight to represent the soil organic matter content percentage of that replicate.

3.3.5. X-ray Computed Tomography

Before X-ray scanning the samples was kept dry to prevent sample deterioration, all soil samples were scanned non-destructively using the X-ray µ CT scanner model v| tomex |M (Hounsfield Facility, The University of Nottingham- Sutton Bonington, Leicestershire) at 58 µm resolution. The scanning time was 30 minutes for both soil

structure investigation and root segmenting, additionally, a 0.5 copper filter was placed between the soil sample and the X-ray source.

3.3.6. Soil structure image analysis

The X-ray µCT grey scale 2D images (image stack) were merged and build into one 3D image, then this3D image was processed using the Image J software to calculate the soil physical parameters such as soil total porosity, mean pore size and soil pore circularity. The procedure of the image processing was by converting the X-ray µCT scan into an image stack then importing it by the image J software. The automated threshold tool was used to segment the images and the pore characteristics were outputted from Image J to excel.

3.3.7 Growth room specifications

The growth room had a day temperature of 20 °C for 16 hours, night temperature 15 °C for 8 hours durations. Humidity 70% and the daylight period was 08:00 till 18:00 and the night period 21:00 till 05:00 and the rest time was containing 3 hours dawn and dusk intervals.



Figure 3.2 (Right at week 1 and left at week 0) the soil cores with the wheat (cv. Rialto) seeds grown into the growth room for three weeks.

3.3.8 Root Segmentation

The root segmenting process was achieved by using the RooTrak software and the manual method using VG Studio Max, this hybrid procedure was adopted as it resulted in the maximum root architecture with minimum time and effort (Mairhofer et al. 2012).

First of all, the X-ray µCT images were visually examined to detect the path of roots and if there are any obstacles e.g. stones that hinder the root segmentation, in this case small connection areas can be added to keep the root segmentation continuous. The X-ray µCT scan stack was then imported by VG Studio Max^{TM} and subsequently to RooTrak. The image brightness was calibrated to enhance the difference between the soil and root material. The automatic segmentation process was initiated by group of seed points to start the segmentation process, this process controlled by brightness comparison between the current and the next segmentation point and roundness distribution ability to decide which particles are similar to the root material. Then after supervision of the iterative process the root architecture was calculated and analysed.

In all cases the soil was removed from the roots at the end of the experiment and the root architecture assessed using WinRhizo as described in full in section 2.2

3.3.9 Statistical analysis

The analysis of variation (ANOVA) test was conducted by the GenStat 18 edition on all treatments. For each treatment an ANOVA with time as a factor was undertaken to assess if there were difference between data collected between 2014 and 2016. In all cases there was no significant differences between years thus the data was pooled

providing 12 replicates. All data was normally distributed as was confirmed by visual inspection of the plot of residuals.

3.4. Results

3.4.1. X-ray µCT scan images

The X-ray µCT scan images for the soil structure at 58µm resolution are shown below in Figure 3.3.

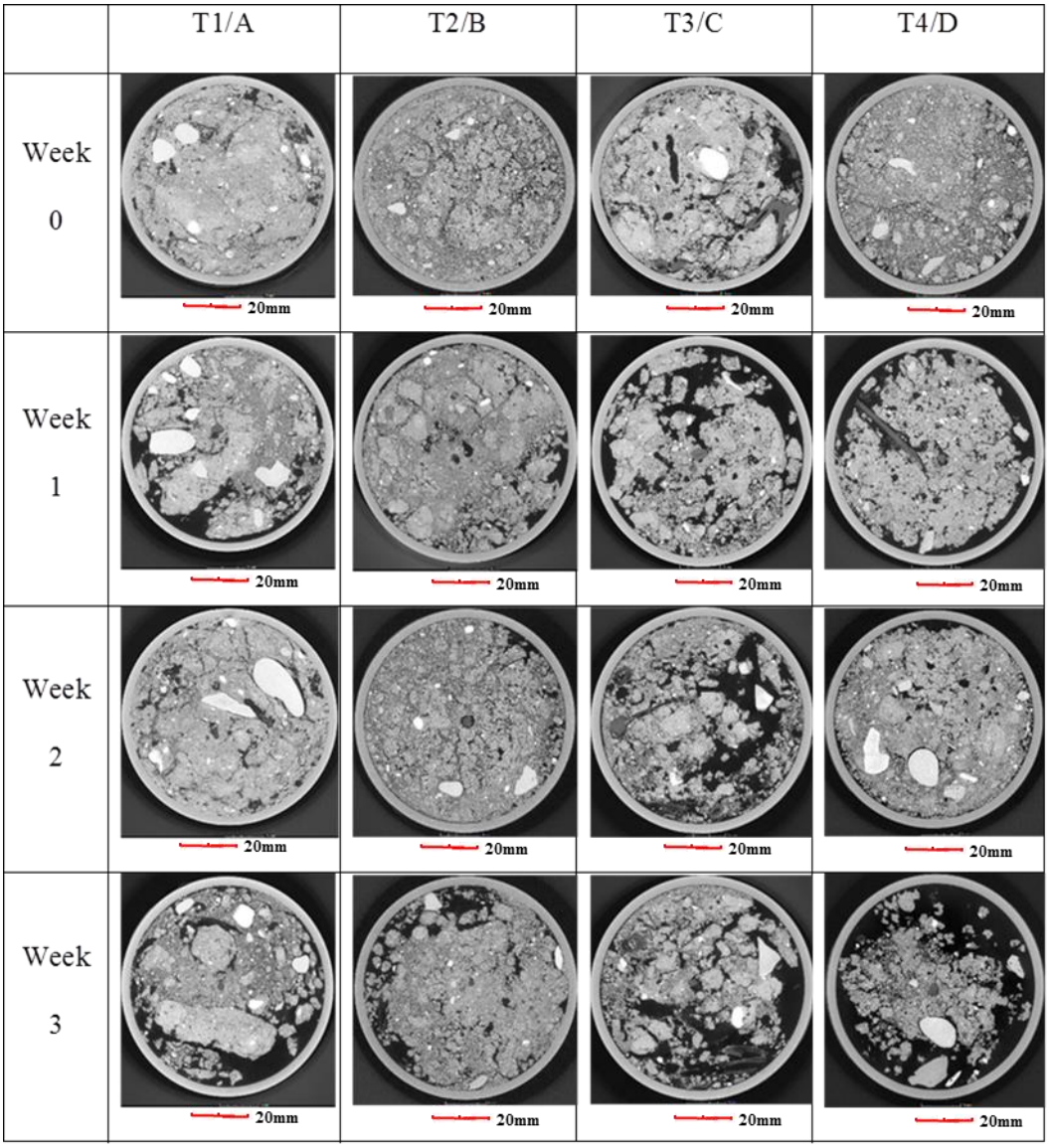


Figure 3.3 Soil structure X-ray µCT images (grey scale) at 58 µm resolution.

3.4.2. X-ray µCT image processing

Pore structure images were obtained after processing in VG Studio Max^{TM} 2.1 and then using Image J free software to measure the soil physical parameters as shown below in Figure 3.4 where the threshold process was conducted by Image J software.

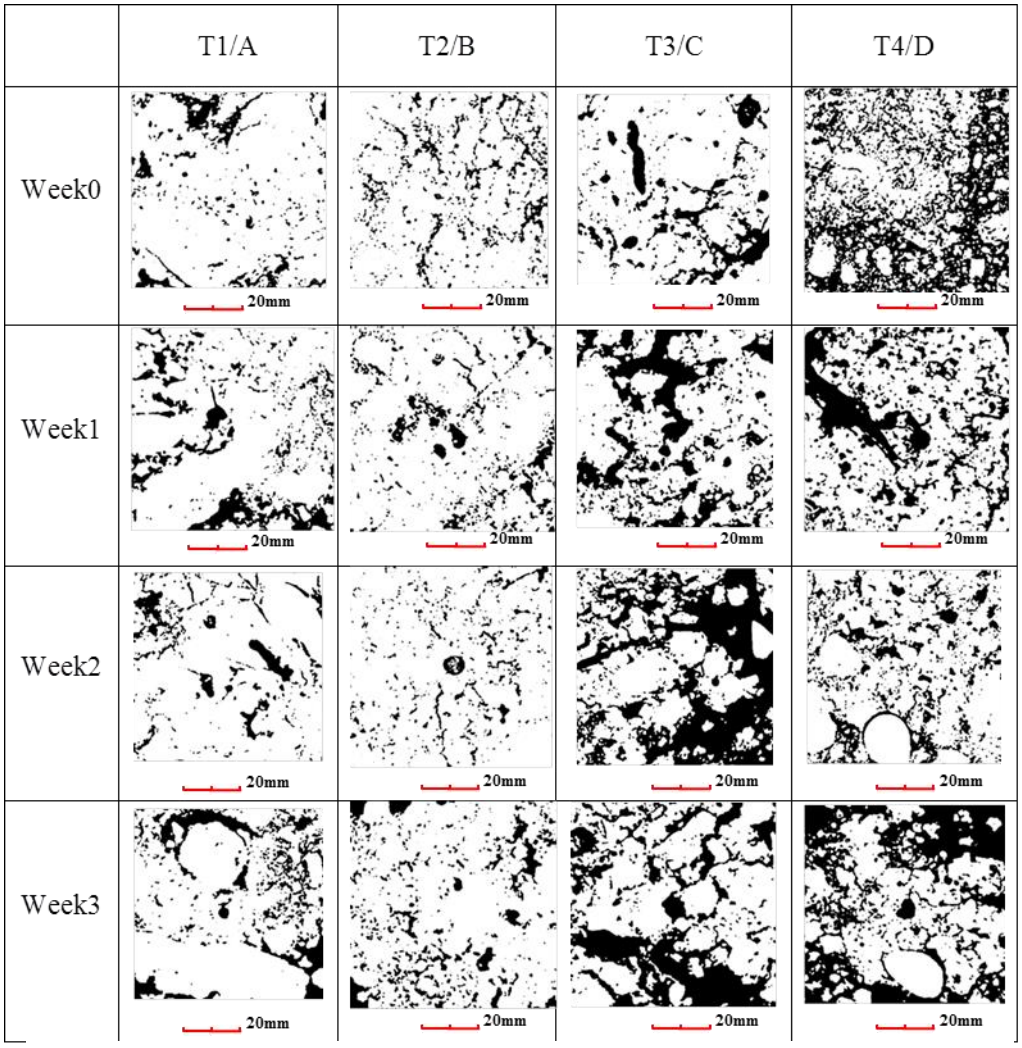


Figure 3.4 Soil structure X-ray µCT processed images after processing with Image J

3.4.3. Soil Physical Parameters

3.4.3.1. Soil particle size analysis

The soil particle size analysis results had showed that the four treatments were significantly different (P<0.05) in clay, sand and silt contents percentage; however they had the same soil texture type classification according to the soil survey of England and Wales classification soil particle size analysis was Sandy Loam soil types as shown in Figure (3.5). Additionally, the organic matter was significantly different (P<0.05) Table 3.2 between the four treatments/ location according to their soil cultivation history, (as mentioned previously in table 3.2) where each treatment/location had a different soil cultivation history depending on the nature of the land usage.

Table 3.2 Soil content particles analysis according to UK and North of Ireland soil texture analysis combined with soil organic matter content for plant life period.

Soil Particle Analysis				
Tr.	Clay %	Sand %	Silt %	OM %
A/T1	15.70	65.45	18.85	4.49
B/T2	13.84	68.52	17.64	3.80
C/T3	17.43	57.39	25.18	6.82
D/T4	16.45	63.99	19.56	5.1

L.S.D. between treatments was 2.2% .

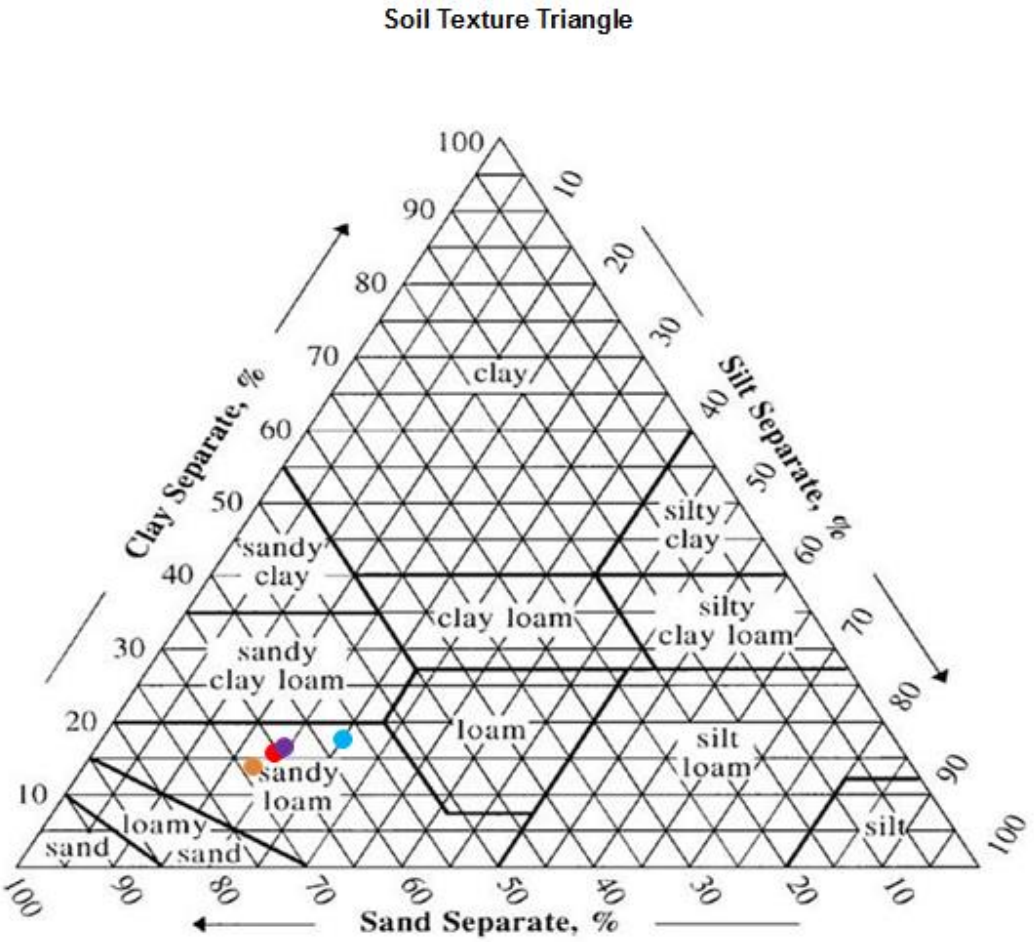


Figure 3.5 Results of soil texture classification according to soil particle size analysis; all the treatments had a sandy loam soil type according to the colours mentioned in Table 3.2.

3.4.3.2 Soil organic matter content

The soil organic matter content of each location was different as shown in table 3.2.

3.4.3.3 Soil Total Porosity

Soil total porosity was significantly different between treatments ($P<0.05$) where T3 treatment had recorded the higher mean value (23.4) than T4 treatment mean (21.1) and the last had been significantly different ($P<0.05$) than T1 mean (17.6). Although T2 had the lower mean value (15.9) and it was not significantly different than T1.

Soil total porosity was significantly different ($P<0.05$) between the four treatments since initial case or prior to the seed sowing (Week 0/W0) and through the plant life span for three weeks later (W1, W2 and W3) as shown below in figure 3.6. The effects of time on the same treatment were analysed where most of the measurements had been significantly affected ($P<0.05$,) by the time of 3 weeks of wheat seed plantation as shown in figure 3.6. Soil total porosity in T1, T2 and T3 significantly varied over time ($P<0.05$), while treatment T4 was not significantly different.

3.4.3.4 Soil Water Content

The soil water content was significantly different ($P<0.05$) between treatments at the initial status where T3/location had a higher water content percentage (15.1%) than T4, T1 and T2 treatments as shown below in figure 3.7 T4 treatment had been significantly different ($P<0.05$) than T4 and T2. Although T1 treatment water capacity percentage had overcome T2 treatment, the difference was not enough to be significant. All the treatments were significantly different ($P<0.05$) over the time period of three weeks of the plant life span as shown below in figure 3.7.

3.4.3.5 Soil Mean Pore Size

The mean pore size was significantly different ($P<0.05$) between treatments where T3 was greater than T1 and T2 but this difference was not significant at week 0. Although, at week 3, the difference in T3 was significant ($P<0.05$) in comparison with T4, T1 and T2 treatments as shown in Figure 3.8.

3.4.3.6. Soil Pore Circularity

The soil pore circularity significantly different between treatments ($P<0.05$,) where T3 treatment had the higher mean value (0.58) than the mean values of T4, T1 and T2 treatments (0.47, 0.43 and 0.38 respectively) and T4 treatment had been significantly different than T2, although this difference was not significant in comparison with T1 treatment as can be shown in figure 3.9.

However, the effect of time was not significant over the three weeks life period of the plant.

3.4.3.7. Soil Penetration Resistance

Soil penetration resistance significantly different between treatments ($P<0.05$) where T2 treatment had the highest mean value (334.6 kPa) which was greater than T1, T4 and T3 treatment mean value (252.6, 255.4 and 242.1 kPa respectively) as can be shown in figure 3.10 the other treatments had been not significantly different between each other. This value was the soil penetration average for top 40 cm depth from soil surface.

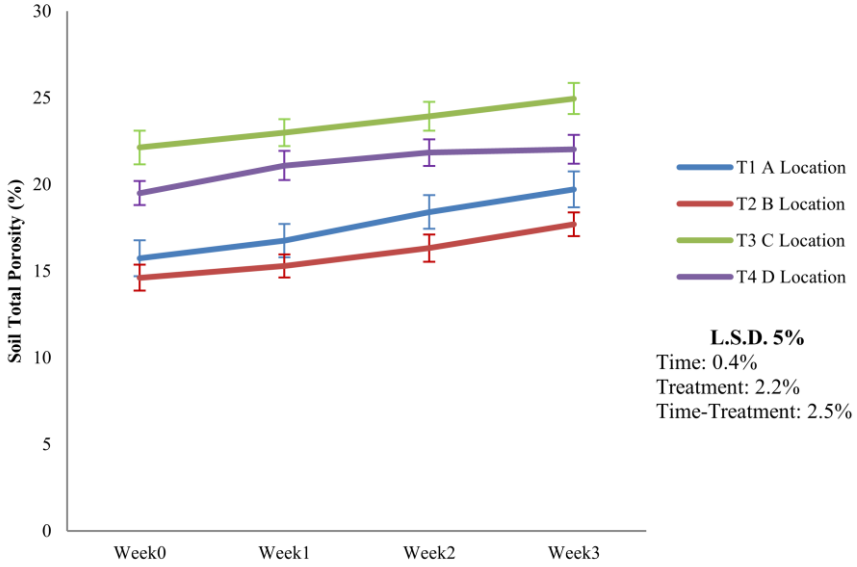


Figure 3.6 Soil total porosity (%) for four weeks, error bars are standard error bars.

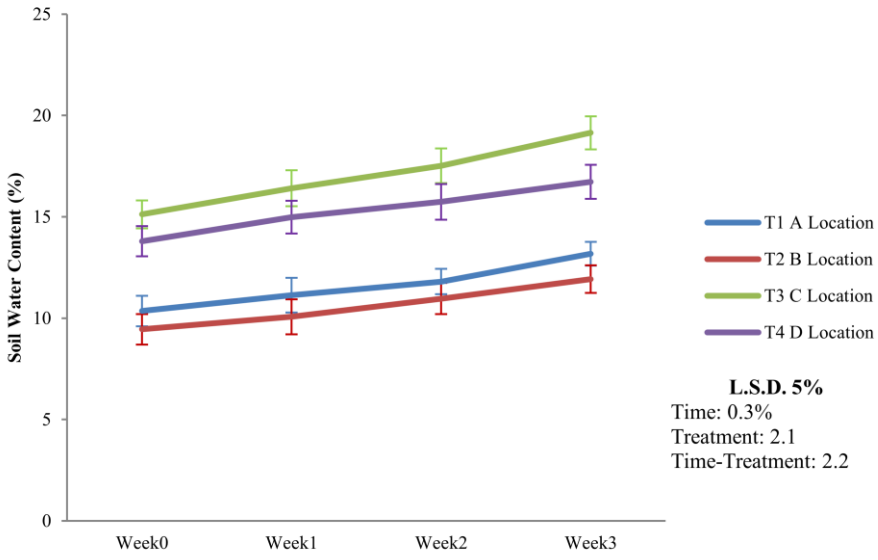


Figure 3.7 Soil water content (%) for four weeks, error bars are standard error bars. The undisturbed soil core samples were irrigated manually each 3 days for 10 cc.

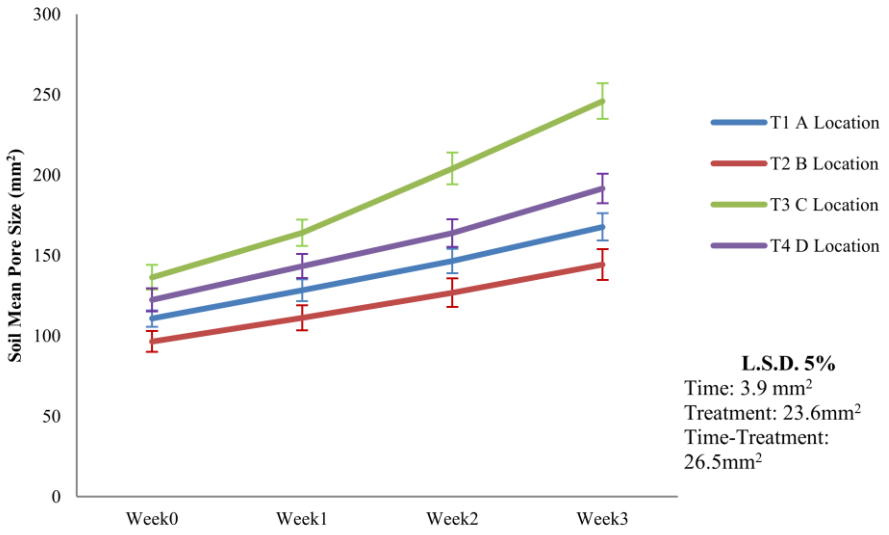


Figure 3.8 Soil mean pore size mm² for four weeks, error bars are standard error bars.

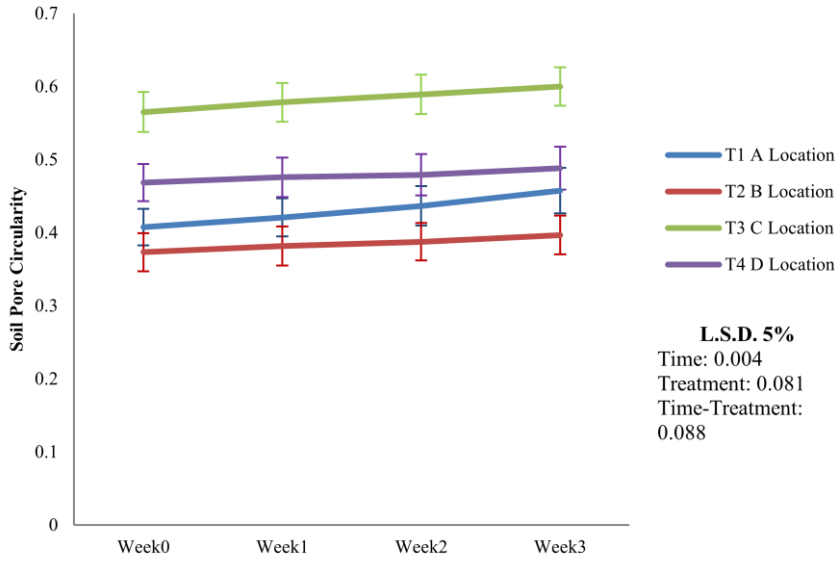


Figure 3.9 Soil pore circularity for four weeks, error bars are standard error bars. Note 1=a perfect circular shape.

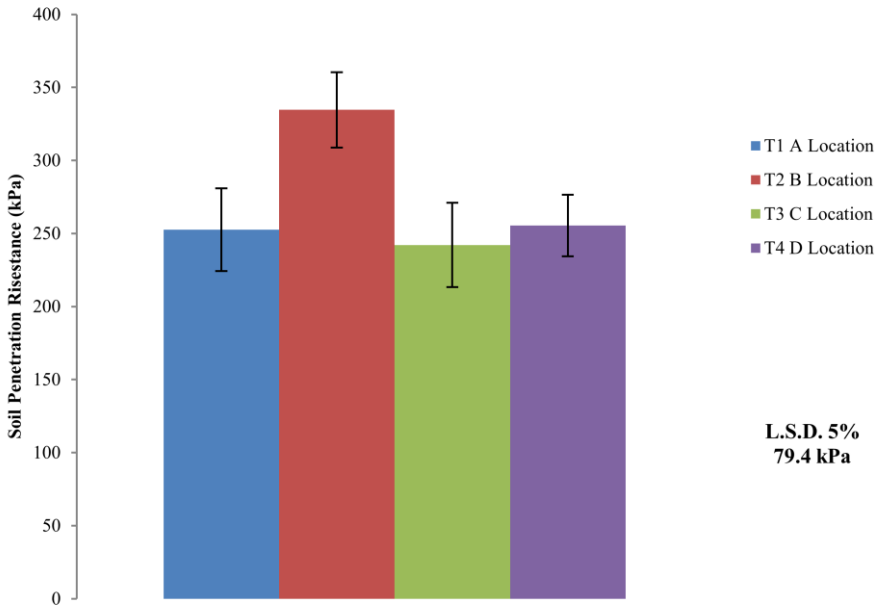


Figure 3.10 Soil mean penetration resistance (kPa) for four weeks, error bars are standard error bars. This test was accomplished in the field for the same locations of the undisturbed soil core samples for the year 2016 lot.

3.4.4. Plant shoot and root parameters

3.4.4.1. Plant Shoot Height

The plant shoot significantly different ($P<0.05$) between treatments where T2 treatment had recorded the highest plant height mean value (13.7 cm) over T4 (10.9 cm), T1 (8.7cm) and T2 (7.3cm). T4 treatment also significantly higher than T1 and T2 treatments, T1 treatment mean value had been different than T2, but it was not enough to be significant as shown in figure 3.11.On the other hand, the effect of time on the same treatments also significantly different ($P<0.05$) for all treatments over three weeks of plant life span as shown in figure 3.11.

3.4.4.2. Root Volume

Plant's root volume, measured from the X-ray µCT scans and analysed by RooTrak, was significantly different ($P<0.05$) between the treatments where T3 treatment was the greatest (180.9 mm^3) compared to T4, T1 and T2 treatments mean values (140.1, 119.8 and 95.8 mm^3 respectively) as shown in Figure 3.12a. Root growth over time significantly increased ($P<0.05$) the root volume treatment for all four treatments as can be illustrated in Figure 3.12b as expected.

Meanwhile, the same parameter measured by WinRhizo™ (at the end of the plant 3 weeks life span) showed a significant difference between the treatments ($P<0.05$) with T3 the highest (320.5 mm^3) compared to T4, T1 and T2 (276.6, 242.2 and 193.6 mm^3 respectively) and even when T4 and T1 was not significantly different between each other they had significantly ($P<0.05$) to T2 Figure 3.12c.

3.4.4.3. Root Surface Area

Root surface area measured from the X-ray µCT was significantly different between the treatments ($P<0.05$) where T3 treatment was the greatest (44.18 mm^2) compared to T4, T1 and T2 (34.73, 28.61 and 24.38 mm^2 respectively).

Similarly, the time effect on treatment was also significant ($P<0.05$) as illustrated in Figure 3.13a. When measured by WinRhizo™ at the end of the third week of plant life, the results showed that the differences between the treatments were also significant ($P<0.05$) where T3 (82.0 mm^2) recorded the highest in comparison with T4, T1 and T2 mean value treatments (69.7, 54.3 and 49.1 mm^2, respectively figure 3.13b).

3.4.4.4. Root Diameter

The results showed that the root diameter parameter had significant differences ($P<0.05$) between the four treatments as can be shown in Figure (3.14a). Similarly, time had significant effects ($P<0.05$) on all treatments. Additionally, by measuring the same parameter with WinRhizo™ root scanning system the results had showed that there was a significant difference ($P<0.05$) between treatments where T2 treatment had the highest root average diameter as shown in Figure 3.14b.

3.4.4.5. Root Length

Root length significantly different ($P<0.05$) where T3, T4 and T1 mean values (107.33, 99.67 and 98.48 mm respectively) had overcome T2 mean value (91.71mm) as shown in figure 3.15a. The root length had significantly ($P<0.05$) affected all the treatment over the plant life time of 3 weeks. And when this parameter had been measured by destruction method of WinRhizo root scanner the results showed that T3 significantly different ($P<0.05$) than T4, T1 and T2 treatments. Additionally, T4 and T1 were not significantly different but T4 (which was not significantly different than T2) was significantly different than T2. And when measuring this parameter by WinRhizo root scanning technique there were no significant differences between treatments, although T3 treatment had the higher mean value as shown in figure 3.15b.

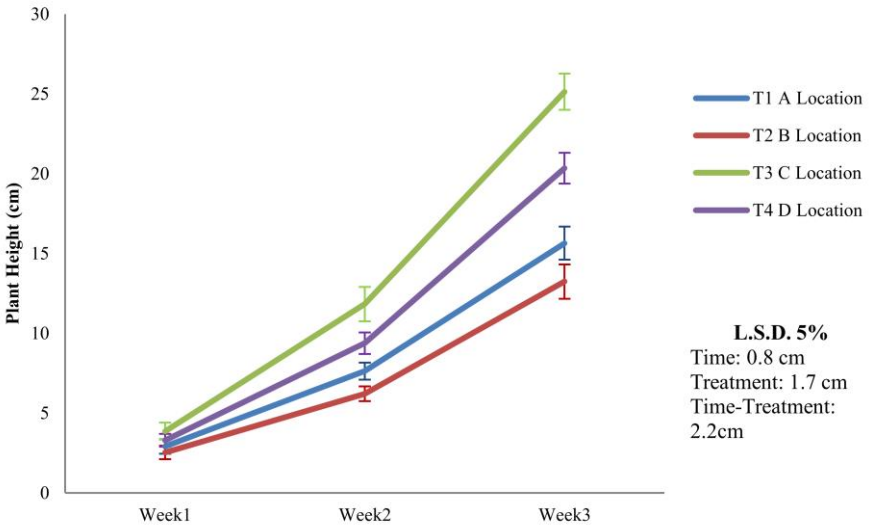


Figure 3.11 Plant height for three weeks of plant age, error bars are standard error bars.

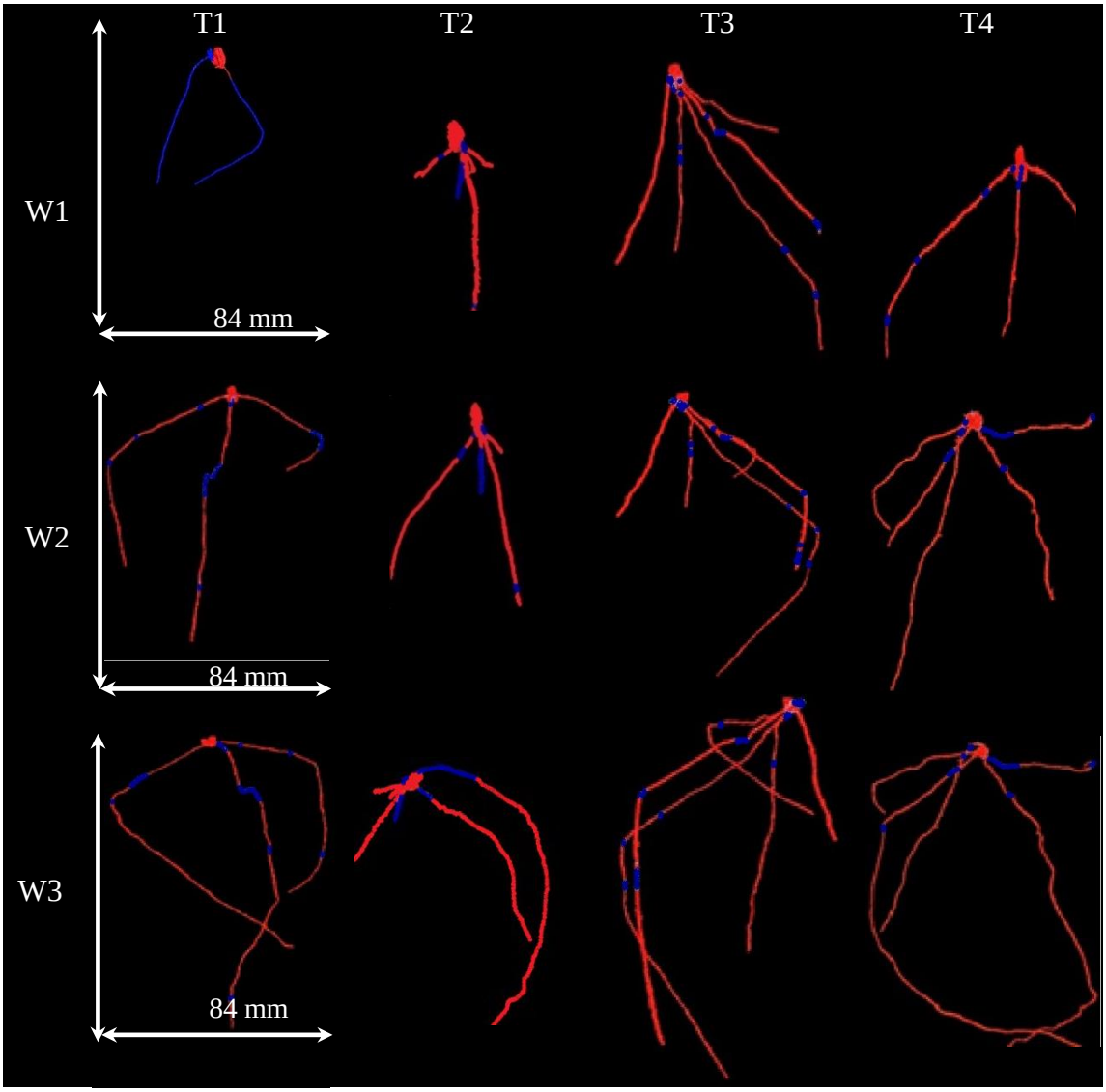


Figure 3.12a Root architecture development for the four treatments for three weeks. The red coloured area was automatically segmented by RooTrak and the blue are segmented by using VG StudioMax^{TM}.

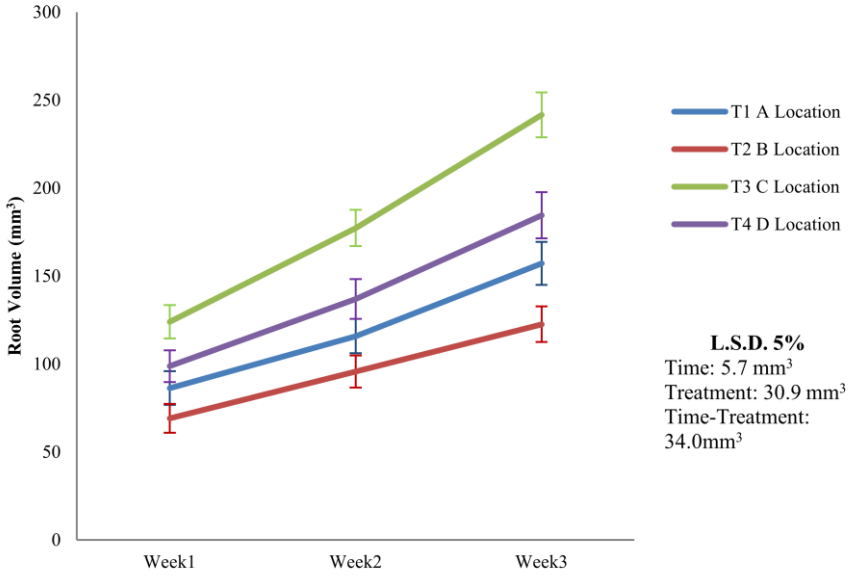


Figure 3.12b Root volume (mm^3) calculated by X-ray µCT images for three weeks of plant age, error bars are standard error bars.

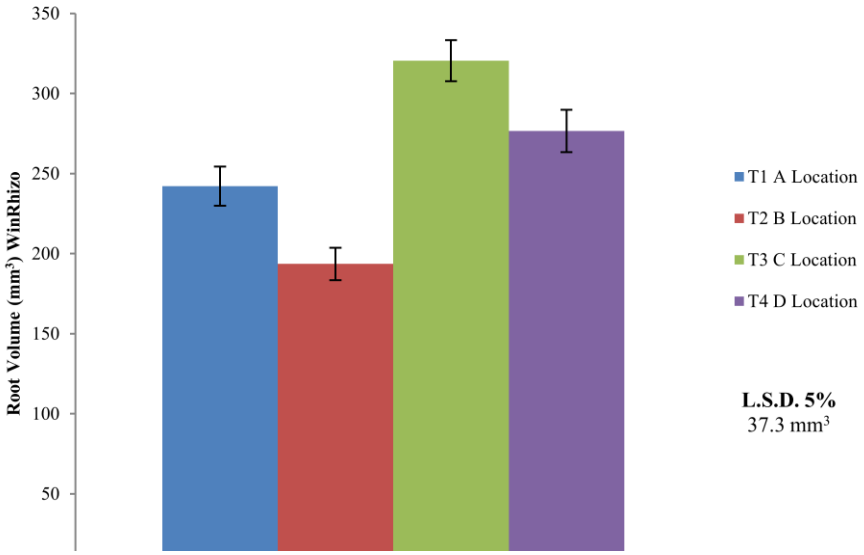


Figure 3.12c Root volume (mm^3) calculated by WinRhizo™ images for third week of plant age, error bars are standard error bars.

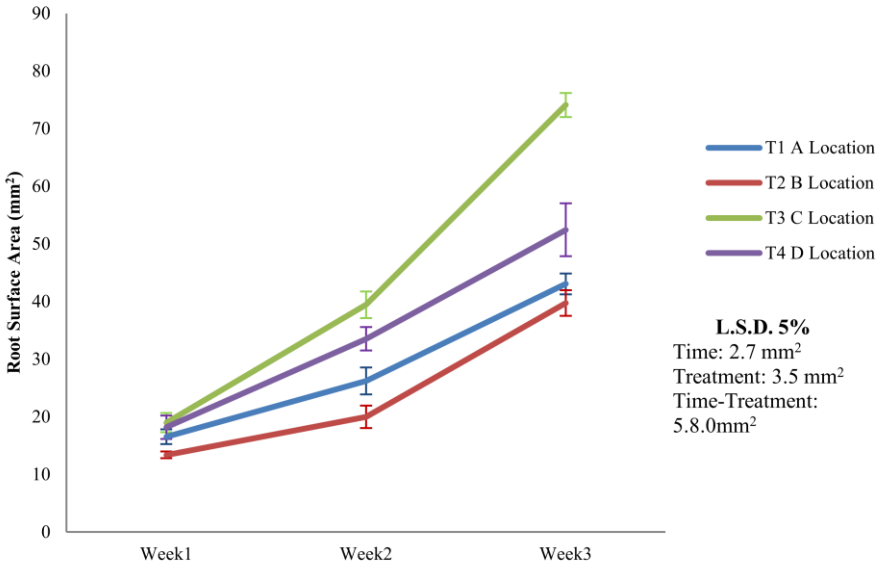


Figure 3.13a Root surface area (mm^2) calculated by X-ray CT images for three weeks of plant age, error bars are standard error bars.

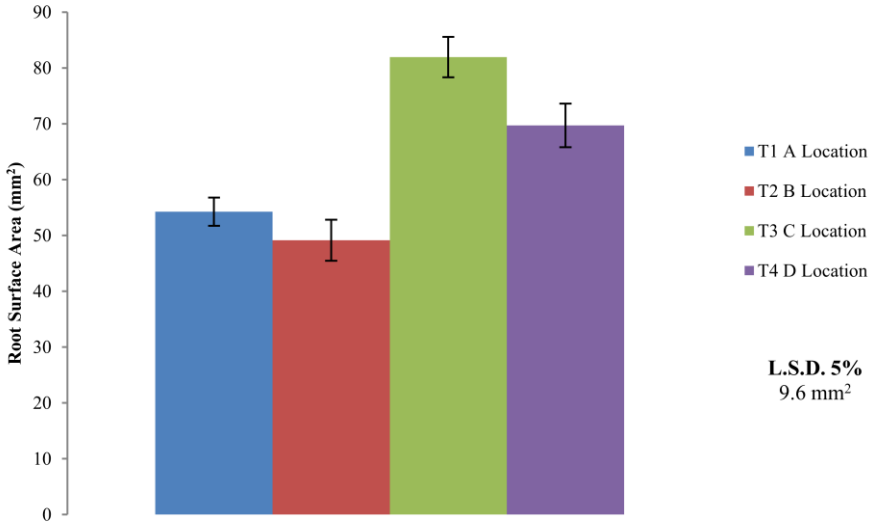


Figure 3.13b Root surface area (mm^2) calculated by WinRhizo™ images for third week of plant age, error bars are standard error bars.

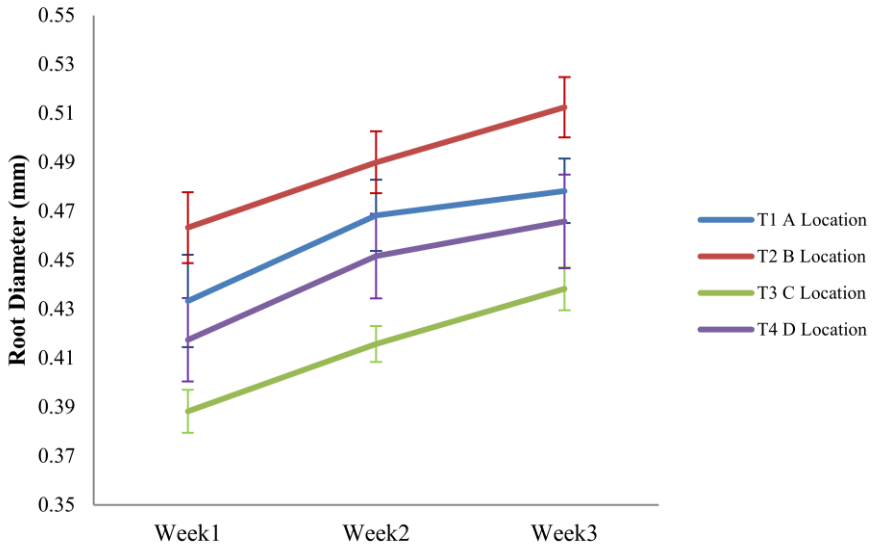


Figure 3.14a Root diameter (mm) calculated by X-ray CT images for three weeks of plant age, error bars are standard error bars.

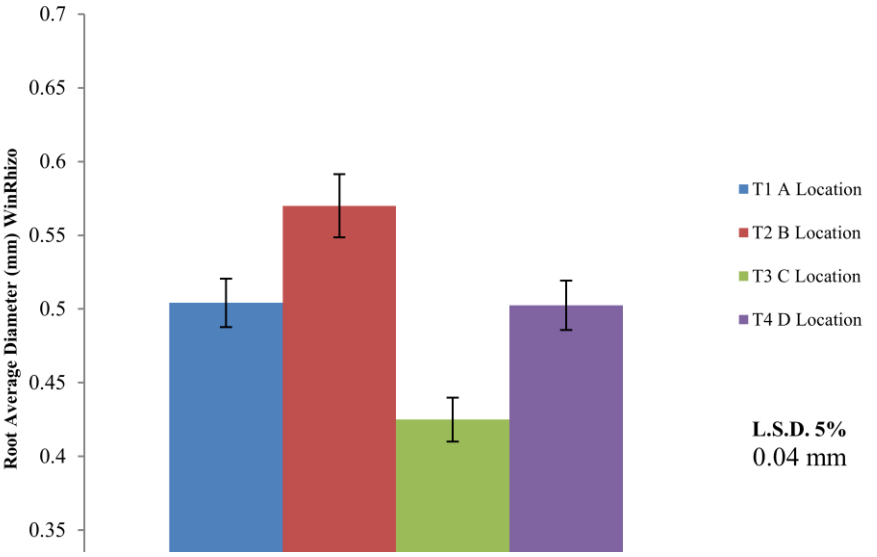


Figure 3.14b Root diameter (mm) calculated by WinRhizo™ images for third week of plant age, error bars are standard error bars.

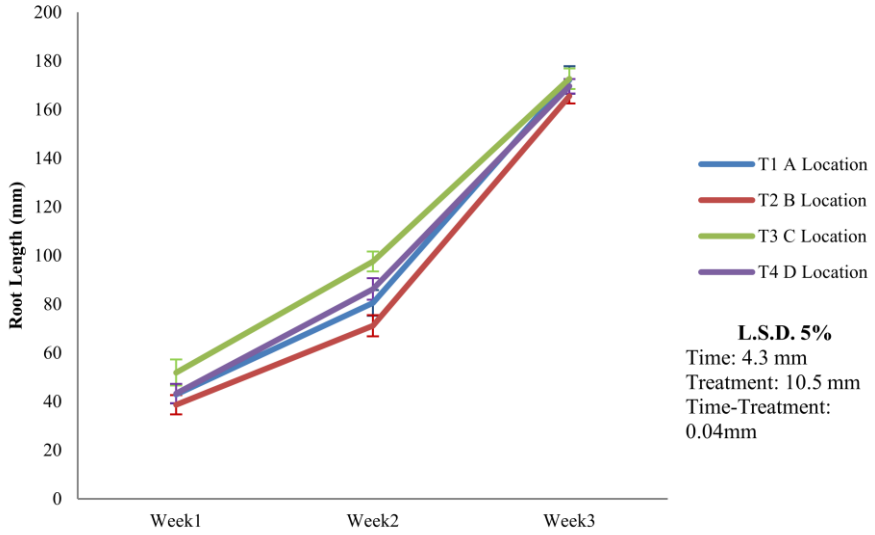


Figure 3.15a Root length (mm) calculated by X-ray CT images for three weeks of plant age, error bars are standard error bars.

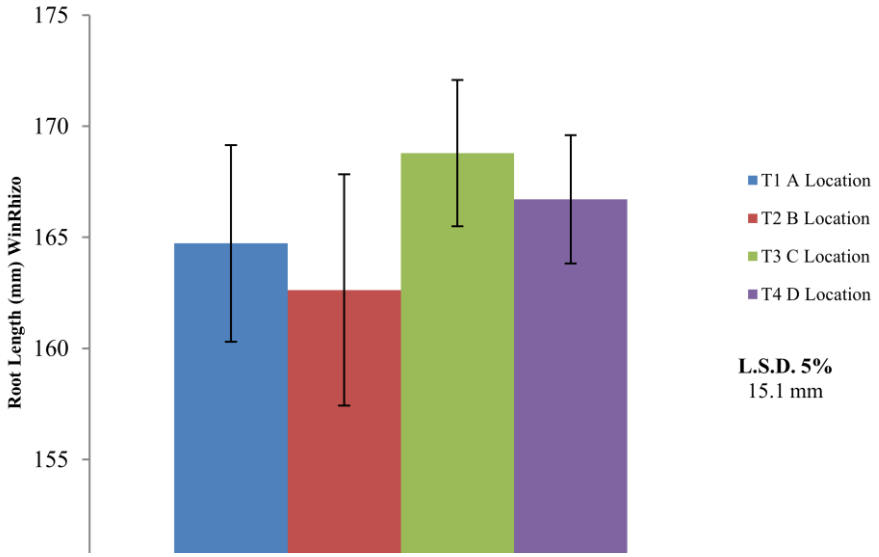


Figure 3.15b Root length (mm) calculated by WinRhizo™ images for third week of plant age, error bars are standard error bars.

3.4.5. Correlations between Plant and Soil Parameters

Soil total porosity was positively correlated with the root surface area (r=0.60) and had a strong negative correlation with the soil penetration resistance (r=0.30) as shown in figures 3.16a and 3.16b as would be expected. Root area increases in the more porous soil as the roots can penetrate more readily, where soil porosity is reduced the soil penetration, a measure of hardness increases. Soil water content had a positive correlation with plant height (r=0.61) (figure 3.17a) and root volume (r=0.56) as shown in figure 3.17b and with root surface area (r=0.58) (figure 3.17c). This illustrates the importance of water where in this stud more water meant improved root growth and not negative impact of too much water was recorded. Figures 3.18-19 demonstrate the relationship between soil pore size, shape (circularity) and plant height. Interestingly large but more rounded pores appear to beneficial for plant growth as measured by root surface area.

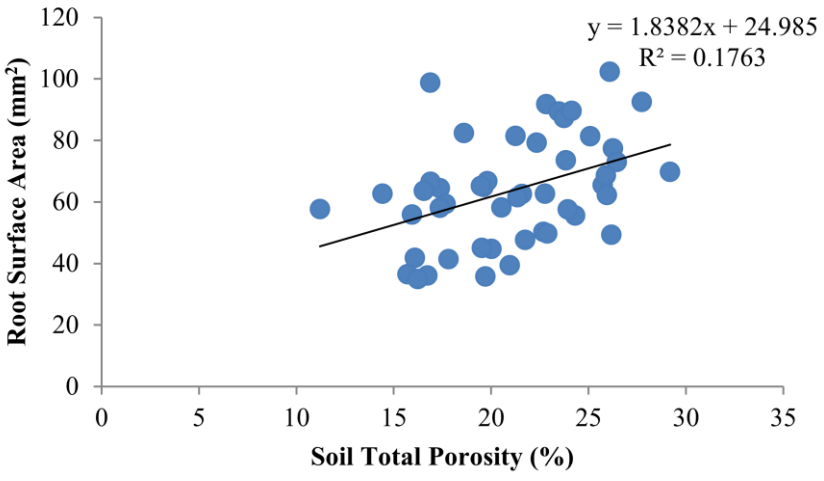


Figure 3.16a Linear regression between Soil Total Porosity and Root Surface Area. R^2=0.1763, Significant P<0.01, df=46.

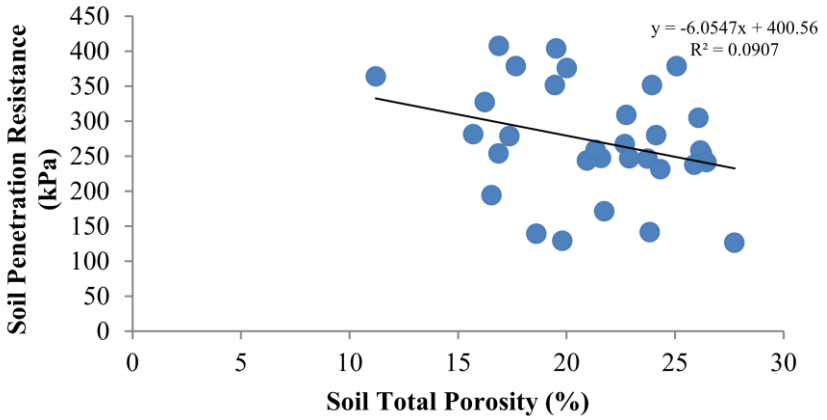


Figure 3.16b Linear regression between Soil Total Porosity and Soil Penetration Resistance. P<0.05, df=30.

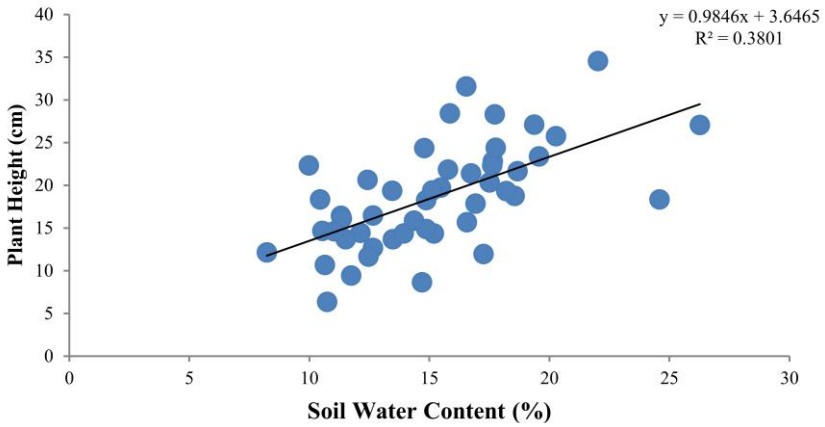


Figure 3.17a Linear regression between Soil Water Content (%) and Plant Height. P<0.01, df=46.

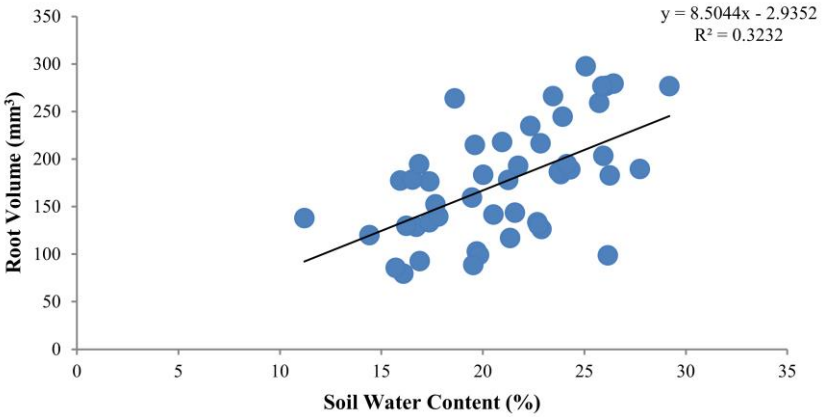


Figure 3.17b Linear regression between Soil Water Content (%) and Root Volume. P<0.01, df=46.

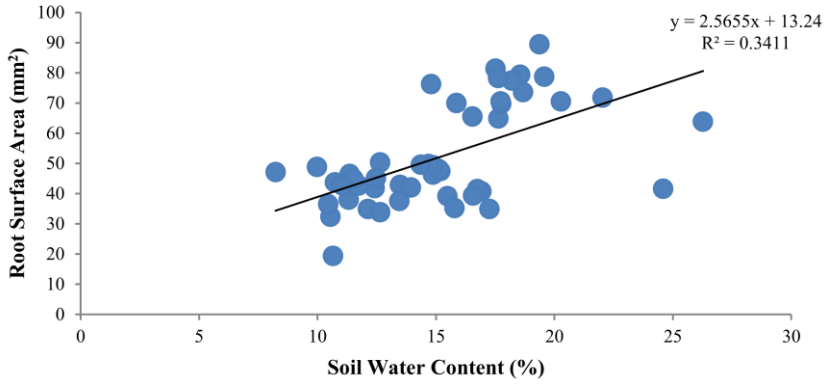


Figure 3.17c Linear regression between Soil Water Content (%) and Root Surface Area. P<0.01, df=46.

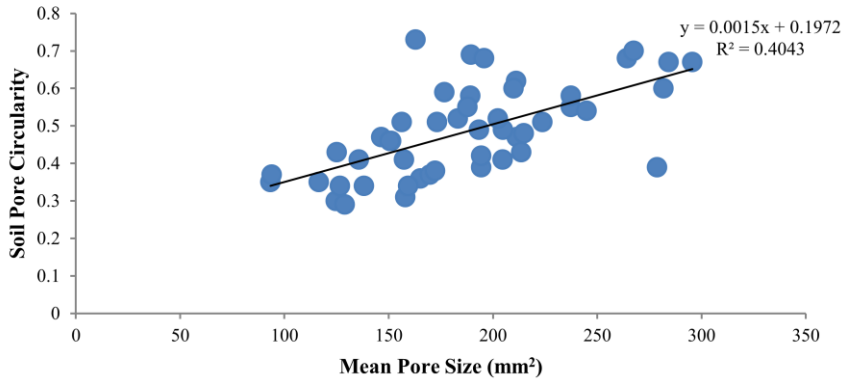


Figure 3.18 Linear regression between Soil Mean Pore Size and Soil Pore Circularity. P<0.01, df=46.

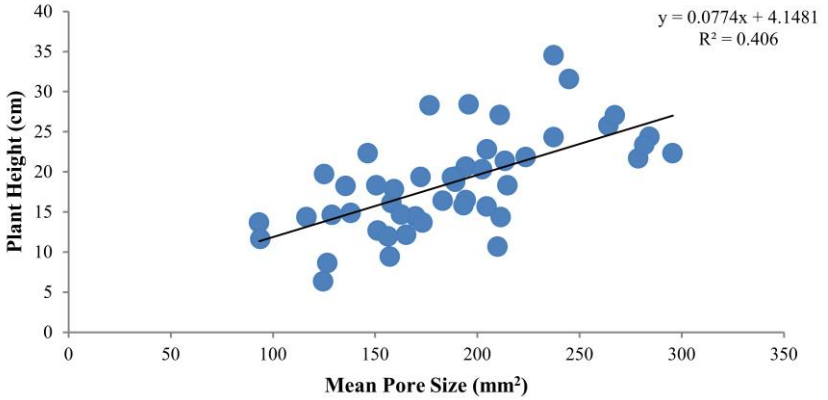


Figure 3.19a Linear regression between Soil Mean Pore Size and Plant Height. P<0.01, df=46.

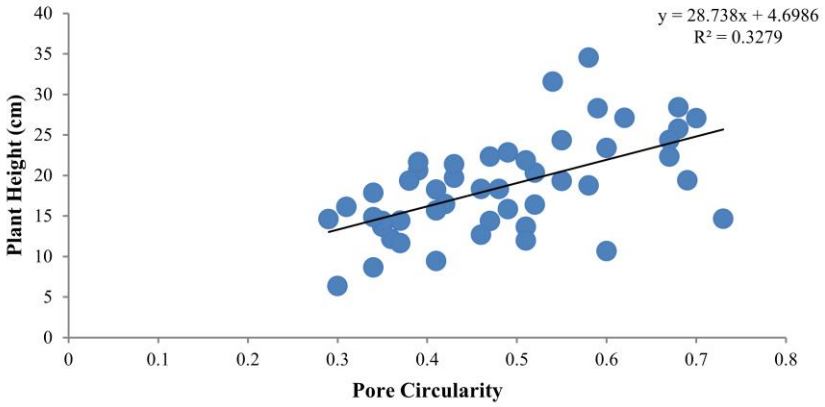


Figure 3.19b Linear regression between Pore Circularity and Plant Height. P<0.01, df=46.

3.5. Discussion

Soil total porosity was significantly different (P<0.05) between treatments ranging between 14-22% soil with higher organic matter having a positive relationship (r=0.57) with the soil total porosity. Soil organic matter can enhance the soil stability to overcome the soil compaction over time through increased aggregation stability (Aridsson 1998).

The different soil cultivation history produced significantly different (P<0.05) soil water contents (P<0.05) ranging from (1-20% and significantly different penetration resistance ranging from 242-335 kPa which can control the soil exploration by the plant root system. There was a strong positive correlation (r=0.68) relationship between the soil organic matter content and soil water content. The results show the benefit of enhanced organic matter on soil porosity (r=0.57), soil water content (r=68), pore circularity (r=0.60) and root surface area (r=0.56). It was negatively correlated with soil penetration resistance parameter (r=0.25) and that can affect the

plant reaction to the moisture and nutrient in each soil structure type. This result is supported by Bècel et al. (2012) where high soil penetration resistance reduced roots growth and development, depending on the soil resistance that the roots had faced into the soil structure.

Soil initial soil porosity was significantly different ($P<0.05$) between the treatments and over time for each treatment ranging from 14-23% at week zero and 17-25% at week three. This demonstrates a small increase in porosity by the root system development. The soil treatment with higher organic matter (T3 and T4) developed higher soil porosity, water content; mean pore size, pore circularity and lower soil penetration resistance.

Hence, the soils with the highest OM, T3 and T4 had preferred formation and growth of the plant shoot and root parameters such as plant height, root volume, root surface area, root length and root diameter. That might be due to the variation in water and nutrient availability coming from the soil porosity, organic and water contents. These findings are also supported by the results of Arvidsoon (1998) where the soils with a greater amount of added organic matter content produced plants with the 11% more yield than the soils with less organic matter content that had been exposed to conventional soil compaction causes.

The root system can deform the soil structure, the extent of this deformation process will depend mainly on the soil structure and the availability of moisture and nutrients inside the soil volume. The plant height, root volume, root surface area, root diameter and root length had been significantly different for each treatment over time ($P<0.05$), most of these parameters had been correlated to the soil total porosity

and soil water content where the soil total porosity had been positively correlated to the root surface area (r=0.60).

The other soil parameters had also were affected significantly ($P<0.05$) by the plant growth and development over time for the parameters soil water content had raised (10-16%) at week zero to (13-20%) at week three of the plant age, soil mean pore size ranging (96-137 mm^2) to (144-246 mm^2) at week three and soil pore circularity ranging (0.37-0.57%) at week zero to (0.39-0.60%) at the third week of the plant age. That can demonstrate the effects of the plant root and shoot growing on the soil structure physical parameters and this effect's magnitude was depending mainly on the soil structure status which had been produced by due to the soil history cultivation. Angers and Caron (1998) successfully described the role of the plant in modifying the soil structure, where the root will form the soil macropores and develop the soil porosity, at the same time the root system will distribute into the soil enhancing the porosity. The trend here with respect to soil structure as measured by porosity and plant growth is clear, the plants responded better to soils with increasing porosity. The fact that plant growth is limited in low porosity soil is well known (Bengough et al 2011). Atkinson et al. (2009) albeit at a different scale of observation noted that while low porosity could have a negative impact on root growth, high porosity could be equally limiting which they attributed to reduced anchorage. Helliwell et al. (2017) recently showed that root architecture can vary significantly between plants when grown in different soil textures, however this work shows that this variation in plant shoot and root characteristics can occur between soils of the same texture where they are structured differently.

3.6. Conclusions

X-ray μCT imagery showed soil structure was different initially between the four soil treatments/location that have the same soil texture classification type, but different soil cultivation history.

The quantified data showed that the soil cultivation history was a major contributor in the formation of soil structure, where soils with higher organic matter content developed higher total porosity. This led to a higher mean pore size, water contents and higher pore circularity values. The high water content associated with larger mean pore size is a surprise as soils with larger pores tend to drain faster and thus have a reduced water content. However, one must note in this case that porosity is limited by imaging resolution and there is a significant portion of the total porosity not measured by this approach which could account for the higher water content. In these soils it is likely that the root system can readily penetrate the soil with less consumed power likely capturing more soluble nutrients than in other compacted soil had fewer nutrients. This phenomenon affected the formation and development of the rooting system which will directly affect the plant shoot system formation.

Plant growth and development induced changes in the soil structure over plant's life time; these changes depended on the initial soil structure status, where the soil with preferential physical characteristics can provide the plant with higher levels of moisture and nutrients, consuming less energy to penetrate and distribute into the soil. While the treatments with compacted soil structures caused by poor soil cultivation history had less organic matter content which developed less soil porosity and higher soil penetration resistance that the root system had faced to penetrate and distribute. These kinds of soil structures need the root system to

consume more energy to overcome the soil hardness and at the same time, the soil moisture and nutrients capacity were lower than the other soil types. Therefore, the produced shoot and the entire plant formation was affected directly by the soil structure physical formation and development.

Chapter 4:

Assessing the role of exposure to weather conditions on soil structural development and subsequent effects on crop yield

This chapter focuses on factors influencing the formation of soil structure and the effect of surface coverage on soil structure formation until after seedling emergence. These effects were examined using X-ray µCT imaging of undisturbed soil samples from four treatments that had the same field conditions. Wheat (cv. Rialto) shoot and root samples were examined to investigate the effect of the physical structure of the soil on their development. This experiment was carried out over the entire growing season in 2014/2015 which was 289 days.

4.1. Abstract

Soil structure formation affects crop development and yield; rainfall influences the soil structure formation process during the early establishment of the seedbed and seed emergence. Intensive rainfall on freshly sowed soil can imply physical force that can affect the root formation. There is little-quantified data concerning the influence of rainfall-induced soil structure compaction on the crop from seedling establishment until the maturity stage and grain production. The timescale of soil structure formation, seedling emergence and development of environmental factors are identified and considered in this paper. Pore circularity and water content were significantly correlated with root volume, plant height, crop yield and crop harvest index. Protecting the seedbed soil structure from rainfall-induced soil compaction

for the first 30 days increased the crop yield by 27% (1.33 Mg/ ha) in comparison with an uncovered soil.

4.2. Introduction

Soil structure formation is a natural process influenced by many physical, chemical and biological factors such as harrowing, rainfall, microbial community, soil porosity (Dexter 1991). This timing of this process is usually at the same time of as seedling emergence. Soil structure formation can be started after wetting and drying cycles caused by rainfall intervals faster than the seed emergence process. Additionally, soil temperature and heavy rainfall can affect the seed emergence activity, therefore soil structure can be formed sooner than root system formation and that can raise the soil strength that the root tip will need to penetrate.

Soil structure can control the growth and development of plants by determining the availability of soil water and limiting macronutrients that the plant can capture from seed emergence to maturity. Therefore, it is vital to analyse the timescales of soil structure formation and development during the seedling emergence. The intensity and quantity of rainfall can control the of soil structure formation especially at the early plant growth stages where the plant canopy is covering a minimum area of the soil surface, and the roots are starting to penetrate the soil structure. The plant canopy can protect the soil surface from erosion and runoff caused by rainfall and wind, and this protection will vary depending on plant type and age (Mohammad and Adam 2010). Vázquez *et al.* (2008) successfully soil porosity reduction due to rainfall by examining the effect of simulated rainfall on freshly tilled showing that soil porosity was significantly affected by rainfall-induced compaction.

Soil structure is influenced by rainfall especially when converting the soil from perennial crop to annual crops due to regular soil tillage which will cause the soil structure formation (Karunatilke and van Es, 2002). Simulated rainfall can decrease soil porosity and cause erosion especially in the top 3 cm and can cause soil slaking, mechanical disruption of aggregates and compaction (Rousseva *et al.* 2002).

Seedbed porosity can affect the seed establishment and development where the seedbed soil medium will be first intact with the root system, and that can determine the nature of the root activity. The root system function can be partially modified depending on penetration resistance level (Acuña et al., 2007). Additionally, Jin *et al.* (2013) referred to the soil penetration resistance role in controlling the root activity from transporting soil moisture and nutrients to penetrate the hard soil structure showing factors as root angle, root stiffness a influence how the root will penetrate the soil structure. Roots can send root-shoot biological signals that turn the entire plant on focusing on penetrating the soil structure, and that can affect the crop shoot and yield outcome.

Additionally, Jakobsen and Dexter (1987) used a simulation model to examine the effect of soil texture on wheat yield and this model showed a direct impact of soil structure on early shoot growth and development and impacting final grain yield. The soil with high penetration resistance can produce a crop with lower yields due to less water and nutrients availability due to the increased power energy needed to penetrate the compacted soil structure (Jakobsen and Dexter, 1987).

The aim of this experiment was to investigate the effects of soil physical parameters such as total soil porosity and soil pore circularity on the early formation of the plant

root system and subsequent effect on crop yield. This was achieved by manipulating soil structure formation by controlling the soil rainfall exposure and duration.

4.3. Materials and Methods

4.3.1. Experimental treatment and design

The trial was set up as a randomised block design with four treatments and four replicates. Each trial replicate plot 12x1.6 m in length and width respectively (Table 4.1, Figures 4.1a-4.1l) that shows photos of the field for the wheat growing season 2014/2015. The treatments were based depending on the time and duration of soil surface coverage, control was always uncovered and exposed to rainfall (T1), always covered from the rainfall (T2), covered for the first month only after seed sowing (T3), and covered during rainfall only and exposed for the rest of the time (T4).

The coverage was achieved by using cloches with open sides (110 cm length x 50 cm width x 45cm height) that covered the soil surface. A light meter (Sunche model HS 1010) was used to measure the light intensity inside and outside the cloches to confirm that there was no significant difference between the light magnitude inside and outside the cloches.

The soil surface coverage for T4 treatment (covered for rainfall only) was achieved manually by removing the cloches from the covered area when the weather was not raining and replacing them back before rainfall. The local and national weather forecast was used to predict the timing of this manual process. Each trial replicate plot 12x1.6 m in length and width respectively (Table 4.1, Figures 4.1a-4.1l) that shows photos of the field for the wheat growing season 2014/2015.

Table 4.1 showing the trial plan and the treatments details for wheat growing season 2014/2015.

T3R4	T1R4	T2R4	T4R4
T1R3	T4R3	T3R3	T2R3
T4R2	T3R2	T1R2	T2R2
T2R1	T1R1	T4R1	T3R1

Letter	Treatment
T1	No Cover
T2	Always Covered
T3	Covered for first month
T4	Covered to rain
R1-R4	Replicate number



Figure 4.1a. Soil surface of field trial at early November 2014 after seed sowing



Figure 4.1b. Soil surface of field trial at mid of November 2014 after rainfall.



Figure 4.1c. Photos of field trial at early December 2014.



Figure 4.1d. Photos of field trial for at end of December 2014.



Figure 4.1e. T2 treatment at early January 2015.



Figure 4.1f. T4 treatment at early January 2015.



Figure 4.1g. Photos of field trial at early January 2015.



Figure 4.1h. Photos of field trial at end of March 2015.



Figure 4.1i. Photos of field trial at early May 2015.



Figure 4.1j. Photos of field trial T4 treatment at mid of June 2015.



Figure 4.1k. Photos of field trial T1 at early of July 2015.



Figure 4.1l. Photos of field trial T3 treatment at end of July 2015.

4.3.2. Environmental measurements

Hourly environmental data was collected from The University of Nottingham-Sutton Bonington Campus weather station.

4.3.3. Soil Sampling

Soil sampling was conducted as detailed below:-

4.3.3.1. Soil texture sampling (soil particle analysis)

Soil texture sampling was conducted following the same protocol been used in the previous chapter, by firstly taking 50g of loose soil in bags from the field and secondly taking the mechanical analysis hydrometer reading after calibration from the cylinder that contain the soil sample (sieved <2mm and dried overnight and then hydrogen peroxide 6%, sodium hexa meta phosphate 5% and sodium carbonate in 1 litre of distilled water was added), thirdly shaking soil suspension by plunger and the readings of the hydrometer and recorded for time intervals. Finally, the percentages of sand, silt and clay will be recorded about the time and were plotted on the soil triangle to determine the soil texture type according to the UK and Northern Ireland soil particle analysis triangle (Rowell 1994, Laker and Dupreez, 1982 and Day 1965).

4.3.3.2. Soil organic matter sampling

The soil organic matter analysis were conducted by drying a 50 g sieved soil sample overnight at 105 °C to remove all the moisture inside the soil including the hygroscopic moisture. The soil sample was then heated for 72 hours at 500 C° to remove the soil organic matter content inside the soil sample. The weight difference

between treatments will be the soil organic matter weight, calculated as a percentage of the total soil sample weight.

4.3.3.3. Undisturbed soil structure sampling

The undisturbed soil sampling was collected by gently knocking a wooden block fixed on the top of PVC pipe core (170mm height, 84mm in diameter) into the soil, then digging the soil around the core until reaching the core bottom and cut it from the bottom. Soil cores were wrapped with cling film and stored at 5 °C before scanning. The PVC pipe cores were weighed before and after sampling for measurement purposes.

4.3.3.4. Soil moisture sampling

Soil moisture sampling was based on the soil weight measuring method; using the difference in sample weight after drying at 105 °C for 24h.

4.3.3.5. Soil penetration resistance sampling

Soil penetration resistance was measured using a soil cone penetrometer (Rimik model CP40II http:wwwrimik.com). The readings were recorded for each plot. The instrument readings were equalised for minimum reached depth, due to variable field soil penetration (such as gravel and stones in the presence of the penetrometer path) that the instrument can reach. The soil penetration value was averaged for the top 40 cm of soil section.

4.3.3.6. Root sampling

Root sampling was conducted for the last two sampling months (May and July 2014), targeting the plant in the middle of the core, and then the cores were wrapped and stored in the cool store on 5 C° to maintain soil microbial activity. Root sampling was conducted within 24 hours to prevent any root decay. Additionally, all soil samples containing roots were washed and scanned using a WinRhizo root scanner to measure the same root parameters a the different destructive method.

4.3.4. Plant Sampling

The following plant traits were measured:-

4.3.4.1. Plant height

Plant height was measured weekly and then averaged on a monthly basis using a measuring tape in three locations in each experimental plot (at the centre and the two edges).

4.3.4.2 Normalised Difference Vegetation Index (NDVI)

Normalised Difference Vegetation Index parameter was measured using a handheld crop spectradiometer sensor (GreenSeeker© manufactured by Trimble www.trimble.com). Each experimental plot was sampled in April and May 2015.

4.3.4.3. Crop yield and Harvest Index

Crop yield was measured after harvest in July 2015; each experimental plot (2 adjacent rows for 50 cm length (0.13 m^2)) was harvested manually after taleing the root (soil core sampling) and then weighed before and after drying the shoot in two stages (at 45 C° for 72 hours in a glasshouse and then in an oven at 80 C° for 72 hours). The entire plant was separated from each other and weighed (stem, leaves,

ears, grains, and chaff) to calculate the dry weight of the plant, number of grains per ear and the weight of 1000 grain after accounting for the total number of plants with and without ears. Finally, the crop yield was calculated in kilogram per square meter then converted to Mg/ha. Harvest index parameter was calculated by the ratio of total crop grain to total above ground dry shoot weight. This reflects the efficiency of the plant in converting soil nutrients into shoots and grains; therefore, it is important to measure this parameter in addition to the crop yield.

4.3.5. Undisturbed soil structure X-ray µCT scanning

All the soil undisturbed cores were sampled using the previously mentioned procedure (Chp 2) and stored at 5 °C, then scanned for 30 minutes in the X-ray CT scanner model v| tomex |M for 30 minutes for soil structure and for 45minutes for roots at a 58 µm resolution.

4.3.6. X-ray µCT image analysis

X-ray µCT image analysis was conducted by reconstruction of the 3D soil sample image from the 3400 individual 2D images, then making an image stack using VG Studio Max® 2.1 software. Image J was used to crop the round area of the soil core into a square area that was consistent for all samples. The grey scale image was converted to a binary image (the black is the soil pore and the white is the soil particles) after choosing a suitable threshold mask filter (in this case it was Li algorithm). Total porosity; mean pore size and soil pore circularity was then calculated for each image stack.

4.3.7. Root Segmenting

Roots were segmented using a combination of RooTrak and the semi-automated selection method in VG Studio Max® 2.1 software. Each root was tracked from the top to the bottom of the soil sample core and the data were exported to RooTrak software to quantify root volume, surface area, diameter, and length.

4.3.8. Statistical analysis

All data were recorded on MS Excel worksheets in a suitable format for export to GenStat© software for statistical analysis. The data were first tested for normality and transformed where appropriate. Subsequently the data were subjected to repeated measures ANOVA in Genstat v18.

4.4. Results

4.4.1. X-ray µCT image scans

The X-ray µ CT image scanned by the CT scan model v| tomex |M on 58 µm resolution for 30 minutes scan duration were as shown below in figure 4.2.

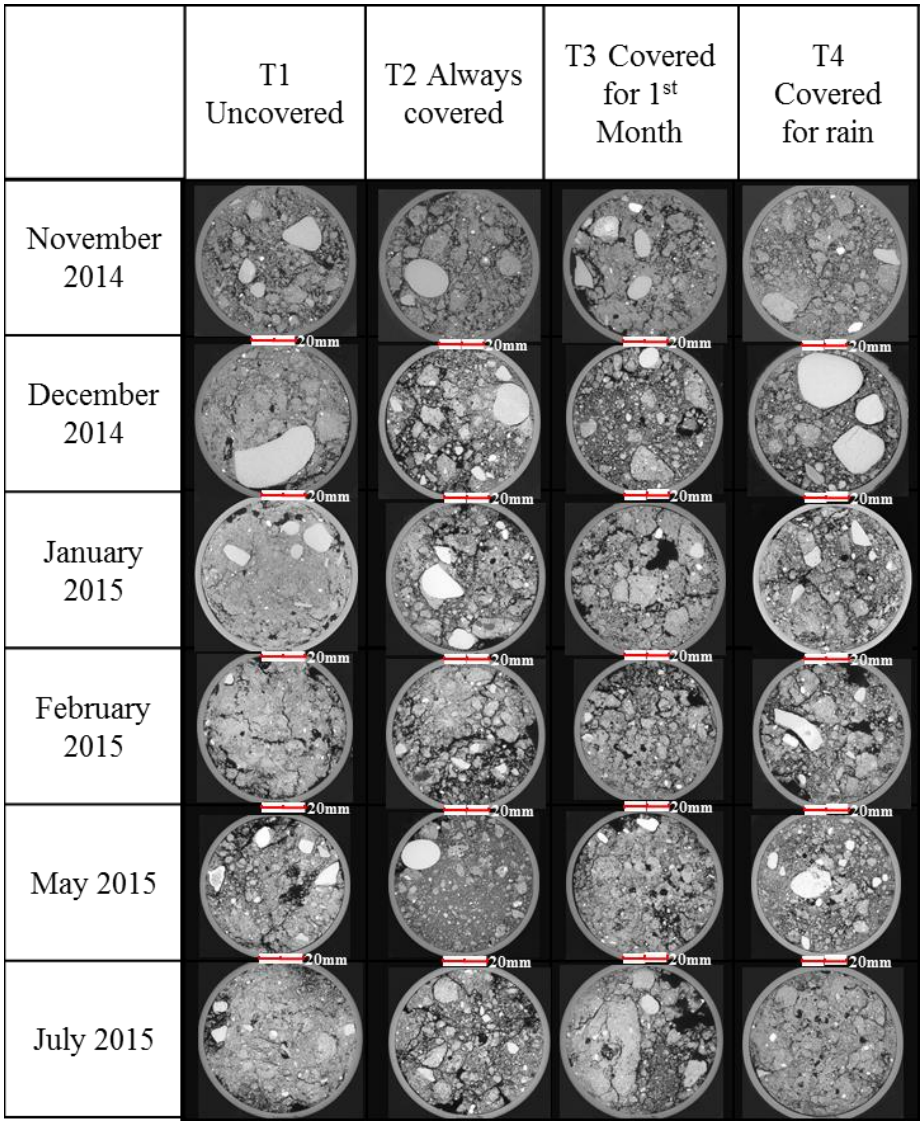


Figure 4.2 X-ray CT scan images for the undisturbed soil cores (17 cm depth) for wheat growing season 2015/2015. The scan resolution was 58 µm, and the scanning duration was 30 minutes.

4.4.2. X-ray µCT scans processed images

The X-ray µCT image scans processed by Image J free software were as shown in Figure 4.3 below.

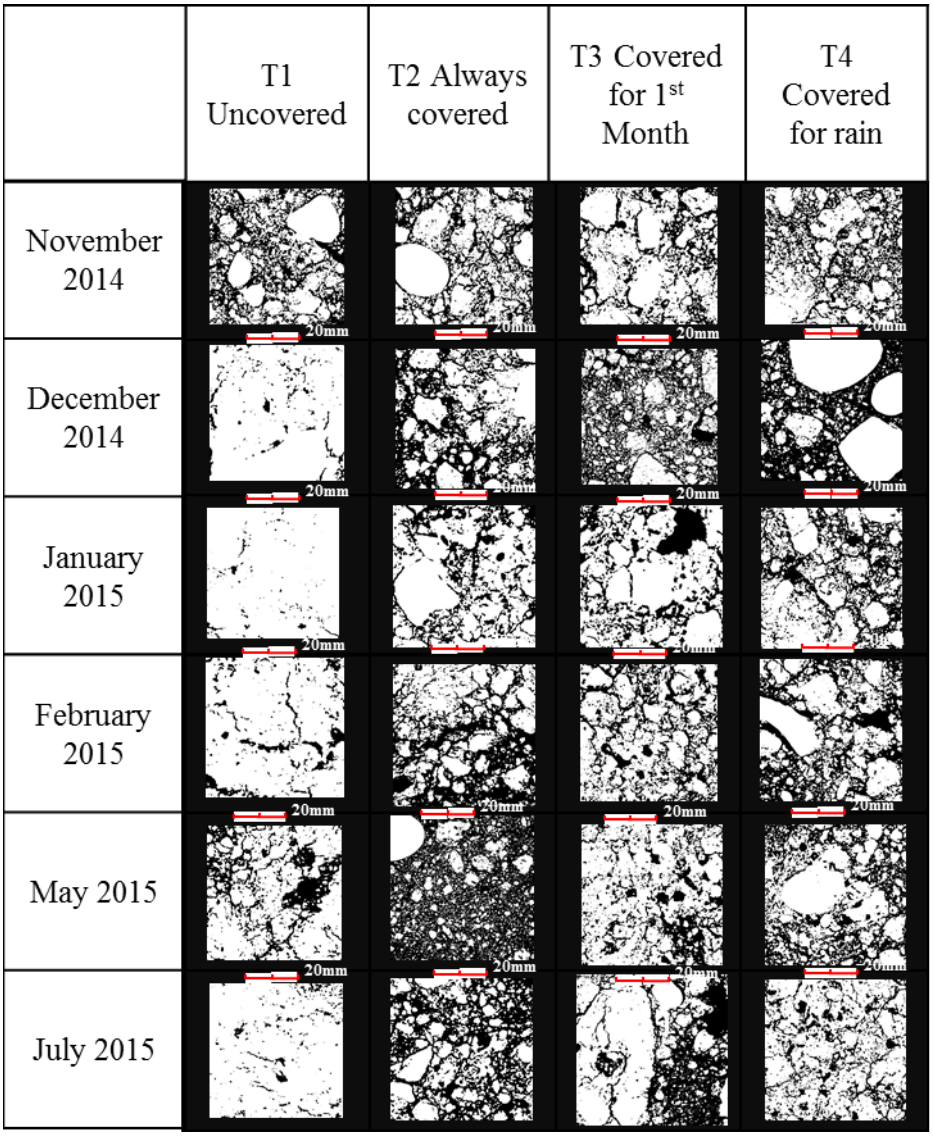


Figure 4.3 X-ray CT scan processed images by Image J software for the soil undisturbed (17 cm depth) cores for wheat growing season 2014/2015.

4.4.3. Environment Conditions

4.4.3.1. Total Rainfall

Total rainfall varied from 9 mm per month in April to 68.8 mm in July (Figure 4.4). During the crop emergence, rainfall was 62.71 mm in November and 53.2 mm in December.

4.4.3.2. Average Monthly Temperature °C

Temperature varied between -2 °C in January to 23 °C in July; with the lowesr temperatures recorded during crop emergence (Figure 4.5).

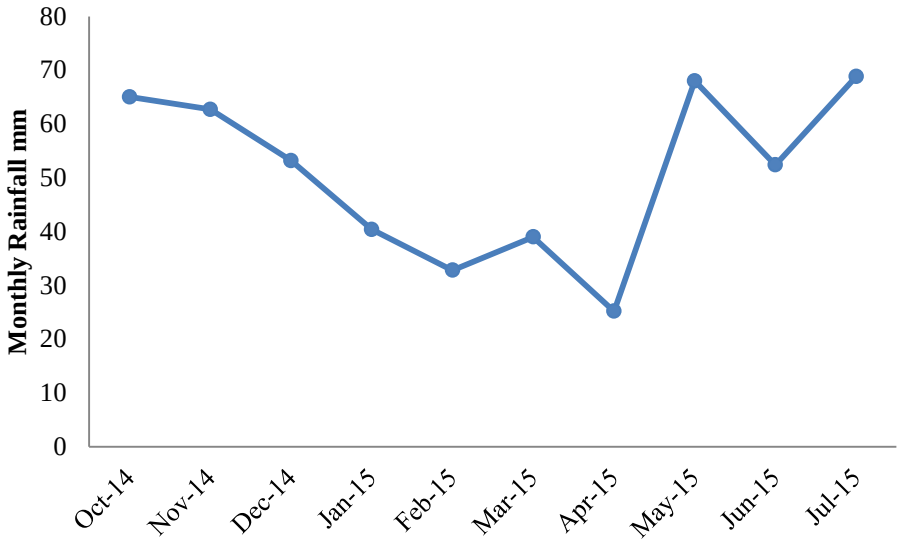


Figure 4.4 Monthly rainfall for wheat season 2014/2015 Data from the University of Nottingham Sutton Bonington campus weather station

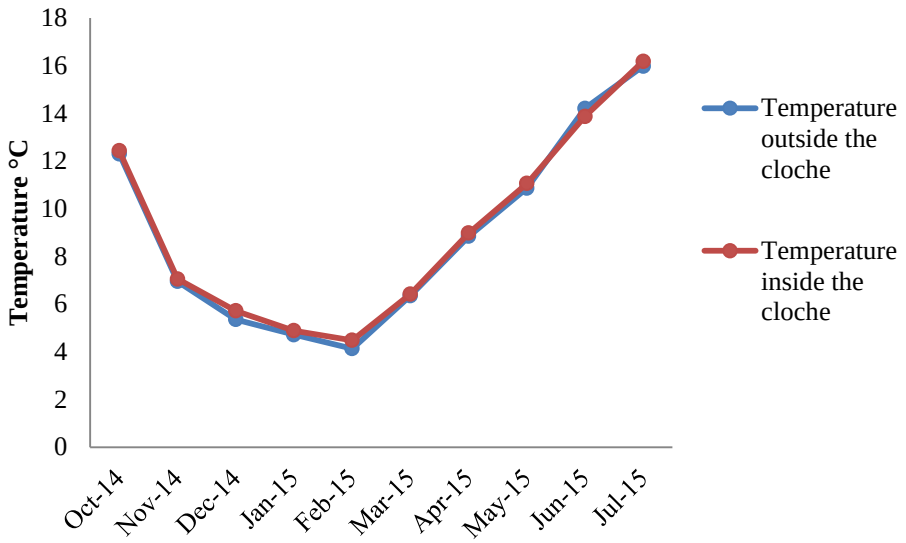


Figure 4.5 Mean monthly temperatures for wheat season 2014/2015 for inside and outside of the cloches. Data from the University of Nottingham Sutton Bonington campus weather local station

4.4.4. Soil Physical Parameters

4.4.4.1. Soil Particle Size Analysis

The soil particle analysis results showed that the soil of the trial field was a Sandy Loam according to the England and Wales soil classification, (Rowell 1994, Laker and Dupreez, 1982 and Day 1965).

4.4.4.2. Soil Organic Matter Content

The mean soil organic matter was 6.18%.

4.4.4.3. Soil Water Content

Soil water content was significantly different ($P<0.05$) between treatments; except for in November 2014 when it ranged from 11-12% when the soil surface had no rainfall compaction effects (Figure 4.6). After, T1 (always uncovered) had dropped 3% after being exposed to rainfall at December 2015 and at January 2015 T3

(covered 1st month) had the same impact after its soil surface had been directly exposed to the rainfall. Treatments T1, T3 and T4 were significantly different ($P<0.05$) over the lifetime of the experiment whereas treatment T2 (always covered) the soil water content increased over time.

4.4.4.4. Soil Total Porosity

Total soil porosity was not significantly different between treatments at the start of the experiment in November 2014 (Figure 4.4). However, porosity was significantly reduced ($P<0.05$) in December 2014 in treatment T1 (always uncovered) where soil surface was exposed to the rainfall for only one month and its porosity was decreased from 35-21%. Treatment T3 (covered for the first month) showed significantly lower porosity ($P<0.05$) after January 2015 when the soil surface was exposed directly to the rainfall with. porosity reducing from 35% in December 2014 to 26% . All treatments showed a significant reduction in porosity different over the duration of the experiment ($P<0.05$).

4.4.4.5. Soil Mean Pore Size

The mean pore size was significantly different ($P<0.05$) between treatments ranging from 165 to 258 mm^2. Only T1 treatment (always uncover) and T3 (cover 1st month) were significantly different ($P<0.05$) over time, while T1 (always uncovered) and T2 (always covered) treatments were not significantly different over time as shown in Figure 4.8. There was a large drop in mean pore size for T1 from November to December 14 approximately 250 to 100 mm^2; thereafter it increased to 160 mm^2 by July 15. The mean pore size in the T2 and T4 treatments hardly changed over the course of the experiment.

4.4.4.6. Soil Pore Circularity

The pore circularity was significantly different (P<0.05) between treatments ranging from 0.37 to 0.53 between treatments, T3 (covered 1st month) recorded the highest values. All treatments had a significant effect difference (P<0.05) over time ranging from 0.29 to 0.77 as can be shown in Figure 4.9. The main trend was increasing circularity (less complex) over time were the largest differences in T3.

4.4.4.7. Soil Penetration Resistance

The soil penetration resistance parameter was significantly different (P<0.05) between treatments were the mean value was ranging from 161-337 kPa. However, there was no significant effect over time for this parameter for the same treatment as shown in Figure 4.10.

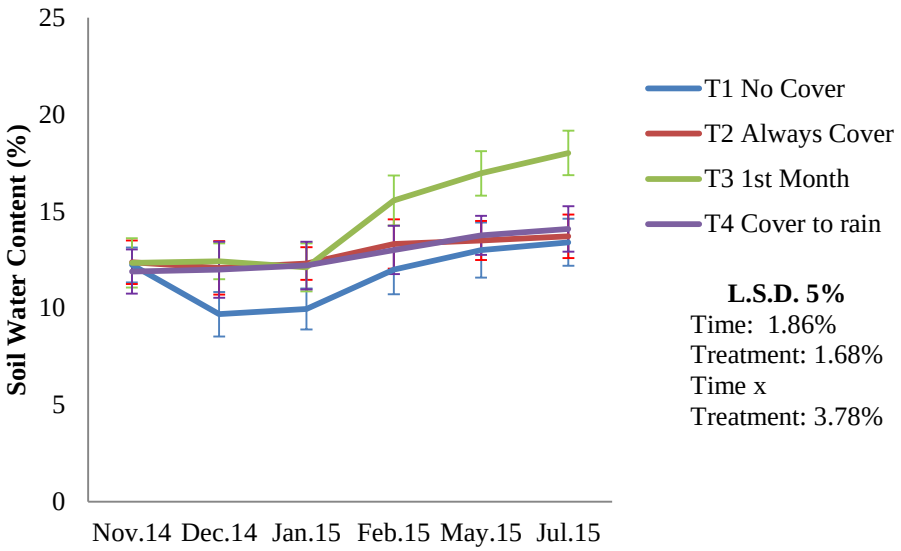


Figure 4.6 Soil water content % calculated by soil gravimetric method for wheat growing season 2014/2015 Error bars: standard error.

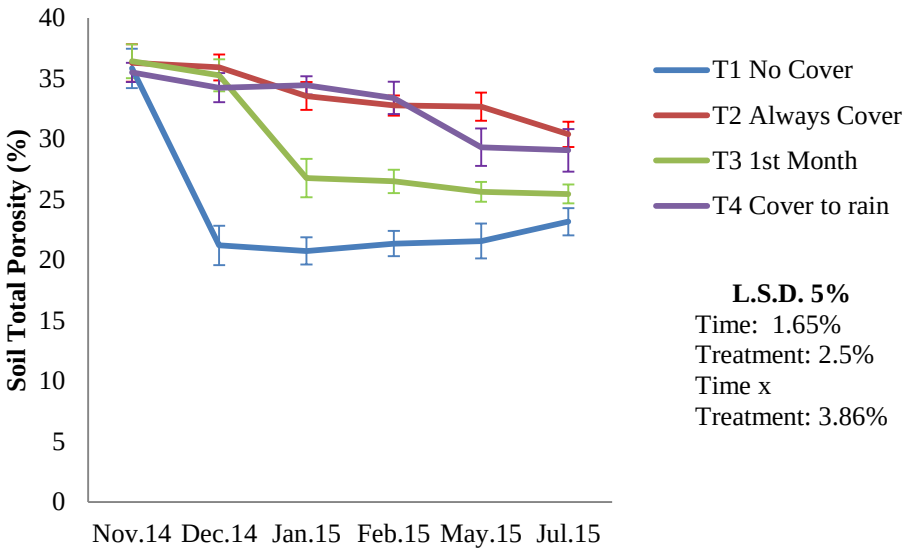


Figure 4.7 Soil Total Porosity (%) calculated by X-ray µCT images for wheat growing season 2014/2015 Error bars: standard error.

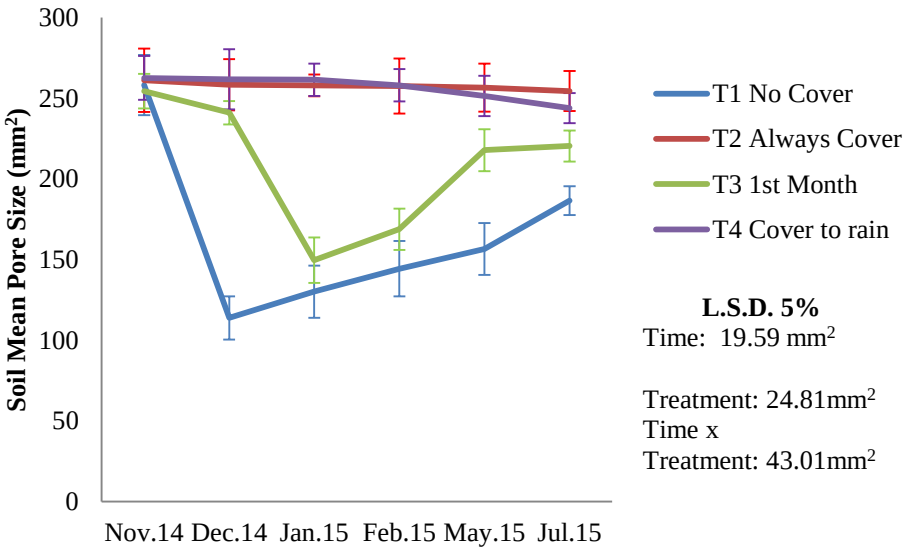


Figure 4.8Soil mean pore size calculated by soil X-ray µCT scan images for wheat growing season 2014/2015 Error bars: standard error

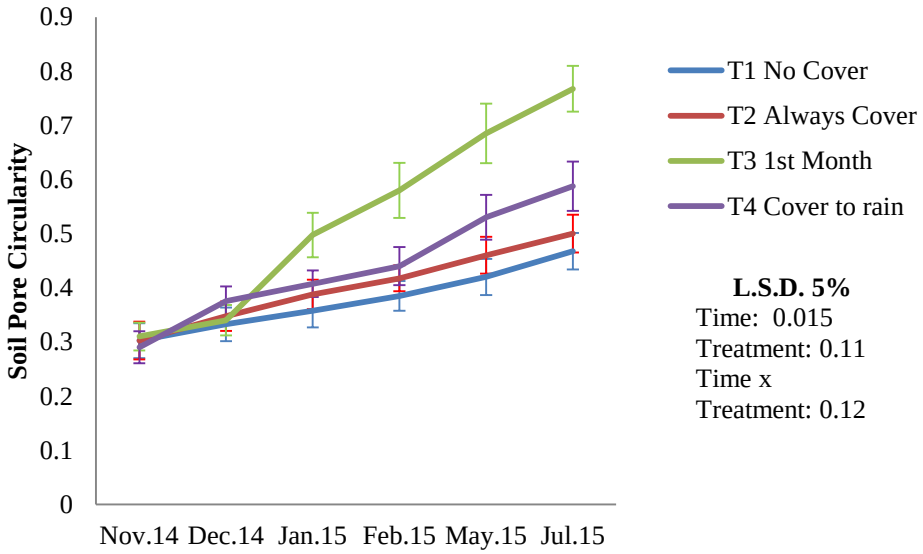


Figure 4.9 Soil Pore Circularity calculated by soil X-ray µCT scan images for wheat growing season 2014/2015 Error bars: standard error

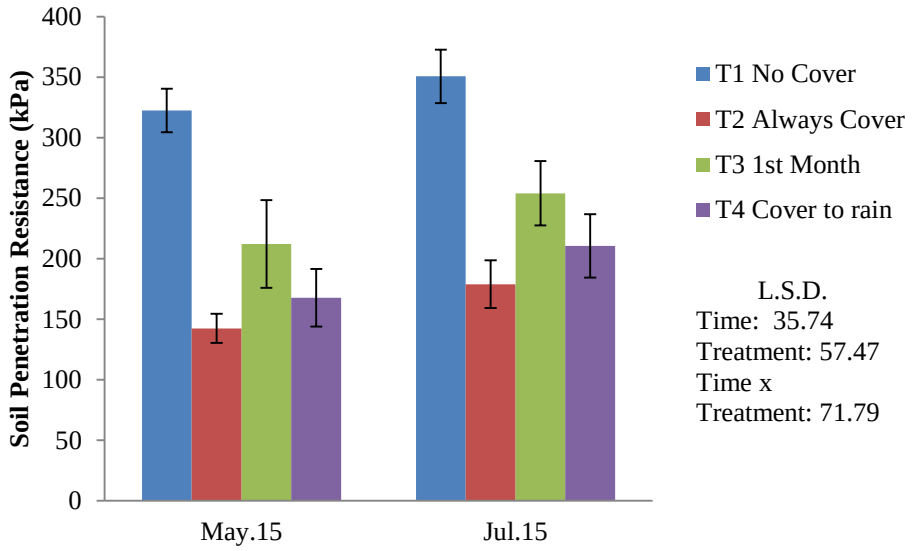


Figure 4.10 Soil Penetration Resistance kPa calculated by soil penetrometer field measurements for wheat growing season 2014/2015, Error bars: standard error.

4.4.5. Plant Root Parameters

4.4.5.1. Root Volume

Root volume measured from X-ray µCT images was significantly different ($P<0.05$) over time with the means were ranging (216-248 mm^3) and a root segmented image of each treatment shown in Figure 4.11a-4.11d. However, the time treatment effect was not enough to be significant for all treatments (Figure 4.9f). Root values were highest in T3 (covered for 1st month) and lowest in T1 (uncovered).

Similarly, the same parameter measured by WinRhizo™ technology was significantly different ($P<0.05$) over time, were mean values were ranging (217-286 mm^3). The difference between treatment was significantly different were mean ranging (231-308 mm^3) and even the time treatment was different for all treatment mean ranging (185-350 mm^3) (Figure 4.11f).

4.4.5.2. Root Surface Area

The root surface area parameter was significantly different ($P<0.05$) over time were the means values were ranging 56-63 mm^2. The treatment was significantly different ($P<0.05$) were mean values were ranging 53-70 mm^2 and the time treatment also was significantly different ($P<0.05$) with the mean values ranging 50-73 mm^2 (Figure 4.12a) Highest root surface areas were in T3 (covered 1st month) and lowest in T1 (uncovered).

When this same parameter was measured by WinRhizo™ technology the results were significantly different ($P<0.05$) over time, with the mean values were ranging 68-79 mm^2, the treatments were significantly different ($P<0.05$) with the mean

values ranging 66-83 mm^2 and the time treatment was also significantly different ($P<0.05$) with the mean values were ranging from 62-87 mm^2 (Figure 4.12b).

4.4.5.3. Root Diameter

The root diameter parameter was significantly different ($P<0.05$) over time where the mean values were ranging 0.049-0.52 mm, the difference between treatments was significant ($P<0.05$) where the mean values were ranging 0.43-0.57mm. The highest root diameters were in T1 (uncovered) and smallest in T2 (always covered) (Figure 4.13a).

Similarly, the same parameter measured by the destructive method of WinRhizo™ was significantly different ($P<0.05$) over time where its mean values were ranging 0.53-0.56 mm; the difference between treatments was also significant ($P<0.05$) where the mean values were ranging 0.47-0.61 mm as can be shown in (Figure 4.13b).

4.4.5.4. Root Length

The root length parameter measured from X-ray µCT images was significantly different ($P<0.05$) over time, the mean values were ranging 129-144 mm. The difference between treatments was also significant ($P<0.05$) and the mean values were ranging 115-166 mm, although, the time treatment was not significant (Figure 4.14a) The highest root length were in T3 (cover 1^{st} month) and lowest in T1 (uncover).

Similarly, the same parameter when measured by WinRhizo™ technology was also significantly different ($P<0.05$) over time (mean values were ranging 137-153mm) and the treatment were significantly different ($P<0.05$) where the mean values were

ranging (131-160 mm). However, the time treatment was not significantly different (Figure 4.14b).

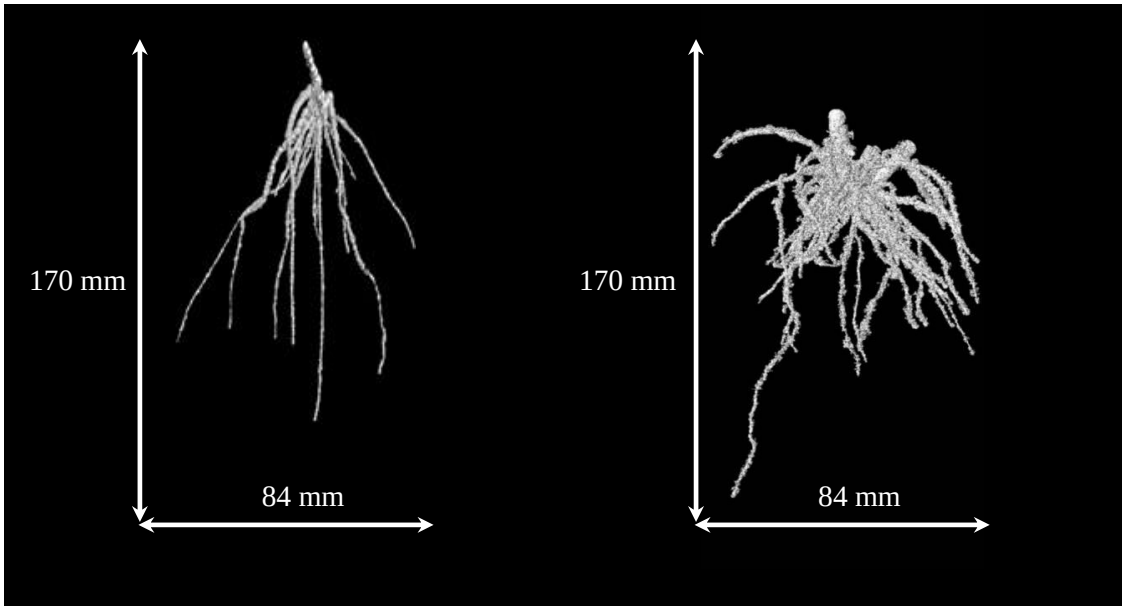


Figure 4.11a Root architecture grey scale image for T1 (uncover)

Figure 4.11b Root architecture grey scale image for T2 (always cover)

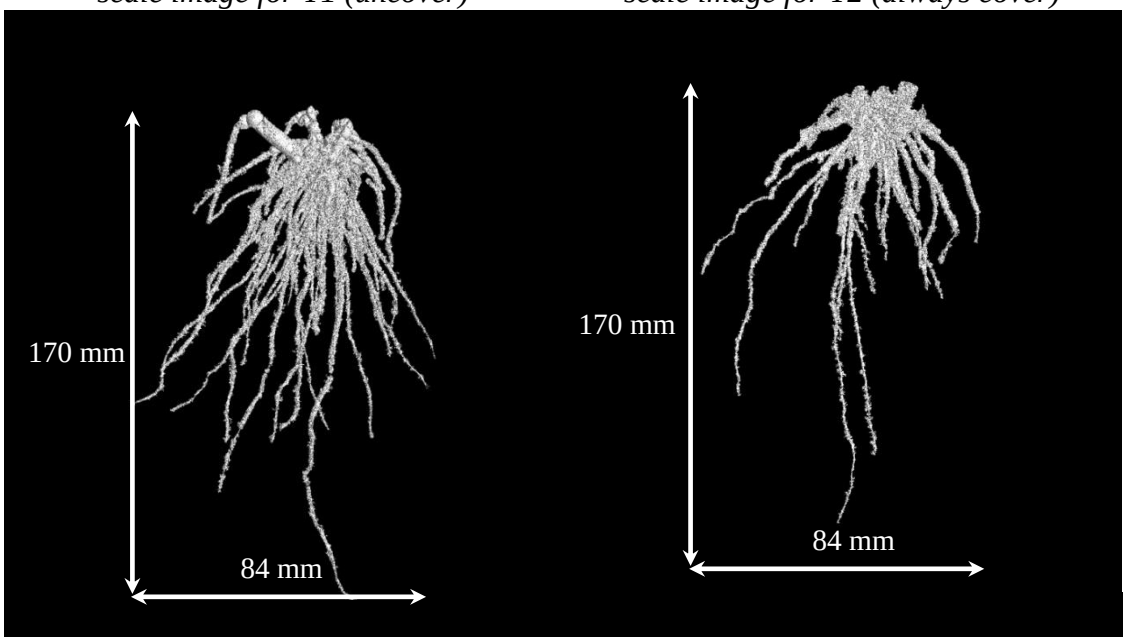


Figure 4.11c Root architecture grey scale image for T3 (covered for 1st month)

Figure 4.11d Root architecture grey scale image for T4 (covered for rain)

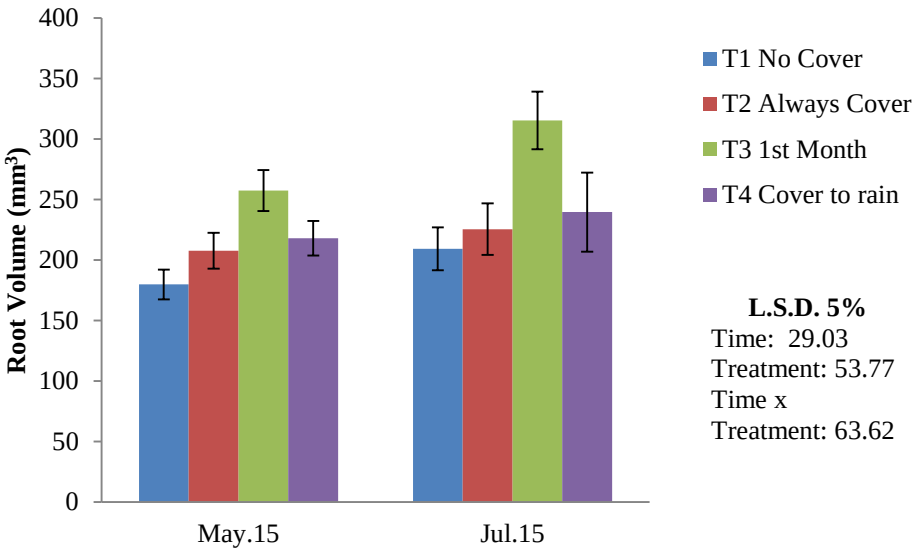


Figure 4.11e Root Volume calculated by soil X-ray µCT scan images root segmentation for wheat growing season 2014/2015, Error bars: standard error.

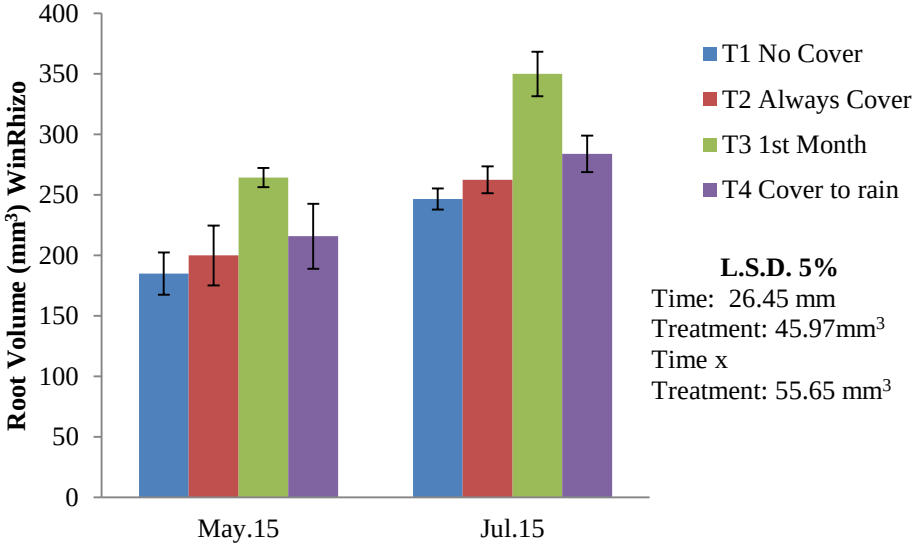


Figure 4.11f Root Volume calculated by WinRhizo™ for wheat growing season 2014/2015, Error bars: standard error.

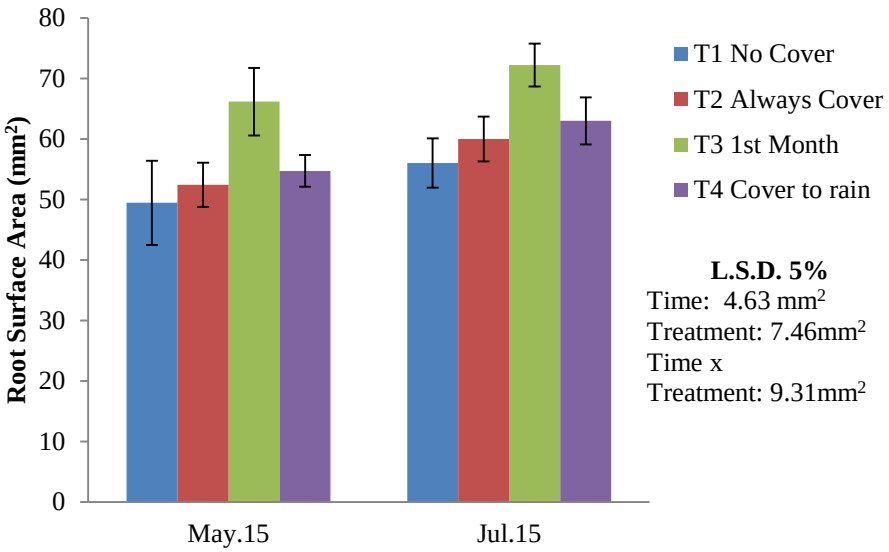


Figure 4.12a Root Surface Area calculated by soil X-ray µCT scan images root segmentation for wheat growing season 2014/2015, Error bars: standard error.

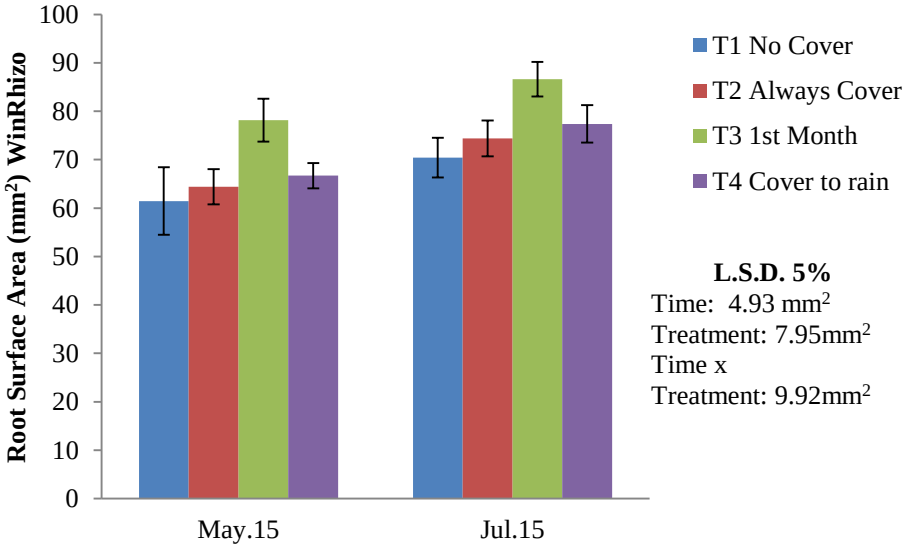


Figure 4.12b Root Surface Area calculated by WinRhizo™ for wheat growing season 2014/2015 Error bars: standard error.

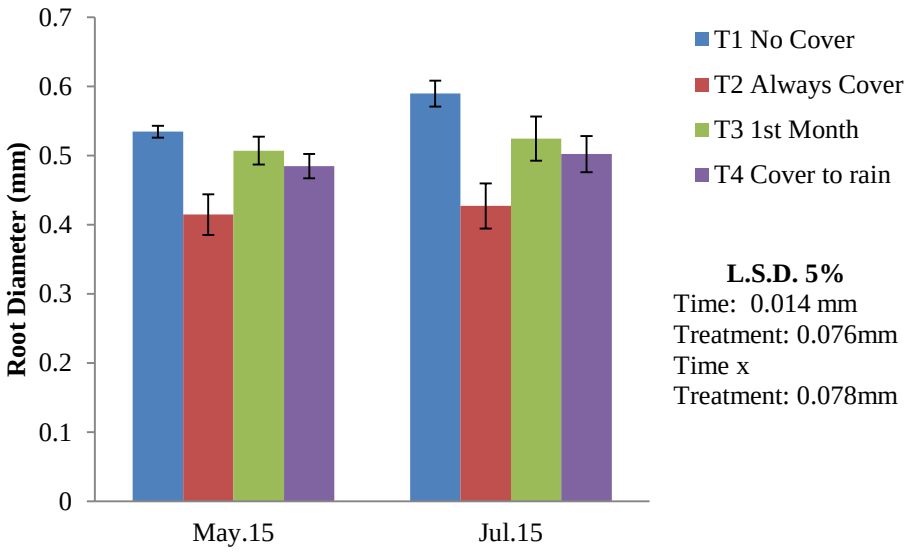


Figure 4.13a Root Diameter calculated by soil X-ray µCT scan images root segmentation for wheat growing season 2014/2015, Error bars: standard error.

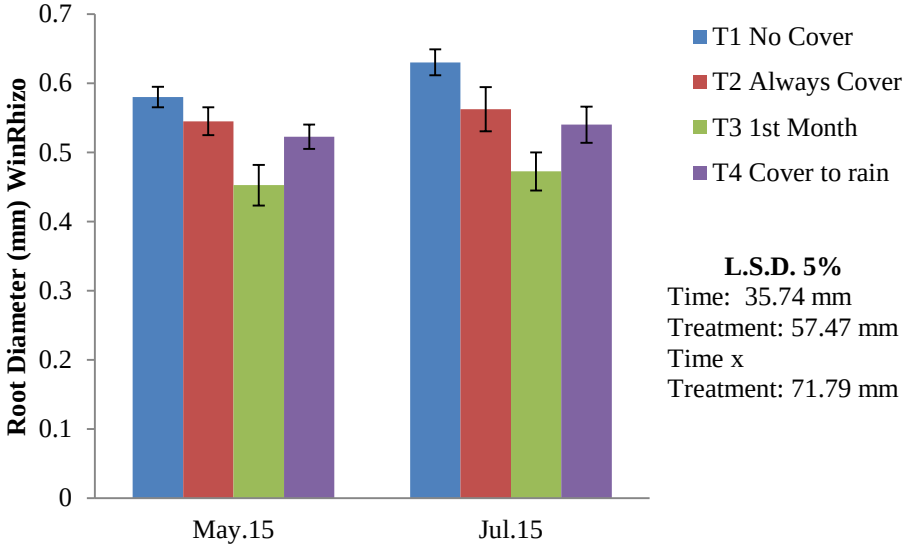


Figure 4.13b Root Diameter calculated by WinRhizo™ for wheat growing season 2014/2015 Error bars: standard error.

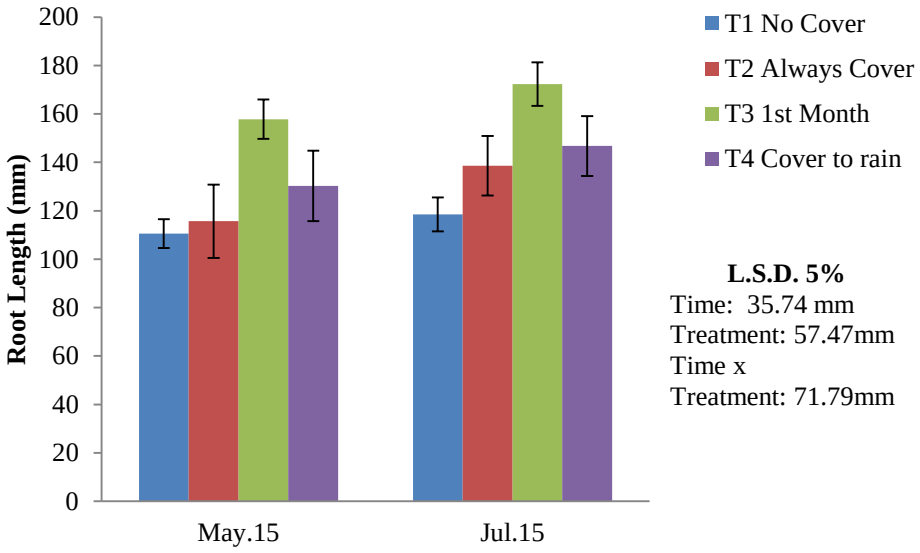


Figure 4.14a Root Length calculated by soil X-ray µCT scan images root segmentation for wheat growing season 2014/2015, Error bars: standard error.

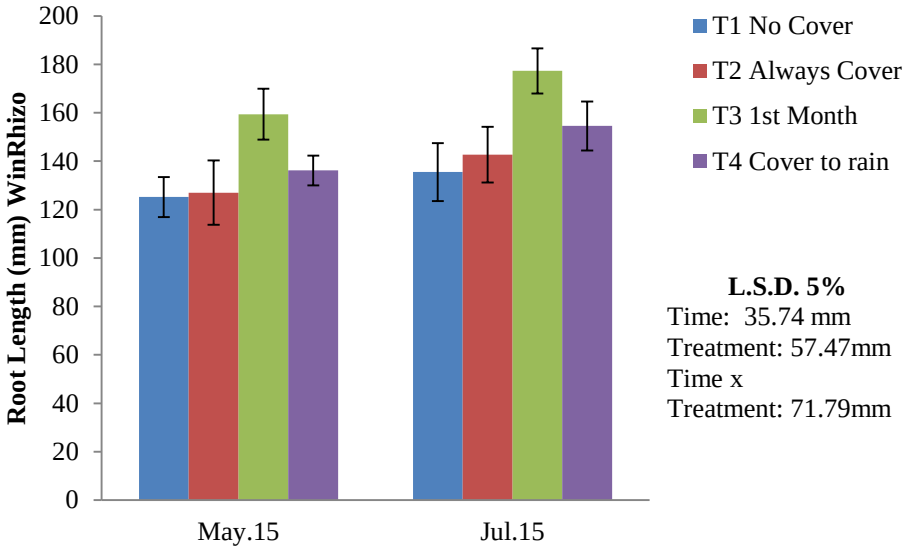


Figure 4.14b Root Length calculated by WinRhizo™ for wheat growing season 2014/2015, Error bars: standard error.

4.4.6. Crop Parameters

4.4.6.1. Plant Height

Mean plant height was significantly different ($P<0.05$) over time (mean values ranging 95-99 cm), different significantly ($P<0.05$) between treatments (mean values ranging 45-53 cm) and different significantly ($P<0.05$) over time (mean values ranging 6-107 cm) as can be shown in Figure 4.15.

4.4.6.2. Plant Normalised Difference Vegetation Index

The results showed that the Normalised Difference Vegetation Index measurement was not significant over time, but it was significantly different ($P<0.05$) between treatments where the mean values were ranging 0.65-0.77 as can be shown in Figure 4.16.

4.4.6.3. Crop Yield

The crop yield results were significantly different ($P<0.05$) between treatments where the mean values were ranging 5-7 Mg/ha when the manual harvesting was conducted as can be shown in figure 4.17. This parameter was not significantly different over time because it was conducted at the end of the season for one time after the crop maturity.

4.4.6.4. Harvest Index

The harvest index parameter was significantly different ($P<0.05$) between treatments where the mean values were ranging between 0.46-0.57 as can be shown in Figure 4.18.

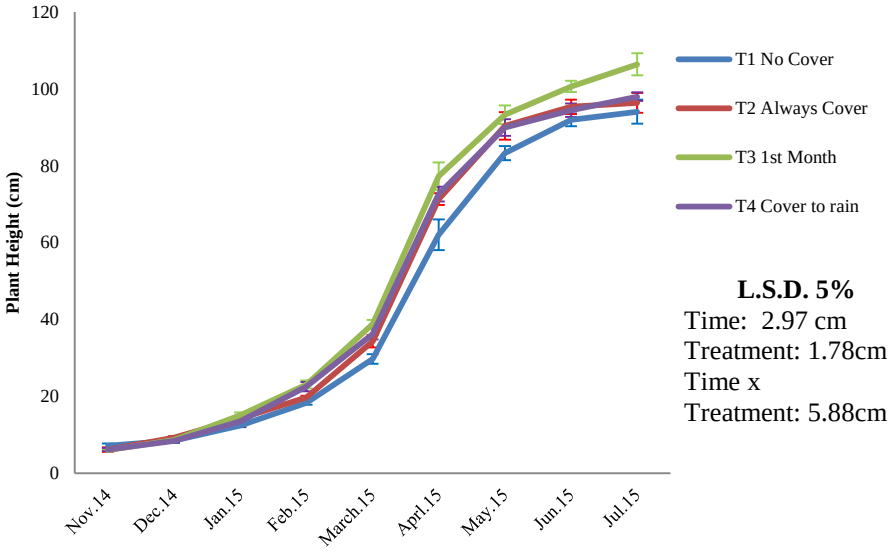


Figure 4.15 Plant Average Height for wheat growing season 2014/2015 Error bars: standard error.

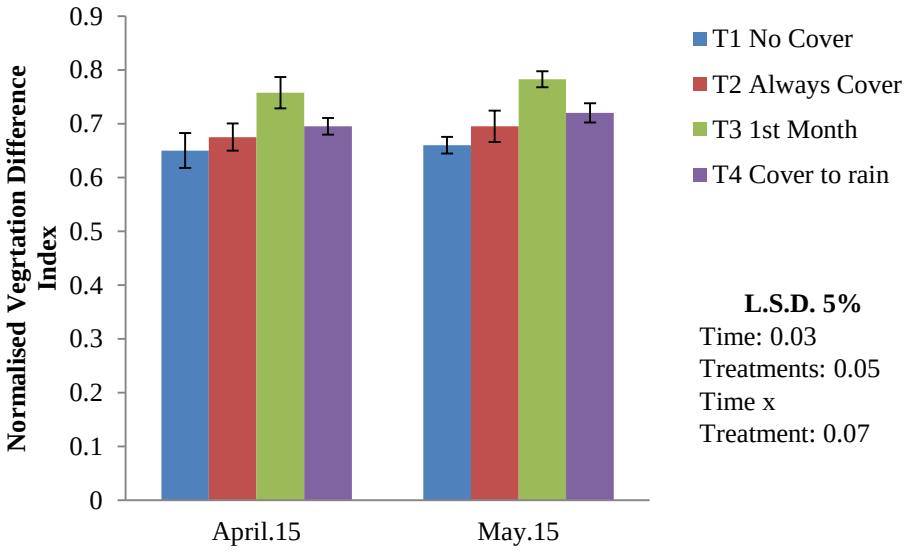


Figure 4.16 Normalised Difference Vegetation Index calculated by using GreenSeeker© reading for wheat growing season 2014/2015 Error

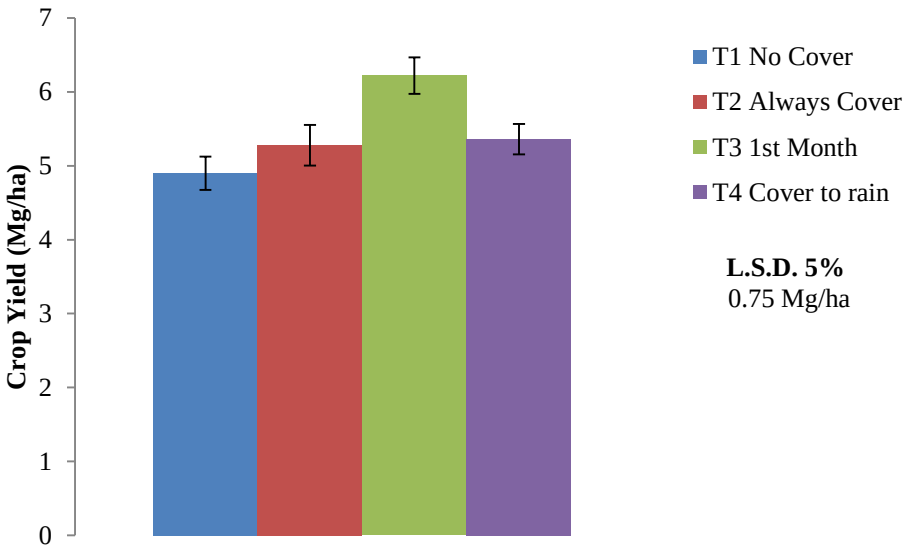


Figure 4.17 Yield Crop for wheat growing season 2014/2015, Error bars: standard error.

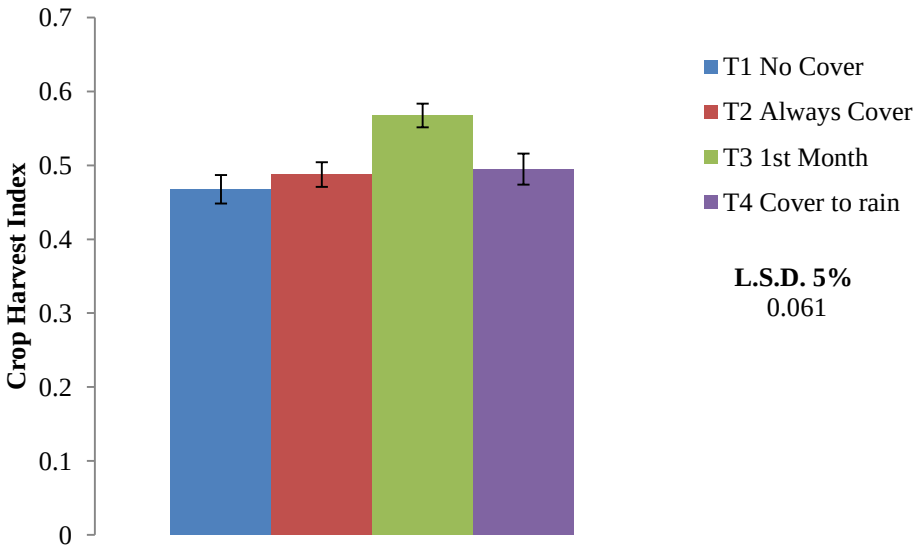


Figure 4.18 Crop Harvest Index for wheat growing season 2014/2015, Error bars: standard error.

4.4.7. Correlations between Plant and Soil Parameters

There were positive correlations between the root volume (measured by WinRhizo™) and the crop yield (r=0.78), crop harvest index HI (r=0.74), soil water content% (r=0.56), the root volume measured by X-ray µCT images and crop yield (r=0.64) and finally the root volume (measured by WinRhizo™ technique) was positively correlated with the soil pore circularity (r=0.74) as can be shown in Figures 4.19a-4.19e. Additionally, the soil pore circularity was positively correlated with the soil water content % (r=0.32), plant height (r=0.67), Normalised Difference Vegetation Index (r=0.58), crop yield (r=0.52) and harvest index (r=0.62) as can be shown in Figures 4.20a-4.20e. Finally, soil penetration resistance parameter was negatively correlated with root volume (r=0.17), plant height (r=0.17), crop yield (r=0.19) and positively correlated to root diameter (r=0.40) as can be shown in Figures 4.21a-4.21d.

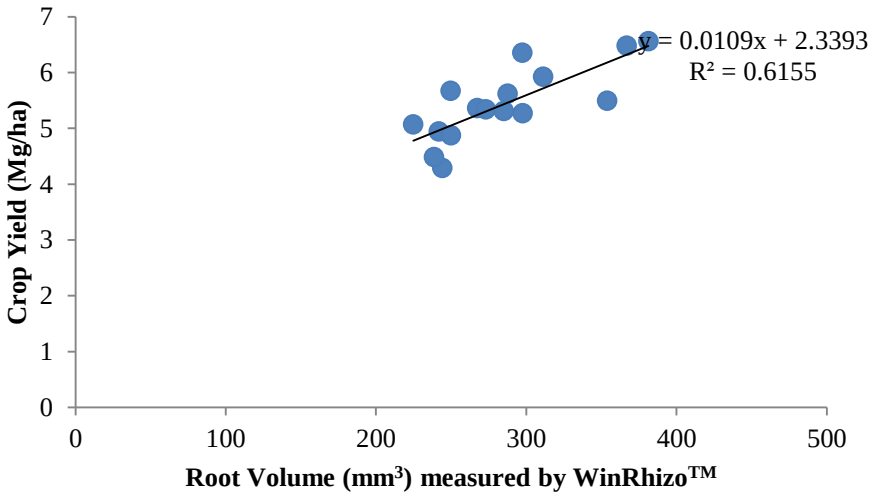


Figure 4.19a Linear regression between Root Volume (measured by WinRhizo™) and Crop Yield. P<0.01, df=14.

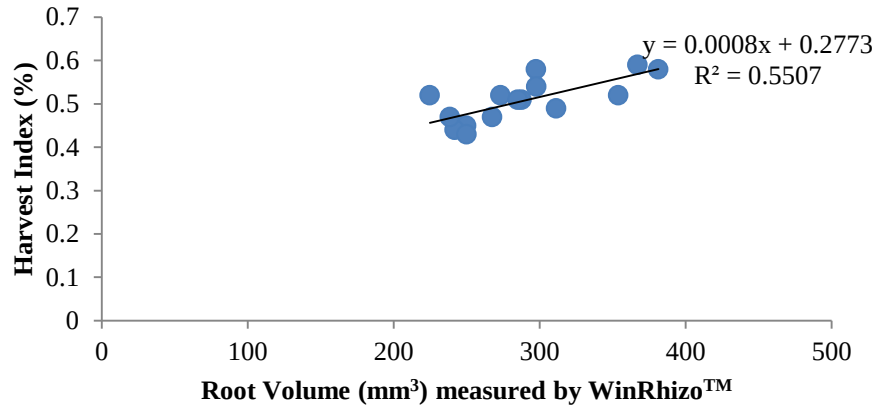


Figure 4.19b Linear regression between Root Volume (measured by WinRhizo™) and Crop Harvest Index. P<0.01, df=14.

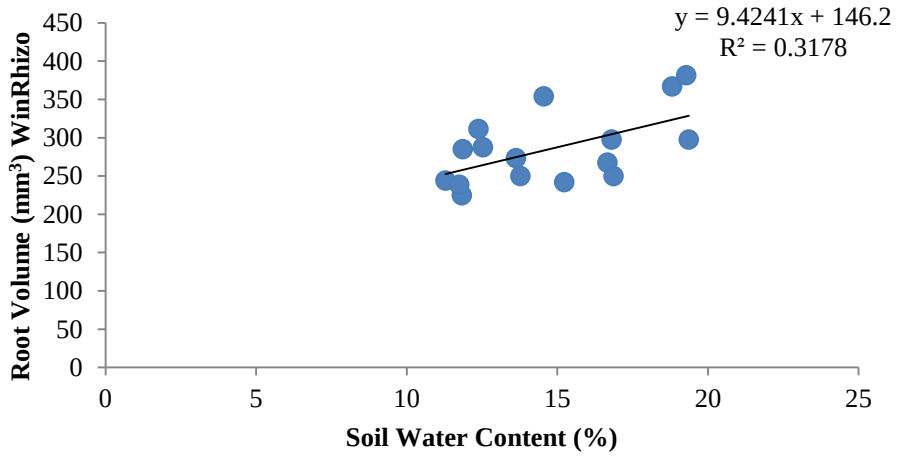


Figure 4.19c Linear regression between Root Volume (measured by WinRhizo™) and Soil Water Content %. P<0.01, df=14.

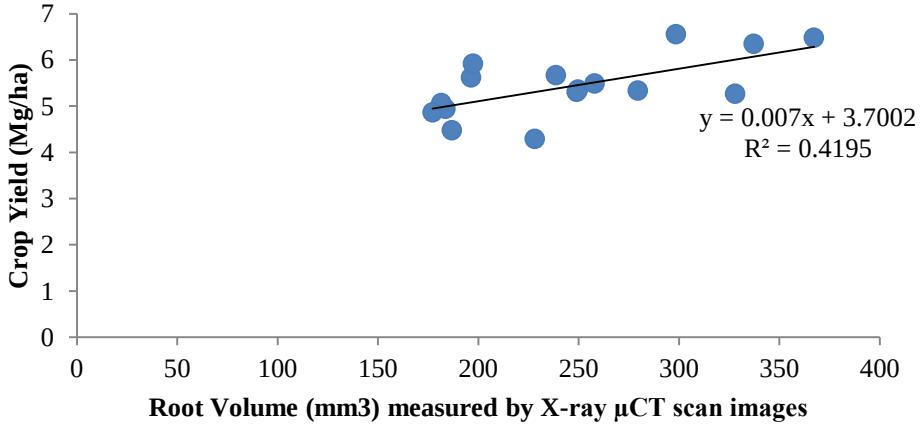


Figure 4.19d Linear regression between Root Volume (measured by X-ray CT segmented roots) and Crop Yield. P<0.01, df=14.

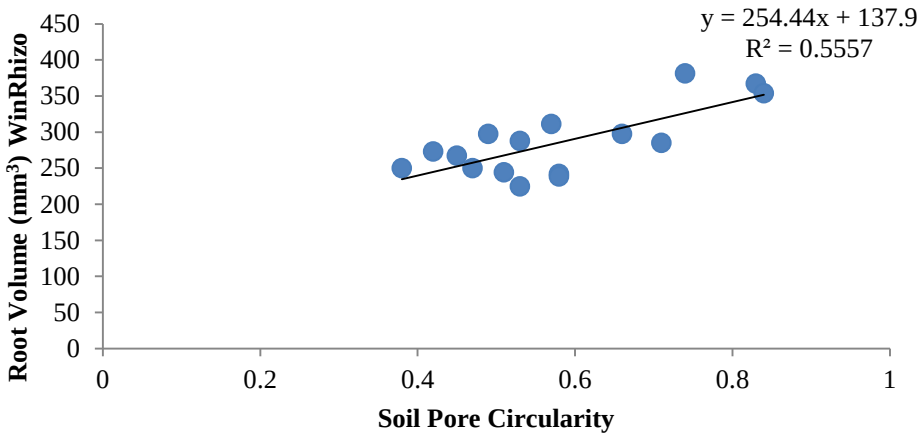


Figure 4.19e Linear regression between Root Volume (measured by WinRhizo™) and Soil Pore Circularity. P<0.01, df=14.

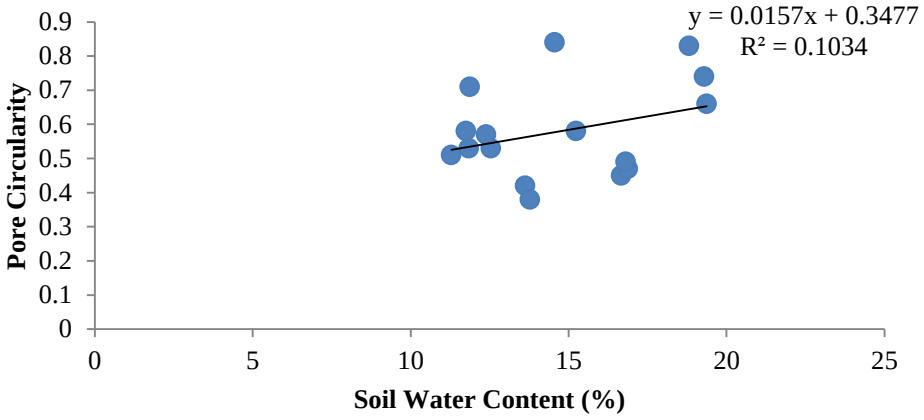


Figure 4.20a Linear regression Soil Pore Circularity and Soil Water Content %. P<0.05, df=14.

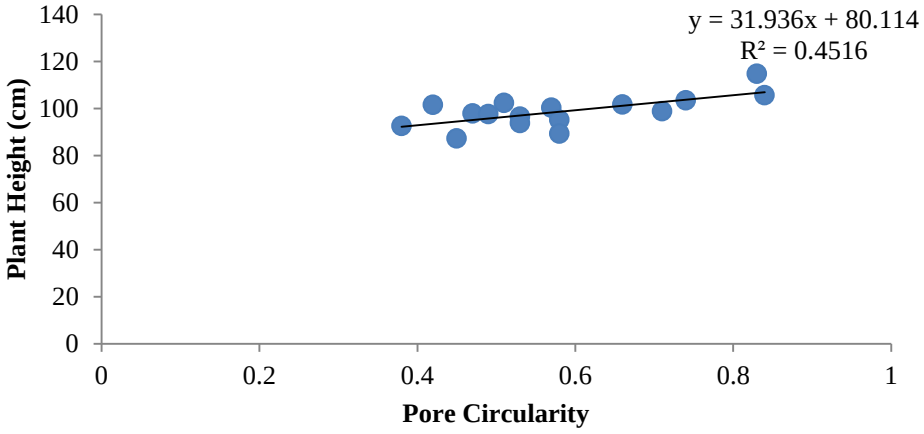


Figure 4.20b Linear regression between Plant Height and Soil Pore Circularity. P<0.01, df=14.

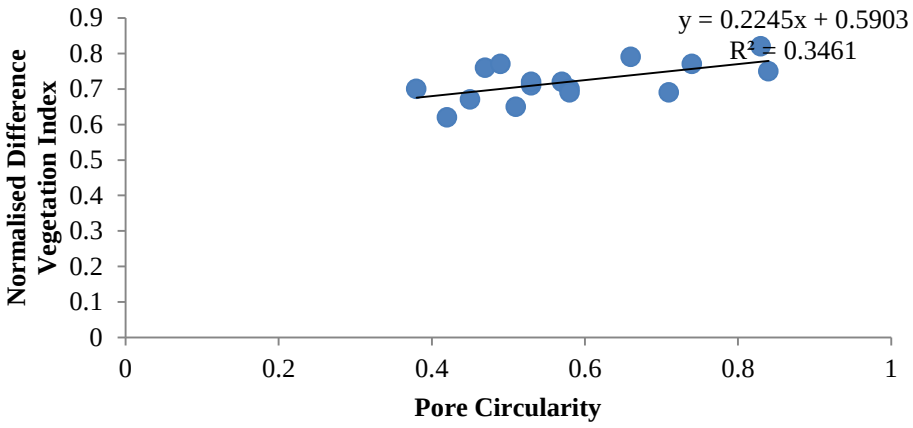


Figure 4.20c Linear regression between Normalised Difference Vegetation Index and Soil Pore Circularity. P<0.01, df=14.

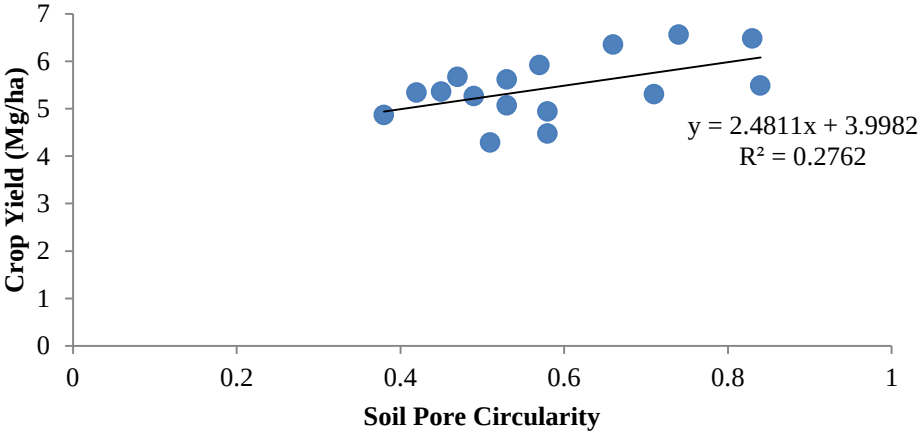


Figure 4.20d Linear regression between Crop Yield and Soil Pore Circularity. P<0.05, df=14.

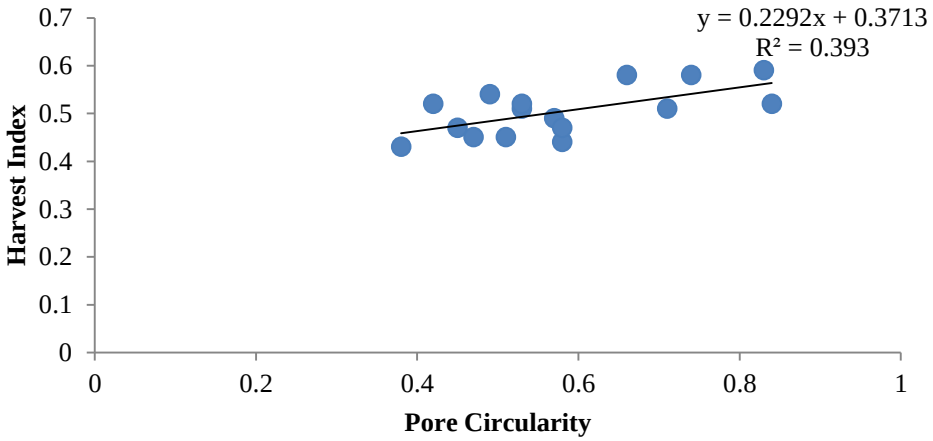


Figure 4.20e Linear regression between Harvest Index and Soil Pore Circularity. P<0.01, df=14.

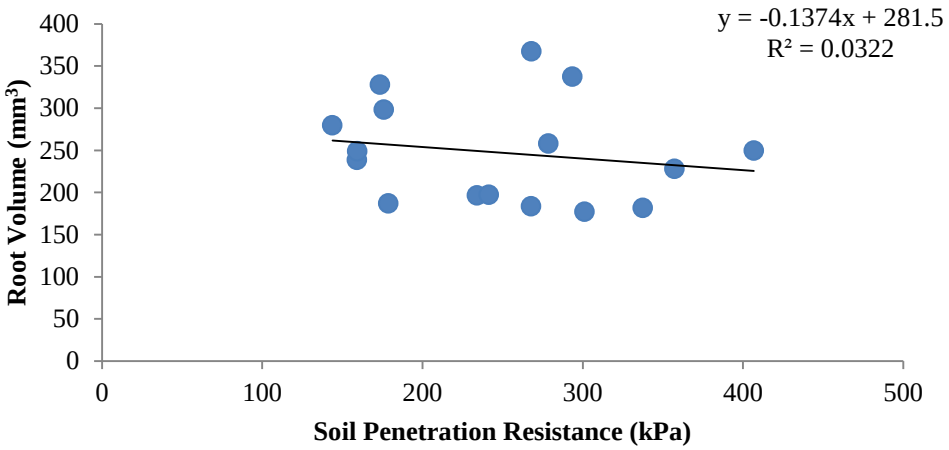


Figure 4.21a Linear regression between Root Volume and Soil Penetration Resistance. P<0.01, df=14.

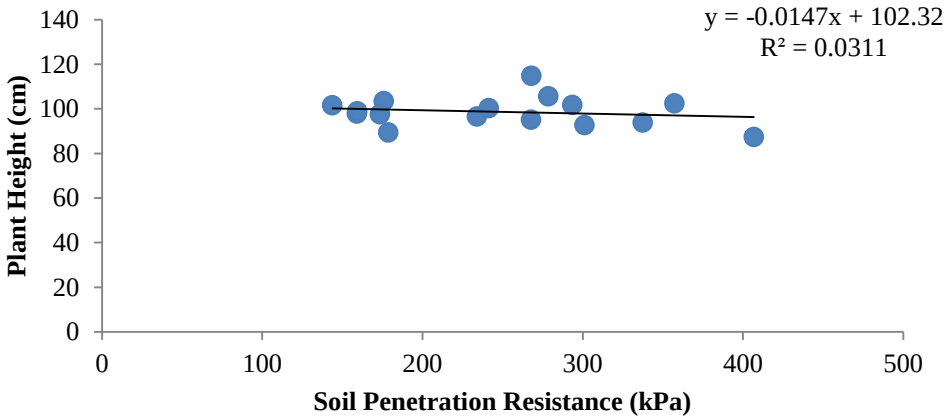


Figure 4.21b Linear regression between Plant Height and Soil Penetration Resistance. P<0.05, df=14.

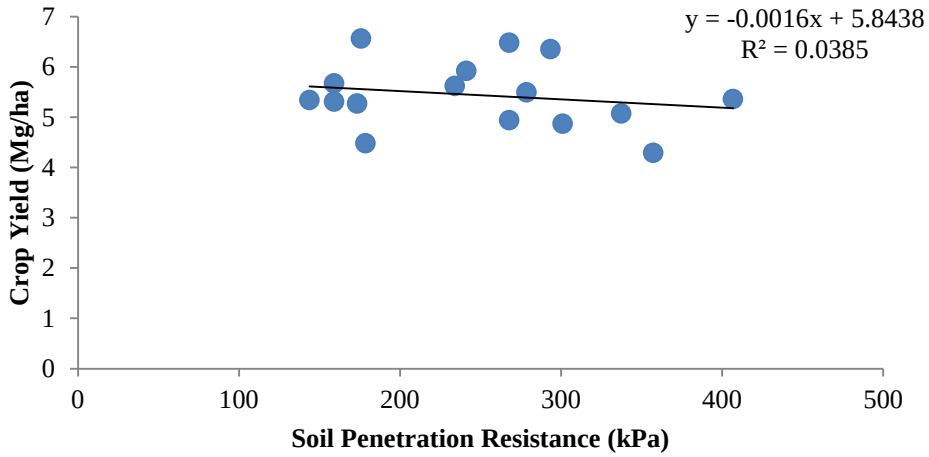


Figure 4.21c Linear regression between Crop Yield and Soil Penetration Resistance. P<0.05, df=14.

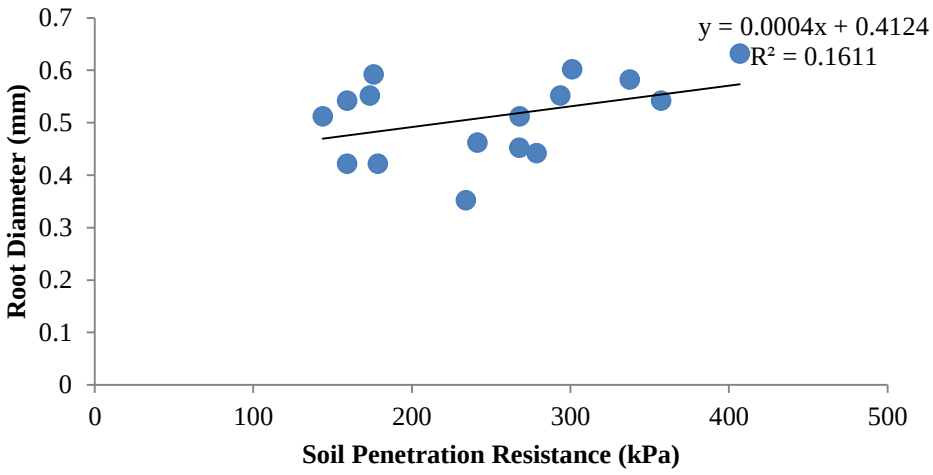


Figure 4.21d Linear regression Root Diameter and Soil Penetration Resistance. P<0.05, df=14.

4.5. Discussion

Using cloches to cover the soil surface created different soil structures, these soil structures types were significantly different (P<0.05) in soil porosity and soil pore circularity and they produced significantly different (P<0.05) crop yield and harvest index through the wheat growing season 2014/2015. Aggelopoulou and Gemtos (2011) reported that soils with varying physical parameters produced different yields for apple with a positive correlation between the yield and soil physical properties such as soil porosity and pore distribution.

Protecting soil from rainfall for one month allows the plant root system to grow into a more porous medium instead of less porous-structured soil, where the root will not face high soil penetration resistance and can grow easily. Subsequent exposure to rain allows soil structure to develop with the roots already established. This may impact on plant development by allowing more resources to be directed to the acquisition of water and nutrients. A potential confounding issue may have been an increase in temperature brought about through the cloches, however in this case the

cloches were open to the atmosphere at the sides and elevated from the soil surface. Both temperature and sunlight were measured both within and outside of the cloches and no significant differences were recorded.

Many of the examined soil physical and root parameters measured by X-ray μCT images were directly correlated to crop yield and harvest index. Soil pore circularity was positively correlated to root volume (r=0.74) which was also highly positively correlated with the crop yield (r=0.78). Covering the soil surface for only the first month created a soil structure with greater soil pore circularity which resulted in higher values for root volume, plant height, NDVI, crop yield and harvest index values. This early coverage protected the root system from rainfall-induced soil compaction during a period of total rainfall of 127.75 mm for the first two months of seedling emergence (Table 4.4).

Table 4.2 Timeline of crop seedling emergence for the second experiment wheat (cv. Rialto) growing season 2014/2015. Weather data from the University of Nottingham Sutton Bonington campus local weather station.

Parameter	Treatment	Crop Emerging Timeline (CET)			
		Nov. 14	Dec. 14	Jan. 15	Feb. 15
Rainfall mm	All	62.71	53.2	40.4	32.8
Average Temperature C°	All	6.95	5.35	4.72	4.13
Porosity%	T1	35.8	21.2	20.7	21.3
	T2	36.2	35.9	33.5	32.7
	T3	36.4	35.2	26.7	26.4
	T4	35.5	34.2	34.4	33.3
Soil Pore Circularity	T1	0.30	0.33	0.35	0.38
	T2	0.30	0.34	0.38	0.41
	T3	0.31	0.32	0.49	0.58
	T4	0.29	0.37	0.40	0.44
Plant Height cm	T1	7.1	8.8	12.3	18.2
	T2	6.3	9.2	14.2	19.7
	T3	5.8	8.6	15.1	23.1
	T4	6.5	8.4	13.5	22.5

The plants in treatment T3 (covered for the first month) had enough time to establish into a porous medium with no effect rainfall-induced surface compaction. On subsequent exposure to rainfall, soil structure then forms around a healthy root architecture that had already penetrated into the soil loose strucutre consuming minimum resources at early stages. That had created higher pore circularity values

directly after soil surface exposure on December 2014 as shown above in table 4.4 and produce soil structure.

In contrast, in the control treatment (T1, uncovered), direct exposure to rainfall resulted in earlier formation of soil structure at the same time as root architecture formation at the seedling emergence stage into the soil which may have resulted in higher soil penetration resistance in comparison with the other treatments. Therefore, the soil penetration resistance value was the higher in comparison with the rest of the treatments. The plant root system in this treatment would not have had the same delay in soil structure formation, affecting soil porosity, pore circularity and water content which were directly impacting plant growth parameters and as a result reducing crop yield and crop harvest index.

Coverage of the soil surface in both treatments T2 and T4 (always covered and covered for rain respectively) produced a more porous soil structure than the other treatments (Table 4.4), in which the root system can better penetrate the less-compacted soil structure.

Finally, the manipulating of soil structure formation timing after gaining the plant some time to emerge the seed and penetrate a soft structure can minimise the consumed plant power. That can be because of root penetrating into a loose soil structure resulting in saving most of the root's energy to form a crop with greater shoot biomass which produced greater crop yield and harvest index. That can be achieved because of the coverage timing and period, where the plant at early stages needs a physical protection against the rainfall and soil structure that will have high strength due to soil structure formation. The soil surface coverage action can be

replaced by many easier means such as previous crop hay or disposal recycled materials.

4.6. Conclusions

Analysis of X-ray μCT scans of the soil structure revealed that soil structure formation directly affected plant development and caused significantly effects on yield for a winter wheat crop. An increase in crop yield and harvest index was found after delaying rainfall-induced soil compaction for the first thirty days after seed sowing.

Delaying soil structure formation until seedling establishment produces a soil with greater pore circularity, leading to higher water content and less soil penetration resistance which may enable the plant to grow and develop in a medium that is more favourable, conserving resources to be used later for shoot production and eventually increasing grain yield. Rainfall-induced soil compaction in the field affected seedling emergence and development; the root system faced greater soil penetration resistance in the control treatments compared to covered or protected treatments, with the former exhibiting lower soil pore circularity and water content. However, permanent cover of the soil surface resulted in less soil physical, root and shoot parameters such as soil porosity and water content in comparison with the partial soil surface coverage due to low soil penetration resistance and loose soil structure. Therefore, delaying the soil structure formation for a certain period until the seed had emerged and developed into a porous soil structure and then exposing the soil surface to rainfall compaction with the roots already formed into the soil structure produced the highest values for plant growth traits and yield.

Chapter 5:

The effect of crop cover on soil surface structure and subsequent crop development and yield.

This chapter foucses on the effects of soil physical parameters on the plant root and shoot development and growth, additionally, determining to what extent the root had a mutual effect on soil structure formation. The aim is to confirm the findings of the last chapter and explore the role of the presence of the roots on the formation of the soil structure and soil pore circularity, using the same four soil-coverage treatments but two types of planting system, an uncultivated soil (bare soil) and a cultivated soils (winter wheat cv. Rialto).

5.1. Abstract

Soil structure and crop development have mutual effects on each other; however, there are few previous studies that have considered this issue from the soil physics perspective. The effects of root growth on soil physical parameters such as soil total porosity, soil water content, soil mean pore size, soil pore circularity and soil penetration resistance on were quantified. To achieve this serial X-ray μ CT scan images for undisturbed soil structure samples (170mm depth and 84mm diameter) were taken and processes at key stages during the winter wheat season 2015/16 which lasted for 298 days from sowing to crop harvesting. Additionally, the environmental data were regularly collected to quantify the rainfall quantity, air and

soil temperature and explore the effects of environment on the soil structure and crop formation. There were eight experimental treatments combinations based on

four soil-cover treatment and two planting system treatment soil type (soil cultivated with winter wheat cv. Rialto or soil fallow (bare soil)) with four replicates for each treatment combination. The X-ray μ CT scans were conducted at four assessment dates distributed across the growing season, while other measurements such as soil water content, soil penetration resistance and plant height measurement were conducted routinely throughout the entire season. The objectives were to determine the effects of the presence or absence of the wheat crop on the soil structure formation and to confirm the findings of the previous experiment that early plot (plot sheltered from rainfall for first 70 days after sowing) can increase the plant root and shoot growth. The results showed that early soil coverage increased the crop yield by 31.6% compared to the standard treatment T1 (always uncovered). Delaying the soil structure formation for this period can avoid the root facing a high soil strength and save the plant energy to the shoot and grain formation. On the other hand, the results also determined the effects of the presence/absence of the wheat crop where the soil physical parameters were not significantly different over the season period for all treatments, where this can explain the soil total porosity increased values due to root penetration of the soil structure.

5.2. Introduction

Soil structure formation affects soil properties such as porosity which may constrain soil water and nutrient availability and therefore plant development and growth. Seedling emergence is concurrent with the soil structure formation after seedbed preparation and sowing. However, soil structure formation can be faster than plant

establishment potentially limiting root growth for example, through high soil strength formed by rainfall soil surface compaction.

Root formation and growth can be highly affected by the surrounding soil structure, negatively or positively depending on soil structure physical status (Passioura 1991). Therefore, delaying the soil structure formation until the root system can be distributed deeper in a less compact soil with a minimum soil strength can avoid the plant expending extra energy to overcome high soil penetration resistance produced after rainfall soil surface compaction.

This delaying of soil structure formation can be achieved by the early covering of soil surface after sowing preventing rainfall reaching the soil surface and soil surface compaction until the seedling roots have penetrated deeper while the soil structure has lower soil strength (Dexter 1991). This avoids the roots penetrating a compact surface soil layer having strong bonds between soil particle and aggregates. The soil structure can affect the seedlings emergence significantly at the crop early stages, while the crop can modify the soil structure at later stages (Dexter 1991). Aggelopoulou and Gemtos (2011) mentioned that the apple tree yield was correlated with the increasing of soil physical parameters such as soil porosity and soil pore size distribution.

Soil physical parameters such as porosity can affect the plant establishment and development at early stages, for example a soil which is too porous may have reduced soil-root contact, affecting root and shoot development (Atkinson 2008). Therefore, a soil structure that has a specific combination of soil physical parameters can provide the crop with maximum water content and nutrients consuming minimum energy. One of these parameters is the soil pore circularity (where soil

pore circularity value is nearest to 1 when the pore shape is circular and nearest to zero when the shape is irregular) which is more highly correlated with the soil water content than the soil total porosity (Chp 4).

The main objective of this experiment was to determine the effects of four plot-coverage treatments in a second season and additionally the presence or absence of a wheat crop on soil structural formation with a focus on soil porosity, soil pore circularity and soil water content measurements. The interaction between plot-coverage and planting system was also quantified. The effects of the plot-coverage treatments on root and shoot development and growth were also investigated.

5.3. Materials and Methods

5.3.1. Experimental treatment and design

The experiment used a randomised block factorial design with eight treatment combinations of four plot coverage treatments (preventing rainfall) and two planting systems (sown with winter wheat cv. Rialto and fallow (bare soil)) with four replicates. The plot-coverage treatments were based on the soil surface coverage time and duration; T1 was the control treatment which was always uncovered and exposed to the rainfall, T2 was always covered from sowing, T3 was covered for only the first 70 days after sowing and T4 was covered only from 70 days after sowing.

As in the previous chapter, the soil surface coverage was conducted by using cloches that only prevented direct rainfall. The sides of the cloches were open to ensure heat exchange with the surrounding air minimizing any heat effects inside the cloche. The temperature and radiation were measured inside and outside the cloche to

confirm that the crop and soil in the different treatments had similar temperature and radiation environments, but different rainfall and soil structure environments. The cloche dimensions were (110x50x150cm Length x Width x Height respectively). The bare soil treatment had no crop inside the cloche, although both treatments (cultivated with wheat and bare soils) had the same cloche size to ensure the same coverage effects (Table 5.1 and Figures 5.1-5.7).

Plot size was 6x1.65 m. The experiment was located at Uniersity of Nottingham farm Leicestershire UK (52.834 N, 1.243W) on a sandy loam soil type (Dunnington Heath Series). The sowing date was 08th October 2015. Previous cropping was winter oilseed rape. The field was ploughed and power harrowed before drilling.

For the winter wheat cv. Rialto crop seed rate was adjusted according to 1000 grain weight to achieve a target seed rate of 3000 seeds m-2; rows were 0.13m apart. 90 kg ha-1 nitrogen fertilizers as ammonium nitrate was applied in three-split programme. P and K fertilizers were applied to ensure that these nutrints were not limiting. Plant growth regulator was applied at GS31 to reduce the risk of lodging. Herbicides, fungicides and pesticides were applied as required to minimum effects of weeds, diseases and pets.

Meterlogical data were obtained from the local weather station of The Univeristy of Notingham-Sutton Bonington Campus.

Table 5.1 The experiment field plan and treatments in the experiment in 2015/2016.

T8R4	T2R4	T3R4	T5R4
T4R4	T6R4	T7R4	T1R4
T1R3	T3R3	T6R3	T8R3
T5R3	T7R3	T2R3	T4R3
T4R2	T3R2	T1R2	T6R2
T8R2	T7R2	T5R2	T2R2
T3R1	T5R1	T8R1	T2R1
T7R1	T1R1	T4R1	T6R1

Letter	Treatment
T1	Cultivated no cover
T2	Cultivated always covered
T3	Cultivated covered for first 70 days
T4	Cultivated covered after 70 days
T5	Bare soil no cover
T6	Bare soil always covered
T7	Bare soil covered for first 70 days
T8	Bare soil covered after 70 days
R1-R4	Replicate number



Figure 5.1 Right T7 covered bare soil for first 70 days after sowing and left T6 always covered bare soil.



Figure 5.2 Left and right for T3: covered for first 70 days after sowing



Figure 5.3 Wheat at maturity/late grain filling stage, right T2 always covered and left T3 covered for first 70 days after sowing (DAS).



Figure 5.4 Field trial photos showing on right the plant heights T1: always uncovered, on middle T4: covered after 70 days and on the left T3: covered for first 70 days sowing



Figure 5.5 Showing on right and left T5: always uncovered bare soil



Figure 5.6 Showing on right T6: always covered bare soil, in middle T8: covered after 70 DAS bare soil and on the left T7: covered for first 70 days after sowing bare soil.



Figure 5.7 Showing on right trail photo and left T2: always covered.

5.3.2. Environmental measurement

Environmental data were collected from weather station of The University of Nottingham-Sutton Bonington Campus; the hourly data were accessed online. Mean monthly average were then calculated as total rainfall, temperature, sunlight irradiance and relative humidity. The total rainfall and air and 30 cm of soil depth temperature were recorded.

5.3.3. Soil Sampling

Soil sampling was conducted as described below:-

5.3.3.1. Soil texture sampling (soil particle size analysis)

The soil texture sampling was conducted following the protocol described in chapter 3.3.3 and 4.3.3.1. Briefly 50g of loose soil was taken in bags from the field from 0-17 cm depth, three 150-300g soil samples was taken from 0-17cm depth from each plot. Secondly a mechanical analysis hydrometer reading was taken of the soil sample after calibration of the hydrometer; the soil was sieved < 2mm and dried overnight and then hydrogen peroxide 6%, sodium hexametaphosphate 5% and sodium carbonate in 1 litre of distilled water were added. Then, after shaking the soil suspension by plunger, the hydrometer readings were recorded along with the time intervals and room temperature. Finally, the percentages of sand, silt and clay were

recorded according to the time and particle diameter, before being applied to the soil textural triangle to determine the soil texture type according to the UK and North Ireland classification system (Rowell 1994, Laker and Dupreez, 1982 and Day 1965).

5.3.3.2. Soil organic matter sampling

The soil organic matter analysis procedures are as described in Chapter 4.3.3.2, three 150-250g loose soil samples was taken from 0-17cm depth from each plot. The same that conducted in the previous chapters by weighing a 50gm sieved soil sample then primary drying overnight in the oven at 105 °C to remove the moisture inside the soil. Then the soil sample was dried again in another oven for another 72 hours at 500 °C to burn the soil organic matter content inside the soil sample. Finally, after weighing the soil sample before and after each process, the weight difference was used to derive the soil organic matter weight, then this weight was calculated as a percentage of the total soil sample weight to represent the soil organic matter content percentage of that sample.

5.3.3.3. Undisturbed soil structure sampling

The undisturbed soil sampling used the same general procedure followed in previous chapters (on 15th December 2015, 15th February 2016, 15th June 2016 and 29th July 2016), by randomly choosing the soil sample location in the plot avoiding the plot edges and gently knocking a wooden block fixed on the top of the PVC pipe core (170 mm x 84 mm diam) firmly into the soil to the end of the core height. The soil core was extracted by digging, wrapped in cling film and stored at 5 °C until it scanned.

5.3.3.4. Soil moisture sampling

The soil moisture sampling based on this experiment used a theta probe soil moisture sensor model ML3, Delta-T Devices Ltd. Burwell, Camridgeshire, UK (www.delta.co.uk). This handheld soil moisture sensor provides the soil moisture content based on soil volumetric content percentage. Therefore the readings were recorded weekly for the average of three readings per plot for the whole wheat growing season.

5.3.3.5. Soil penetration resistance sampling

Soil penetration resistance was measured using the soil cone penetrometer Rimik model CP40II (Rimik, Toowamba, Queensland, Australia; http//www.rimik.com) as described in Chapter 4.3.3.5. This measure was conducted on an approximatley monthly basis depending on the instrument availability; then soil penetration readings were recorded for each plot to the maximum depth available for all experiment replicates. This was due to the field soil variation whereby the penetration rod did not reach the same depth for all treatments.

5.3.3.6. Root sampling

The root sampling for this experiment was conducted for the last soil core sampling month on 29th July 2016 where the soil core sampling targeted one plant in the middle of the core to contain the root system. The cores were wrapped in Clingfilm and stored in the cool store at 5 °C to minimise the soil microbial activity that could influence the soil structure development. This analysis was conducted only for treatments T1-T4.

5.3.4. Plant Sampling

The plant sampling was conducted only for treatments T1-T4, as below:-

5.3.4.1. Plant height

The plant height to the tip of the main shoot measured on weekly basis in three locations per plot (beginning, middle, and end of the plot) and the monthly plant height average was recorded to be analysed later.

5.3.4.2. Normalised Difference Vegetation Index (NDVI)

The Normalised Difference Vegetation Index was measured using a handheld spectroradiometer model GreenSeeker© manufactured by Trimble www.trimble.com, each experimental plot was measured by taking the average of 5 readings on 16th March, 18th April, 16th May and 16th June 2016. The measurements were taken between 10.00 and 15.00 on clear sunny days. The Normalised Difference Vegetation Index sensor was held 50 cm above the crop. Normalised Difference Vegetation Index was calculated from measurements of light reflectance in the red and near infra-red (NIR) regions of the spectrum as:

$$NDVI=(R_{900}-R_{680})/(R_{900}+R_{680}) \quad \text{Equation 1}$$

where R_{680} and R_{900} are the reflectance at 680 and 900 nm, respectively.

5.3.4.3. Crop yield and Harvest Index

The crop grain yield parameter was measured at maturity of the wheat crop on 29th July 2016; each experimental plot was harvested manually after removing the root system first (soil core sampling). The sample area was two adjacent rows each 50 cm length (=0.13m^2). The sample was weighed before and then after drying at 80 °C

for 72 hours in the oven). Then the entire plant was separated (into stem and attached leaf sheath, leaf lamina, ear, grain, and chaff) and each component weighed after drying for 48 h at 80 °C to calculate the dry weight of the plant component. The number of grains per ear and the weight of 1000 grain was recorded after drying to 48h at 80 °C. Finally, the grain yield was calculated per unit area converted to Mg/ha. The harvest index was calculated by dividing the grain DM by the above-ground DM.

5.3.5. Undisturbed soil structure X-ray µCT scanning

All the undisturbed soil core samples were X-ray µCT scanned using procedure described in Chapter 3.3.5 after being stored in the cold store on 5 °C. Each scan was taken using the X-ray CT scanner model v| tomex |M for 30 minutes for only soil structure and 45 minutes for roots at 58 µm resolution.

5.3.6. X-ray µCT scan image analysis

The same X-ray µCT image analysis procedure as described in Chapter 4.3.6 was conducted by reconstruction of the 3D soil sample image from the 3600 individual 2D images. The X-ray attenuation density of the root material was such that it could be readily classified as ‘soil space’ without it getting classified erroneously as ‘pore space’.

5.3.7. Root Segmentation

The root segmenting process used the hybrid method using RooTrak for automatic root tracking with Studio Max 3.1 software to secure the whole root selection. After reconstruction of the individual 2D image scans into a single 3D image and calibrating the image lighting, each root was automatically tracked from the top to

the bottom of the soil sample core, and the data transported to RooTrak software to estimate the accurate root volume, surface area, diameter, and length.

5.3.8. Statistical analysis

All data were tested for normality and transformed where appropriate. The data was analysed as a repeated measures ANOVA in Genstat v18.

5.4. Results

The results were classified into X-ray μ CT image scans, X-ray μ CT scans processed images and environmental, soil, root and crop parameters as below:-

5.4.1. X-ray μCT image scans

The X-ray μCT image scanned by the medium CT scanner on 58 μm resolution for 30 minutes scan duration were as shown below in Figure 5.8.

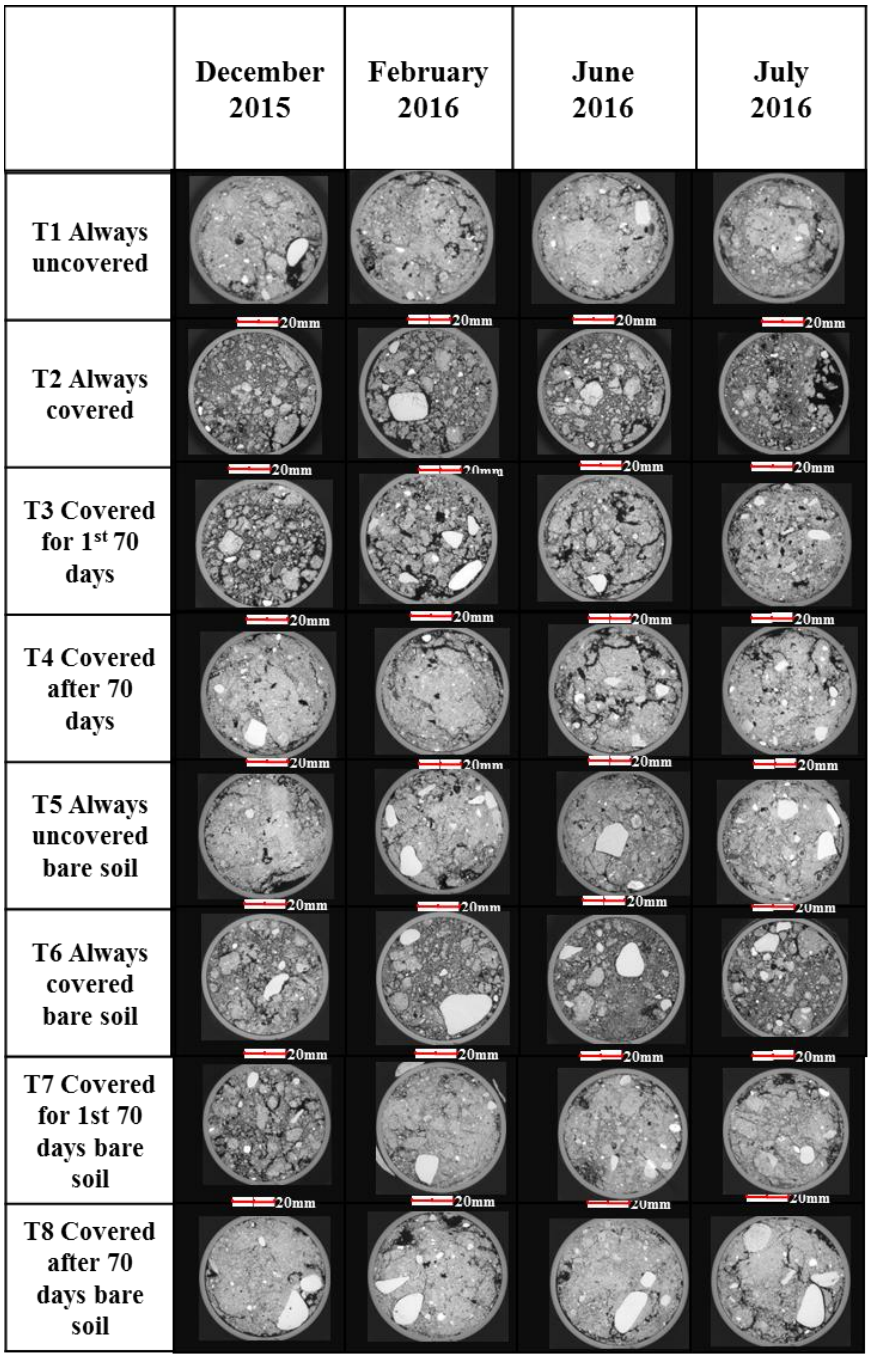


Figure 5.8 X-ray µCT scan grey scale images for the experiment, the resolution was 58 µm, and scanning duration was 30 minutes on the X-ray µCT scanner.

5.4.2. X-ray µCT scans processed images

The X-ray µCT image scans processed by Image J free software were as shown in Figure 5.9 below.

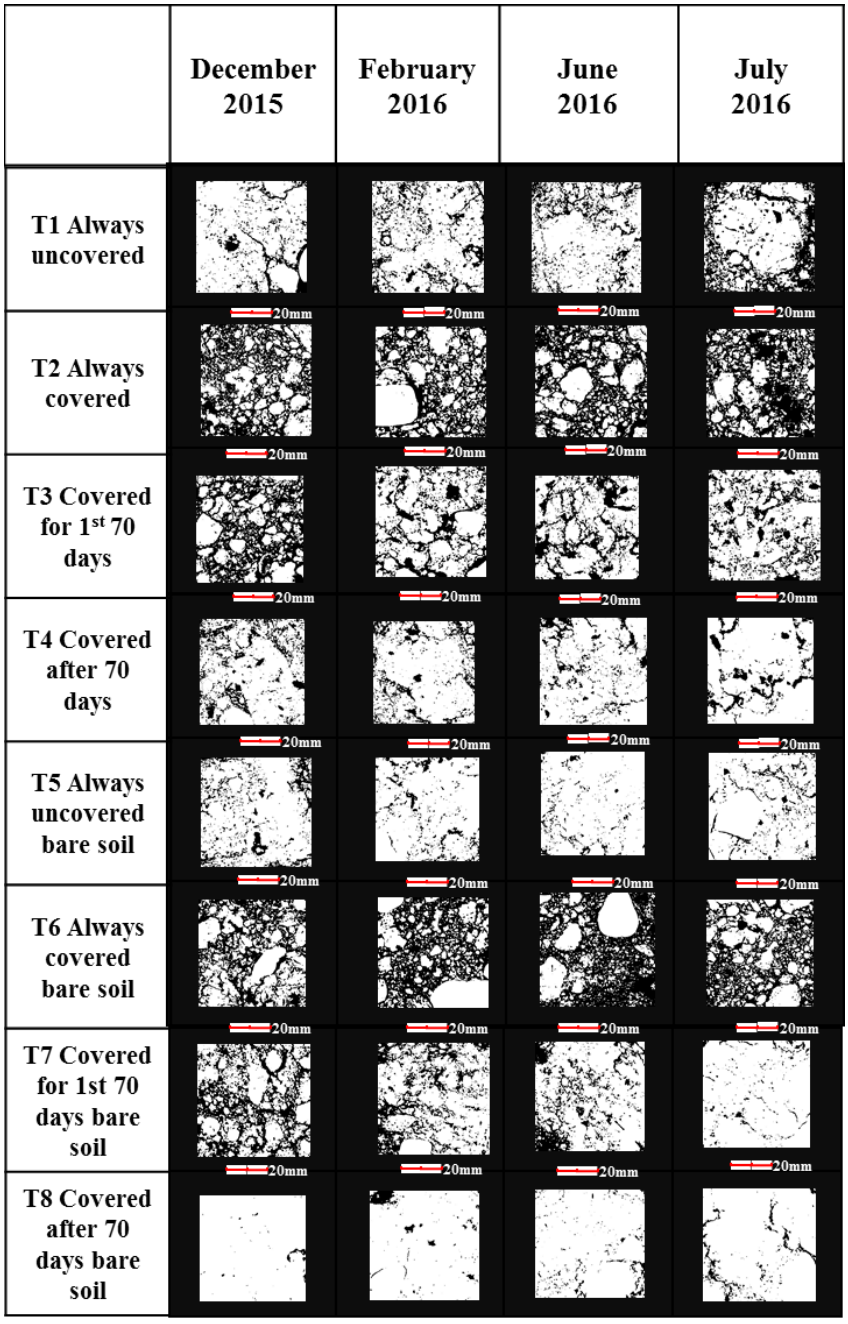


Figure 5.9 X-ray µCT scan images for the experiment after being processed by Image J software using Median filter and Li threshold algorithm to estimate the soil structure parameters.

5.4.3. Environmental Factors

5.4.3.1. Total Rainfall

The total monthly rainfall varied from 37 mm in January to 154 mm in July as shown in Figure 5.10.

5.4.3.2. Average Monthly Air and Soil Temperature °C

The monthly average temperature range was between 0.4-15 °C for the wheat season 2015/2016. While, the crop establishment period had the lowest monthly average temperature ranging 0-9 °C on November 2015, December 2015 and January 2016 as shown in Figure 5.11.

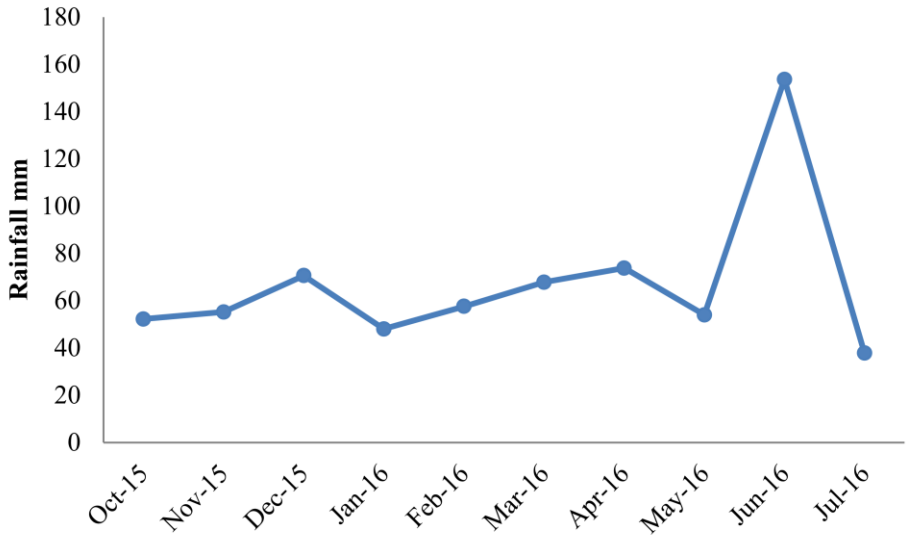


Figure 5.10 Total Rainfall mm for wheat growing season 2015/2016.

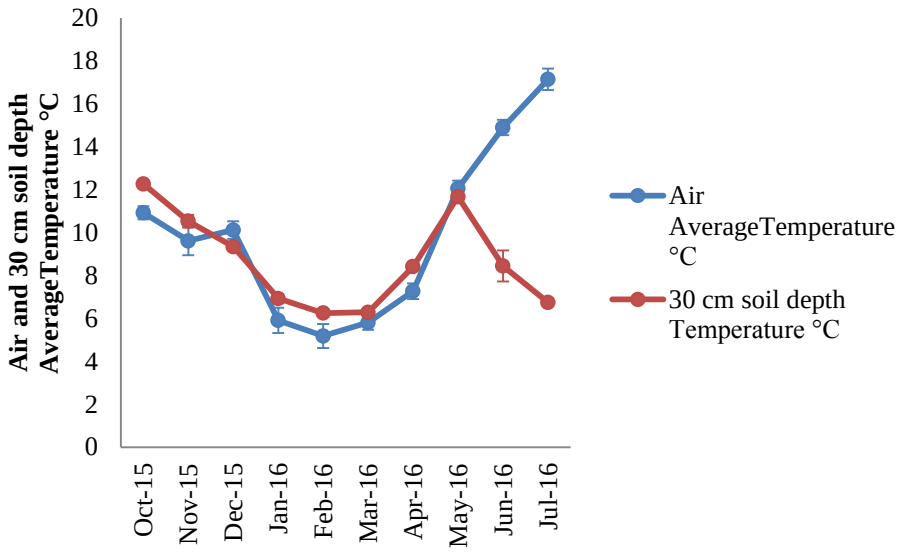


Figure 5.11 Air and Soil Average Temperature ° C for wheat growing season 2015/2016. Error bars are standard error of the mean (SEM).

5.4.4. Soil Physical Parameters

The main soil physical parameters (Soil total porosity, Mean pore size and Soil pore circularity) were measured for December 2015, and for February, June and July 2016. These samples were then scanned by the X-ray μ CT scanner.

5.4.4.1. Soil Particle Analysis

The soil particle analysis results showed that the soil of the field was Sandy Loam according to the UK and Northern Ireland soil classification.

5.4.4.2. Soil Organic Matter Content

The results showed that the soil organic matter percentage was 5.73% of the total soil content.

5.4.4.3. Soil Total Porosity

The total soil porosity was significantly different ($P<0.05$) over time where the mean values of the soil total ranged from 16-32% for the four sample events December 15, February 16, June 16 and July 16 as can be shown in figure 5.12.

Similarly, the difference between treatments was significantly different ($P<0.05$) with values ranging between 21-30% and finally, the time-treatment combinations difference was also significant ranging from16-32% as shown in figure 4.10. The main differences between swinter wheat cultivated and bare soil treatmentswas the planted treatment significantly ($P<0.05$) raised the soil porosity over time, while the other was not.

5.4.4.4. Soil Water Content

The soil water content (%) differed ($P<0.05$) over the sampling timings ranging from 10-16%. The difference between the eight treatments was also significant ($P<0.05$) ranging between 11-17%. The time-treatment combinations were also significantly different with a range of 9-24% as seen in figure 5.13. Obviously, the main differences between peer coverage treatments (winter wheat cultivated and bare soil treatments) were the first type was able significantly ($P<0.05$) to raise the soil water content % over time, while the other was not.

5.4.4.5. Soil Mean Pore Size

The mean pore size was differed ($P<0.05$) over time ranging from 160-188 mm3; among the eight treatments values were ranged 120-272 mm3 and finally time-treatment combinations ranged 116-285mm3 as shown in figure 5.14. The main differences between peer coverage treatments (winter wheat cultivated and bare soil treatments) were the first type was able significantly ($P<0.05$) to raise the soil porosity over time, while the other was not.

5.4.4.6. Soil Pore Circularity

The pore circularity was significantly different ($P<0.05$) over time with mean values ranging 0.28-0.50, between treatments with mean values between 0.28-0.58 and finally between time x treatment combinations with mean values ranging from 0.25 to 0.85 as illustrated in figure 5.15. The same difference between soil cultivation treatment types, where the winter wheat cultivated treatments (T1-T4) had raised the soil pore circularity values over time, while the bare soil treatment (T5-T8) did not have significantly different soil pore circularity values.

5.4.4.7. Mean Soil Penetration Resistance

The soil penetration resistance was different ($P<0.05$) between treatments mean values ranged from 121-272kPa (Figure 5.16). The soil penetration resistance values tend to increase in winter wheat cultivated treatments (T1-T4), while it was stable in the bare soil treatments (T5-T8).

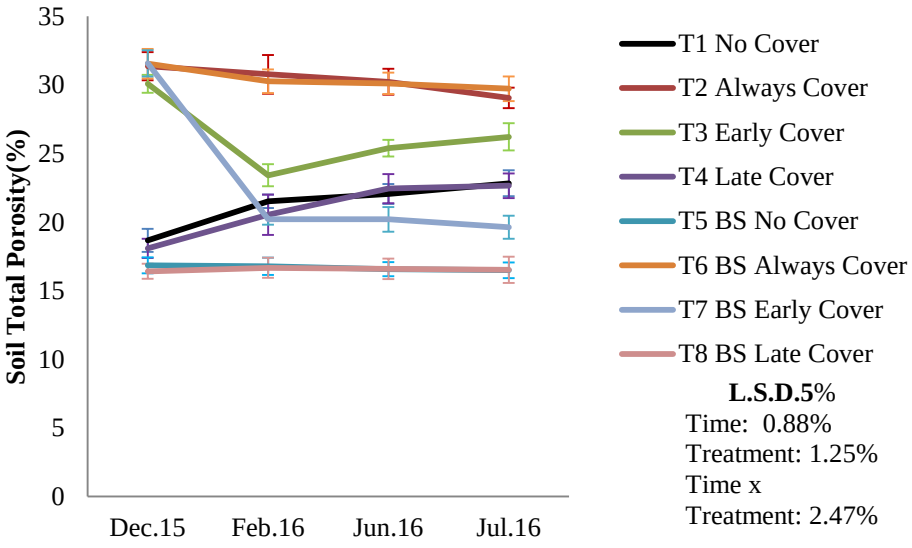


Figure 5.12 Soil total porosity percentage based on the processed X-ray µCT image scans for the winter wheat growing season 2015/2016. The error bars are Standard Error.

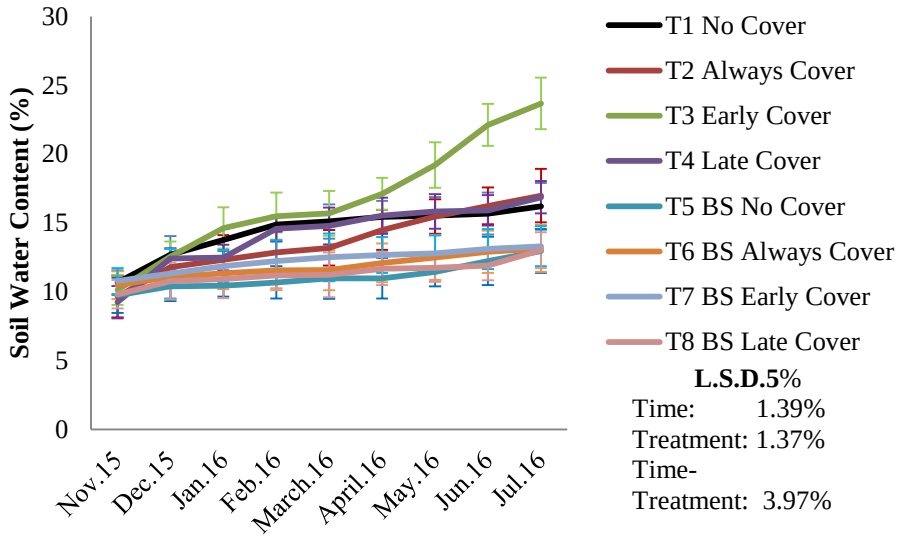


Figure 5.13 Soil water content percentages based on the processed X-ray µCT image scans for the winter wheat growing season 2015/2016. The shown bars are Standard Error.

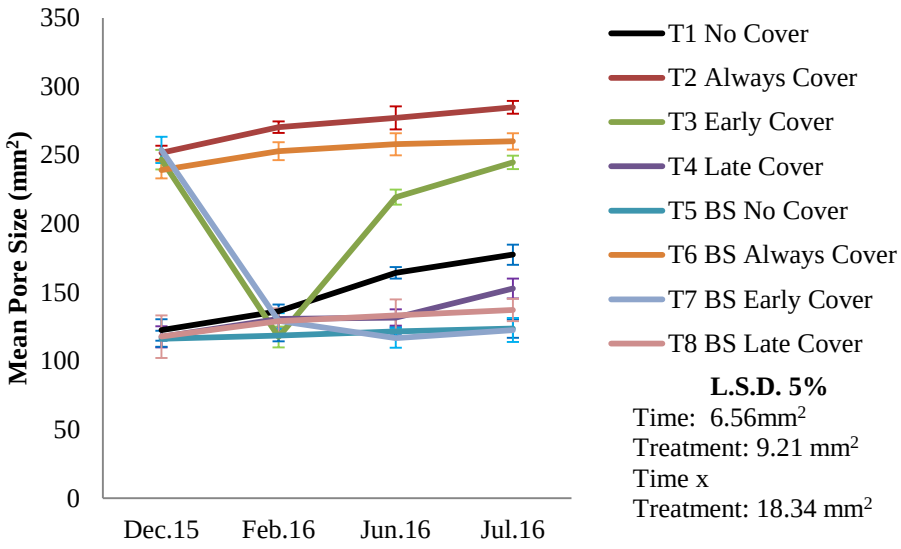


Figure 5.14 Soil mean pore size based on the processed X-ray µCT image scans for the winter wheat growing season 2015/2016. The shown bars are Standard Error.

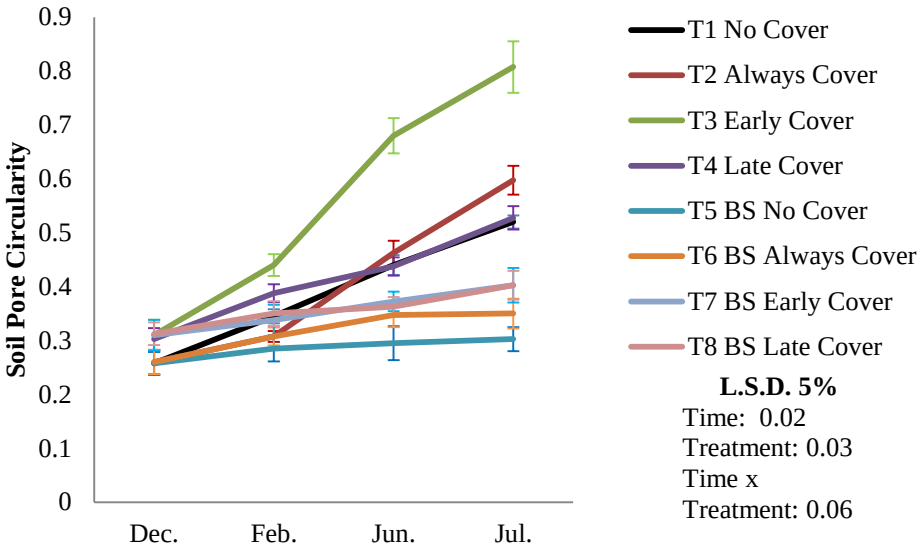


Figure 5.15 Soil pore circularity based on the processed X-ray µCT image scans for the winter wheat growing season 2015/2016. The shown bars are Standard Error.

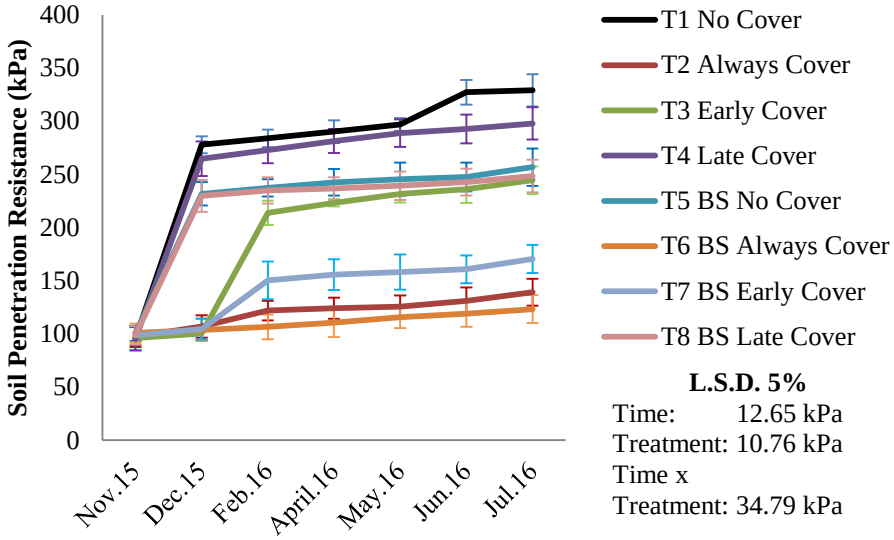


Figure 5.16 Soil penetration resistance based on soil cone penetrometer model CP40II manufactured by Rimik for the winter wheat growing season 2015/2016. The shown bars are Standard Error.

5.4.5. Plant Root Parameters

5.4.5.1. Root Volume

Root volume measured by analysis of the X-ray µCT scan images was significantly different ($P<0.05$) between the treatment ranging from 283-319 mm^3 as shown in Figures 5.17a-5.17d for root architecture and 5.17e for root volume. The treatments were also significantly different ranging from 308-379 mm^3 when root volume was measured by the WinRhizo™ root scanning technique as shown in Figure 5.17f. A clear benefit of early covering is demonstrated with the lowest values in the no cover plots.

5.4.5.2. Root Surface Area

The root surface area measured by the segmented roots from the X-ray μCT scan images was significant ($P<0.05$) between treatments with means ranging from 53-68 mm^2. Similarly, treatments diferences ($P<0.05$) ranged from 54-73 mm^2 for the WinRhizo™ measurements as shown in Figures 5.18a and 5.18b.

5.4.5.3. Root Diameter

The root diameter was different ($P < 0.05$) between treatments from the X-ray μ CT scan images and segmented by RooTrak© and VG StudioMax™ where the mean treatments values ranged from 0.38-0.56 mm as shown in figure 5.19a. The root diameter was also significantly different ($P < 0.05$) between treatments when measured by the WinRhizo technique in range the 40-61 mm as shown in figure 5.19b.

5.4.5.4. Root Length

The root length measured by X-ray μCT scan images was significantly different ($P<0.05$) between treatments ranging from 149-175 mm as shown in figure 5.20a. Root length also differed between treatments ($P<0.05$) when measured by the WinRhizo technique in the range 156-177 mm as illustrated in figure 5.20b.

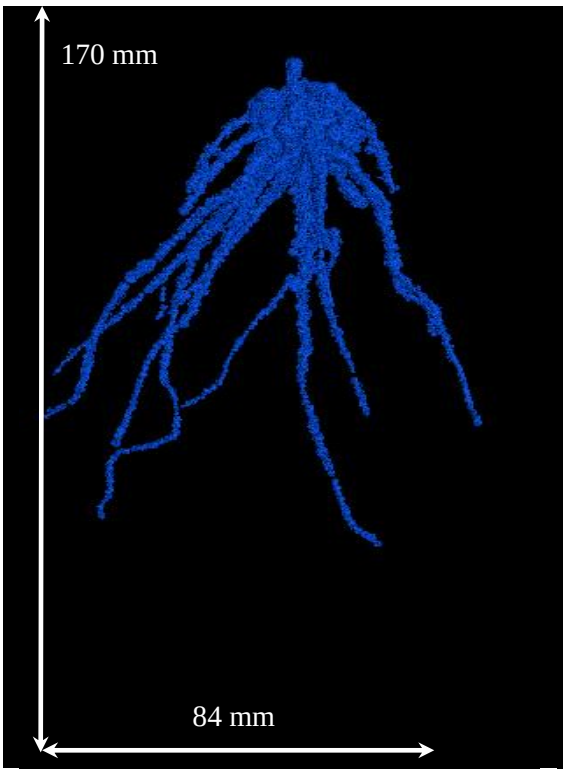


Figure 5.17a Segmented root architecture for T1treatment (always uncovered)

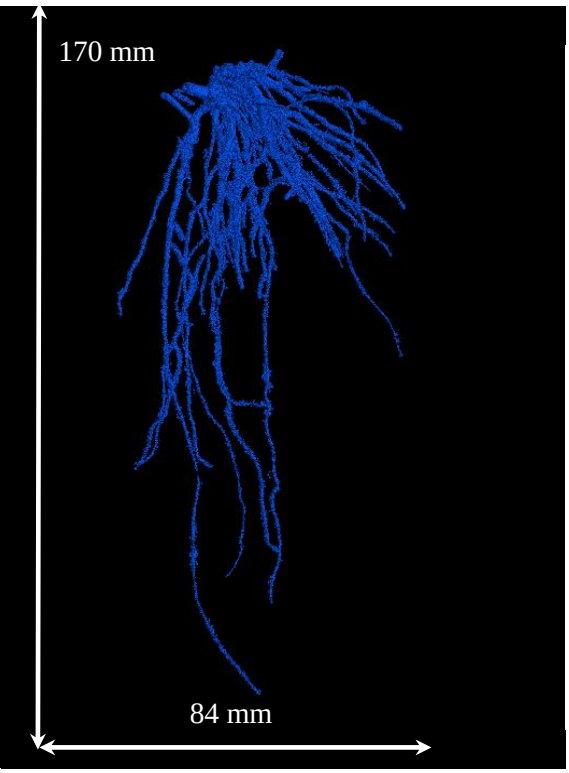


Figure 5.17b Segmented root architecture for T2 treatment(always covered)

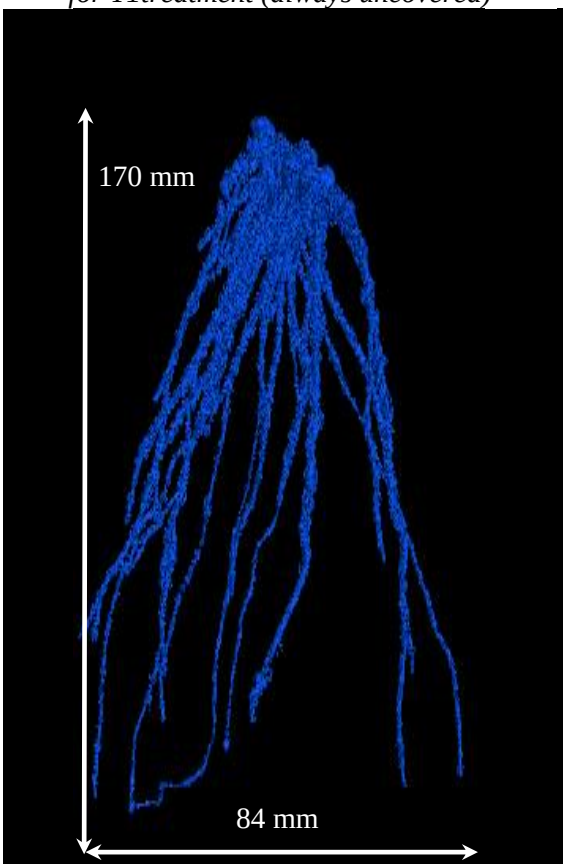


Figure 5.17c Segmented root architecture for T3 treatment(covered for 70 days)

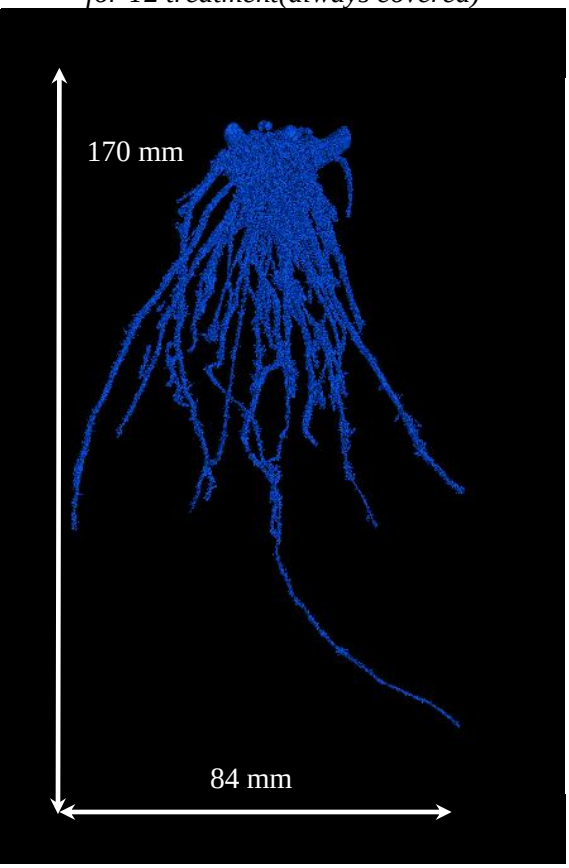


Figure 5.17d Segmented root architecture for T4 treatment(covered after 70 days)

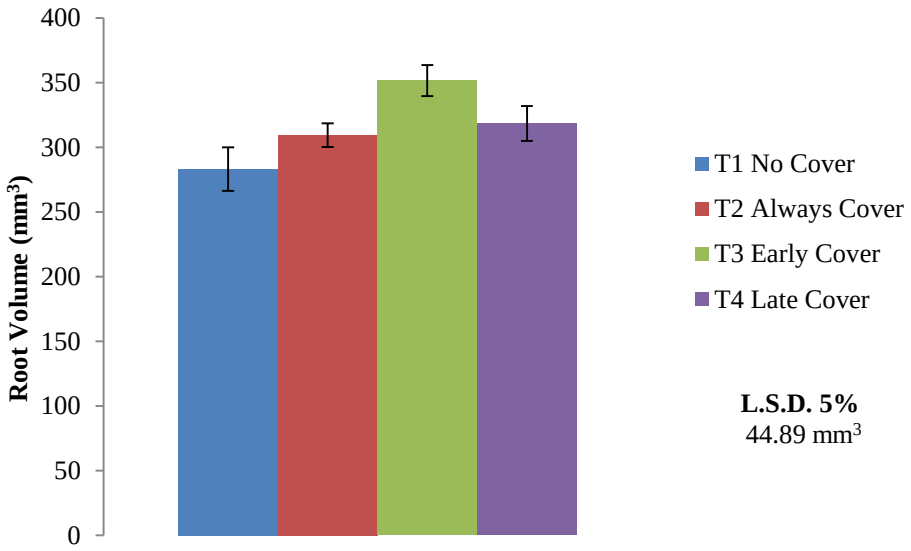


Figure 5.17e Root volume calculated from the segmented roots using RooTrak of the X-ray µCT image scans for the winter wheat growing season 2015/2016. The bars are Standard Errors.

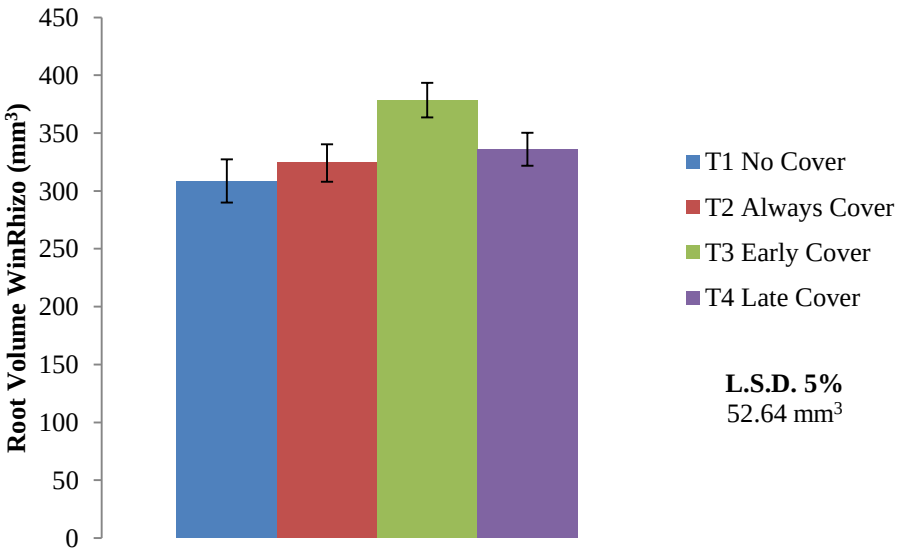


Figure 5.17f Root volume calculated from the scanned washed roots using WinRhizo™ technique for the winter wheat growing season 2015/2016. The bars are Standard Errors.

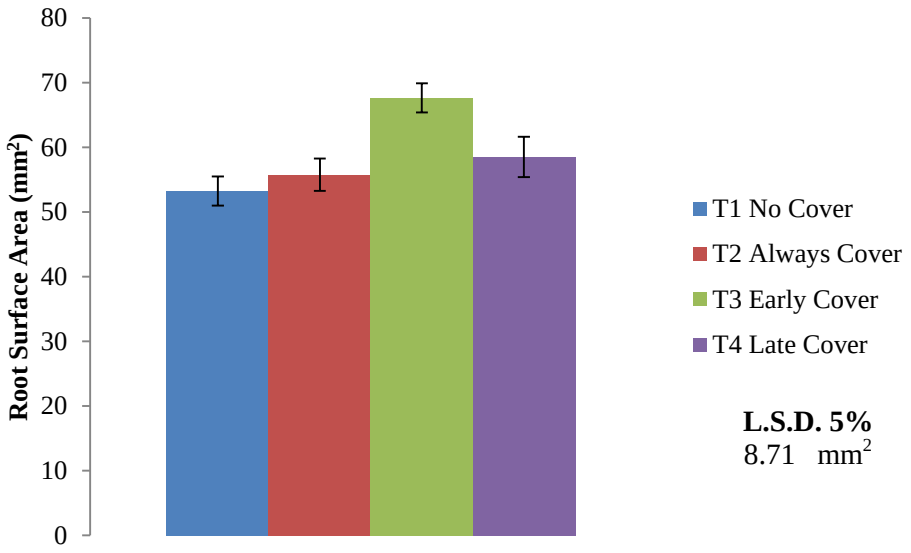


Figure 5.18a Root surface area calculated from the segmented roots using RooTrak© of the X-ray µCT image scans for the winter wheat growing season 2015/2016. The error bars are Standard Errors.

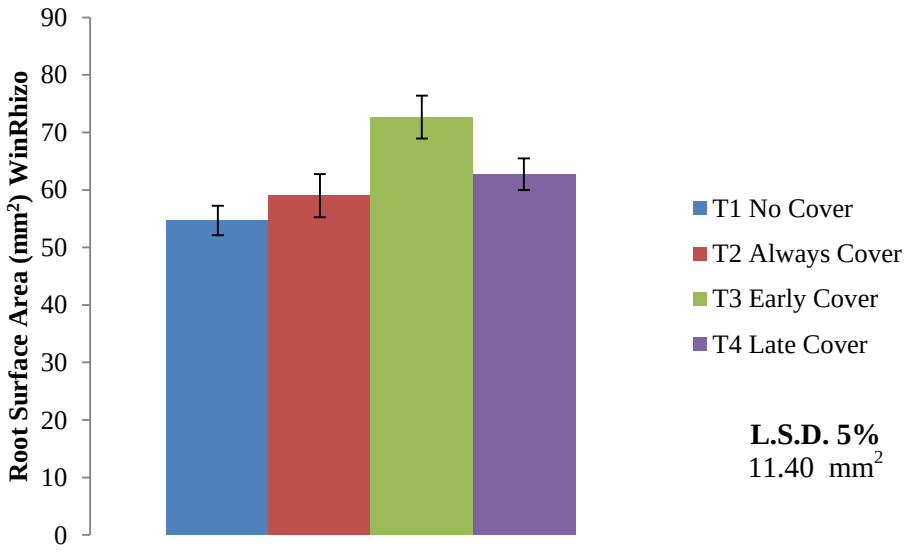


Figure 5.18b Root surface area calculated from the scanned washed roots using WinRhizo™ technique for the winter wheat growing season 2015/2016. The error bars are Standard Error.

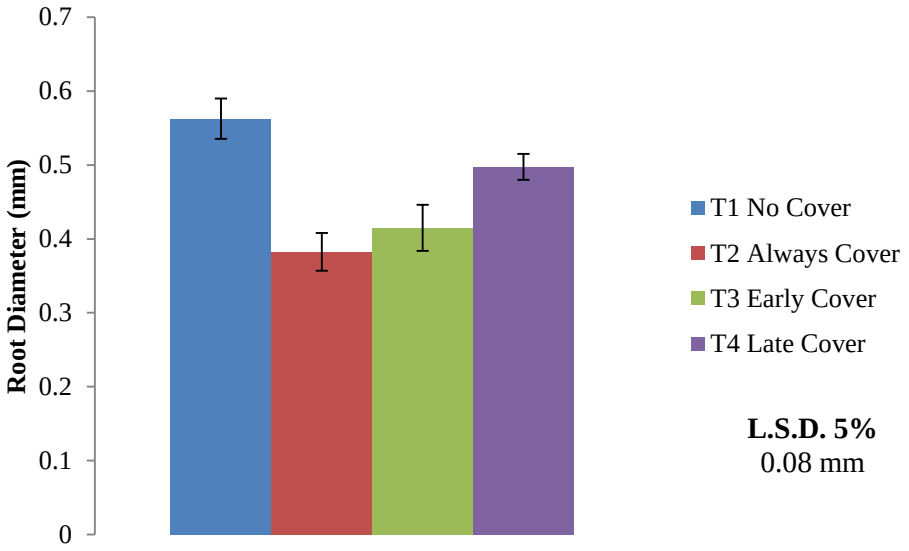


Figure 5.19a Root diameter calculated from the segmented roots using RooTrak of the X-ray µCT image scans for the winter wheat growing season 2015/2016. The error bars are Standard Errors.

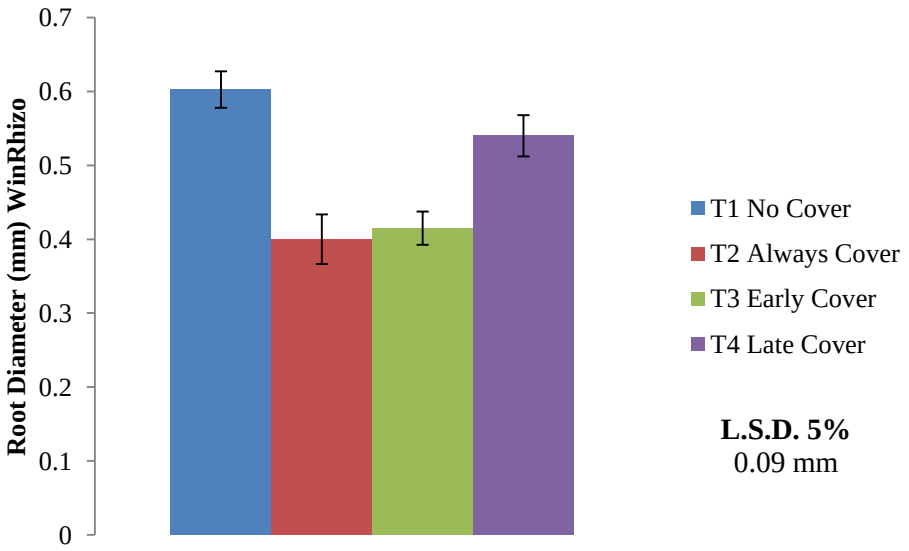


Figure 5.19b Root diameter calculated from the scanned washed roots using WinRhizo™ technique for the winter wheat growing season 2015/2016. The error bars are Standard Errors.

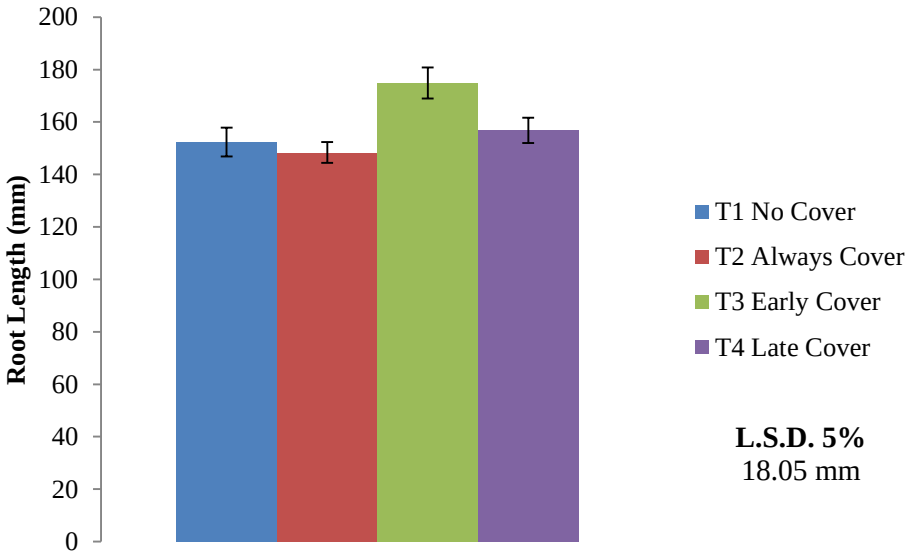


Figure 5.20a Root length calculated from the segmented roots using RooTrak of the X-ray µCT image scans for the winter wheat growing season 2015/2016. The error bars are Standard Errors.

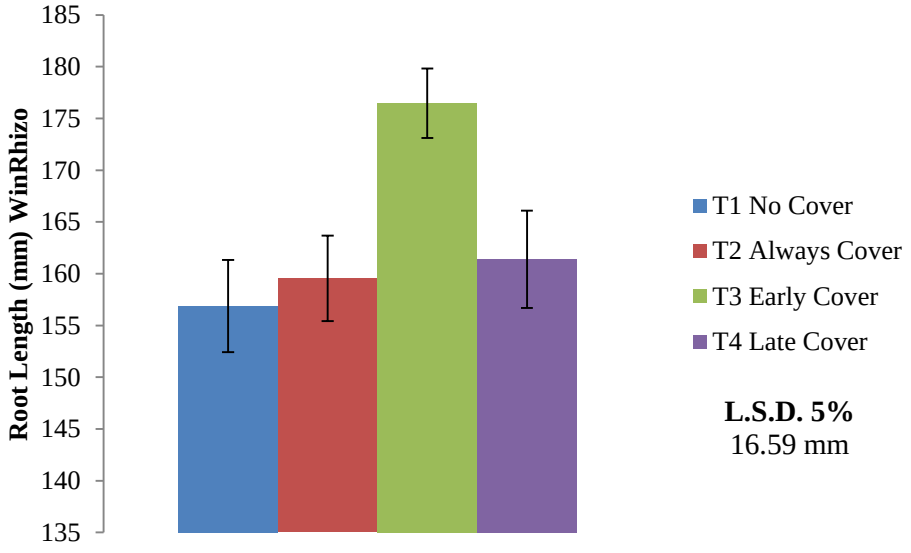


Figure 5.20b Root length calculated from the scanned washed roots using WinRhizo™ technique for the winter wheat growing season 2015/2016. The error bars are Standard Errors.

5.4.6. Crop Parameters

These parameters were only measured for treatments with winter wheat cultivated soil (T1-T4).

5.4.6.1. Plant Height

The plant height was increased ($P<0.05$) over time in the 6-101 cm, and different ($P<0.05$) between treatments (mean values ranging from 46-55cm) and also differed ($P<0.05$) in the time x treatment combinations (mean values ranging from 5-112 cm) as shown in figure 5.21.

5.4.6.2. Plant Normalised Difference Vegetation Index

The results showed that the Plant Normalised Difference Vegetation Index changed over time ($P<0.05$) with mean values ranged from 0.64-0.73, and also differed between treatments with mean values ranging from 0.63-0.77 and between time-treatment combinations where the mean values ranged from 0.59-0.81 as shown in figure 5.22.

5.4.6.3. Crop Yield

This parameter was measured only for the grain yield differed ($P<0.05$) between the treatments in rang 5.42-7.19 Mg/ha as shown in figure 5.23. The highest yield was recorded for T3 covered for 70 DAS, while the lowest was for T4 covered after 70 DAS.

5.4.6.4. Harvest Index

The harvest index also significantly differed ($P<0.05$) between treatments in the range 0.48-0.56 as shown in figure 5.24.

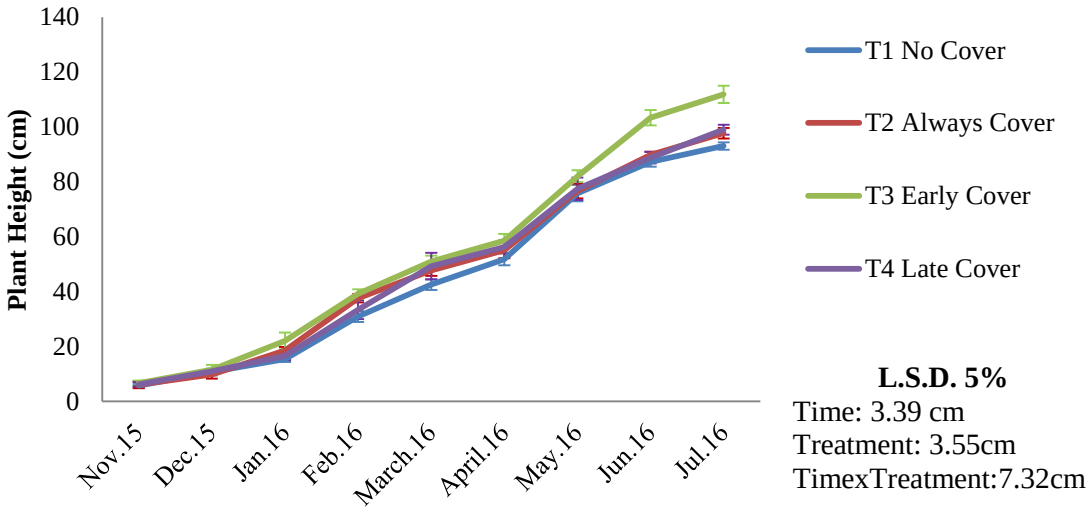


Figure 5.21 Plant height for the winter wheat in 2015/2016. The error bars are Standard Errors.

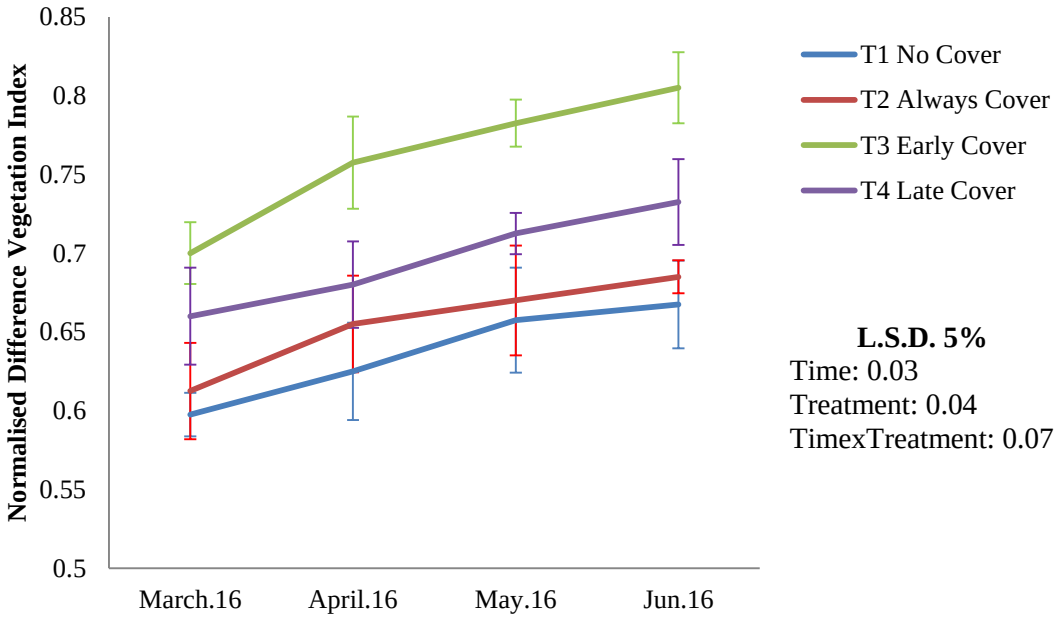


Figure 5.22 Normalised Difference Vegetation Index calculated by using hand held GreenSeeker© for the winter wheat growing season 2015/2016. The error bars are Standard Errors.

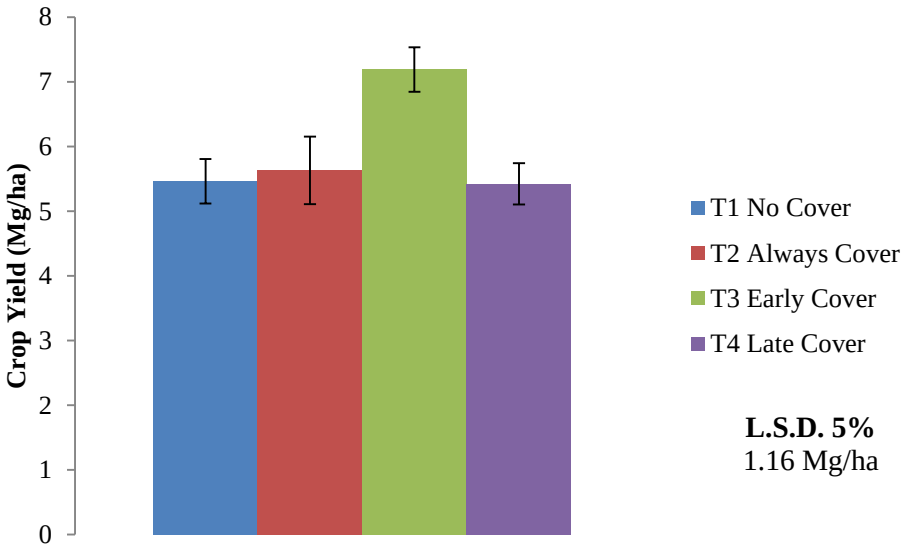


Figure 5.23 Crop grain yield (100% DM) for the winter wheat 2015/2016. The shown bars are Standard Error.

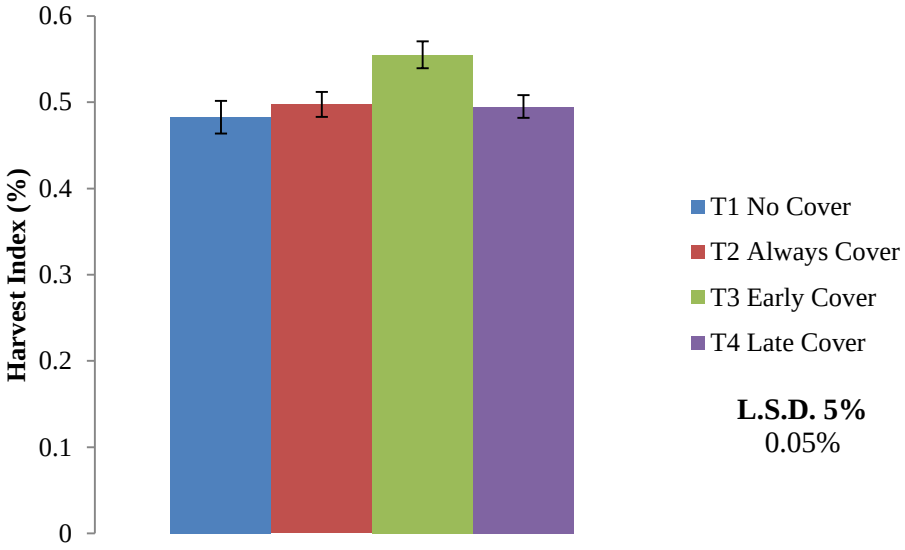


Figure 5.24 Harvest index calculated by manual harvesting for the winter wheat growing season 2015/2016. The error bars are Standard Errors.

5.4.7. Correlations between Plant and Soil Parameters

Several of the soil, root and shoot parameters had correlations between each other. Firstly, soil total porosity percentage positively correlated with the followings; soil pore circularity (r=0.38, P<0.05), root volume (r=0.07, P<0.05), plant height (r=0.17, P<0.05), crop yield (r=0.37, P<0.05) and negatively with soil penetration resistance (r=0.75, P<0.05) as can be shown in figures 5.25a-5.25b.

Soil water content percentage was correlated amongst the eight positively with soil pore circularity (r=67, P<0.05), soil total porosity (r=0.16, P<0.05), plant height (r=0.69, P<0.05), NDVI (r=0.52, P<0.05), harvest index (r=0.75, P<0.05) and negatively with soil penetration resistance (r=0.13, P<0.05) as can be shown in figures 526a-5.26f. Additionally, mean pore size was correlated positively with the soil pore circularity (r=0.48), root volume (r=0.27, P<0.05), plant height (r=0.26, P<0.05), harvest index (r=0.25, P<0.05) and highly negative with the soil penetration resistance (r=0.89, P<0.05) as illustrated in figures 5.27a-5.27e.

The soil pore circularity was correlated positively with root volume (r=0.58), plant height (r=0.89, P<0.05), NDVI (r=0.65, P<0.05), crop yield (r=0.70, P<0.05), harvest index (r=0.68, P<0.05) and negatively with the soil penetration resistance (r=0.25, P<0.05) as shown in figure 5.28a-5.28e. Finally, soil penetration resistance was also negatively correlated with root volume (r=0.15, P<0.05), plant height (r=0.15, P<0.05), crop yield (r=0.07, P<0.05), harvest index (r=0.12, P<0.05) and exceptionally positive correlation with root diameter (r=0.72, P<0.05) as can be shown in figures 5.29a-5.29e.

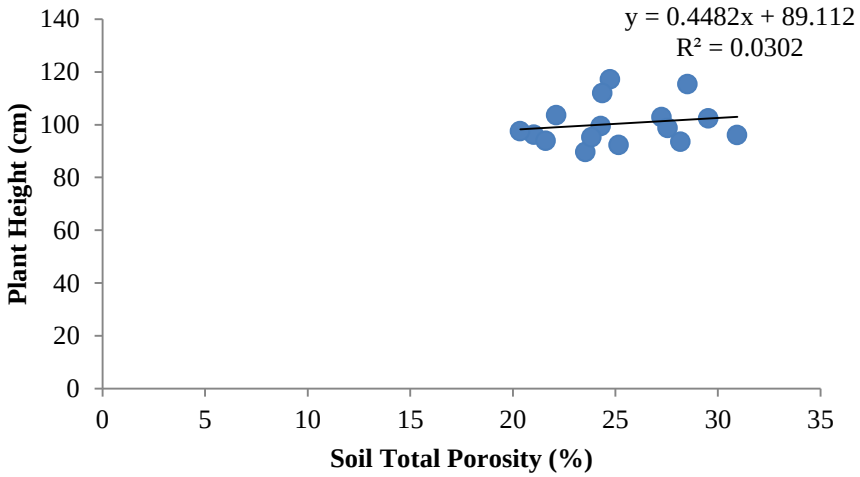


Figure 5.25a Linear regression between Soil total porosity % and Root Volume mm³. P<0.05, df=30.

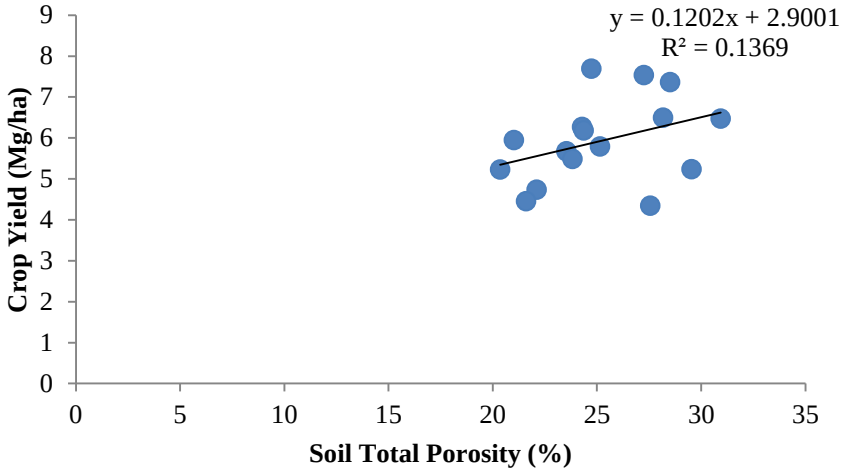


Figure 5.25b Linear regression between Soil total porosity % and Crop Yield Mg/ha. P<0.01, df=30.

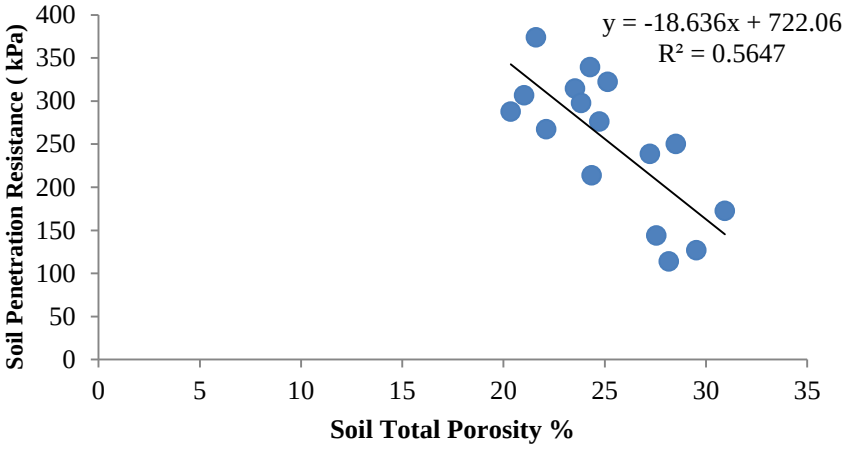


Figure 5.25c Linear regression between Soil total porosity % and Soil Penetration Resistance kPa. P<0.01, df=30.

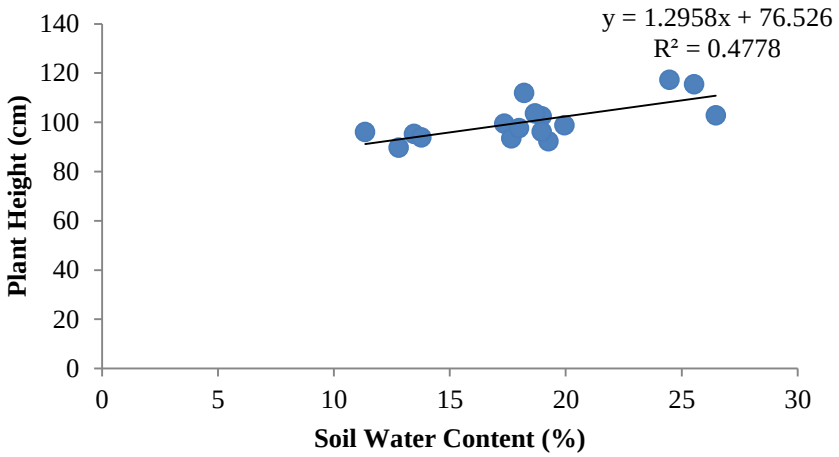


Figure 5.26aLinear regression between Soil water content % and Plant height cm. P<0.01, df=30.

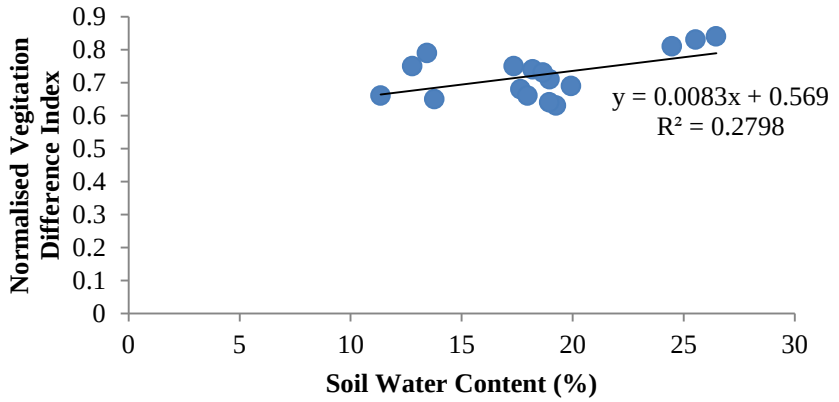


Figure 5.26b Linear regression between Soil water content % and Normalised Difference Vegetation Index. P<0.05, df=30.

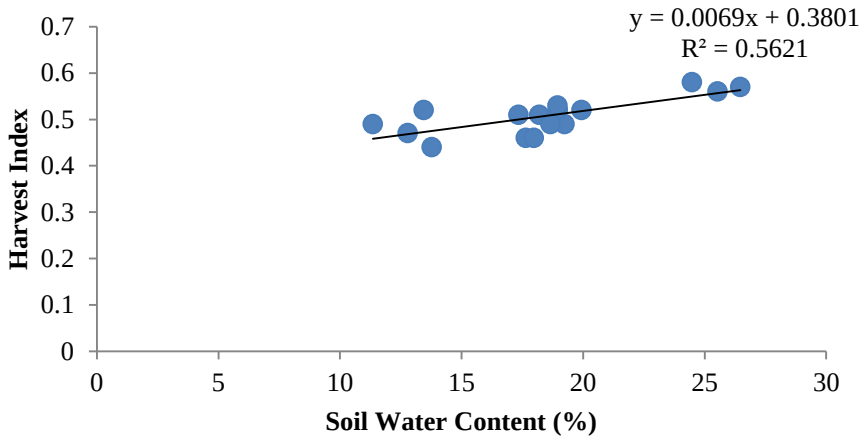


Figure 5.26c Linear regression between Soil water content % and Harvest Index. P<0.01, df=30.

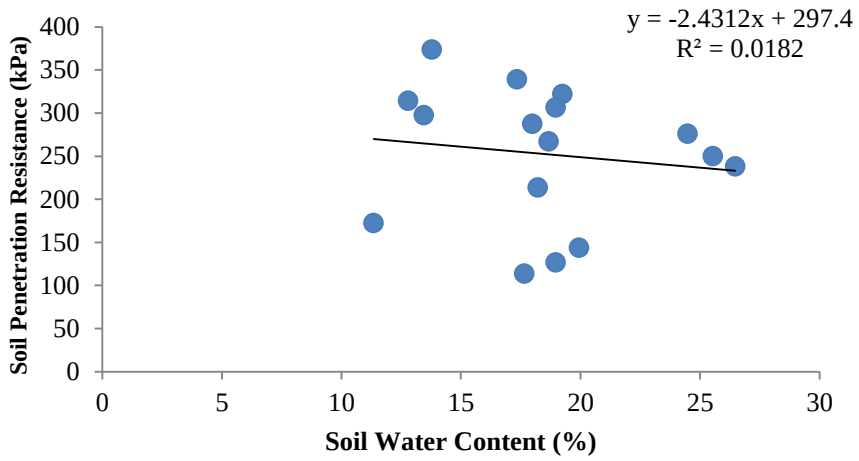


Figure 5.26d Linear regression between Soil water content % and Soil Penetration Resistance kPa. P<0.05, df=30.

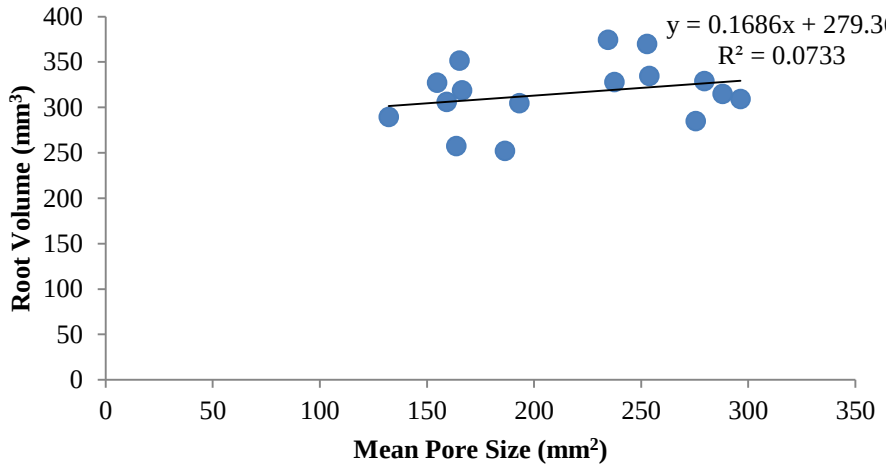


Figure 5.27 Linear regression between Soil mean pore size mm^2 and Root volume mm^3. P<0.05, df=30.

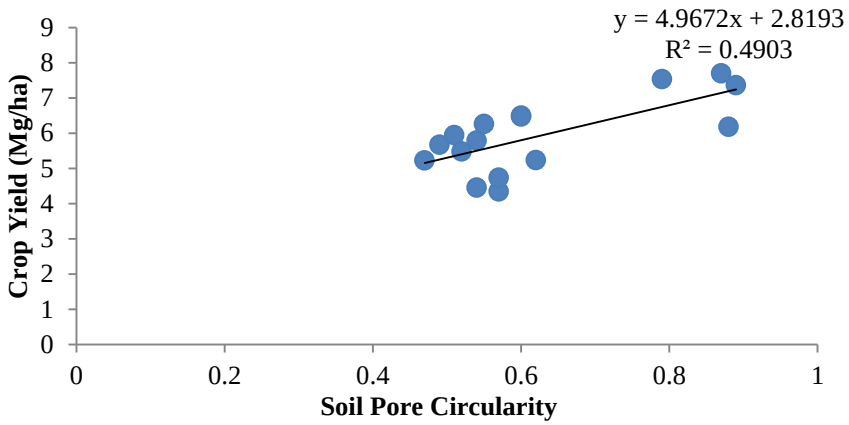


Figure 5.28a Linear regression between Soil pore circularity and Crop yield Mg/ha. P<0.01, df=30.

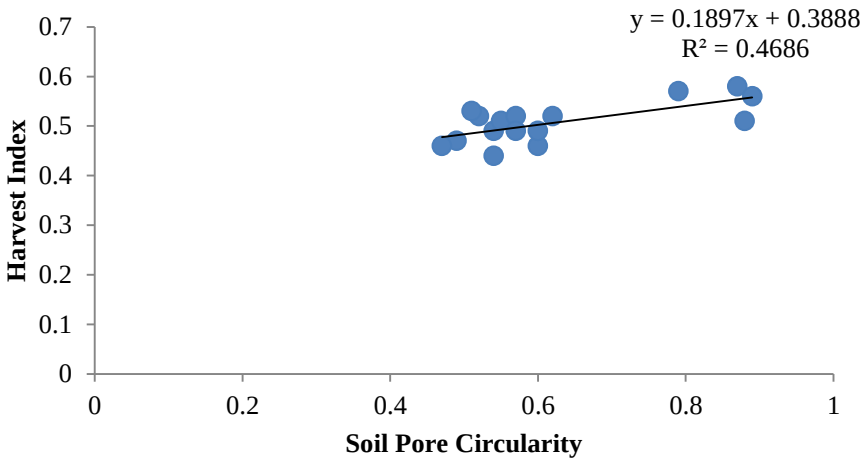


Figure 5.28b Linear regression between Soil pore circularity and Harvest index. P<0.05, df=30.

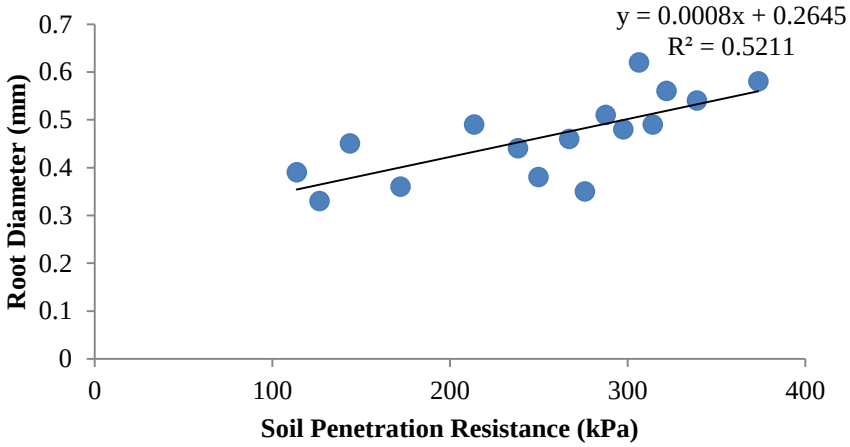


Figure 5.29 Linear regression between Soil penetration resistance kPa and root diameter mm. P<0.01, df=30.

5.5. Discussion

5.5.1. Effects of soil surface cover on soil structure and crop establishment and development

Early cover of the soil surface(treatment T3) produced a greater soil porosity, pore size and pore circularity than the other treatments; this soil physical enhancement enabled the soil structure to hold more water in comparison with the rest of the treatments as illustrated in table 4.4. Moreover, the root penetration process in this treatment likely required less energy because the early soil surface coverage led to the delaying of rainfall surface compaction until the root had penetrated the soft soil in the upper few centimetres within the first seventy days of plant growth. Therefore, the soil structure was weathered after the roots had already penetrated and distributed in; the coverage period was for the first 70 days which represent almost the first quarter of the growing season (72 of 289 days). However, the effect of a shorter period of coverage, which might be more practical from a farming perspective was not assessed here. Astonishingly this early plot coverage was significant enough to increase the crop yield by 31.6% in T3 in comparison with the standard treatment (T1) due to improved soil structure which supported greater plant root and shoot development as can be shown in table 4.4. This is an enormous yield difference linked directly to soil structure like of which has not been previously reported in the literature. Direct comparison with previous work i.e. the effect of soil

structure versus yield is limited in the literature. Mangalassery et al. (2015) compared the yield from tilled and untilled soils and found that for over 100 studies there was no significant advantage for either management on yield despite them developing very different soil structures. The data from 2016 also confirms the finding from 2014 (Chapter 4). Although, the previous yield in (chapter 4) for T3 treatment was 6.2 Mg/ha, lower than in 2016, this can be linked to the different weather conditions and coverage periods between the two experiments, where extra days of cover may have allowed the plant to establish better leading to higher crop yield and harvest index.

Soil pore shape can be an important factor influencing the soil water content, and this conclusion was supported by the high positive correlation between the soil pore circularity and soil water content (r=0.67). Here it was shown that a higher soil water content lead to greater plant shoot and root parameters. Soil pore circularity was also positively correlated with root volume (r=58), plant height (r=89), NDVI (r=0.65), crop yield (r=0.70) and harvest index (r=0.68). This is because roots penetrate in a less compacted soil and the plant can divert energy to extracting water and nutrient from the soil

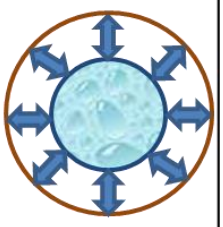
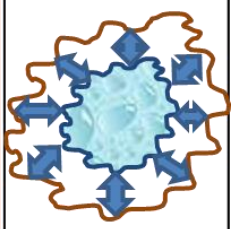
Conversely, the soil penetration resistance was negatively correlated with soil total porosity (r=0.75), soil pore circularity (r=0.25), root volume (r=0.15), harvest index (r=0.12) and exceptionally highly positive correlated with root diameter (r=0.72).

In the case of the standard treatment T1 (always uncovered) the root system had to overcome a higher soil penetration resistance to form the root architecture through the soil structure, where the root system would need to develop thicker roots with greater diameter to overcome the soil strength. This is due to the weathering and subsequent slumping of the soil that was observed in the field less than seven days after drilling. The above-ground plant system was potentially affected by this process in TI due to greater investment in root development and growth, especially in the field couple of weeks at the expense of the shoot and grain formation compared to T3 treatment. A question that remains is why does covering the soil surface impact of significantly on yield. Whilst different time scales of cover were not considered in this work, visual observation suggest that the biggest changes occur on the soil surface during the first few weeks of exposure to the prevailing weather conditions. This is a crucial stage in plant development as it coincides with both germination and establishment. The aim of tillage is to provide an environment conducive to seed germination which is a mixture of access to air and water via contact with the soil (Blunk et al. 2017). It is likely that the subsequent weathering of the soil surface creates as sub-optimal environment for germination and that the effect of the cover is to preserve the 'idealised' pore structure created by tillage. A further possibility is that the weathering process initiates the formation of a seal/crust on the soil surface or at the least a reduction of the pores connected at the

soil surface. This could limit water infiltration and gaseous diffusion both of which could impact on growth and potentially yield.

Crop establishment and development is highly affected by the soil seedbed porosity status (Atkinson et al. 2008). Soil structures with low porosity and water content can stimulate the plant rooting system to produce a hydraulic signal to the shoot to overcome the high strength soil, resulting in a plant with less shoot and root volume (Amato and Ritchie 2002). Conversely Atkinson et al. (2008) also showed that soils where the porosity is too high can infer a negative impact on plant growth most likely due to reduced anchorage.

Table 5.2 Comparison between T1: always uncovered (the standard treatment) and T3: covered for first seventy days after sowing in soil physical parameters.

Parameter	Treatment	Value	Root system	Pore Circularity
Soil pore circularity	T1	0.52	T3: Early coverage for 1st 70 days	
	T3	0.80		
Soil Water Content %	T1	16.19		
	T3	23.67		
Soil penetration resistance kPa	T1	330		
	T3	245		
Root Volume mm^3	T1	284		
	T3	352		
Root Diameter mm	T1	0.56	T1: No coverage standard treatment	
	T3	0.41		
Plant Height cm	T1	94		
	T3	112		
Crop Yield Mg/ha	T1	5.5		
	T3	7.2		
Harvest Index	T1	0.48		
	T3	0.55		

5.5.2. Exploring the role of plant presence on soil structure formation

Soil structure formation is influenced by physical, chemical and biological factors to form the final soil structure type. This research aimed to explore the effects of the plant presence on the soil structure formation and to what extent can the root system enhances the soil structural properties over time.

This this chapter the same plot-coverage treatments from 2014 were repeated but this time with bare soil (in 2016), this was important to quantify the effects of the presence of a existence on the soil structure formation and development for the entire season. The results clearly showed that the positive effect of the root systems of soil structure. . For example, in T5 (always uncovered bare soil) the total porosity ranged from 16.4-16.8% between December 2015 to July 2016, while the soil total porosity in the same coverage type (always uncovered) but with wheat cultivation (T1) ranged from 18.6-22.8%. This soil total porosity difference at the end of the crop cycle in July 2016 coupled with the yield advantage suggested the activity of the plant's roots and shoots in overcoming the rainfall soil surface compaction. Similarly, the soil pore circularity was affected by the existence of the root system whereby this parameter was correlated with soil water content (r=0.67), mean pore size (r=0.48), root volume (r=0.58) and plant height (r=0.89). Whilst in the example of T5 there is not a clear reduction in porosity associated with weathering, a clear increase in porosity is observed for the comparable treatment but with wheat planted. The benefits of increased porosity for the plant during the grow stage included increased access to water and potential nutrients, plus enhanced soil aeration conditions.

Table 5.3 Soil physical parameters comparison between cultivated and bare soil treatments for the same soil surface coverage type measured X-ray CT scans for July 2016.

Treatments		Soil Physical Parameters July 2016			
		Soil Pore Circularity	Soil Water Content %	Soil Total Porosity %	Soil Penetration Resistance kPa
Always uncovered	T1: Cultivated	0.52	16.1	22.8	329
	T5: Bare soil	0.31	12.9	16.4	256
Always covered	T2: Cultivated	0.59	16.9	29.0	140
	T6: Bare soil	0.35	13.1	19.4	123
Covered for1st 70DAS	T3: Cultivated	0.81	23.6	26.2	245
	T7: Bare soil	0.39	13.3	17.7	171
Covered after 1st 70DAS	T4: Cultivated	0.53	16.8	22.6	289
	T8: Bare soil	0.40	12.7	16.5	248

DAS= Days after sowing

Soil structure formation is clearly influenced by the existence of the plant root systems as compared to bare soil, and these effects can be noticed in the above soil physical parameters in table 4.5 above. The pore circularity values were higher in the soil cultivated treatments (T1-T4) than the bare soil treatments (T5-T8) for the same soil surface coverage. Therefore, the presence of the root system in the soil can lead to greater soil porosity and water content to hold more water and provide the crop with more water to produce a greater yield. In general the treatments with the planted crop had higher soil penetration resistance values than the ones with bare soil even for the same soil surface coverage type, probably due to the interaction of

the penetrometer with root system inside the soil which lead to higher soil penetration resistance values. In addition to the coverage of the surface providing a yield advantage it would appear from these data that early coverage is preferable over later coverage and that the length of time (i.e. longer) can also have beneficial effects though appropriate time intervals were not assessed in this work to draw solid conclusions.

As these data reveal the significant yield advantage that can be conferred for wheat by covering the soil surface, especially during the germination and establishment, a key question is how might farmers utilise this information? Clearly covering the soil surface as undertaken in this research would not be appropriate for most farming systems due to the scale of operations, though it is worth noting that for smaller scale horticultural enterprises as similar approach may be possible. Thus in reality farmers will need to seek a lower cost alternative. Many conservation agriculture approaches already adopt a similar procedure through the application of crop residues to the soil surface (Mangalassery et al. 2014) which is a low cost option. An alternative option is the plasticulture systems (Espi et al. 2006) that have gained in popularity especially for crops with a high value or where the impact of frost is particularly damaging. The consideration of options for soil surface cover has financial implications for the farmer as well as potential logistical issues associated with installation, and possibly soil health issues is soil surface temperature is increased to levels that enhance disease build-up. However, given the enormous yield advantage reported here, it is quite likely that most cover systems could still be beneficial and economical, though it is likely to be climate and crop dependent. Future research should explore the environmental, economic and logistical

implications of soil surface cover as a means to significant improve soil structure, crop growth and yield.

5.6. Conclusions

Soil structure formation can be affected by the rainfall induced surface compaction, and that can influence the crop establishment and development. Partial coverage of the soil surface during the establishment phase can delay soil structure formation induced by the rainfall allowing the root distribution to grow into a softer soil thus consuming less plant energy. When the soil structure is then exposed to rainfall after seventy days there is a better establishment due to increases in the root-soil contact area.

The presence of the root system in the soil appeared to affect soil physical parameters such as total porosity, water content, mean pore size, soil penetration resistance and soil pore circularity. The higher soil pore circularity in the soils cultivated with wheat than bare soils led to greater soil water content by holding the soil water with a more equally distributed force allowing more water and nutrients to be taken up by the crop.

Exposing the soil surface to rainfall compaction can produce soil structure with greater soil penetration resistance so the crop rooting system will need to overcome the high soil strength. That can affect the root and shoot activity and resulted in reduced harvest-index and crop yield. Therefore, the soil structure with greater soil pore circularity, rather than soil porosity can increase soil water content for crop uptake. In summary, the early cultivated soil surface coverage treatment T3 achieved

the greatest root penetration and distribution which resulted in the highest harvest index and grain yield of the eight treatments.

Chapter 6:

General conclusions and future work

6.1. Interactions between soil structure characteristics

1. The soil particle size analysis does not express alone the variation in soil physical characterises. Soils with the same soil texture classification can have different soil structures depending on the environmental factors and soil cultivation history. This subsequently has a profound effect on early stage root growth due to the established network of macropores.
2. The soil water content is correlated with the soil pore circularity; with the more soil circular shaped pores linked to a higher water content while soils with less soil pore circularity values had lower soil water contents.

6.2. The soil pore circularity impact on soil structure and plant development

1. Soil water content and mean pore size were positively correlated to the soil pore circularity, where the more circular pore shapes was linked to higher water contents.
2. The early soil surface coverage protected the soil allowing the soil structure to develop and promote plant growth. Exposure to rainfall led to a reduced soil porosity and higher soil penetration resistance which impacted negatively on plant growth.

6.3. Effects of environmental factors on soil structure and plant development

1. Soil structure strongly affects the seedling activity and the plant's root and shoots development. The seedbed porosity can determine the development rate of root activity as either prioritising penetrating soil structure in the case of compacted soil that have high soil strength, or prioritising the nutrients absorption and then the soil structure penetration when soil have a suitable soil strength and the roots can penetrate the soil structure moderately. That can affect the plant shoot height where it was significantly higher with soils that had an idealised soil porosity i.e. not too porous or too dense.
2. Covering the soil surface by just 1 month led to an enormous yield advantage. Where the soil was exposed to the rainfall soil surface; yield dropped by more than 27 % with 1 month. It is likely these plants had to face a highly soil strength and reduced aeration that contributed to the plant consuming significant energy in penetration that affected the total root, shoot and yield. This was confirmed across two years of experiments and stresses the importance of the soil surface and management practices that protect it like zero tillage. That can save the farmers a high costs to protect their crops and produce more yield at the same time.

6.4. Plant feedbacks on soil structure

1. Root systems can improve soil porosity over time, but that can reduce the root and shoot development, where soil is compacted plants are required to consume much higher energy to overcome the soil strength. While, the soils

with more suitable porosity can save the plant's energy to produce shoot and yield. In this case the crop yield was significantly different between soils type with different porosity.

2. The root impact in the soil was the main factor of increasing the soil structure characteristics such as soil total porosity, soil water content, soil mean pore size and soil pore circularity. Where these parameters were measured in all experiment, but the third experiment focused on the bare effects of the root existence by have the same soil coverage treatment with wheat (cv. Rialto) cultivated soil and bare soil.

6.5. Future work

1. Early stage coverage of the soil surface can avoid the crop from consuming much energy to penetrate the soil structure, however the application of this method needs much studies to make an appropriate soil surface coverage that can be applicable to the user (the farmer) to protect the whole cultivated area. One option might be transparent sheets that are supported on a suitable pegs 10-25 cm height from the surface just to absorb the rainfall impact and avoid blowing them off during storms. Then this device can be removed and stored for the next season after been used for only first 50 days of the wheat growing season. An alternative would be organic residues such as straw but their impact on surface properties has not been evaluated here.
2. The importance of soil pore shape, in particular, pore circularity is one of the main findings in this project, therefore further study is needed to connect it with the soil biological and earthworm activity. This connection can explore

the relationship between soil structure and soil biological community and how can this correlation be used in the field to increase the yield of wheat. The next step could be to quantify the biopores percentage to the soil total porosity and how did the biopores developed over time and over soil structure development.

3. The increase in wheat (cv. Rialto) yield was highly correlated to soil structure characteristics such as soil water content and soil pore circularity. Further research might consider other parameters such as soil chemical status slike soil pH, soil cation exchange and soil nutrients availability.
4. The results of this research could be beneficial to the local farmers where they can avoid losing wheat yield by protecting the soil surface for limited time, although for the best method for achieving this coverage particularly in terms of potential recyclable materials has yet to be determined.

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