A Thesis Submitted for the Degree of Doctor of Philosophy at

Harper Adams University

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Harper Adams University

THE EFFECTS OF SOIL PHYSICAL CONDITIONS ON THE ANCHORAGE OF WHEAT (*Triticum asetivum L.*)

By

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(BSc & MSc)

Thesis submitted to Harper Adams University for the award of the Degree of

Doctor of Philosophy

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Declaration

I declare that this thesis has been composed entirely by myself and has not been submitted or accepted in any previous application for a degree. The work, of which it is a record, has been done by myself. Quotations have been distinguished by quotation marks, and sources of information have been specifically acknowledged.

Nyaz Fouad Sulaiman

Abstract

The anchorage provided by the adventitious roots of cereal crops is essential to keep the plant upright and prevent toppling over, known as lodging. Plant anchorage depends on adventitious root development and the physical conditions of the surrounding soil. The research aims to determine the effect of soil conditions on anchorage and yield of wheat. This entailed investigating the effect of soil physical conditions, namely, bulk density, moisture content and cultivation systems on the plant properties associated with lodging incidence, focusing primarily on adventitious root development, anchorage moment and the grain yield of winter wheat. The effect of bulk density (treatments 1.1, 1.3 and 1.5 Mg m^{-3}) in sandy loam and clay loam soil on the anchorage moment of wheat plants grown in pots was significant in both soil types: the plant anchorage moment increased by 40% and 3% with increasing soil bulk density from 1.1 to 1.3 and 1.5 Mg m^{-3}, respectively.

The adventitious root development and plant anchorage moment was significantly influenced by cultivation systems: under control traffic condition, zero tillage resulted in increased values of the soil physical and adventitious root properties. Consequently, plant anchorage moment increased by 9% and 32% compared to shallow and deep tillage systems, respectively. Nevertheless, the results indicated 35% reduction in the yield due to the tramline effects in zero tillage system compared to shallow and deep tillage systems. Under non-controlled traffic condition, however, the results of determining four tillage treatments showed no effect on the soil physical conditions, adventitious root development and plant anchorage moment

Furthermore, wheat plants subjected to the reduced moisture content of 50% - 65% of field capacity before flag leaf emergence were estimated to be 25% more likely to root lodge compared to plants grown at 85% - 100% moisture content of field capacity.

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First and foremost I offer my sincerest gratitude to my supervisor, Dr. Mitch Crook, who has supported me with continuous guidance, support and encouragement and most importantly, his friendship throughout my PhD studies. One simply could not wish for a better or friendlier supervisor.

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Last but not the least, I thank my parents for their love and support and always encouraging and believing in me and allowing me to be as ambitious as I wanted.

Dedication

This thesis is dedicated to my family especially my Father, Mother and my wife, could not have come this far without you

Part of this work has appeared previously

Sulaiman, N., Crook, M., 2014. Effect of soil type and bulk density on the stem and root lodging resistance of wheat, in: 20th World Congress of Soil Science. Korean Society Of Soil Sciences And Fertilizer, Jiju Island - Korea, pp. 161–161.

Sulaiman, N., Crook, M., Misiewicz, P., White, D., Godwin, J.R., 2014. The effect of tillage systems on soil strength properties and the anchorage moment of winter wheat. the American Society of Agricultural and Biological Engineers, Montreal, Quebec, Canada, p. 1 19. doi:doi: 10.13031/aim.20141907324

Sulaiman, N., Crook, M., Misiewicz, P., White, D., Godwin, R.J., 2014. The effect of soil type and bulk density on the above ground properties and the anchorage of winter wheat, in: ASA, CSSA, & SSSA International Annual Meeting. American Society of Agronomy, Long Beach, CA, USA, p. 70.

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Chapter 1

1.1 General introduction

Lodging in cereals is when a free standing plant leans toward the ground and is no longer in an upright position (Pinthus & Brady, 1974). Two types of lodging have been recognised, stem lodging which is the buckling or breaking of the lower internode of the stem while the roots are held firmly in a strong soil. Root lodging is when the stems lean toward the ground because of the weaknesses in the upper layer of soil or in the root properties (Pinthus, 1967).

It has been more than two centuries since lodging was first reported as a main constraint to the yield and profit in wheat production (Atkins, 1938). Later studies have largely recognised the above ground plant characteristics (Brady, 1934; Pinthus, 1967; Hintikka, 1972), and the root system characteristics (Hamilton, 1951; Hansel, 1960) associated with lodging.

Despite its significance and the large body of research to date, little is known on the development of adventitious roots whose function is to anchor the plant and resist being lodged in different soil conditions at which plant anchorage can be optimised. This could be of great benefit in attempting to minimise the loss of yield resulting from lodging. Despite the earlier studies, lodging in small grains (namely in wheat) is still a major yield constraint (after disease and pests) making wheat production less profitable and reducing the potential to feed the increasing population of the world.

Wheat is the most important crops cultivated in the world; the total area cultivated worldwide reached up to 220 million hectares producing more than 650 million tonnes (Jeremy, 2013). In the UK, 16.6 million tonnes of wheat were harvested from 1.9 million hectares in 2014 (DEFRA, 2014).

Depending upon the severity and the stage of plant at which lodging occurs, the reduction in the harvestable yield of wheat ranges from 45% (Berry & Spink, 2012), 60% (Rajkumara, 2008) to 80% (Acreche & Slafer, 2011). In the UK, serious problems of wheat lodging occur on average once every four to five years. For example, in 1994 the cost of lodging was estimated to be more than £130 million when only about 15% of the UK's wheat crop lodged (Tams et al., 2004; Berry & Spink, 2012). In addition to the yield loss, lodging can also result in poor grain quality due to the difficulties of harvesting (Pinthus & Brady, 1974; Baker et al., 1998). Although, stem lodging have been reported earlier (Neenan & Spencer-Smith, 1975; Easson et al., 1993); in the UK, wheat lodging due to anchorage failure or root lodging is likely to be predominant (Ennos, 1991a; Sterling et al., 2003; Yao et al., 2011).

More extensively, the plant anchorage moment does not only depend on the adventitious root properties, it also depends on the strength properties of the surrounding soil (Goodman & Ennos, 1999; Sposaro et al., 2008). As the strength of the surrounding soil increases, the resistance to over-turning generated by the roots also increases, to resist the lateral forces acting upon the stems and transmitted to the roots (Crook & Ennos, 1993, 1994, 1995). Additionally, the strength of the surrounding soil affects the plant root development (Holloway & Dexter, 1991; Schjonning & Rasmussen, 2000; Huang et al., 2012; Tracy et al., 2012b).

The anchorage moment generated by the plant is usually measured when soils have been brought to field capacity, and the shear strength of the soils is low. This simulates conditions typical of a field at which anchorage failure is more likely to occur. The anchorage of maize (*Zea mays*), wheat (*Triticum aestivum)*, rice (*Oryza sativa*) and teff (*Eragrostis tef*) have been investigated at shear strengths of less than 15 kPa (Ennos et al., 1993; Crook & Ennos, 1995; Oladokun & Ennos, 2006; van Delden et al., 2010). Therefore in all cases, whilst the shear strength of the soils is low in wet conditions (with the soil shear strength increasing to over 200 kPa in very dry conditions), the strength of the soil is an important factor in determining the resistance to root lodging.

The plant properties associated with lodging susceptibility and the conditions which cause lodging have been identified by Crook & Ennos (1994); Keller et al. (1999); Berry et al. (2003a, 2004); Khakwani et al. (2010); Berry & Spink (2012) and Peng et al. (2014). Simple static models which explain important properties, ranking susceptibility to lodging of different varieties or treatments affects and dynamic models which explain the process and the environmental conditions necessary for lodging to take place have been developed by Crook & Ennos (1993); Baker et al. (1998); Berry et al. (2003c); Martinez-Vazquez & Sterling (2011) and Berry & Spink (2012). In addition, the work of Coutts (1983, 1986) and Ennos (1989, 1990) has focussed on the mechanisms by which roots provide anchorage in a range of species. As a result both simple and complex models of plant anchorage incorporate the shear strength in the prediction equations (Crook & Ennos, 1993; Berry et al., 2003c, 2006; Martinez-Vazquez & Sterling, 2011; Berry & Spink, 2012).

The effect of precipitation over the growing season on plant growth including root development have been extensively researched (Gales et al., 1984; Grando & Ceccarelli, 1995; Liu et al., 2004; Shi et al., 2014), nevertheless, most of these studies investigated the fine absorption roots which their function is to absorb water and nutrient. Little is known on how rainfall regime affects adventitious (structural) roots at the stages during which they develop (Crook et al., 1994; Sahnoune et al., 2004; Yang et al., 2006).

Current crop management practices seek to optimise the yield, although they cannot prevent lodging, they seek to reduce likelihood of lodging by spring decision of fertiliser timing and the application of plant growth regulators (Berry et al., 2008). Previous studies of cereal anchorage have used plants grown in clay soils (Baker et al., 1998; Berry et al., 2003a; Scott et al., 2005b; Martinez-Vazquez & Sterling, 2011). Little is known about the adventitious root development and mechanism of anchorage in sandy loam soils. Whilst little consideration has been made to optimise the physical conditions of soil and root development throughout the growing season, this project will therefore, focus on how soil management practices affect the anchorage properties of crops, furthermore, how anchorage root development is affected by soil moisture at critical times through the growing season. The study will focus primarily on wheat, as it is a crop grown most in the UK.

1.2 General project aim

Determine the effect of soil conditions on the anchorage and the yield of wheat.

1.3 General project objectives

1. To identify the effect of soil type and soil bulk density on the soil shear strength and anchorage moment of wheat.
2. To determine the effect of different cultivation systems on soil physical conditions and the anchorage moment of wheat.
3. To determine the effects of drought stress on the adventitious root development and the anchorage of wheat.

1.4 Project hypothesis

The anchorage and yield of wheat can be optimised through manipulating the physical conditions of the soil.

1.5 Outline methodology

To investigate the project hypothesis that the anchorage and yield of wheat can be optimised through manipulating the physical conditions of soil, a glasshouse experiment was first conducted to investigate the concept of soil bulk density affects adventitious root development and accordingly plant anchorage moment of pot grown Cadenza winter wheat (*Triticum asetivum L*.).

Based on the outcome of the first experiment, in which soil bulk density has shown significant effects on the adventitious root development and accordingly plant anchorage moment, two field experiments have been conducted at which the effect of soil physical conditions on the adventitious root development and plant anchorage moment was examined throughout cultivation systems.

Moreover, similar to the soil physical conditions, the adventitious root properties are highly affected by soil moisture content or the amount of rainfall during the growing season. Thus, a pot experiment in glasshouse was conducted to examine the effect of soil moisture content on the adventitious root development and consequently plant anchorage moment of Cadenza winter wheat (*Triticum asetivum L*.).

Under the conditions in which the experiments were conducted, and taking the yield into account, the most appropriate cultivation system has been identified at which plant anchorage moment and the yield were maximised. Additionally, the risk of root lodging or anchorage failure in winter wheat was predicted based on the available soil moisture content at early growing stages at which the adventitious roots develop.

Chapter 2

2. Literature review

2.1 Lodging in wheat

Lodging is a permanent displacement of a plant from its vertical position (Pinthus & Brady, 1974). Lodging occurs two to three months before harvesting at early grain filling stage, when the ears are heaviest (Crook et al., 1994; Hai, 2006). Lodging is a serious problem in the UK and worldwide, up to 80% reduction in the yield due to lodging was reported (Rajkumara, 2008; Acreche & Slafer, 2011; Berry & Spink, 2012). Depending upon the severity of lodging, which might occur once every four to five years, the cost of lodging may reach up to £130 million in the UK (Sterling et al., 2003; Tams et al., 2004). Two types of lodging have been identified: stem lodging (Figure 2.1a) and root lodging (Figure 2.1b). Stem lodging is the buckling or breaking of the lower internode of the stem; it occurs when the self-weight moment generated by a single tiller exceeds the strength of the lower internode (Baker et al., 1998; Berry et al., 2003b). Stem lodging therefore, depends on the stem properties such as strength, wall width and diameter. Root lodging is a movement of the whole plant in the soil; it occurs when the self-weight moment generated by the whole plant exceeds its anchorage moment. Hence, root lodging depends on the adventitious root development and the physical conditions of the surrounding soil (Crook & Ennos, 1993; Baker et al., 1998; Goodman & Ennos, 1999).

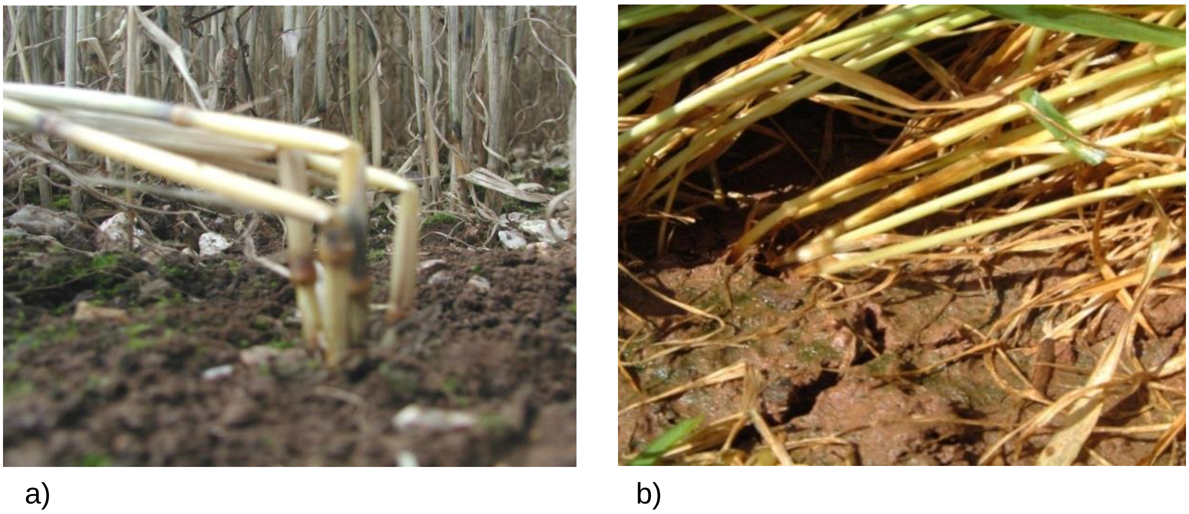

a) b)

Figure 2.1. Lodging in wheat, a) stem lodging (buckling or breaking of the lower internode of the stem), b) root lodging (movement of the whole plant in the soil), adopted from Berry et al. (2004).

2.2 Wheat roots and the mechanics of lodging

The below ground tissues of plant, exploring soil as a branching network are called the root system (Scott et al., 2005a). Wheat as a cereal crop, belongs to the grass family that has a monocotyledonous root system (Rich & Watt, 2013). It has two types of roots, which emerge from the outline base of the stem: first, the fine (seminal) roots, mostly responsible for obtaining and storing soil resources; and second, the adventitious (coronal) roots that generally provide mechanical support to anchor the plant (Fig. 2.2), while the distal roots emerge from the end of the adventitious roots and play no or little role in anchoring the plant, because these distal roots are not stiff in bending like the adventitious roots (Ennos, 1991a). Unlike the fine absorption roots, the adventitious roots resist bending and are strongly adhered to the surrounding soil through the hair roots. Hence, under field conditions, the adventitious roots resist the lateral forces transmitted through the stems and act as the required rigid element preventing lodging and anchoring the plant (Ennos & Fitter, 1992).

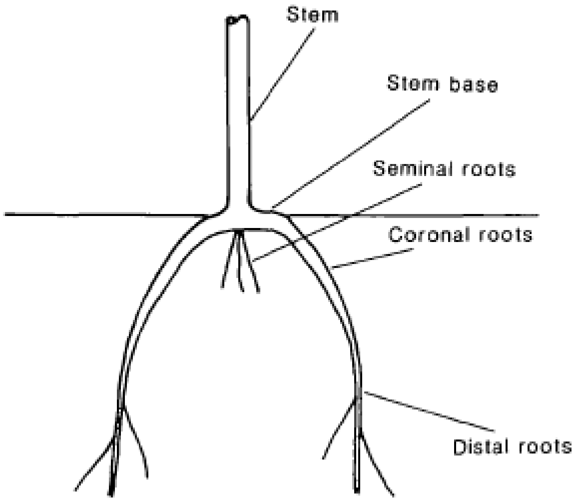


Figure 2.2. Root system of wheat, adopted from Ennos (1991a).

Nevertheless, the mechanics of root lodging demonstrated in (Figure 2.3a and 2.3b) is different in winter wheat to spring wheat. In spring wheat, when the stems are subjected to a lateral force, the roots start to rotate in the surrounding soil, the adventitious roots which are bent at their base (because of the lateral force applied to the stems) rotate into and out of the soil around their centre which forms about 10 - 15 mm below the stem base in the soil as illustrated earlier in Figure 2.3a (Ennos, 1991a). In winter wheat, in case of the small inclination of the stems, the movement of the adventitious roots is the same as in spring wheat. However, when the stems are subjected to a greater lateral forces, the stem inclination from vertical will be due to the rotation of the whole plant in the soil as the soil beneath the stem base sinks to a lower level opposite the direction where the lateral force come from, and the centre of the rotation moves down to about 10 - 20 mm toward the direction where the lateral force come from (Figure 2.3b) (Crook & Ennos, 1993).

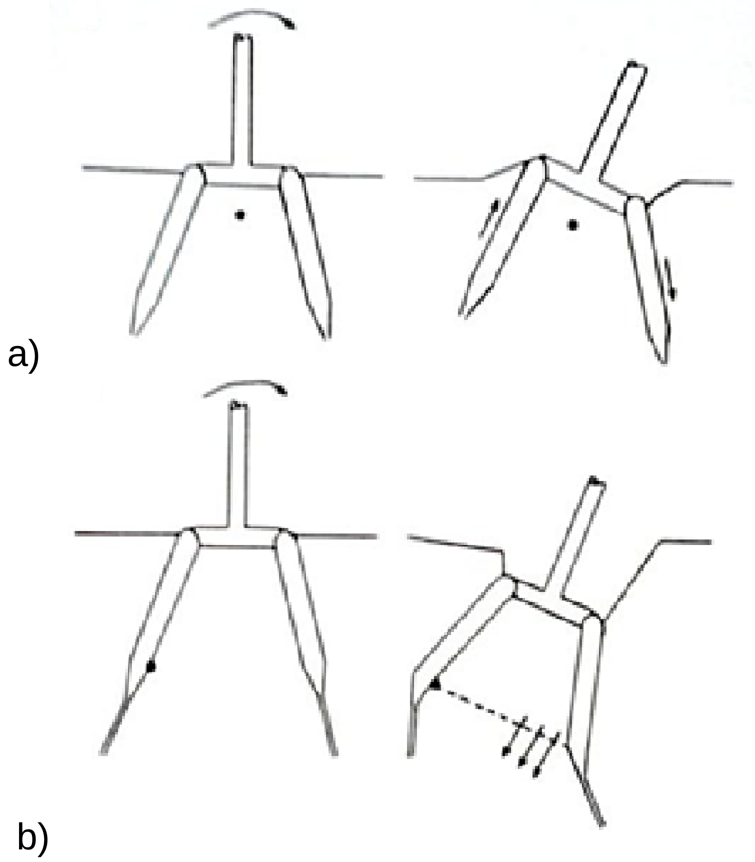


Figure 2.3. Movement of roots during lodging incidence, (a) in spring wheat during lodging process, the adventitious roots rotate into and out of the soil around their centre which forms about 10 - 15 mm below the stem base. (b) in winter wheat the whole plant rotates in the soil as the soil beneath the stem base sinks to a lower level opposite the direction where the lateral force come from, and the centre of the rotation moves down to about 10 - 20 mm toward the direction where the lateral force come from, adopted from Crook & Ennos (1993).

2.3 Soil physical properties and lodging incidence

The physical properties of soil including soil bulk density, shear strength and penetration resistance are important in terms of plant anchorage. They provide the plant with favourable conditions for root development (Bengough & Mullins, 1990; Aggarwal et al., 2006; Huang et al., 2012), and support the plant by preventing it from being lodged (Ennos, 1991b; Berry et al., 2003c; Sposaro et al., 2010). Due to the vital role of soil physical properties namely shear strength, therefore, earlier researchers have considered shear strength in the produced lodging models to determine the base bending moment against anchorage failure or stem failure (Crook & Ennos, 1993; Baker et al., 1998; Berry et al., 2003b).

Soil shear strength is a term used in soil mechanics, which describes the amount of shear stress that soil can resist before failure occurs. It is an important factor associated with the anchorage strength provided by the plant (Ennos, 1991a; Goodman & Ennos, 1999) because, according to the lodging model developed by Crook and Ennos (1993), the shear strength of the surrounding soil will be affected due to the root movement when plant is lodged. Soil retains its strength from the cohesion and frictional forces in between the particles as expressed in the Mohr-Cuolomb Equation (Equation 2.1).

$$\tau = c \ + \sigma \ tan\varphi \qquad \text{(Eq. 2.1)}$$

Where τ the is soil shear strength, c is the cohesion forces between the particles, σ is the normal stress to cause shear failure and φ is the friction angle between the soil particles. From Equation 2.1, soil shear strength depends firstly on the cohesion force which is an independent factor and differs from one soil type to another as it depends on the nature of the soil; secondly on the friction angle between the soil particles which increases with the applied stress. Soil shear strength is different from sandy soils to clay soils because of the variations in the cohesion force and the friction angle between the soil particles, where clay soils are well known as cohesive soils with $\varphi = 0$ compared to the non-cohesive sandy soils where $\varphi \neq 0$.

It can be derived that at low confining pressure (which will be useful for maximising plant anchorage), the shear strength will be greater in clay soils (Crook, 1994), whereas, the increase in shear strength in sandy soils will be greater with increasing the applied stress. Additionally, since most of the soils are mixed of clay and sand, thereby based on the Equation 2.1, the variation in soil shear strength due to the normal stress can be expressed as in Figure 2.4 (University of Wisconsin Stout, 2015).

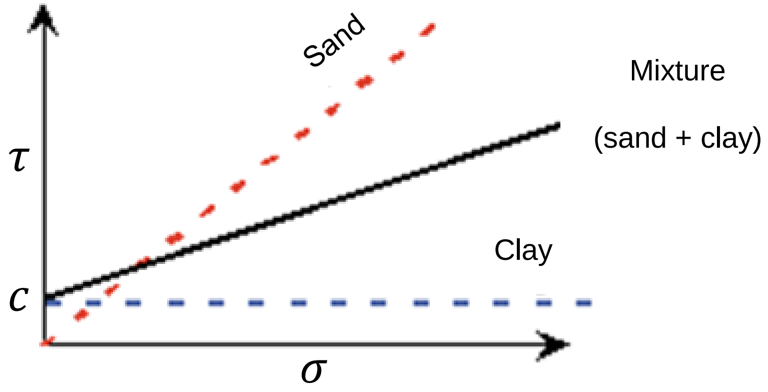


Figure 2.4. Soil shear strength vs normal stress in sand, clay and mixture soil, τ = soil shear strength, c = is the cohesion force between soil particles and σ is the normal stress to cause shear failure, adopted from University of Wisconsin Stout (2015).

Furthermore, the cohesion force and the friction angle between the particles are highly influenced by the amount of soil moisture content, which in turn affects soil shear strength (John et al., 1986; Ayers, 1987; Whalley et al., 2006). Soil shear strength is proportional to soil bulk density and penetration resistance that can be manipulated through cultivation systems; the greater the soil bulk density and penetration resistance the greater the soil shear strength (Su et al., 2004; Lemenih et al., 2005; An et al., 2015).

Nevertheless, the amount of anchorage provided by the plant also depends on the root properties, specifically adventitious roots (Ennos, 1990; Berry et al., 2003a; Korndorfer et al., 2008; Yang et al., 2015) which in turn are affected by cultivation system (Atwell, 1993; Bengough et al., 2011; Wang et al., 2014a; Guan et al., 2015). Thus, a review of the literature on the factors that influence soil strength, root development and consequently plant anchorage strength such as cultivation systems, soil compaction, soil moisture content and soil bulk density was required and is given below.

2.3.1 Soil strength and moisture content

Soil shear strength differs from one soil type to another, not only because of the differences in cohesion and the internal friction angle (Ohu et al., 1985), but also due to its moisture content. John et al*.* (1986) developed a shear strength model in consideration of soil moisture content, organic matter and compaction. The relation between soil shear strength and moisture content was observed in each of clay, clay loam and sandy loam soils with organic matter of 3%, 10% and 17% respectively. The soils were subjected to three levels of compaction (5, 15 and 25 blows of standard compaction hammer). Increasing gravimetric moisture content up to 55% of the liquid limit of each soil type resulted in an increase in soil shear strength, before it started to reduce with further increasing moisture content (Figure 2.5, 2.6, 2.7). This is because an increase in moisture (limited) will result in an increase in soil cohesion before creating bigger water pores in the soil, hence less cohesion and accordingly reduced shear strength. Further reduction in soil shear strength was observed with incorporating more organic matter to soil (John et al., 1986).

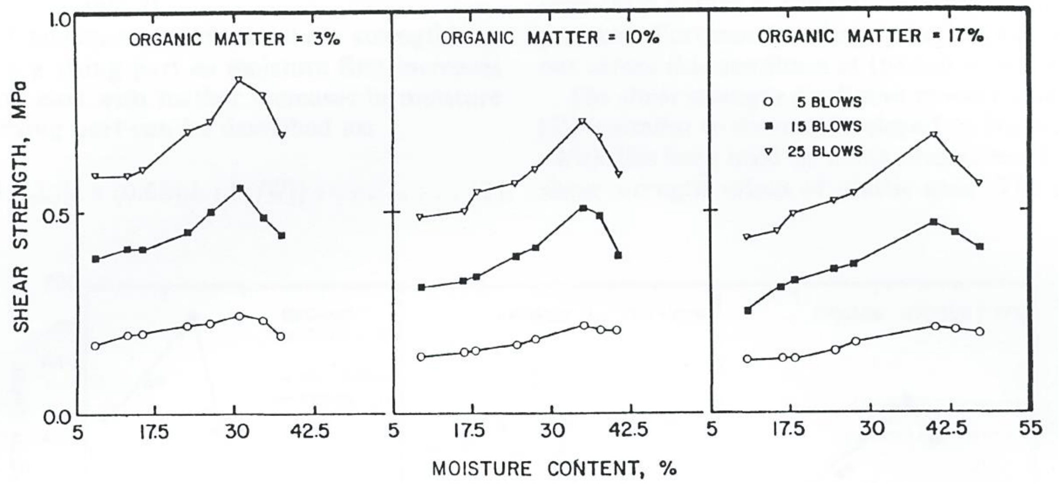


Figure 2.5. Shear strength vs. moisture content of clay soil at different organic matter and compaction, adapted from John et al. (1986).

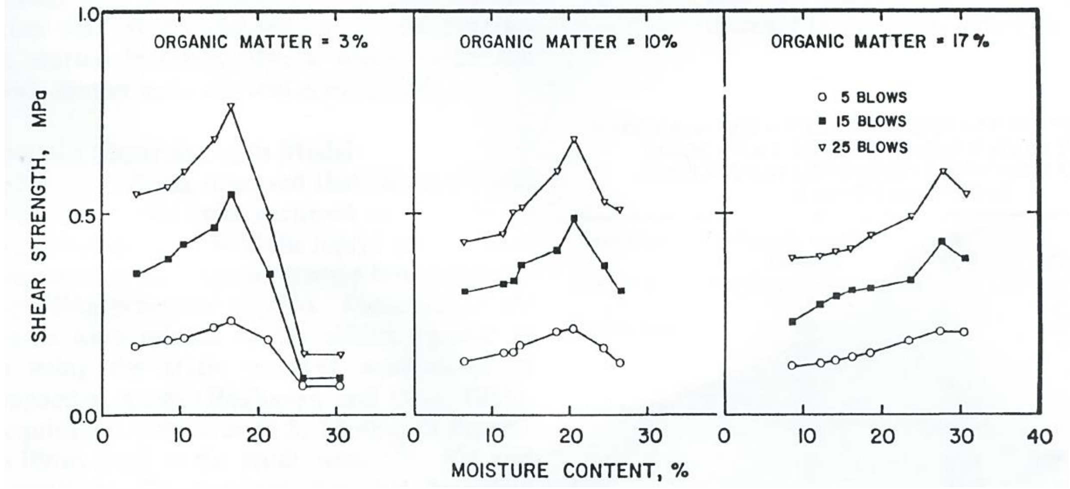


Figure 2.6. Shear strength vs. moisture content of clay loam soil at different organic matter and compaction, adapted from John et al. (1986).

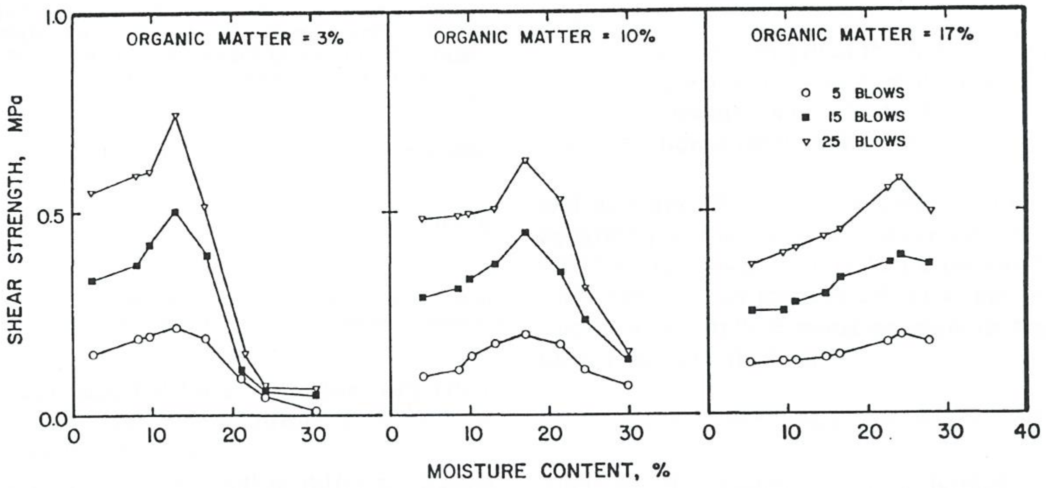


Figure 2.7. Shear strength vs. moisture content of sandy loam soil at different organic matter and compaction, adopted from John et al. (1986).

Likewise, in addition to the soil shear strength, the study of Ayers (1987) also included soil cohesion and angle of internal friction in between soil particles in relation to a range of soil densities and moisture content in two sandy loam soils (Ruston and Fuquay). The author reported that soils with lower clay content have lower shear values because of smaller cohesion force between the particles. This is similar to the finding of John et al. (1986) and Ayers (1987) who reported that at low moisture content, soil shear strength increases with an increase in moisture content. However, further increase in moisture content will decrease soil shear strength components (cohesion and friction angle) in case of given soil density (Figure 2.8). Soil shear strength components at given soil moisture responded differently to an increasing soil density in the two soil types (Figure 2.9) (Ayers, 1987). These results were consistent with later results Figure 2.10a, 2.10b reported by Ekwue and Stone (1995).

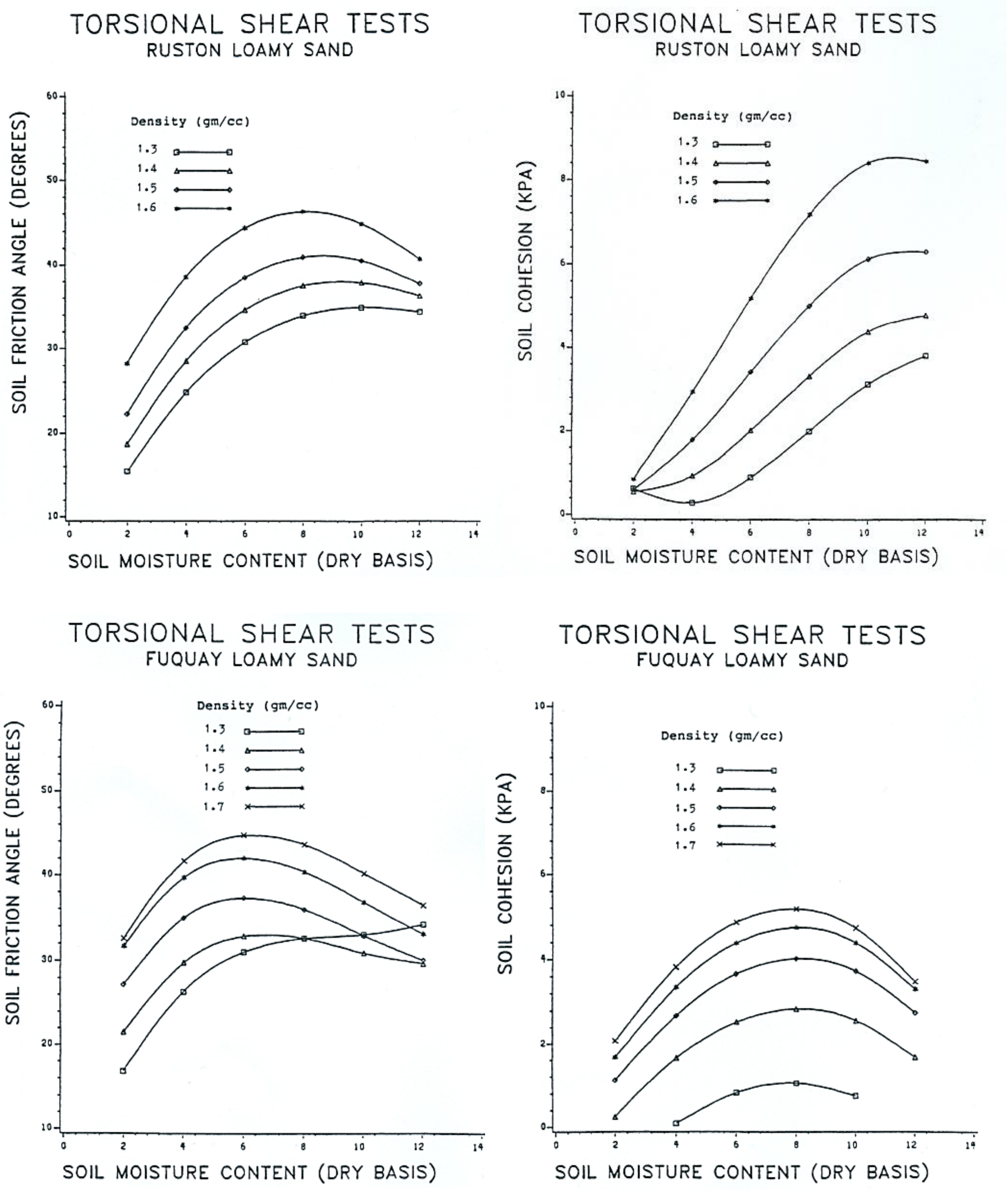


Figure 2.8. Moisture content vs. soil friction angle and soil cohesion in two sandy loam soils, adopted from Ayers (1987).

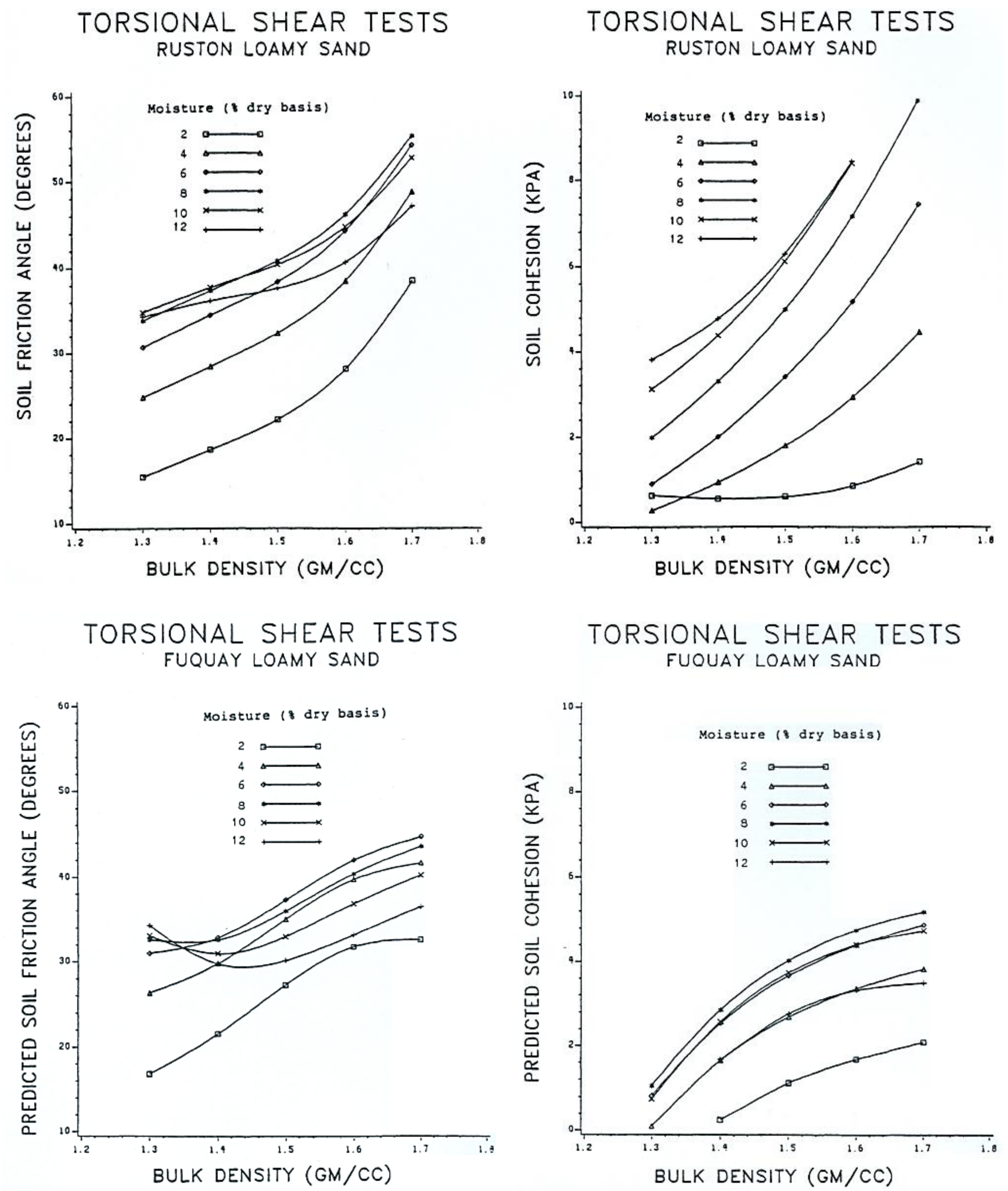


Figure 2.9. Bulk density vs. soil friction angle and soil cohesion in two sandy loam soils, adopted from Ayers (1987).

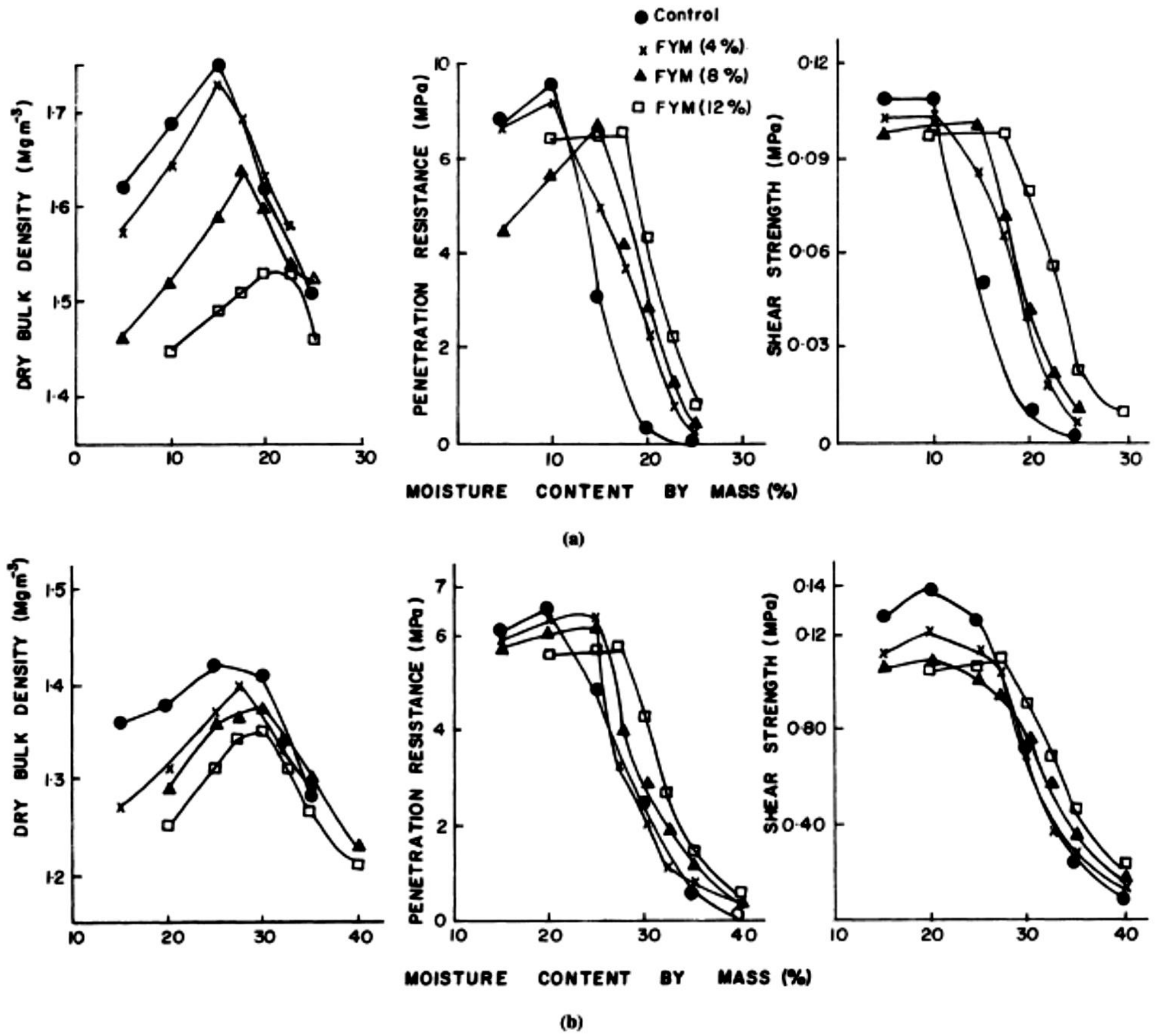


Figure 2.10. Variation of bulk density, shear strength and penetration resistance with moisture content at different frame yard manure applications, (a) in sandy loam soil, (b) in clay soil, adopted from Ekwue and Stone (1995).

The relationship between soil bulk density, soil water content and penetration resistance was investigated by Aggarwal et al. (2006) under two different soil practices (bed planting and conventional system) when wheat crop was sown into a sandy loam soil. They concluded that irrespective of soil bulk density, when volumetric water content increased from 5% to 16%, penetration resistance decreased from more than 2 MPa to about 0.8 - 1.6 MPa. Also irrespective of water contents, when bulk density increased from 1.3 to 1.5 Mg m^{-3}, penetration resistances increased up to 2 MPa which is the limit at which root growth and elongation are restrained and reduced by 50% (Bengough et al., 2011).

This increase in penetration resistance was lower in the bed planting system as the soil was less compacted than conventional soil. Thus, penetration resistance increased with an increase in bulk density and decrease in soil water content.

Furthermore, tillage techniques have a significant effect on soil moisture content due to the effect of soil tillage on soil structure (Jiuhao et al., 2007). Figure 2.11 illustrates the effect of three different tillage systems, as deep loosening in two vertical directions to the depth of 450 mm (ADL), shallow tillage after deep loosening to the depth of 450 mm (SDL) and conventional tillage to the depth of 300 mm (DT) on the volumetric moisture content of tropical soil (latosol). During the experimental period of about 400 days, Jiuhao et al. (2007) highlighted that due to the changes in soil structure caused by tillage systems, volumetric moisture content at different depth was significantly affected. ADL and SDL tillage systems compared to DT system, increased the water holding capacity and porosity of the soil while reducing soil bulk density and penetration resistance.

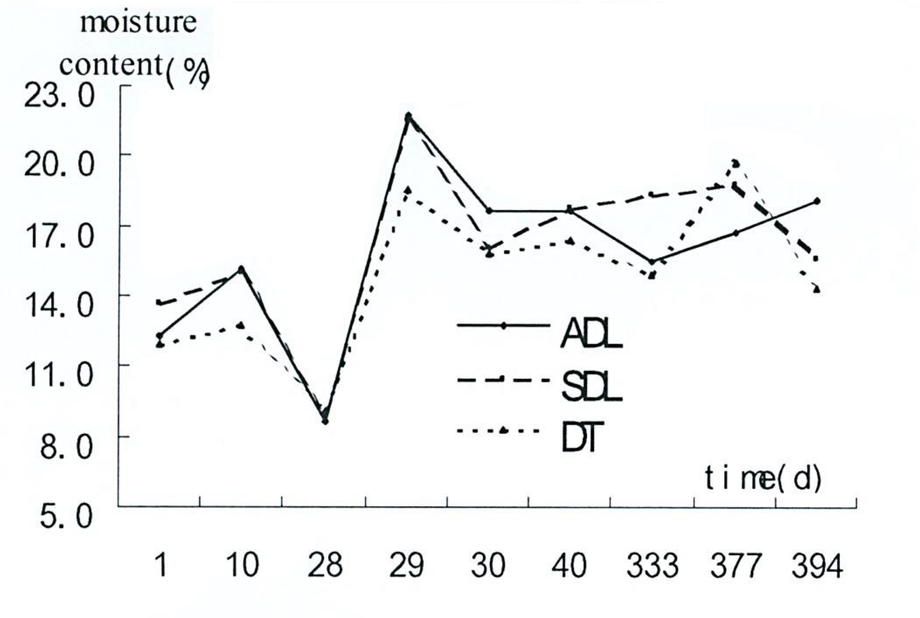


Figure 2.11. Effect of different tillage systems on the volumetric water content at a depth of 0 - 100 mm. ADL = deep loosening in two vertical directions, SDL = shallow tillage after deep loosening and DT = conventional tillage, adopted from Jiuhao et al. (2007).

Benjamin & Mikha (2010) studied the prediction of winter wheat yield loss from soil compaction on a weld loam soil, which was artificially compacted using an automatic soil compacter. A range of compaction levels (1.4 - 1.54, 1.5 - 1.7 g cm^{-3} bulk density) were achieved by applying different pressure to the soil under different water content. A correlation was established between soil bulk density and water content to calculate the Least Limiting Water Range (LLWR; method which is the upper limit of water content at field capacity that provide the proper aeration of plant roots growth, minimum air filled porosity of 10%) so the loss yield of winter wheat could be predicted. Although there was a huge variation in soil bulk density after each applied load, a correlation was established between the pressure applied to the soil and soil water content, so bulk density could be determined. For instance, applying 174 kPa at 0.10 - 0.20 g g^{-1} water content resulted in 1.4 - 1.54 g cm^{-3} bulk density, and increasing the applied pressure to 614 kPa resulted in 1.5 - 1.7 g cm^{-3} bulk density. Nevertheless, the applied method which minimises the variations between the treatments should be considered to create different bulk density levels. In conclusion, the increase in the compacting pressure is accompanied by a reduction in the water content. Thus a 500 kg ha^{-1} loss of winter wheat yield would be expected with each 0.05 reduction in least limiting water range LLWR (Benjamin & Mikha, 2010).

Kadziene et al*.* (2011) reported an increase in soil penetration resistance above 1.5 MPa associated with direct drilling and harrowing from the soil surface to the depth of 120 mm; which was an indicator of studying the effect of tillage intensity on root growth condition in the top soil. For all the treatments, the decrease in water potential increased penetration resistance, thus LLWR was halved to 0.11 m^3 m^{-3} for direct drilling comparing to 0.21 m^3 m^{-3} for ploughing system to 200 mm depth.

Hence the root growth of spring barley was restricted by high penetration resistance resulting from surface tillage systems as a consequence of soil compaction (Kadziene et al., 2011).

2.3.2 The effect of crop residue and vegetation on soil physical properties

The force required to lodge or fail a plant is not only dependent on the root system, but also on the soil physical condition, which in turn is affected by its vegetation. The presence of a root system increases the measured soil shear strength and improves soil stability (Fattet et al., 2011; Liu et al., 2014). Mamo & Bubenzer (2001) studied the influence of the presence of ryegrass roots, grown in pots filled with silt loam soil on soil shear strength. During the growing season, soil shear strength and root length density were measured at three stages. The first measurement was taken eight weeks after planting, the second and the third measurements were taken within four weeks intervals from the first measurements. Compared to the initial measurements, the average soil shear strength was 4% greater in the fallow soil due to the confine soil pressure and soil settlement. Additionally, the greater effect was for the presence of roots and increase in its length density during the growing season, which raised soil shear strength by 50% compared to the initial measurements of 16 Nm^{-2} (Mamo & Bubenzer, 2001).

Comino and Druetta (2010) reported an increase in soil shear strength due to the presence of roots of *Poaceae* grasses. Three soil types as silty sand, well graded sand and well graded sand with silt located at three different sites were sown with two grass species of *Festuca pratensis* and *Lolium perenne*. The average increase in soil shear strength across the three soil types due to the roots of the grasses ranged between 49% to 325% compared to the fallow soils (Comino & Druetta, 2010).

In addition to the increased soil shear strength due to the presence of root system (Silva et al., 2011; Wang et al., 2014b), the nature of roots being in the soil also has a further effect on soil physical condition based on the model developed by (Crook & Ennos, 1993). The soil below the root-ball cone of a lodged roots is further compressed and pushed to the deformation limit compared to the presence of the none-lodged roots (Crook & Ennos, 1993); This movement of the root-soil cone and the soil beneath affects the physical conditions of soil (Schjonning & Rasmussen, 2000; Benjamin & Mikha, 2010).

Tams et al. (2004) therefore, conducted a study where winter wheat plants sown in clay, silty loam and sandy loam at 100 and 400 seeds m^{-2} were artificially root lodged, when the soils were near the field capacity conditions. The lodged roots of plants sown in clay loam and sandy loam soils sown at 400 seeds m^{-2} reduced soil porosity by 3.7% and 1.7%, respectively. Up to 50% reduction in the number of pores was observed in the high density wheat plots in clay loam soil. In general, a 3.8% reduction in soil porosity was observed due to root lodging in winter wheat (Tams et al., 2004). Soil porosity is in a reverse relationship with soil bulk density and shear strength; the less the soil porosity the greater the soil bulk density and shear strength (Schjonning & Rasmussen, 2000; Pravin et al., 2013).

Nevertheless, crop residues did not always cause an increase in soil bulk density and shear strength, as a reverse results were reported by Fernaindez et al. (2010). Soil bulk density was found to be greater in the upper 0 - 50 mm of no-tilled silty loam soil; winter wheat crop residues reduced soil bulk density in the 0 - 50 mm of silty loam soil by about 12% as a result of soil swelling and air entrapment between soil particles. Moreover, a greater gravimetric water content by 36% in un-grazed treatments compared to grazed treatments contributed to the reduction in soil bulk density (Fernaindez et al., 2010). Furthermore, seed rate can be used to manipulate soil shear strength by the amount of vegetation. For maximised yield, depending upon the date of planting, wheat growers seek lower seed rates in the early growing season and increased seed rates in the late growing season (HGCA, 2008). Nevertheless, the seed rates should be carefully considered and not to leave fallow areas in the field or expose the plants to stem lodging due to high seed rates (Easson et al., 1993; Rademacher, 2009).

2.3.3 The effect of tyre size, design and inflation pressure on soil strength properties

The risk of soil compaction is increasing due to the increased use of heavy agricultural machineries associated with underlying high productivity (Oussible et al., 1992; Antille et al., 2008). Soil compaction causes increased soil physical properties and restrained root growth (Schjonning & Rasmussen, 2000; Chen & Weil, 2011; Glab, 2013), and thereby affects plant anchorage. With less developed adventitious roots associated with greater soil compaction, plants are more exposed to root lodging as plant anchorage is dependent on soil physical properties and adventitious root development dependent (Crook et al., 1994; Berry et al., 2003c; Sun et al., 2011).

Alternatively, different management practices are adapted to alleviate or minimise soil compaction including tillage systems (Guclu Yavuzcan et al., 2002; Gao et al., 2012; Whalley et al., 2012) and vehicle configuration as its weight, tyre inflation pressure, size and design (Ansorge & Godwin, 2009; Berisso et al., 2013; Rosca et al., 2014).

The effect of tyre inflation on soil strength was investigated by Keller & Arvidsson (2004). The effect of three tyre inflation pressures of 100, 150 and 250 kPa fitted to a sugarbeet harvester weighing 220 kN (unloaded) was investigated on soil stress in a clay loam soil. Soil vertical stress varied due to the different tyre pressure under the same wheel load of 86 kN; increasing tyre pressure from 100 kPa to 250 kPa at the depth of 30 cm resulted in 25% greater soil vertical stress (Keller & Arvidsson, 2004).

Likewise, the effect of tyre size on soil deformation and changes in soil bulk density was researched by Antille et al. (2008), using soil with two different bulk densities of 1.2 g cm^{-3} and 1.6 g cm^{-3}. The results of their experiment showed lowest soil deformation up to 50%, hence smallest increase in soil bulk density, resulting from the biggest tyre section, load and the lowest inflation pressure 900/10.5/1.25 (mm/ton/bar) compared to 800/10.5/2.5 and 680/10.5/2.2, respectively. This was due to the distribution of the machine's load on a greater contact area produced by the tyre with low inflation pressure. The greater contact area with lower inflation pressure of the tyre caused a reduction in soil penetration resistance compared to other tyres. The results of Antille et al. (2008) was in agreement of the finding of Ansorge & Godwin (2007) who reported a 34% reduction in the dry soil bulk density due to the reduced inflation pressure of 1.25 bar compared to 2.5 bar inflation pressure for tyre with 800 mm width section. Moreover, Ansorge & Godwin (2007) also investigated the effect of different tyres with different inflation pressures and loads compared to rubber track system (Table 2.1) under controlled laboratory condition. Sandy loam soil was used in a soil bin with 20 m length, 1.8 m width and 1 m depth, soil bulk density, penetration resistance and soil vertical displacement were measured. Compared to the use of tyres, the use of rubber track caused up to 40% less soil displacement and 24% less increase in the soil bulk density (Ansorge & Godwin, 2007). Thus, the change in soil bulk density and penetration resistance could be used as an indicator in calculating or determining soil shear strength as it is in direct proportion to soil bulk density and penetration resistance (John et al., 1986).

Table 2.1. Tyre and track specification, adopted from Ansorge & Godwin (2007)

Under carriage system	Load (t)	Inflation pressure (bar)	Abbreviation Section width/load/inflation pressure
680/85 R32	10.5	2.2	680 mm/10.5 t/2.2 bar
800/65 R32	10.5	2.5	800 mm/10.5 t/2.5 bar
900/65 R32	10.5	1.9	900 mm/10.5 t/1.9 bar
800/65 R32	10.5	1.25	800 mm/10.5 t/1.25 bar
Class Terra Trac	10.5	0.75[a]	T 10.5 t
Class Terra Trac	12	0.86[a]	T 12 t
500/70 R24	4.5	2.3	500-70 mm/4.5 t/2.3 bar
500/85 R24	4.5	1.4	500-85 mm/4.5 t/1.4 bar
600/55-26.5	4.5	1.4	600 mm/4.5 t/1.4 bar
710/45-26.5	4.5	1.0	700 mm/4.5 t/1.0 bar

[a] Mean pressure assuming a contact patch of 1.4 m^2

Nevertheless, the finding of Ansorge & Godwin (2007) was in contrast to the earlier results of Servadio et al. (2001) who conducted research on a clay soil to evaluate the effect of two tractors (rubber tracked and wheeled tractor) on soil strength parameter after 1 and 4 passes of each tractor. They reported that wheeled tractors cause less soil compaction in comparison with rubber track tractors (greater contact area with soil). After four passes at the depth of 100 - 150 mm, they reported an increase in penetration resistance by about 11.5% in wheeled tractor treatments compared to about 18% in rubber track tractor treatments. Likewise, bulk density at the depth of 0 - 200 mm, increased up to 14% in wheeled tractor treatments compared to 20% in rubber track tractor treatments. At the depth of 300 mm and compared to the 68 kPa for the control treatments, shear strength increased by 24% in wheeled tractor treatments compared to 29% for the rubber track tractor treatments.

Additionally, the rubber-track tractor caused more soil damage in the upper 200 mm layer of soil compared to the wheeled tractor. Based on these results, Servadio et al. (2001) concluded that wheeled tractors cause less soil compaction in comparison with rubber track tractors because the greater increase in soil strength properties such as shear strength, penetrometer resistance and bulk density associated with the use of rubber track tractor compared to the wheeled tractor.

2.3.4 The effect of soil compaction on root development

Plants can either be uprooted or toppled depending on the amount of anchorage provided by their roots and the physical properties of the surrounding soil (Ennos, 1990; Berry et al., 2003c; Yang et al., 2015). The greater the soil strength, the greater the anchorage from the restoring moment resisting over-turning (Goodman & Ennos, 1999). Manipulating the shear strength by cultivations (Wilhelm & Mielke, 1988), or compacting the soil, may have an adverse effect on root development and impair plant growth. Therefore, the effect of different cultivation systems and soil compaction on the root development is discussed in this section.

An increase in soil penetration resistance and reduced porosity due to soil compaction was reported by Lipiec & Haykansson (2000). Five levels of soil compaction of 81, 86, 91, 93 and 101 degrees were created with a combination of different weights, ground pressures and number of passes (however, Lipiec & Haykansson used a non-standard method of quantifying soil compaction as degrees). Wheat was grown in loamy sand, light loam, silty loam and clay loam soils, which were ploughed with mouldboard to the depth of 25 cm. In all soil types, penetration resistance increased from 1 MPa to 4 MPa and porosity reduced more the 60% with increasing soil compaction from 81 degrees to 101 degrees. The increased soil compaction was associated with less root development of winter wheat, hence, more than 20% reduction in the yield (Lipiec & Haykansson, 2000). Following the same pattern, a reduction in root length density and the obtained yield of winter wheat as a result of an increase in soil strength properties was reported by Ishaq et al. (2001). Due to soil compaction (created artificially using the modified compacted mould and hammer), soil bulk density and penetration resistance, measured at the depth of 0 - 150 mm, increased from 1.65 Mg m^{-3} and 1.00 MPa to 1.93 Mg m^{-3} and 4.83 MPa, respectively. Accordingly, a 39% reduction in the root length density of winter wheat was observed, which reflected in a 37% reduction in the obtained yield in the first growing season and 8% in the second growing season of winter wheat grown in a sandy clay loam soil during the experiment conducted between 1997 - 1999 by Ishaq et al. (2001).

In another study, a reduced root length density was also reported due to soil compaction. Saqib et al. (2004) planted two different genotypes of wheat (Aqaab and MH-97) in pots of 310 x 230 mm (height x diameter). Sandy clay loam soil was artificially compacted at 10% moisture content up to 1.61 Mg m^{-3} bulk density (compacted soil); un-compacted soil remained at 1.2 Mg m^{-3}. Root length density was reduced by 38% for both genotypes of wheat used in this study, as a result of a 25% increase in soil bulk density. Root length density decreased from 6.5 to 4.8 mm cm^{3} for Aqaab and from 6.7 to 4.6 mm cm^{3} for MH-97, respectively (Saqib et al., 2004).

A cultivation process is needed to prepare a good seedbed; however, it is very likely to cause soil compaction if it is practiced improperly. The effect of three cultivation systems (no-till, chisel plough and mouldboard plough) was investigated on the root characteristics of corn by Ali Akbar et al. (2004). Corn was planted in a fine loamy soil at which three rates of manure of 0, 30 and 60 Mg ha^{-1} were incorporated to the soil. Compared to roots in the chisel plough and mouldboard plough treatments, the roots produced under no-till system were generally shorter, heavier, and thicker. The average measurements of root length varied from 2.79, 2.96 and 3.47 mm, root diameter of 1.54 mm, 1.22 mm and 1.26 mm, the root weight to length ratio of 0.21 g m^{-1}, 0.13 g m^{-1} and 0.14 g m^{-1} for the no-till, chisel plough and mouldboard plough, respectively. Root characteristics were therefore reduced under the no-till system compared to the rest of the tillage systems (Ali Akbar et al., 2004). However, the no-till system is still a recommended tillage practice to minimise and alleviate soil compaction, but, more studies are required to maintain the obtained yield (Schjonning & Rasmussen, 2000; Gemtos et al., 2002; Ali Akbar et al., 2004; Jiuhao et al., 2007).

Trukmann et al*.* (2008) reported an increase in soil penetration resistance by 1.8 - 1.96 MPa and in soil bulk density by 0.08 Mg m^{-3} as a result of soil compaction with six passes of a MTZ-82 tractor on a sandy loam soil. This increase in soil bulk density and penetration resistance resulted in a decrease in a roots mass of spring barley by 74% compared to un-compacted soil. Trukmann et al*.* (2008) noticed a small but significant reduction of 2.3% in root and shoot weight of spring barley with each 0.01 Mg m^{-3} increase in soil bulk density. Nevertheless, the values of penetration resistance and bulk density in compacted and un-compacted soils were not given in the paper.

In contrast, Munoz-Romero et al*.* (2010) reported a significant increase in the root length of winter wheat grown under the no-till system compared to conventional tillage. In a three year experiment where winter wheat was grown in a clay-rich soil, the effect of the no-till system and conventional tillage system was investigated on the root properties and the grain yield of winter wheat. During the experiment period, with no effect of tillage system on root diameter, root length was always greater in no-till treatments compared to the conventional system. The greatest variation of 60% in the root length observed in the first year of the experiment that received the highest rainfall of 704 mm compared to the 402 mm and 414 mm rainfall in the next two following years. Consequently, grain yield was also greater in no-till system [grain yield = 0.31 root length + 2.64] because it increased with increases in the root length (R^2 = 0.96). Nevertheless, no significant variations were found in soil bulk density due to the tillage systems (Munoz-Romero et al., 2010).

To evaluate wheat root elongation and the change in their ability to penetrate a hardpan layer below the surface, an experiment was conducted at Merredin in south-western Australia by Acuna et al*.* (2012). For the treatments containing a hardpan layer, a 3 mm thickness of hardpan formed from 35% paraffin wax to 65% petroleum jelly (equivalent to mechanical impedance of 0.45 MPa) was placed at a depth of 0.25 m in columns of 0.15 x 1 m (diameter x height). Sandy loam soil was packed in layers to 1.35 g cm^{-3} bulk density in the other columns, hence two treatments of with and without hardpan layers were prepared. At a depth of 20 mm, the columns were sown with four Australian wheat genotypes (selected out of 24 genotypes based on their ability to penetrate hardpan layers). In this experiment, subsoil compaction represented by the wax layer hardpan significantly affected seminal root development. During the growing stages and regardless of the genotype, plants grown in columns with a wax layer produced shorter seminal roots by 20% - 25% compared to those without a wax layer; also the number of nodal roots above the wax layer was found to be four times greater in the columns with a wax layer compared to without a wax layer (Acuna et al., 2012).

Moreover, Grzesiak et al*.* (2013) studied the effect of soil compaction on the root structures of maize and triticale planted in plexiglas boxes with 25 cm width and 4 cm depth. Three rates of compaction were created in two soil types (loamy soil and silt-sand loam) with bulk density of 1.1 g cm^{-3} as a low compacted rate and 1.34 and 1.58 g cm^{-3} as medium and high compacted rates, respectively. Those bulk densities were equivalents to 0.84, 1.23 and 1.99 MPa mechanical impedance, respectively. As the roots of cereals, the roots of both maize and triticale are very sensitive to soil compaction (Hassan et al., 2007; Tracy et al., 2012b); the increase in the mechanical impedance from low to medium and high used in this study reduced seminal root length in maize by 20% and 27%, respectively and by 13% and 15% in triticale, without affecting the number of the seminal roots. The dry mass of roots in both plants was also affected by soil compaction; in medium and high compaction levels, the dry mass of roots in triticale reduced to 87% and 69% compared to the low compaction level; in maize the reduction was 70 and 62%, respectively (Grzesiak et al., 2013).

Further reduction in the length of the roots of tomato was reported by Tracy et al. (2012b), who conducted an experiment in un-compacted and compacted (1.2 and 1.6 g cm^{-3}) loamy sand and clay loam soils, respectively. A significant reduction in root length of 41% in compacted loamy sand and of 17% in compacted clay loam soil compared to un-compacted soils was highlighted, and the reduction in total root volume was 44 % in compacted loamy sand soil and 53% in compacted clay loam soil. Consequently, the average mean root diameter increased by 19% in the compacted soils compared to the un-compacted soils. The roots in the compacted soils developed lateral roots which were 12% greater compared to un-compacted (Tracy et al., 2012b).

2.3.5 The effect of soil compaction on soil strength properties and plant growth

According to Hemsath & Mazurak (1974) and Bengough et al. (2011) severe soil compaction and mechanical impedance above 2 MPa restrain root growth in which the reduction in root elongation could reach to 50%. Ball & O'Sullivan (1982) measured the population of spring barley due to increased soil bulk density in direct drill treatments compared to mouldboard plough treatments in sandy loam soil. They reported 11% increased bulk density in direct drilled treatments (measured at the top 100 mm), reduced barley population by 18% compared to mouldboard plough treatments. Similar results in the above ground properties of wheat were also found by Wilhelm & Mielke (1988). The data of the above ground properties of wheat plants grown in silt loam soil at two soil bulk densities of 1.3 Mg m^{-3} and 1.8 Mg m^{-3} was evaluated. Increasing soil bulk density reduced plant height by 15%, leaf area by 19% and above ground dry matter by 26%. However due to soil compaction, no statistical variations in the number of tillers and shoot-root ratio were reported, whereas root length density and root mass decreased by 25% and 21%, respectively (Wilhelm & Mielke, 1988).

In a more recent study, Hassan et al. (2007) highlighted a decrease in wheat yield with an increase in soil compaction level. A silt loam soil was artificially compacted to bulk density of 1.37 (control), 1.57, 1.61 and 1.72 Mg m^{-3}, respectively using a 7 ton roller 1.5 x 1.22 m (length x diameter). An average increase of 20% in soil bulk density resulted in 27% decrease in total soil porosity, 7% spike m^{-2}, 18% grain $spike^{-1}$, 18% thousands grain weight and 27% reduction in grain yield per hectare. As bulk density increased from 1.37 to 1.57, 1.61 and 1.72 Mg m^{-3}, the grain yield reduced from 4.1 to 3.9, 3.3 and 3 t ha^{-1}, respectively (Hassan et al., 2007). Furthermore, the effect of soil compaction on crop growth and the yield vary from one soil to another depending on how wet and compact is the soil (Pringle & Lark, 2007). In soils with fine particle size (clay), both top and subsoil compaction were negatively linked with the obtained yield of wheat grown over two seasons. In contrast, in soils with larger particle size (coarse), yield was increased with increasing soil strength up to 2 MPa, and negatively linked with soil strength (Pringle & Lark, 2007).

Nevertheless, with severe soil compaction restraining the root growth, limited soil compaction is required for better root-soil connection, greater root development, grain yield and thereby better anchorage (Lipiec & Haykansson, 2000; Scott et al., 2005b).

Thus, an increased soil bulk density and penetration resistance had improved seedling emergence of winter barley (Sidiras et al., 2000). An increase in bulk density and penetration resistance in a no-tillage system by 23% and 24%, respectively, and in a minimum tillage system by 12% and 9% compared to conventional tillage increased seedling emergence by 18% and 14%, respectively. This increase in seedling emergence was related to the increase in soil moisture content because of higher compaction.

More importantly, Scott et al. (2005b) reported that the anchorage strength of 2.3 Nm of plants grown in edge rows in three different soil types (sand, silty clay loam and clay) was significantly greater compared to 1.4 Nm for plants grown in the centre rows. In the edge rows, bulk density of 1.45, 1.61 and 1.31 g cm^{-3} was greater in sandy, silty clay loam and clay soils compared to 1.31, 1.27 and 1.12 g cm^{-3} in the centre rows, respectively. Consequently, penetration resistance at 100 mm depth was higher in edge rows and was equal to 49, 52 and 38 kPa for the evaluated soils compared to 44, 30 and 26 kPa in centre rows, respectively. Anchorage strength in the edge rows of sand, silty clay loam and clay was associated with a greater number of shoots of 7.5, 13.6 and 9.8 compared to 4.3, 7.2 and 7.1 in the centre rows, respectively. The total root length of 637, 565 and 861 cm in the edge rows was also greater compared to 366, 299 and 758 cm in the centre rows for the same soil type order, respectively. Thus, the increase in soil bulk density in the edge rows compared to the centre rows resulted in up to 58% greater anchorage strength and improved plant growth, respectively (Scott et al., 2005b).

2.3.6 The effect of different cultivation systems on soil physical properties

The process of manipulating soil physical conditions to prepare a good seedbed is known as cultivation (tillage). Cultivation system therefore, has a significant effect on the soil physical properties and the root development (Mackie-Dawson et al., 1991; Ferreras et al., 2000; Huang et al., 2012; Wang et al., 2014a), and consequently plant anchorage moment (Goodman & Ennos, 1999; Ennos, 2000; Berry et al., 2003c).

The effect of four different tillage systems: mouldboard plough, chisel plough, para plough (local tool) and no-tillage on soil strength and bulk density were investigated in two soil types (clay loam and silt loam) at 75 -150 mm depth in one season under wet conditions, and at 75 - 150, 225 - 300 mm depth in another season under dry conditions. A fall-cone penetrometer was used for measuring shear strength of soil with aggregates between 20 - 30 mm in diameter, while bulk density was measured using gamma-ray attenuation. Surprisingly, soil strength was not affected by the depth; it was affected in silt loam soil by tillage systems as bulk density was affected too. The tillage system (mouldboard plough) which loosened the soil more, resulted in a greater reduction in soil bulk density, hence a greater reduction in shear strength compared to the no till system (Benjamin & Cruse, 1987).

Schjonning & Rasmussen (2000) studied the effect of direct drilling and mouldboard ploughing on the soil shear strength and the porosity of three soil types (sand, sandy loam and silty loam) at three different depths (4 - 8, 14 - 18, 24 - 28 cm). The results showed that direct drilling in comparison with mouldboard ploughing resulted in higher bulk density, shear strength, cohesion and internal soil friction for the two upper depths (4 - 8, 14 - 18 cm). Compared to mouldboard plough, direct drill had 5% and 26% greater shear strength at the depth of 4 - 8 cm and 14 - 18 cm, respectively, in sandy loam soil and similarly, 30% and 15.5% greater shear strength recorded in silt loam soil. Consequently, direct drilling had less porosity compared to mouldboard plough at all depths in all treatments, the greatest reduction of 8.6% in porosity was observed at the surface soil layer (4 - 8 cm) in sandy soil (Schjonning & Rasmussen, 2000).

Similar to soil bulk density, shear strength and penetration resistance, tillage systems affect soil stability (aggregate size and distribution) which is essential for air exchange and water entry in the soil, accordingly root growth (Graf & Frei, 2013; Menon et al., 2015). In four years of field study on a clay loam soil, the effect of seven different tillage systems on soil stability and wheat yield production was evaluated by Hajabbasi & Hemmat (2000). The treatments used were chisel plough with disc, chisel plough with rotary tiller, double chisel plough with disc and khishchi (local cultivator) with disc as a non-inversion tillage systems, mouldboard plough with disc as a conventional tillage system, both till-planting and no-till with a cultivator combined drill as a direct drilling system. At the first 15 cm depth, direct drilling system improved soil stability by resulting in 4.4% more fine (< 2 mm) soil aggregates compared to 3.2% for conventional tillage system. Hajabbasi & Hemmat (2000) reported lower yield of 4.7 and 5.6 t ha^{-1} for direct drilling systems compared to 7.2 t ha^{-1} for mouldboard treatment. However, no specific values of soil moisture are mentioned apart from the field been irrigated six times from March until harvesting time in July, because the yield of wheat is highly influenced by the amount of soil moisture available during the growing season (Ram et al., 2013).

The effect of soil compaction on soil shear strength, penetration resistance and bulk density was investigated in a clay loam soil cultivated with three different tillage systems: conventional tillage, rotary till by horizontal and vertical axis. The studied parameters were measured at a depth of 30 cm after tillage, planting and harvesting. The use of conventional tillage, rotary tillage-horizontal axis and rotary tillage-vertical axis reduced soil shear strength from 70, 76 and 72 kPa to 22, 13 and 18 kPa respectively. Soil shear strength increased after planting to 50, 40 and 48 kPa and to 84, 85 and 88 kPa after harvesting in conventional, rotary tillage-horizontal axis and rotary tillage-vertical axis, respectively. Penetration resistance was increased from 576 kPa after tillage to 826 after planting for conventional tillage and from 555 to 784 kPa and 614 to 828 kPa for rotary till horizontal and vertical axis, respectively. The greatest increase in shear strength and penetration resistance after planting was in conventional tilled soil, hence, the highest level of compaction was related to the greatest loosening in soil caused by the conventional tillage compared to the other two cultivation systems. The vehicle traffic during harvesting process re-compacted the soil to almost the same value of shear strength as before tillage for conventional tillage (Guclu Yavuzcan et al., 2002).

Similarly on a clay loam soil, Gemtos et al*.* (2002) investigated the effect of plough, heavy cultivator, rotary cultivator, disk harrow and no tillage system on soil bulk density and weed control in a five year crop rotation included cotton, corn, sugar beet and winter wheat. No-tillage system was found to increase the soil bulk density up to 1.60 g cm^{-3}, soil organic matter reached up to 2.78% in the first 10 cm compared to 1.12 g cm^{-3} and 1.56% for plough (conventional) tillage system respectively, also, weed populations increased after four years of no-tillage system. These parameters consequently led to an increase in soil shear strength. No tillage system yielded about 20% less sugar beet compared to conventional tillage system, the highest plant emergence rate was observed in reduced tillage treatment (Gemtos et al., 2002).

A field experiment was conducted by Munkholm et al. (2003) over three years to examine the spatial and temporal effects of two different direct drill systems (culture and single disc drill) on soil strength parameter in seedling environment in a sandy loam soil. In the first year of the experiment, changing tillage technique from mouldboard plough to direct drill with single disc coulters and direct drill with chisel coulters had increased soil bulk density from 1.4 g cm^{-3} to 1.55 g cm^{-3} and penetration resistance from 0.4 MPa to 1.2 MPa below the seeding depth of 40 mm. A further increase up to 2.2 MPa in penetration resistance was recorded in the second year, whereas both soil bulk density and penetration resistance reduced to stable below 1.5 g cm^{-3} and 2 MPa. The results revealed that even though direct drill tillage with chisel coulters left the above soil layer looser compared to the single disc coulters, nevertheless, the use of direct drill on sandy loam soil had increased the value of soil bulk density and penetration resistance to a limit that root development is restricted. (Munkholm et al., 2003). From the results, it is clear that direct drilling keeps the surface soil stronger with higher bulk density and penetration resistance. However, this research did not provide any data on yield or root development and how these were affected by soil compaction and cultivation systems.

Jiuhao et al. (2007) illustrated that soil physical properties are significantly influenced by different tillage techniques. They evaluated the effect of different tillage techniques, such as deep loosening at two vertical directions up to the depth of 450 mm, shallow tillage after deep loosening to the depth of 450 mm and conventional tillage (300 mm) on soil porosity, penetration resistance and soil bulk density. In the deep loosening at two vertical directions, soil porosity was increased by 11.7% compared to 1.4% and 8% in shallow tillage after deep loosening and conventional tillage, respectively. The small increase in soil porosity in shallow tillage after deep loosening compared to the rest of the treatments was due to the soil compaction caused by the tractor as a result of dual operation. The increase in soil porosity was accompanied with a reduction in soil penetration resistance and bulk density; apart from the first two tillage techniques, penetration resistance at the depth of 250 - 400 mm was increased by about 0.3 kPa because of forming a hard layer at that depth in the conventional tillage system. Moreover, a reduction of about 19%, 20% and 11% in soil bulk density was highlighted in deep loosening at two vertical directions, shallow tillage after deep loosening and conventional tillage, respectively. Similar to soil penetration resistance, the lower reduction in bulk density was found in the conventional tillage (Jiuhao et al., 2007).

Depending upon soil type and time of cultivation practice, root development and distribution respond differently to the different cultivation systems, hence, the obtained yield might be affected too (Dwyer et al., 1996). The increase in penetration resistance by 46% in the top 20 mm of soil in no-tillage system compared to conventional system performed in a sandy clay soil caused a significant increase in root length density of spring wheat by approximately 61% (Martinez et al., 2008). These increases in penetration resistance and root length density led to greater soil aggregate stability and size distribution in no-tillage system by 81% than conventional tillage. In spite of the significant influence of tillage system on the above root and soil properties, different tillage systems did not significantly influence the grain yield of winter wheat (Martinez et al., 2008).

Similar results were also found by Huang et al. (2012). The effect of four different tillage systems on soil bulk density, root development and grain yield of winter wheat in silt loam soil was examined. The different tillage systems were conventional tillage (CT), no-tillage without wheat stubble mulching treatments (NT), no tillage with wheat stubble standing treatments (NTSS) and no tillage with wheat stubble mulching treatments (NTS). The authors reported that at the depths of 0 -10 and 10 - 20 cm, the soil bulk density of 1.22 and 1.42 g cm^{-3} was significantly lower in CT treatments, respectively before sowing, compared to the rest of no-tillage systems. After harvesting, in conventional tillage, bulk density increased to 1.32 and 1.33 g cm^{-3} respectively, to be significantly higher compared to the three no-tillage systems which were not significantly different from each other along the growing season. Additionally, the dry root weight density in CT, NT, NTSS and NTS treatments ranged between 5.22, 6.4, 7 and 7.8 ($\times 10^{-4}$ g cm^{-3}) at the depth of 0 - 10 cm and 1.5, 1.7, 1.8 and 1.9 ($\times 10^{-4}$ g cm^{-3}) at the depth of 10 - 20 cm respectively. Likewise, CT treatments had the lowest yield of 6.5 t ha^{-1} compared to the highest yield of 7.6 t ha^{-1} in the NTS treatments (Huang et al., 2012).

The same pattern of bulk density was recorded earlier by Topa et al. (2011) in a clay loam soil after investigating the effect of disc harrow, para plough, rotary harrow chisel plough and conventional plough (all to the depth of 300 mm). The tillage systems up to the 300 mm depth yielded in a greater bulk density compared to the conventional tillage and the highest value of 1.46 g cm^{-3} was found for disc harrow tillage. However, below the 300 mm depth, higher value of bulk density was reported for the conventional tillage compared to the rest of the treatments because of the hard pan layer as a result of soil compaction (Topa et al., 2011; Acuna et al., 2012). Nevertheless, despite using different tillage practices, the variations in soil physical properties diminish when soil loosening and tillage intensity are less varied.

Celik et al. (2011) reported a similar bulk density created by the use of different cultivation equipment. They examined mouldboard plough, disc plough and experimental plough [mouldboard + disc plough] along with different cultivation speeds (4.5, 5.4 and 6.3 km h^{-1}) in a silty loam soil. With no significant effect of travel speed, bulk density non-significantly ranged between 0.87, 0.92 and 0.93 g cm^{-3} for the experimental, mouldboard and disc plough, respectively. However, in the top 100 mm of the soil ploughed with mouldboard, moisture content was 4.5% and 8.2% less compared to disk plough and the experimental plough (Celik et al., 2011). Likewise, Oyelade & Aduba (2012) highlighted non-significant differences in soil bulk density of 1.40 and 1.36 g cm^{-3} of ploughed and harrowed sandy loam soil, respectively, and 1.373, 1.376 g cm^{-3} of ploughed and harrowed clay loam soil, respectively.

2.4 The effect of agronomy on lodging incidence

2.4.1 Lodging incidence and wheat cultivars

The above ground plant characteristics associated with stem lodging have been identified as stem height, number of tillers per plant, centre of gravity of the stem (the distance from the base of the stem to the balance point on the stem), ear weight, stem strength and stem inner and outer diameter (Berry et al., 2004; Sposaro et al., 2010; Martinez-Vazquez & Sterling, 2011). Adventitious root characteristics such as number of roots, root diameter, root plate, root strength are also associated with root lodging (Ennos, 1991a; Rajkumara, 2008; Rademacher, 2009). Moreover, besides the adventitious root characteristics, soil physical properties also contribute to root lodging or anchorage failure incidence (Crook & Ennos, 1993; Crook et al., 1994; Baker et al., 1998; Goodman & Ennos, 1999; Berry et al., 2004; Yang et al., 2015). Plant characteristics associated with stem lodging are cultivar dependent, and reviewed in this section.

The results of Crook & Ennos (1993) who measured the plant bending moment of two lodging susceptible winter wheat cultivars (Galahad and Widgeon) in relation to the root cone diameter, indicated that varieties with greater cone plate size had greater plant bending moment (plant anchorage moment). The cone plate diameter ranged between 26 mm for Galahad to 29 mm for Widgeon, accordingly plant bending moment also ranged between 0.30 Nm (in soil of 4.12 kPa shear strength) for Galahad to 0.41 Nm (in soil with 9.5 kPa shear strength) for Widgeon. Likewise, root bending moment ranged between 0.004 Nm for Galahad to 0.011 Nm for Widgeon. Therefore, it was concluded that root lodging in wheat depends on its adventitious root properties and soil strength. Furthermore, plants with more diffusivity and greater spreading angles of their adventitious roots resist greater lateral forces before lodging occur (Crook & Ennos, 1993). Plant bending moment is positively correlated with the bending moment of the adventitious roots. Throughout the growing stages of two contrasting wheat cultivars Hereward (lodging resistant) and Galahad (lodging susceptible), Crook et al. (1994) reported that the bending strength of the stems and the bending moment for both cultivars increased from the early stages of emergence (Figure 2.12a and 2.12b).

The safety factor against stem lodging is the resistance value against stem lodging, which is the absolute value between the stem strength and the self-weight moment; the self-weight moment is generated by the stem as a result of the lateral forces acting upon the stem. The safety factor against root lodging is the resistance value against root lodging or anchorage failure and, is the absolute value between the anchorage moment and the self-weight moment generated by the whole plant. Crook et al.(1994) reported that the safety factor against stem lodging increased from emergence stage until flowering time, when the Hereward cultivar had a 12% greater safety factor against stem lodging compared to the Galahad cultivar.

However, the structural development of the stems and the adventitious roots did not last until the harvest time; it ceased at the flowering stage of which the safety factor represented by the structure of stem and root decreased. Nevertheless, for both studied cultivars, plant bending moment was correlated ($r^2 = 0.788$) with the bending strength of the adventitious roots; the greater the bending strength of the adventitious roots the greater the plant bending moment (resistance to overturning) (Crook et al., 1994).

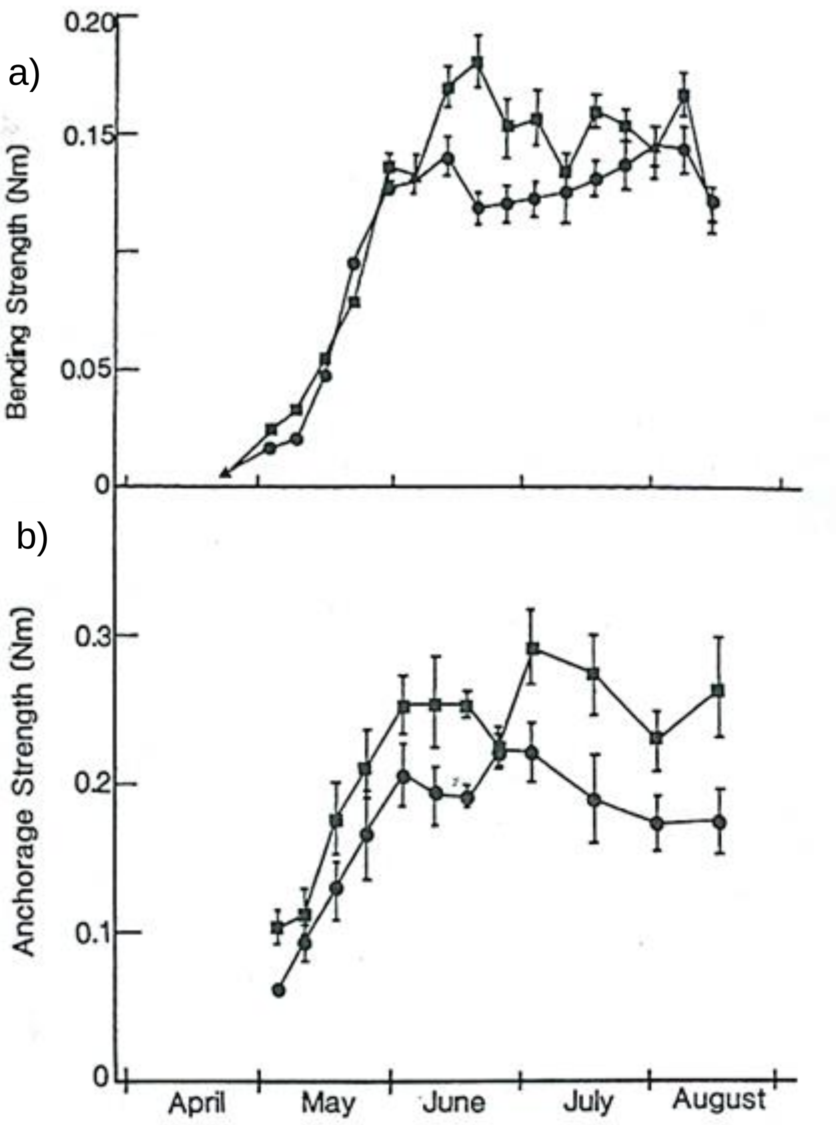


Figure 2.12. (a) Bending strength of the stem, (b) Anchorage strength of the root systems. Circles represent Galahad cultivar, squares represent Hereward cultivar and the triangles represent both cultivars when they have the same value, adopted from Crook et al. (1994).

Kelbert et al. (2004) conducted experiments from 2000 to 2003, in which they investigated the lodging resistance among 25 winter wheat cultivars (ranging from tall to semi-dwarf); those cultivars were sown with two different seeding rates (250 and 500 s m^{-2}) to identify the most lodging resistance cultivar. Apart from the controls, artificial lodging was applied to the treatments at two different stages (GS73-E and GS73-G) when the treatments were scored from 1 (no lodging) to 9 (completely lodged). The authors reported that the 25 genotypes responded differently to the artificial lodging, hence semi-dwarf cultivars in either lodging stages were more lodging resistive compared to tall cultivars which were associated with less number and weight of ears and grain yield.

Kelbert et al. (2004) concluded that the most lodging resistance cultivars (4837.04 and Kohika) were screened with less than 10% reduction in the yield compared to the rest of the treatments and have been adapted by the wheat breeding programme. The reduction in the yield reached up to 40% (from resistive to susceptible to lodging cultivars), which was down to the decrease in the numbers and weight of ears per plant (Kelbert et al., 2004). The results were further supported when Navabi et al. (2006) reported a 50% more lodging incidence in tall wheat cultivars compared to short cultivars. In more than 140 wheat cultivars ranged in three groups based on plant height (tall, intermediate and short), cultivar variation was responsible for 65% of lodging incidence. Nevertheless, despite the non-significant relationship between plant height and lodging susceptibility reported by Tripathi et al. (2005), the tall cultivars which showed 50% greater lodging, produced 13% less yield compared to the short cultivars (Navabi et al., 2006).

Furthermore, it was reported that the reduction in the yield increases with the severity of lodging; the greater the declination angle of the stems from vertical, the more horizontal leaves of wheat which reduce the amount of photosynthesis process carried by the leaves, as a result of changes in sun light radiation, hence, greater yield reduction (Berry & Spink, 2012).

A decreased wheat yield was also observed in another study conducted by Khakwani et al*.* (2010), where the effect of lodging incidence was assessed based on the yield of six different wheat cultivars grown in a silty clay soil. The yield produced in lodged cultivars was about half of the yield in the non-lodged cultivars. The reduction in the grain numbers, weight per spike and the weight of thousand grains along with the increase in wilted grain numbers among the varieties led to yield reduction. The highest yield of 6.3 t ha^{-1} was recorded for non-lodged compared to 3.9 t ha^{-1} for lodged cultivars (Khakwani et al., 2010).

Accordingly, stem characteristics associated with stem lodging have been extensively researched (Crook & Ennos, 1995; Scott et al., 2005b; Martinez-Vazquez & Sterling, 2011; Niu et al., 2012). Hence, it can be concluded that the risk of stem lodging in wheat has been reduced by up to 20% because of producing shorter wheat plants with dwarf genes and identifying the more lodging resistant cultivars (Berry et al., 2003a; Shearman et al., 2005; Peng et al., 2014). Nevertheless, lodging is still a problem in wheat production, and also plants cannot be shorten more to maintain the yield. Further research therefore, is required to increase the resistance of root lodging or anchorage failure, which is more likely to occur in wheat and depends on the adventitious root properties along with the physical properties of the surrounding soil (Crook & Ennos, 1993; Easson et al., 1993; Sterling et al., 2003; Reynolds et al., 2009; Yang et al., 2015).

2.4.2 The effect of seeding rate and weather conditions on lodging

For a maximised yield, wheat growers in early growing season from September to late October, use low seed rate around 300 to 350 seed per m^2 targeting around 260 plants per m^2. Nevertheless, the seed rate needs to be increased by an extra 50 plants for each month delay in sowing date, so the reduced tillering due to the late sowing date can be compensated (HGCA, 2008).

While a reduced seed rate may increase the risk of fallow patches in the field, a high seed rate increases the risk of both stem lodging and root lodging (Berry et al., 2000; Hoad et al., 2001). The increased seed rate increases the risk of stem lodging through reduced stem diameter and less stem strength along with higher stems; in addition there is greater risk of root lodging through declined adventitious root development in terms of number, and diameter (Berry et al., 2003a; Li et al., 2008). The higher the seed rate the less the lodging resistance (HGCA, 2008).

On the similar them, Easson et al*.* (1993) investigated the effects of seed rates, weather condition and cultivars on lodging and yield of four wheat cultivars sown at six different seed rates (50, 100, 200, 400, 800 and 1600 seed m^{-2}) in sandy clay loam soil. When wind speed exceeded 50 km hr^{-1}, severe lodging occurred in cultivars with longer tillers that were sown at high seed rates of 800 and 1600 seed m^{-2}. The yield reduction in these treatments reached up to 80% and decreased rapidly in the treatments with lower seed rates of 50 and 100 seed m^{-2} where no lodging occurred. The severe lodging was associated with the highest amount of rainfall (70 mm) during grain filling stage from mid-July to mid-August. Moreover, the results showed that the increase in the percentage of lodging reduced plant properties such as grain yield, fresh weight and weight of 1000 grains. Hence, based on the outcomes of this study, Easson et al*.* (1993) suggested that to minimise the risk lodging and maintaining high yield in winter wheat, lodging resistance cultivars with reduced seed rates based on date of sowing will be beneficial (Easson et al., 1993).

Furthermore, despite the influence of the surrounding environments on the stems and roots properties of wheat, to some extend plants are able to resist and adapt to the surrounding environment conditions (Crook & Ennos, 1996). A study of the influence of wind factor on the measurements of the stem and root properties in Hereward winter wheat, reported greater measurements of stem and root properties (angle of spread of the adventitious roots, total number of roots, total root length, total root bending strength and anchorage strength) of free standing wheat plants compared to frame supported plants (field grown). Safety factor against stem failure and anchorage failure were 8% and 31% greater in the free standing plants compared to the frame supported plants. The greater safety factor against stem lodging and root lodging in the free standing plants was caused by an up to 30% increase in the values of the angle of spread of the adventitious roots, total number of roots, total root length, total root bending strength and anchorage strength compared to the frame supported plants (Crook & Ennos, 1996).

2.4.3 Soil moisture content and plant properties

Similar to soil properties, plant characteristics are also highly influenced by soil moisture (Cannell et al., 1984; Newman & Moser, 1988; Blum, 2005; Zhang et al., 2015). The amount of water available to the plant affects its above ground properties (Nouri-Ganbalani et al., 2009), cultivar’s tolerance and sensitivity to drought stress (Stone & Nicolas, 1994; Chen et al., 2012) and the yield (Dickin & Wright, 2008; Zhang et al., 2014). More importantly, it affects the development of root system (Malik et al., 2002; Izzi et al., 2008; Labdelli et al., 2014) which is the main focus of this study because it contributes to the plant anchorage moment or root lodging (Berry et al., 2003a; Yang et al., 2015).

Adventitious root development starts from the three-leaf stage in most cereal crops including wheat and barley (Newman & Moser, 1988). However, adventitious roots development may be limited or stopped if the plants are exposed to a severe drought stress or waterlogging condition at the stage when the adventitious root growth is taking place (Gales et al., 1984; Carr, 1989; Gorny, 1992).

The effect of four different levels of drought stress (25%, 50%, 75% and 100% of field capacity) on five barley cultivars was investigated by Sahnoune et al. (2004), and the seminal root characteristics were observed. The volume and the length of the absorption roots were significantly reduced with the decrease of the water content; root length decreased more than three fold when drought stress intensity increased from 100% to 25% of field capacity. Depending upon the time and severity of the drought stress, roots may stop growing or even die (Sahnoune et al., 2004).

Likewise, Liu et al. (2004) reported an increase in root dry weight and the root-shoot ratio due to the effect of drought stress. They investigated the effect of three levels of water content (80%, 50% and 25% of field capacity) on two spring wheat cultivars (drought sensitive (Longchun 8139-2), drought tolerant (Dingxi 24)) grown in clay soil in pots of 120 cm length and 10 cm diameter. In the drought sensitive cultivar, increasing drought stress intensity from 80% to 25% of field capacity increased root dry weight and root-shoot ratio by 0.4% and 12%, respectively. In the drought tolerant cultivar, a 13% increase in root dry weight and 26% in root-shoot ratio was observed due to the 50% increase in drought intensity (Liu et al., 2004). These results were supported by the results of Adda et al. (2005) who reported a similar pattern of reduction in root length accompanied by an increase in root volume and root-shoot ratio. Furthermore, in the drought stress intensity of 25% of field capacity, root length reduction reached more than 30% when the effect of drought stress on eight wheat cultivars was investigated (Adda et al., 2005). Hence, more than 90% of the root volume was localised in the top 15 cm of the sandy soil.

In contrast, Izzi et al*.* (2008) found no differences in wheat root development between three wheat cultivars subjected to drought stress, when the three wheat cultivars (Hamam 1, Dem 6 and Cham 5) were grown on a fine clay soil subjected to four levels of irrigation (rainfed, irrigated to field capacity, 66% of field capacity and 33% of field capacity). No significant differences were detected in root development due to irrigation system; this was down to applying the irrigation treatments at a stage at which the roots were fully developed, after the booting stage (Izzi et al., 2008).

In the United Kingdom, wheat plants are also prone to waterlogging, which is more likely to occur when the plants are at early growth stages, and effects on root growth and development during this period may subsequently reduce yield (Cannell et al., 1984).

The effect of waterlogging on two winter wheat cultivars (Deben and Xi-19) sown at 264 and 132 plant m^{-2} was examined by Dickin & Wright (2008). Wheat plants, grown in clay loam and sandy loam soils were subjected to different waterlogging (44 days waterlogged after 93 days of sowing and 58 days after 64 days of sowing). Waterlogging resulted in a 50% reduction in tiller number per plant and up to 35% reduction in adventitious root number, thus a positive linear relationship (r^2 = 0.72) was observed between tiller number and adventitious root number. Yield reduction reached up to 20% and 24% for plants subjected to 44 and 58 days of waterlogging (Dickin & Wright, 2008).

However, no reduction in the adventitious root properties was reported when wheat plants grown in pots were subjected to waterlogging (Malik et al., 2002). Wheat plants were waterlogged for different period of 0, 3, 7, 14, 21 and 28 days starting from 21 days after sowing when the adventitious roots start to develop (Newman & Moser, 1988). Despite the waterlogging, adventitious roots unlike the fine absorption roots, were able to survive and grew to a maximum of 15 cm during the waterlogging period, and even recovered and grew further through the drained duration (Malik et al., 2002).

2.4.4 Lodging responses to the applications of nitrogen and plant growth regulator

It is generally accepted that fertiliser application and most importantly, nitrogen application is required to increase the yield of wheat. However, too high rate of nitrogen application may have a negative effect on the plant as it decreases the light interception that provide a suitable environment for diseases (Tripathi et al., 2005); and increases the risk of lodging in winter wheat (Crook & Ennos, 1995; Berry et al., 2003a).

An increase of 2.5% in plant height, hence, the centre of gravity of shoots in two winter wheat cultivars (susceptible Galahad and resisting Hereward to lodging) were reported by Crook & Ennos (1995) as a result of applying 240 kg ha^{-1} of nitrogen compared to 160 kg ha^{-1}. Moreover, the number and rigidity of adventitious roots was greater in plants with a low rate of nitrogen application. Therefore, the increase in nitrogen application reduced both stem and anchorage strength of plants by 20% and 17%, respectively, compared to the plants with a reduced rate of nitrogen (Crook & Ennos, 1995).

In a more recent study, the increase in lodging resistance in winter wheat with the reduction in input rate of nitrogen application was also observed by Loyce et al. (2008). The effect of four crop management systems starting from high to low input rates of nitrogen application, seed rate, fungicide protection and plant growth regulator on lodging incidence and the yield of 19 wheat cultivars was examined. Over three growing seasons, the wheat plants were sown in loamy clay and sandy soil, loamy clay and clayey calcareous soils over 10 locations.

In all cultivars, a mean difference of 1.4 was highlighted in lodging intensity between the crop management one and crop management four (a low-input management where no fungicide and plant growth regulator applied and less nitrogen fertiliser and seed rate by 90 kg ha^{-1} and 40%, respectively, compared to crop management one). The effect of fertiliser application and plant growth regulator combined with sowing density was greater compared to the cultivar tolerance; 40% less lodging intensity was reported due to 40% reduced sowing density and 60 kg ha^{-1} nitrogen application less than crop management two which was adjusted to the recommended rates (Loyce et al., 2008).

From the agronomic point of view, the uptake of phosphorus (P) and nitrogen (N) has a major effect on wheat production depending upon the application time in terms of the stage of crop development (Oladokun & Ennos, 2006). Nevertheless, increasing the fertiliser application leads to an increase in ear weight and size, which consequently increases the risk of stem lodging.

The risk of stem lodging can be minimised or controlled through reducing plant height by applying plant growth regulator (PGR). An increase in wheat yield up to 19.1% was reported because of increasing the photosynthesis rate, leaf area index and dry matter accumulations resulted from applying plant growth regulators such as chlormequat (CCC) (Shekoofa, 2008) and Terpal growth regulator (Crook & Ennos, 1995).

In a more recent study, where two wheat varieties (JM22 lodging resistance and SN16 susceptible to lodging) where sown on a loamy clay soil, Peng et al. (2014)

investigated the effect of application of two types of exogenous PP_{333} and AG_3 on the wheat stem characteristics associated with lodging. In both wheat varieties and unlike the application of AG3 exogenous, PP_{333} exogenous reduced the plant height by 5.4%, the length of the basal internode by 12% and increased the diameter and the wall thickness of the basal internode by 5.8% and 12.8%, respectively. Thereby, the application of PP_{333} exogenous increased the breaking strength of the basal internode at dough stage (at which the stems were taken from the field and subjected to mechanical test) by 11.3% and, hence, the culm lodging resistance index increased by 12.5%. The increased breaking strength of the basal internode and culm lodging index resistance was caused by a 12% increase in lignin accumulation, due to PP_{333} application compared to the control treatments with no application (Peng et al., 2014).

It was reported that the mechanics and patterns of lodging in rice are similar to that in wheat (Oladokun & Ennos, 2006), Bhiah et al. (2010) conducted a glasshouse experiment to investigate the effect of potassium (K) addition on the susceptibility of lodging in three different species of rice which were grown in a non-sodic and non-saline black vertosol. The application of potassium reduced the risk of lodging in all three cultivars as a result increasing the plant height by 30%, stem diameter by 32% and stem strength by up to 30%. Thereby, an increase in the yield up to 30% was observed (Bhiah et al., 2010).

2.4.5 Stem lodging and stem characteristics

Stem lodging in the wheat crop is a buckling of the stem at a basal internode, therefore, strong stems are needed to minimize and prevent stem lodging. The strength of the stem depends upon the stem characteristics such as stem height, inner and outer diameter, strength, weight and wall properties (Crook et al., 1994;

Berry et al., 2003c; Wang J Fau - Zhu et al., 2012). In a two year experiment on a gleyic and eutric cambisol soil, Zuber et al*.* (1999) investigated the effect of stem characteristics (plant height, stem length, stem diameter, ear weight, stem weight and stem weight per stem length) on lodging resistance of 15 genotypes of spring wheat. The genotypes have been classified into three breeding lines according to their height (short, medium and tall) and the lodging resistance (scored from 1 - 9. 1 for completely upright and 9 for completely lodged). It was highlighted that genotypes with greater diameter and heavier stems showed higher lodging resistance scores, the diameter and the weight of the stems explained 48.5% and 49.7% of lodging variation among the genotypes. More than 70% of the variation in lodging resistance in the 15 used genotypes was linked to their stem weight per length and ear weight (Zuber et al., 1999).

Furthermore, Niu et al*.* (2012) also addressed plant height, centre of gravity and stem bending strength as important properties in terms of stem lodging in wheat. In a two year experiment, stem characteristics (ear number per m^2, plant height, centre of gravity, stem bending strength, stem and plant lodging resistance strength) of 10 Chinese winter wheat were measured using a lodging resistance electronic measuring device (Figure 2.13). Taking into account plant ear weight and centre of gravity as they vary across growing stages, a significant negative correlation was found between the plant height and stem lodging for all cultivars. Plant height was negatively correlated with single stem lodging resistance (R^2 = -0.771), stem bending strength (R^2 = -0.518) and plant lodging resistance (R^2 = -0.876). Lodging resistance reduced with an increasing plant height, centre of gravity and ear weight (Niu et al., 2012).

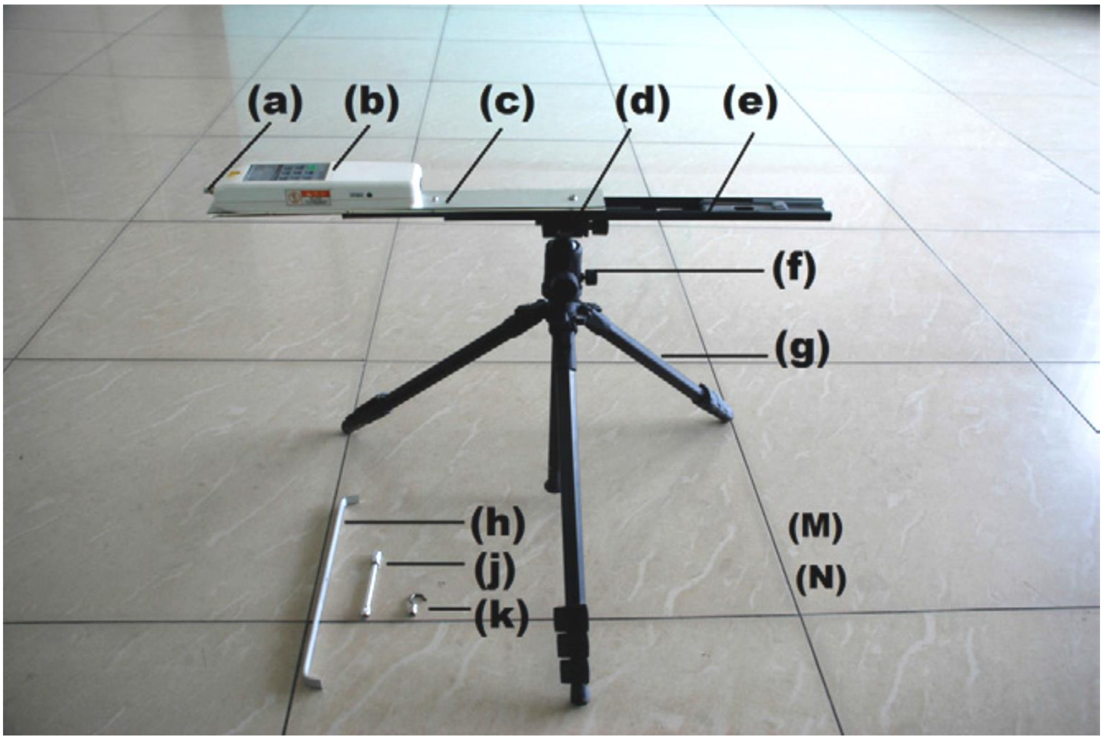


Figure 2.13. The crop lodging resistance electronic measuring device. (a) Probe installation location, (b) force measurement unit, (c) dust and connection plate, (d) quick release plate, (e) ball guideway, (f) ball joints, (g) adjustable multi-functional tripod, (h) wheat population lodging resistant strength measurement probe, (j) “V” shape probe (stalks bending strength measurement probe), and (k) wheat sing stalk lodging resistant strength measurement probe, adopted from Niu et al. (2012).

Later, in more recent research about the associated stem characteristics of four Chinese spring wheat lines (two solid stems and two hallow stems), Kong et al. (2013) reported that the width of the mechanical tissue layer of the stem might explain 99% of the variation in lodging resistance in wheat. The solid stem genotypes showed 3 - 4 times greater lodging resistance compared to hollow stem genotypes, which could be due to greater stem wall and mechanical support tissues. Furthermore, the researchers found positive correlations between the lodging resistance and width of the mechanical tissue layer (r = 1.000), stem diameter (r = 0.972) and weight of the three lower internodes (r = 0.986). Hence, they concluded that wheat breeders should consider stem characteristics and its solidity as they play a vital role in increasing lodging resistance among wheat genotypes (Kong et al., 2013).

Although lodging in wheat can be either by stem lodging or root lodging depending on the weather conditions and plant properties (Baker et al., 1998; Berry et al., 2003c), root lodging is more prevalent in the UK (Graham, 1983; Easson et al., 1993; Crook et al., 1994; Berry et al., 2002). Nevertheless, stem characteristics affect root lodging too (Martinez-Vazquez & Sterling, 2011; Berry & Spink, 2012; Yang et al., 2015), thus, they are important and need to be considered.

2.4.6 Stem lodging and disease infection

Wheat plants grown in field conditions are subjected to diseases and insect infection. Diseases and insects affect the plant physical properties associated with lodging and increase the likelihood of lodging. Pesticide and disease control applications, therefore, are essential to avoid the risk of lodging and yield reduction (Easson, 1995; Berry et al., 2008).

The effect of disease control (Impact Excel (active ingredients Clorothalonil + flutriafol, 2.5 litre per hectare) and Sportak Alpha (active ingredients Carbendazim + prochloraz, 1.5 litre per hectare)) application on winter wheat characteristics sown in sandy loam and sandy clay loam soils was examined in a three year experiment conducted by Easson (1995). Compared to the control treatments with full application, the absence of disease control increased the average height of the plant by 3.5, 7.6 and 10 cm respectively. A significant lodging percentage from 9% to 50% (of the plot area 2 m x 15 m) was observed in the last growing season, furthermore, the absence of disease control application, reduced grain yield by 19%, 21% and 22%, respectively, during the three years of the experiment (Easson, 1995).

In another study, Ray et al. (2006) examined the effect of eyespot caused in inoculated winter wheat with moderate and severe lesions of *Oculimacula yallundae* or *Oculimacula acuformis* on the safety factor and bending strength of the wheat stem. Ray et al. (2006) reported that, the safety factor against stem lodging decreased with increasing the concentration of the lesions. The moderate eyespot infection of 157 and 27 pg ng^{-1} DNA of *O. acuformis* and *O. yallundae* had reduced the safety factor from 7.65 to 6.67 and 6.60, respectively. The safety factor was further decreased to 4.19 and 5.14 with severe eyespot infection of 234 and 40 pg ng^{-1} DNA of *O. acuformis* and *O. yallundae*, respectively. Due to the eyespot infection, stem lodging is more likely to occur compared to root lodging, assuming the roots are not affected and remain the same. Although the reduction in the safety factor was caused by a decrease in the above ground properties associated with lodging, nevertheless, the 11% and 6% reduction in the yield was not to the same extent as the 36% and 33% reduction in the safety factor caused by severe eyespot infections of *O. acuformis* and *O. yallundae* respectively (Ray et al., 2006).

Apart from disease infections, plant stems are also prone to insect infections in which lodging occurred and the yield is reduced. Sawfly is one of the major insect pests that affects winter and spring wheat. It damages and weakens the stem and then the stem's ability to resist lateral forces is reduced so lodging occurs (Hein & Specialist, 2007). Moreover, due to the sawfly infection, 27% of lodging in resistant cultivars was reported by Cook et al. (2004), while Weiss & Morrill (1992) addressed 60% lodging in susceptible cultivars.

2.5 Measurement of plant properties associated with lodging

Lodging is the permanent displacement of plants from their upright position (Pinthus & Brady, 1974). Although lodging does not occur every year, it occurs once every four to five years (Berry et al., 2003a). Most years it will be difficult to differentiate between lodging susceptible and resistant cultivars, whereas in severe lodging years, all varieties lodged. Hence, despite the difficulties associated with methods of quantifying lodging resistance, the increase in lodging incidence has led researchers to focus on identifying more lodging resistance cultivars (Crook & Ennos, 1994; Berry et al., 2003a), and enhancing plant anchorage strength (Graham, 1983; Crook et al., 1994; Berry et al., 2003a). Moreover, creating more practical methods to determine plant properties associated with lodging is essential so that cultivars can be compared in terms of their resistance to lodging.

Crook & Ennos (2000) developed a portable lodging meter and tested the device upon two wheat cultivars. They demonstrated that the lodging device was successfully able to highlight significant differences in plant anchorage moment between the two different cultivars of wheat, and the results were comparable with results obtained previously using laboratory methods such as using a universal Instron machine where stems or roots are subjected to a three-point bending test (Crook et al., 1994) . Thus, an inexpensive and portable lodging device was produced (Figure 2.14) which can easily be used *in situ* to measure lodging resistance parameters. As shown in Figure 2.14, the torque screwdriver is free to rotate within its housing, causing the lodging arm to rotate, thereby pushing the plant over. The resistance to rotation or plant anchorage moment can be read through a digital readout meter that is connected to the devise and the secured spikes keep the outer casing motionless during the test (Crook & Ennos, 2000).

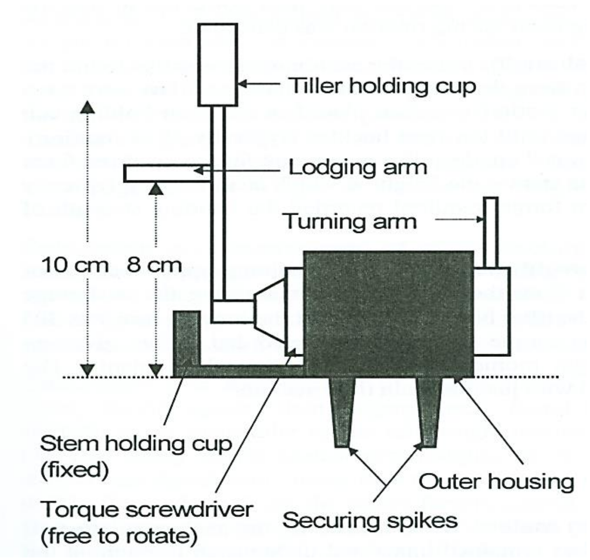


Figure 2.14. Plan of the lodging meter. The torque screw driver is free to rotate within its housing, causing the lodging arm to rotate, thereby pushing the plant over. The secured spikes keep the outer casing motionless during the test, adopted from Crook & Ennos (2000).

The root system anchors plants, and prevents plant lodging and keeps the plant upright until harvesting season. The pull-out force of a plant and the soil-root interaction has been examined by Sun et al. (2011) using a motorised pull-out machine with modified clamps (Figure 2.15a and 2.15b). They acknowledge that for some plant species like maize and sunflower, root anchorage strength (pull-out soil-root interaction forces) could be measured and determined through both stem diameter and shoot height. However, root measurement is preferred for multi-branched plants. This difference is related to the linear relation of the peak value of the pull-out force to the height of the shoot or stem diameter.

The coefficient of calculation were higher in single branch species like maize and sunflower ($R^2 \geq 0.798$) than those of multiple branched species such as fat-hen ($0.66 \leq R^2 \leq 0.69$); this was because of the difference in stem morphology (Sun et al., 2011). Nevertheless, the stem and root properties measured with the pull-out machine, do not represent the resistant to overturning or lodging incidence, but they might be related to it, because pulling out the plant is obviously different from lodging or overturning.

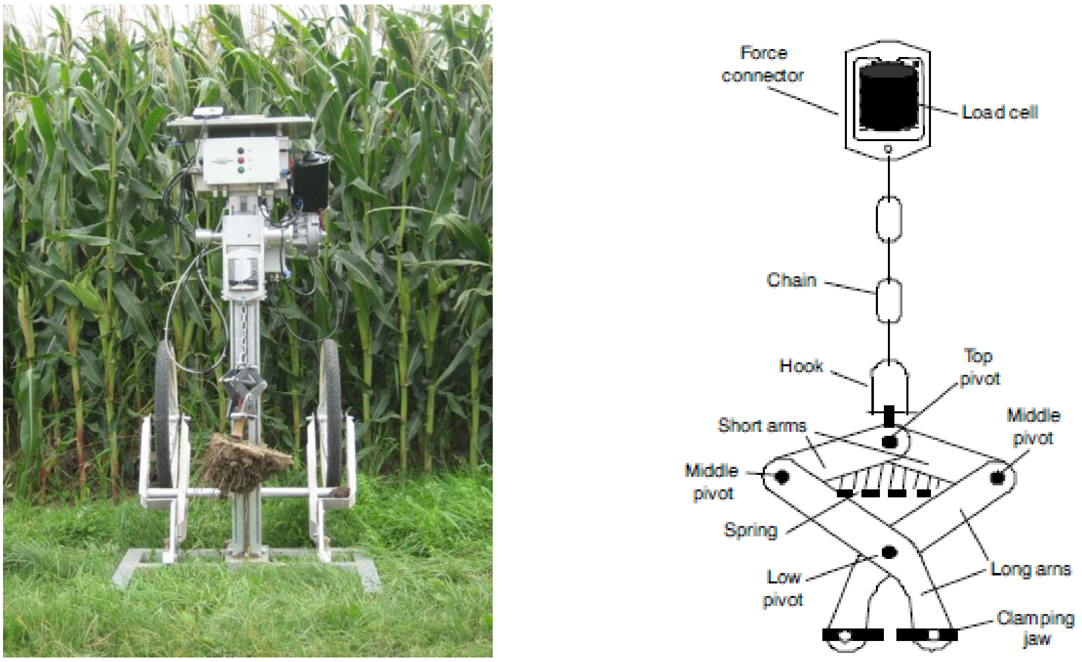


Figure 2.15. A motorised pull-out machine (left), schematic diagram of a clamp (right), adopted from Sun et al. (2011)

2.6 Lodging models

Early research investigating lodging in cereals focussed on identifying plant properties correlated with lodging incidence (Neenan & Spencer-Smith, 1975; Crook & Ennos, 1994; Berry et al., 2003b; Martinez-Vazquez & Sterling, 2011).

Research in 1980's and 1990's focussed on explaining how and why plant properties are important, hence, static models of lodging in cereals were produced (Neenan & Spencer-Smith, 1975; Crook & Ennos, 1994; Baker, 1995). These produced simple models; whilst highlighting which varieties are susceptible or resistant to lodging, they are limited in that provide no means of predicting whether lodging will occur or not. This is because these models require dynamic loading *in situ* to be factored such as weather conditions, which generate loading upon the plant. More recent work especially that of Baker et al. (1998); Berry et al. (2003b; c) and Martinez-Vazquez & Sterling (2011) have investigated the conditions required to cause lodging, and produced models accordingly.

Stem buckling in wheat was first considered by Neenan & Spencer-Smith (1975) as a predominant feature compared to anchorage failure. Based on their theory, the resistance of the stem against wind forces or rain depends upon the stem characteristics, the taper degree and elasticity of the stems.

When the ear is pushed away from the vertical axis by rain or wind force, the stem that carries the ear will be subjected to bending force and start to form a curve along its length. Buckling occurs at a point at which the radius of the curve formed on the stem reaches the maximum, because of the continuous wind force or rain applied to the ear and bending of the stem (Figure 2.16). At this point, the risk of stem buckling has reached the maximum; hence, one side of the stem is subjected to a maximum extension whereas the highest compression is reached on the other side, and the maximum strain ϵ_l (extension or compression) at either side is calculated using Equation 2.2.

$$\epsilon_l = \frac{r_{1l}}{\rho_l} \qquad \text{(Eq. 2.2)}$$

Where

r_{1l} = the outer radius of the stem at a point of l distance from the roots (mm)

ρ_l = the radius of the curve formed by the stem along its length (cm)

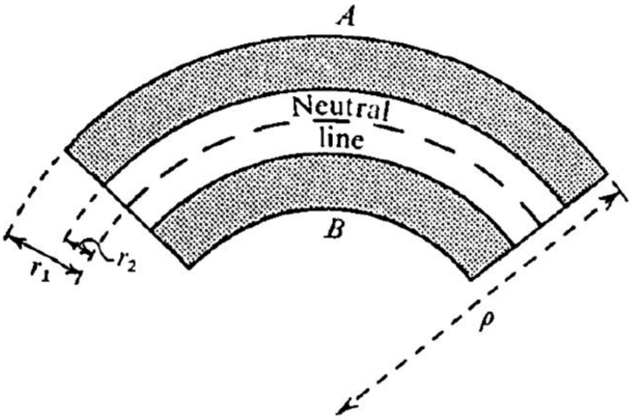


Figure 2.16. Schematic representation of a bent cereal straw. A, Convex surface of straw under stress; B, concave surface of straw under stress; r_1, external radius of culm; r_2, internal radius of culm; ρ, radius of curvature, adopted from Neenan & Spencer-Smith (1975)

ρ_l was calculated by Neenan & Spencer-Smith (1975) using Equation 2.3.

$$\rho_l = \frac{IE}{W(L-l\ )} \frac{\pi}{4} \frac{E}{W} \frac{(R_1^4 - R_2)_4^2}{(L-l\ )} \frac{(L+\alpha+l\ )^4}{(L+\alpha)^4} \qquad \text{(Eq. 2.3)}$$

Where
I = the moment of inertia of the cross section (kg.m^2)
E = the Young's modulus of the stem (g cm^{-2} x 10^6)
W = wind force acting upon the ear of the stem (g)
L = total length of the stem (cm)
l = a point distance from the root (cm)
R_1= outer radius of the stem at the base (mm)
R_2 = internal radius of the stem at the base (mm)
α = distance from the ear to the point at which strain (tension and compression) is maximum (cm)

The stem buckles or flattens because of the deformation in the cross sectional of the stem at the point where the strain is maximum and reaches a critical value; the critical value of the force causing deformation and stem buckling is proportional to r_1/t where t is the wall thickness of the stem at this point . Additionally, Neenan & Spencer-Smith (1975) highlighted the area of the ear as an important factor in determining the necessary wind speed F to cause buckling along with the wind speed based on the Equation 2.4.

$$F = KAV^2 \qquad \text{(Eq. 2.4)}$$

Where
F = is the required force to cause stem buckling
K = constant (0.0066)
A = the area of the ear (cm^2)
V = wind velocity (m sec^{-1})

Based on the outcome of the model, and to determine the required wind speed at which stem buckling is occurred, stems of wheat plants with the average area of 8 ± 2.3 cm^2 were subjected to various wind speeds. Thus, 21.7 m sec^{-1} was found to be the maximum wind speed at which the stem could resist before it buckles (Neenan & Spencer-Smith, 1975). Nevertheless, the stem's frequency was not taken into account by Neenan & Spencer-Smith (1975), hence it was a greater wind speed compared to the 14 m sec^{-1} wind speed observed by Easson et al. (1993) which caused severe lodging in wheat.

In contrast, Crook & Ennos (1993) observed that root lodging or anchorage is more likely to occur compared to stem failure or buckling. During the lodging process, the movement of the adventitious roots in spring wheat is different compared to winter wheat.

In spring wheat, when the stems are subjected to a lateral force, the roots start to rotate in the surrounding soil, the adventitious roots which are bent at their base (because of the lateral force applied to the stems) rotate into and out of the soil around their centre which forms about 10 - 15 mm below the stem base in the soil, as illustrated earlier in Figure 2.3a. In winter wheat and in case of the small inclination of the stems, the movement of the adventitious roots is the same as in spring wheat. However, when the stems are subjected to a greater lateral forces, the stem inclination from vertical will be due to the rotation of the whole plant in the soil. Because the soil beneath the stem base sinks to a lower level opposite to the direction where the lateral force come from, and the centre of the rotation moves down to about 10 - 20 mm towards the direction where the lateral force come from, as shown in Figure 2.3b. Hence, both the strength of the adventitious roots and the cone of soil surrounding them are important to resisting the root movement or lodging.

Nevertheless, taking into account the root soil-cone dimension and the strength of the soil (namely shear strength), the overturning resistance moment (*M*) was calculated using Equation 2.5.

$$M = \frac{9}{8}\tau\pi D^3 \qquad \text{(Eq. 2.5)}$$

Where
τ = soil shear strength (kPa)
D = diameter of the root-soil cone (mm)

To calculate the required force F, which resists the root-soil cone, Equation 2.6 was used. Thus, lodging in wheat is due to the anchorage failure which depends on both soil shear strength and the root-soil cone plate dimensions (Crook & Ennos, 1993).

$$F = \frac{9}{4}\tau\pi D^2 \qquad \text{(Eq. 2.6)}$$

Furthermore, the possibility of both stem failure and anchorage failure or root lodging is present and depends on weather conditions, plant and soil properties based on the lodging model developed by Baker et al. (1998) and Berry et al. (2003a; c). According to the model developed by Baker et al. (1998), stem failure occurs when the self-weight moment of a single tiller exceeds the strength of the lower internodes of the stem. Root failure, conversely, occurs when self-weight moment of a plant is greater than its anchorage moment. Anchorage failure moment (B_R) was calculated using Equation 2.7 (Baker et al., 1998), which is:

$$B_R = k_5 S d^3 \qquad \text{(Eq. 2.7)}$$

Where
k_5 = constant 0.43
S = soil shear strength (MPa)
d = the diameter of the root-soil cone plate (mm)

Also, taking the weather conditions, root and soil properties into account, the authors calculated soil shear strength S using Equation 2.8.

$$S = S_D - \frac{i}{\left(\frac{\rho_S}{\rho_W}\right)(f - W)l} (S_D - S_W) \qquad \text{(Eq. 2.8)}$$

Where

S_D = value of soil shear strength at permanent wilting point (MPa)
i = daily rainfall (mm)
ρ_S = the density of soil (g cm^{-3})
ρ_W = the density of water (g cm^{-3})
f = the soil moisture content at field capacity (g g^{-1})
W = the soil moisture content at permanent wilting point (g g^{-1})
l = the structural rooting depth (mm)
S_W = value of soil shear strength at field capacity (MPa)

Baker et al. (1998) developed Equation 2.9 to calculate the base bending moment of the shoot (B) which was further developed to Equation 2.10 by Berry et al. (2003a) to be used for the calculation of the stem failure moment (B_s).

$$B = \frac{1}{2}\,\rho A C_d X V_g^2 \left(1 + \frac{g}{(2\pi n)^2 X}\right)\left(1 + e^{-\pi\xi\frac{\sin\left(\frac{\pi}{4}\right)}{\frac{\pi}{4}}}\right) \qquad \text{(Eq. 2. 9)}$$

Where

ρ = the density of air (1.2 kg m^{-3})

A = the area of the ear (m^2)

C_d = drag coefficient of the ear (1.0)

X = the height of the centre of gravity (m)

V_g = the gust speed (m s^{-1})

g = acceleration due to gravity (9.81 m s^{-2})

ξ = plant damping ratio (0.08)

n = natural frequency of the shoot (Hz)

Additionally, if the required force for breaking (F_s) and the length (h) of the internodes are known, the stem failure moment B_s can be calculated using Equation 2.10 (Berry et al., 2003a).

$$B_s = \frac{F_s h}{4} \qquad \text{(Eq. 2.10)}$$

Combining and reorganizing the Equations 2.7, 2.8, 2.9 and 2.10, enabled Berry et al. (2003a) to determine the required wind speed to cause anchorage failure V_{gR} in Equation 2.11 and stem failure at first internode V_{gs1} in Equation 2.12; or even above the first internode such as second internode V_{gs2} using of Equation 2.13.

$$V_{gR} = \sqrt{\frac{2B_R}{N(\rho AC_D X)\left(1+\frac{g}{(2\pi n)^2 X}\right)\left(1+e^{-\pi\xi\frac{\sin\left(\frac{\pi}{4}\right)}{\frac{\pi}{4}}}\right)}} \qquad \text{(Eq. 2.11)}$$

$$V_{gS1} = \sqrt{\frac{2B_{S1}}{(\rho AC_D X)\left(1+\frac{g}{(2\pi n)^2 X}\right)\left(1+e^{-\pi\xi\frac{\sin\left(\frac{\pi}{4}\right)}{\frac{\pi}{4}}}\right)}} \qquad \text{(Eq. 2.12)}$$

$$V_{gS2} = \sqrt{\frac{2B_{S2}}{\left(\frac{X-h_1}{X}\right)(\rho AC_D X)\left(1+\frac{g}{(2\pi n)^2 X}\right)\left(1+e^{-\pi\xi\frac{\sin\left(\frac{\pi}{4}\right)}{\frac{\pi}{4}}}\right)}} \qquad \text{(Eq. 2.13)}$$

Where the number of the shoots per plant is N and the length of the first internode is $h1$

Hence, taking into account the weather conditions, plant and soil properties, from the values calculated in the Equations 2.7, 2.9, 2.10 and 2.11 stem or anchorage failures could be determined. Stem failure occurs when the value of the base bending moment of the shoots in Equation 2.9 is greater the value of stem failure moment in Equation 2.10. Anchorage failure occurs when the value of wind speed in Equation 2.11 is greater than the value of anchorage failure moment in equation 2.7 (Berry et al., 2003a).

In a more recent model to predict lodging in wheat developed by Martinez-Vazquez & Sterling (2011), an ideal wheat plant, as demonstrated in Figure 2.17, needs to overcome the lateral forces and resist lodging (stem or anchorage). Therefore, the horizontal reaction force generated below the ground by the root-soil ball (R_h) needs to be equal to the sum reactions generated above the ground of the:

1. inertial force P (l),
2. damping force from the friction in between stem wall fibres and the root P (c),
3. the resistance generated from the stiffness of the stem P (k_s)
4. less the force acting upon the ear generated by the wind P (t), as demonstrated in Equation 2.14.

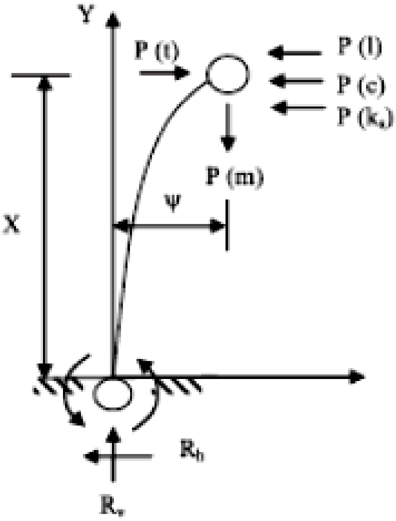


Figure 2.17. Diagram of an ideal wheat plant, adopted from Martinez-Vazquez & Sterling (2011)

$$R_h = P\,(l) + P\,(c) + P\,(k_s) - P\,(t) \qquad \text{(Eq. 2.14)}$$

Additionally, the vertical reaction generated below the ground by the root-soil ball (R_v) needs to be equal to the P (m) which is = mg generated above the ground from the mass of the shoot (m) multiplied by the acceleration due to gravity (g) (Eq. 2.15).

$$R_v = -P\,(m) \qquad \text{(Eq. 2.15)}$$

Unlike Baker et al. (1998), Martinez-Vazquez & Sterling (2011) determined the base bending moment B using Equation 2.17. The plant was considered as two masses (one represents the ear above the ground and the other represents the root-soil below the ground) connected through one bar (representing the stem), as in Figure 2.17.

$$B = \psi\, mg + \psi\, kX \qquad \text{(Eq. 2.16)}$$

Where

B = base bending moment of the plant (Nm)

ψ = displacement of the plant from vertical (m)

m = mass of the shoot of the plant (kg)

g = acceleration due to gravity (9.81 m s^{-1})

k = the resistance generated from the stiffness of the stem

X = height of the centre of gravity of the plant (m)

The displacement factor which was measured and used in Baker's model does not represent the static displacement because it was measured on the plant while it was subjected to wind or rain forces; therefore, the considered dynamic displacement was underestimated. Hence, the plant displacement to measure the moment acting upon the plant (with regards to the Figure 2.17) used in Equation 2.16, was modified to be as written in Equation 2.17 in order to consider the effect of both static and dynamic effect of the plant displacement (ω) (Martinez-Vazquez & Sterling, 2011).

$$\psi = \frac{B}{mg\left(1+\frac{\omega^{-2}}{\Gamma}\right)} \qquad \text{(Eq. 2.17)}$$

Where

ω = circular frequency (rad s^{-1})

Γ = ratio between dynamic and static displacement of the stem ($\psi d\,/\,\psi s$)

ψd = plant's dynamic displacement (m)

ψs = plant's static displacement (m).

Common to the all models produced by Neenan & Spencer-Smith (1975); Baker (1995); Baker et al. (1998) and Berry et al. (2003b), the above ground properties of plant associated with stem lodging were addressed in which the weather factors such as wind speed was also incorporated. Whereas, soil properties namely shear strength along with the adventitious root characteristics were highlighted as the main factors in determining anchorage failure (Crook & Ennos, 1993).

Accordingly, the base bending moment against stem failure and against anchorage failure were determined in the models produced by Baker et al. (1998) and Berry et al. (2003a). Moreover, the actual lodging moment was determined in the model produced by Martinez-Vazquez & Sterling (2011) when more dynamic forces acting upon the plant were considered.

The models produced have identified the plant characteristics incorporated in the equations to determine the moment at which stem lodging or anchorage failure occurs. These characteristics were also adopted in the current studies where plant anchorage moment has been determined.

Unlike the results of Neenan & Spencer-Smith (1975), the overall results of the current studies, at which the safety factor against stem failure was compared to the safety factor against anchorage failure have shown that anchorage failure is more likely to occur as this has been focused on in this project. Furthermore, previous models have considered soil shear strength in determining the moment and the required force to cause anchorage failure in wheat (Crook & Ennos, 1993; Berry et al., 2003b). Critical to the above mentioned models, is identifying the importance of anchorage moment which could be maximised through optimising the physical conditions of soil in order to minimise the likelihood of root lodging in wheat plant.

2.7 Critical review of missing aspects

The literature reviewed highlighted the importance of both stem and anchorage failure (lodging incidence) identified in wheat (Pinthus & Brady, 1974; Neenan & Spencer-Smith, 1975; Crook & Ennos, 1993; Baker et al., 1998), in terms of its cost worldwide and in the UK (Tams et al., 2004), quality and quantity of harvestable yield (Rajkumara, 2008). Additionally, the effective factors influencing both types of stem lodging and anchorage failure have been discussed. This project focuses on anchorage failure in wheat, the more common and predominant type of lodging in wheat (Crook et al., 1994; Navabi et al., 2006; Khakwani et al., 2010). The anchorage of cereal crops depends primarily upon the mechanical properties of the basal adventitious roots and the soil physical properties (Crook et al., 1994; Goodman & Ennos, 1999; Berry et al., 2003a).

Manipulating soil conditions will affect plant anchorage and resistance to lodging (falling over) because this depends upon root development and soil strength, both of which are influenced by cultivation. Therefore, the effect of different cultivation systems on soil physical properties namely bulk density, shear strength and penetration resistance has been reviewed (Schjonning & Rasmussen, 2000; Gemtos et al., 2002; Huang et al., 2012). The amount of moisture available in the soil has a significant effect on the soil physical properties as addressed by John et al. (1986); Jiuhao et al. (2007) and Benjamin & Mikha (2010) and on the root system.

The change in soil structure varies during the cultivation and tillage process, depending upon the cultivation systems, depth of cultivation, moisture content and type of equipment; therefore, this change in soil structure directly affects root properties (Ishaq et al., 2001; Munoz-Romero et al., 2010; Acuna et al., 2012).

From the agronomic point of view, the response of lodging in wheat to the variation in cultivars has been reviewed (Easson et al., 1993; Crook et al., 1994; Berry et al., 2003c; Khakwani et al., 2010).

The above ground properties of the plant have been investigated earlier especially those associated with lodging (stem lodging and root lodging) such as stem height, stem strength, number of tillers (Niu et al., 2012; Kong et al., 2013), the effect of weather conditions and seedling rates (Easson et al., 1993; Crook & Ennos, 1995; Tripathi et al., 2005), nitrogen and plant growth regulators (Oladokun & Ennos, 2006; Bhiah et al., 2010) and disease infection (Ray et al., 2006; Hein & Specialist, 2007).

Thus, stem and anchorage failure have been extensively researched. However, earlier research focused on the absorption roots of wheat; knowledge is scarce about the basal adventitious roots of wheat, which is mainly focused on in this research. Moreover, previous studies of cereal anchorage have used plants grown in clay soils (Baker et al., 1998; Berry et al., 2003a; Scott et al., 2005b; Martinez-Vazquez & Sterling, 2011), and little is known about the adventitious root development and mechanism of anchorage in sandy soils. This also needs further investigation given that cereals are also grown in these soil conditions.

The agronomic aspects such as fertiliser application, seed rates, cultivar choice and plant growth regulator are well studied and investigated to give the best growing margin for crop. Since lodging in wheat still occurs, therefore, the unknown key aspect is identifying the physical conditions of soil through cultivation systems at which plant anchorage moment is maximised through a combination of enhanced soil strength and unrestricted adventitious root development without reducing yield in wheat.

Chapter 3

3. The effects of soil type and bulk density on the anchorage moment of wheat

3.1 Introduction

The effect of increasing soil bulk density on root properties and soil strength properties such as soil shear strength and penetration resistance is well documented as presented in Chapter 2 (John et al., 1986; Ishaq et al., 2001; Ali Akbar et al., 2004; Hassan et al., 2007; Bengough et al., 2011). Nevertheless, in relation to soil bulk density, little attention had been paid to the thick adventitious roots (the basal sections of freestanding cereal plants) that emerge from the base of the plant, whose function is primarily to anchor the plant and prevent it from root lodging (Wang et al., 2014a; Glab & Szewczyk, 2014; Guan et al., 2015). Plant anchorage depends on the adventitious roots, but it is also dependent on soil shear strength (Crook & Ennos, 1993; Berry et al., 2004; Yang et al., 2015).

The adventitious roots along with the soil plate, anchor the plant and resist being pushed into the soil, generating a restoring moment (Ennos, 1991a; Crook & Ennos, 1996; Sparkes et al., 2008; Sun et al., 2011). Hence, the greater the soil shear strength, the greater the anchorage from the restoring moment resisting over-turning (Goodman & Ennos, 1999).

It was reported that increasing soil bulk density impede root growth (Mackie-Dawson et al., 1991; Schjonning & Rasmussen, 2000; Wang et al., 2014a). In contrast limited increase in soil bulk density below the limit at which reported to hinder the roots (Trukmann et al., 2008; Bengough et al., 2011) is beneficial to stimulate the root system to be spread out more horizontally at the upper layers of soil (Busscher et al., 1987; Lipiec & Haykansson, 2000; Lipiec et al., 2003). This will develop a well-established root system, and is essential to minimise the risk of root lodging as the more common type of lodging in wheat (Graham, 1983; Crook et al., 1994; Berry et al., 2003a; Peng et al., 2014). It is therefore, crucial to optimise soil physical conditions, which increase plant anchorage and reduce the likelihood of root lodging through a combination of enhanced soil strength and unrestricted adventitious root development without reducing yield.

Furthermore, stem lodging in wheat in relation to the associated above ground properties has also been reported earlier by Neenan & Spencer-Smith (1975); Easson et al. (1993); Berry et al. (2000); Rademacher (2009) and Acreche & Slafer, 2011). Additionally, due to the effect of the above ground plant properties on root lodging (Baker et al., 1998; Niu et al., 2012), therefore, they are also investigated in this study.

The majority of previous studies of cereal anchorage have used plants grown in clay soils (Baker et al., 1998; Berry et al., 2003a; Scott et al., 2005b; Martinez-Vazquez & Sterling, 2011). Little is known about the adventitious root development and mechanism of anchorage in sand soils. Thus in this chapter, the effect of soil texture (sandy loam and clay loam) and soil bulk density on anchorage moment and adventitious root development are investigated with pot grown wheat plants. Additionally, the predominance of stem lodging or root lodging in winter wheat is addressed.

3.2 Material and methods

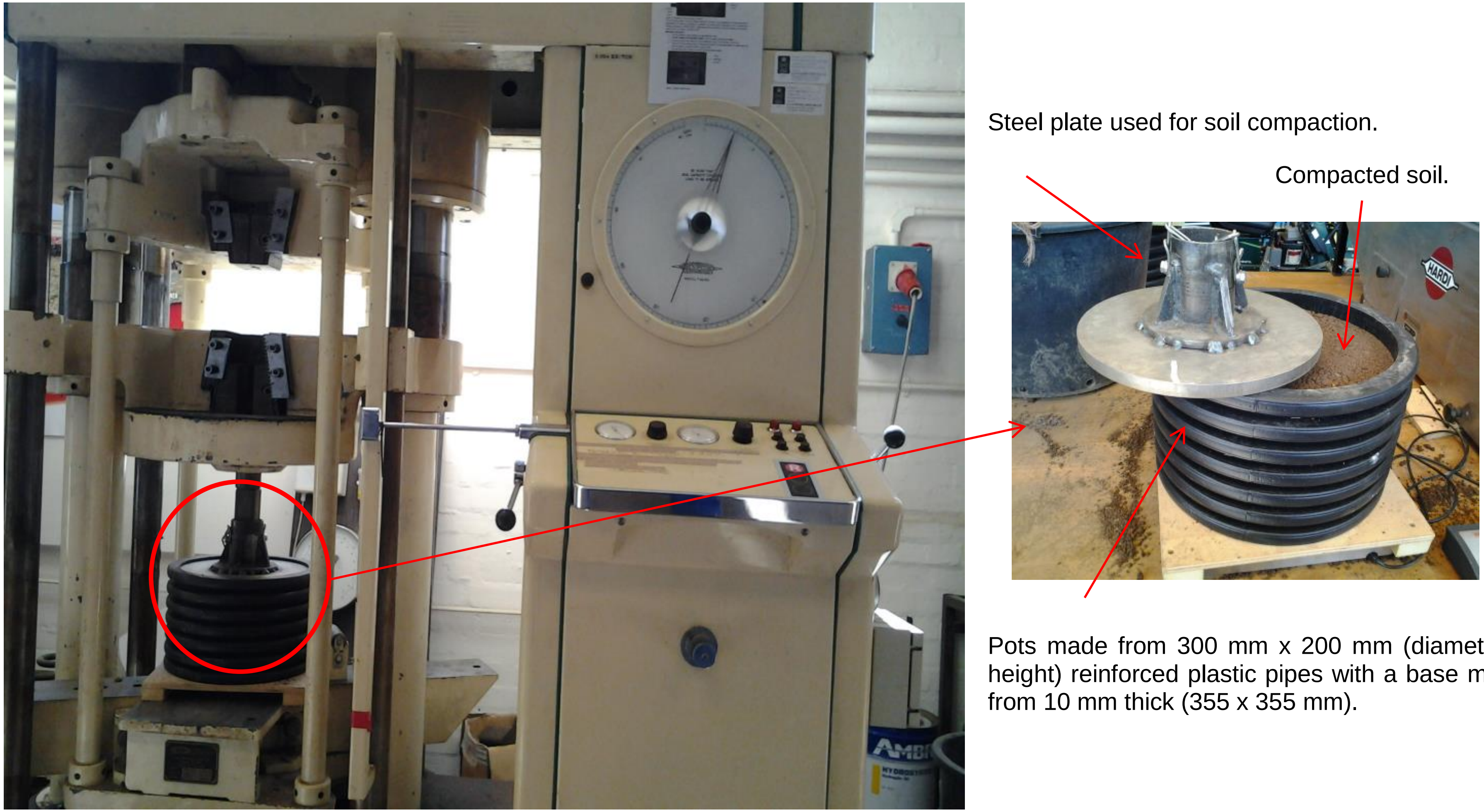
3.2.1 Soil preparations

Winter wheat plants were grown in pots of 300 mm x 200 mm (diameter x height), made from reinforced plastic pipes mounted on a square base made from 10 mm thick (355 mm x 355 mm) wood which contained 12 holes of 8 mm diameter for drainage. The size of the pots was specifically chosen to ensure accurate measurement of both soil shear strength and penetration resistance, by avoiding the container sidewall affecting the results (see Appendix 8.1). The pots were filled with either sandy loam (61% sand, 19% silt and 20% clay) or clay loam soil (41% sand, 28% silt and 31% clay) (the most common soil types in the United Kingdom for winter wheat production (Richter & Semenov, 2005)). These soils were selected from Four Gates field (Latitude 52.772863°, Longitude -2.434845°) and Liberty field (Latitude 52.77738°, Longitude -2.440252°) respectively, at Harper Adams University, United Kingdom. The soil was passed through a 10 mm soil sieve, to remove stones and other debris.

3.2.2 Treatment preparations

A range of soil bulk densities reflecting those possible in field condition was selected, namely, 1.1 c, Mg m^{-3} was selected for low bulk density treatments,

1.3 Mg m^{-3} for moderate bulk density and 1.5 Mg m^{-3} for high soil bulk density treatments. To prepare the low bulk density treatments, each pot was filled with 13.85 kg of sandy loam soil and 14.56 kg of clay loam soil, and gently shaken to ensure even distribution to a height of 180 mm. Wet bulk densities of 1.07 Mg m^{-3} and 1.13 Mg m^{-3} were obtained for the sandy loam soil and the clay loam soil, respectively. For the moderate and high densities, each pot was filled with 16.83 kg and 19.42 kg of sandy loam soil to obtain 1.3 Mg m^{-3} and 1.5 Mg m^{-3}. In moderate sandy loam soil density treatments, the 16.83 kg of soil were separated into three portions each weighing 5.61 kg. Each pot was filled with a layer of soil weighing 5.61 kg which was then subjected to 0.7 kN load with a Denison machine (50 tons capacity, Model number T42. B3) illustrated in Figure 3.1; after this first layer of soil had been compacted, it reached a height of 60 mm in the pot. Next, the second layer of soil was added and compacted to the height of 120 mm in the pot; the third layer of soil was added and compacted to the height of 180 mm in the pot. Thus, the compacted layers of soil ensured a uniform soil compaction in the whole pot, as indicated by John et al. (1986). For the high density treatments of sandy loam soil, 19.42 kg of soil was separated into three parts, each weighing 6.47 kg; the process previously described was repeated and each part of soil was subjected to 3.1 kN load, attaining 1.5 Mg m^{-3}.



Steel plate used for soil compaction.

Compacted soil.

Pots made from 300 mm x 200 mm (diameter x height) reinforced plastic pipes with a base made from 10 mm thick (355 x 355 mm).

Figure 3.1. Instron Denison machine (Model number T42. B3, capacity 50 tons) used for compacting soil in the pots for moderate and high bulk density treatments.

Likewise, based on the soil weight of the low density treatments, for moderate and high clay loam density treatments, 16.75 kg of clay loam soil for moderate density treatments were separated into three parts each weighing 5.58 kg; for high density treatments of clay loam soil, 19.33 kg of soil were separated in to three parts each weighing 6.44 kg. The compaction process described in the paragraph above was repeated using the Denison machine, hence, 1.3 Mg m^{-3} and 1.5 Mg m^{-3} bulk densities were achieved for moderate and high clay loam treatments, respectively.

3.2.3 Sowing, irrigation and fertilising

The prepared 72 pots (soil type = 2 x bulk density = 3 x block (replicates) = 12) were placed in a polytunnel experimental unit at Harper Adams University as shown in Figure 3.2. Each pot was sown with three seeds of winter wheat (*Triticum aestivum* L. var. Cadenza.) on 18th of May 2012. After 2 - 3 weeks of sowing, where the plants were at the two leaf growth stage, the established plants were thinned to leave one plant in each pot. To eliminate the effect of moisture content and avoid any possibility of drought stress, a computerised irrigation system was installed so that the pots received equal amounts of water (0.5 litre day^{-1}). This provided enough available water for the plants during the growing season. The irrigation system was turned off a month prior to harvest.

To ensure comparable soil fertility levels in both soil types and based on the analytical results from NRM Ltd. laboratories and following the fertilizer recommendations guide (Defra, 2010), the plants were fertilized with phosphate, potassium and nitrogen when they were 100 - 150 mm high as illustrated in Table 3.1.

Figure 3.2. The 72 pots randomly distributed in 12 blocks (replicates) over 2 benches in the polytunnel experiment unit.

Table 3.1. Fertiliser application and soil chemical analysis to each soil type

Soil type	Soil	Index				Amount available mg/l				Experiment	Required amount (g/pot)			
	pH	P	K	Mg	N	P	K	Mg	N	pot area* (m^2)	P**	K	Mg	N
Clay loam	7.5	1	2-	4	5	15	140	219	239.0 (kgN/ha)	0.31	5.21	1.86	0	3.65***
Sandy loam	7.4	6	6	3	6	113.2	1053	116	279.7 (kgN/ha)	0.31	0	0	0	3.65***

* The area of each pot was calculated using cylinder area equation: (A = $2\pi rh + 2\pi r^2 \gg$ A = $2\pi \times 0.15 \times 0.18 + 2\pi 0.15^2$ = 0.31 m^2), where the r = the radius of the pot and h= the height of the pot. ** P = Triple Super Phosphate (46% Phosphate), K = Muriate of potash (60% potassium) and N = Ammonium nitrate (34.5% nitrogen). ***Nitrogen index for both soil types were high, however, 40 kg/ha nitrogen was applied for both soil types to ensure available nutrition for both soils.

3.2.4 Measurement of soil shear strength, penetration resistance and moisture content

Soil shear strength measurements were conducted at field capacity using a 19 x 38 mm (diameter x length) (Figure 3.3) shear vane which was connected to a torque meter (AFG-50 Nm Mecmesin). To bring the soil in the pots to a field capacity condition, the pots were submerged in water for 24 hours to saturate, then left for 48 hours to drain under gravity (Crook et al., 1994; Goodman & Ennos, 1999).

Figure 3.3. Shear vane and torque meter used for soil shear strength measurements

Shear strength was measured in each pot, the shear vane tests were performed at two depths of 0 - 50 and 50 - 100 mm. The measurement started by pushing down the shear vane in to the soil to the depth of 0 - 50 mm then rotating it clockwise as illustrated in Figure 3.4. The maximum value of torque was recorded. The shear vane was then further pushed down in the soil to the second depth of 50 - 100 mm and the same process repeated. The maximum shear strength (kPa) indicated on the torque meter was recorded for each depth in accordance to procedure described by Sposaro et al. (2008).

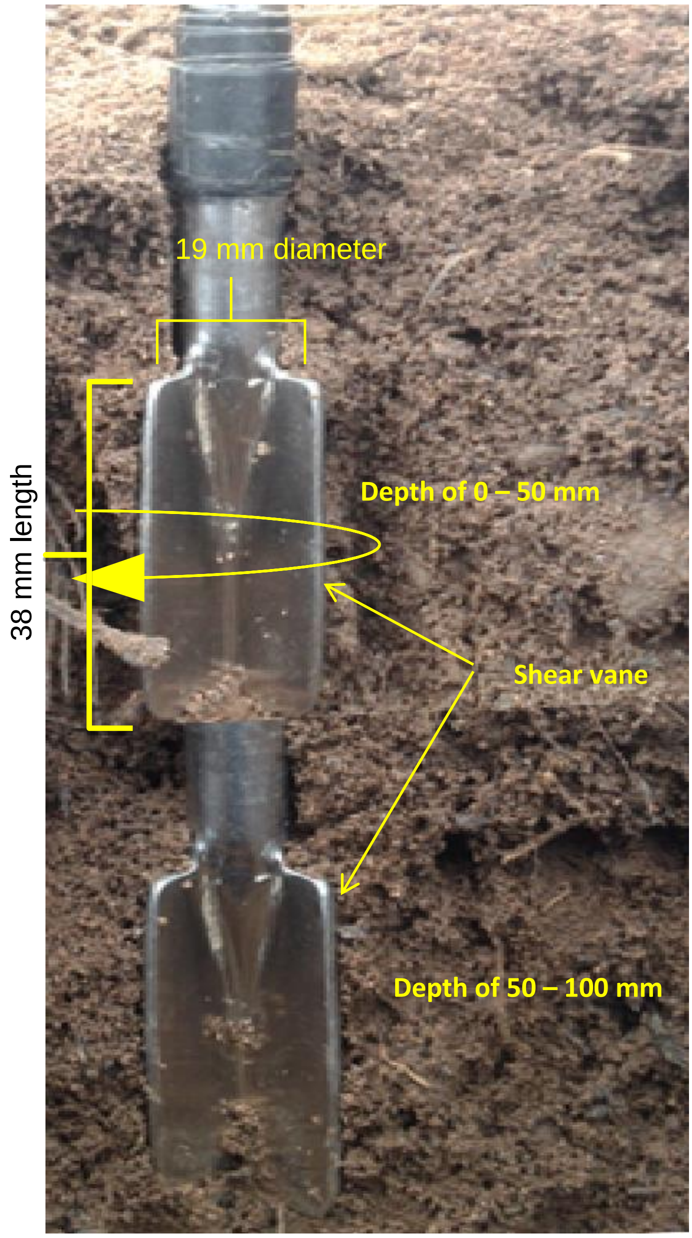


Figure 3.4. Shear vane test at two depths. The first shear strength was measured when the shear vane pushed down to the depth of 0 - 50 mm then rotated clockwise. For the second depth, in the same place, the shear vane was further pushed down to the second depth of 50 - 100 mm and the process was reported.

A digital Eijkelkamp Agrisearch penetrologger (Model 06.15 SA) with a cone of 10 mm diameter and angle of 60° was pushed into the soil and the penetration resistance data (kPa) recorded at 10 mm intervals to a depth of 180 mm.

Volumetric moisture content was measured using a TDR moisture meter at the time when shear strength and penetration resistance were measured (see Table 3.2).

Table 3.2. Moisture content (%) in sandy loam and clay loam soils at three bulk densities

	Soil bulk density Mg m^{-3}	Moisture content (%)
Sandy loam	1.07 (un-compacted)	30.13
	1.3 (moderately compacted)	32.15
	1.5 (highly compacted)	34.99
Clay loam	1.13 (un-compacted)	32.33
	1.3 (moderately compacted)	34.4
	1.5 (highly compacted)	38.05

3.2.5 Measurements of plant properties

3.2.5.1 The above ground plant properties

3.2.5.1.1 Main tiller properties

Prior to harvesting, the main tiller from each plant was excised at the base (close to the soil) and stem height and fresh weight of each tiller were recorded using an electronic KERN scale as shown in Figure 3.5. The centre of gravity was measured by placing the tiller across an index finger and moved until the balance point was reached. The distance from the tiller base to the balance point was classified as the position of the centre of gravity.

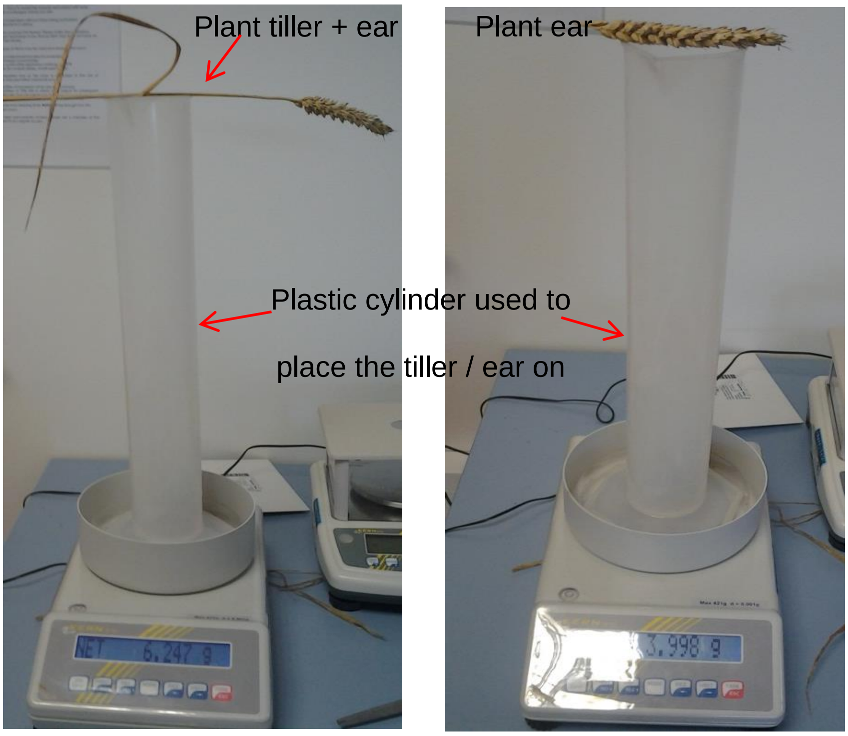


Figure 3.5. KERN electronic scale
(maximum weight of 421 g and accurate to three decimal places)

The self-weight moment for the main tiller (S_w) was calculated in accordance to Crook et al. (1994) using Equation 3.1.

$$S_w = h \times W_t \times sin45 \qquad \text{(Eq. 3.1)}$$

Where
h= is the height of the centre of gravity,
W_t = is the fresh weight of the main tiller.

However, unlike Crook et al. (1994) who measured self-weight moment at 30° inclination from the vertical axis, the self-weight moment of the main tiller and the individual plant was measured at 45° inclination from vertical axis as van Delden et al. (2010). The angle of inclination of an individual plant or the main tiller from the vertical axis is considered in Equation 3.1, therefore, the self-weight moment generated by the individual plant or by the main tiller is greater at 45° from the vertical axis due to the greater value of the sine of 45° compared to the sine of 30° (Figure 3.6). Hence, either lodging type is more likely to occur at 45°.

Although any angle of inclination from vertical could be used comparatively, however, 45° was chosen because of greater value of plant self-weight moment at 45° compared to value of the plant self-weight moment at a smaller angle of inclination from the vertical. Additionally, so as the data of the plant self-weight moment can be compared to the data of plant anchorage moment, which is also measured at the same angle (45°). Additionally, measuring at greater angle reduces equipment accuracy errors as the values are greater, thereby, reducing the error could be caused by the initial slack in the beginning of the test. Thus, in accordance to van Delden et al. (2010) the data achieved at 45° angle were used and analysed to evaluate the effect of soil type and soil compaction on the plant self-weight moment, accordingly, plant anchorage moment.

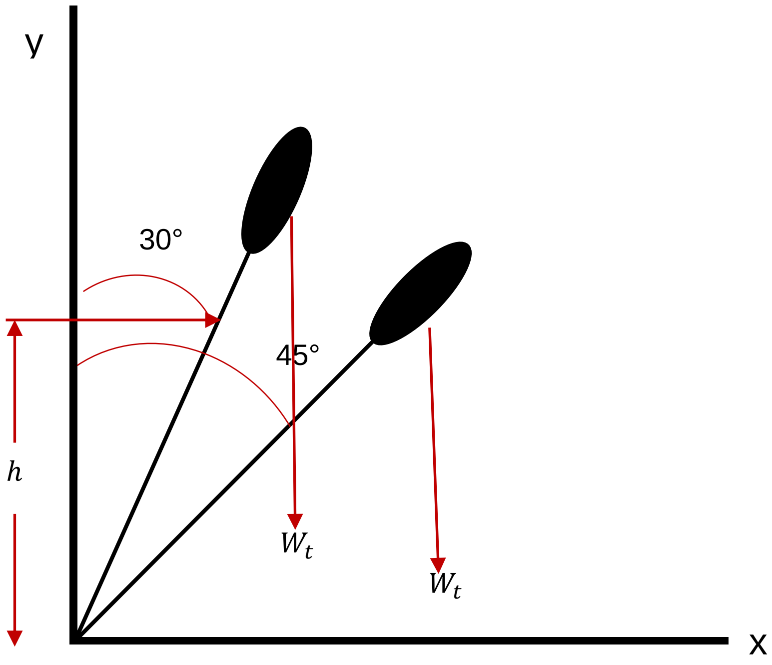


Figure 3.6. Self-weight moment generated by individual plant or single tiller, is greater at 45° compared to at 30°, hence the risk of lodging
$S_w = h \times W_t \times 0.7 > S_w = h \times W_t \times 0.5$

The ear from each tiller was then removed with a pair of scissors and weighed. The first internode of the stem was cut at a 150 mm height from the bottom region of the stem (which had been cut at a height of 150 mm to give the remaining stems more rigidity and assist in measuring the root rather than stem bending). Using a Mitutoyo mini micrometre (model 700-118-20), the diameter of internode was measured in the middle of its length (Figure 3.7) then the first internode was subjected to a three-point bending test. The first internode was placed on two metal supports and a metal blunt probe of 17.5 mm radius, which was fitted to the crosshead of an Instron machine (Model 5543), the metal blunt probe was lowered until it just touched the tiller as illustrated in Figure 3.8. The distance between to metal supports was set to 120 mm where the stem bending moment was measured to avoid overestimating the value of stem bending moment (Robertson et al., 2015).

Figure 3.7. Mitutoyo mini micrometre used for measuring tiller diameter

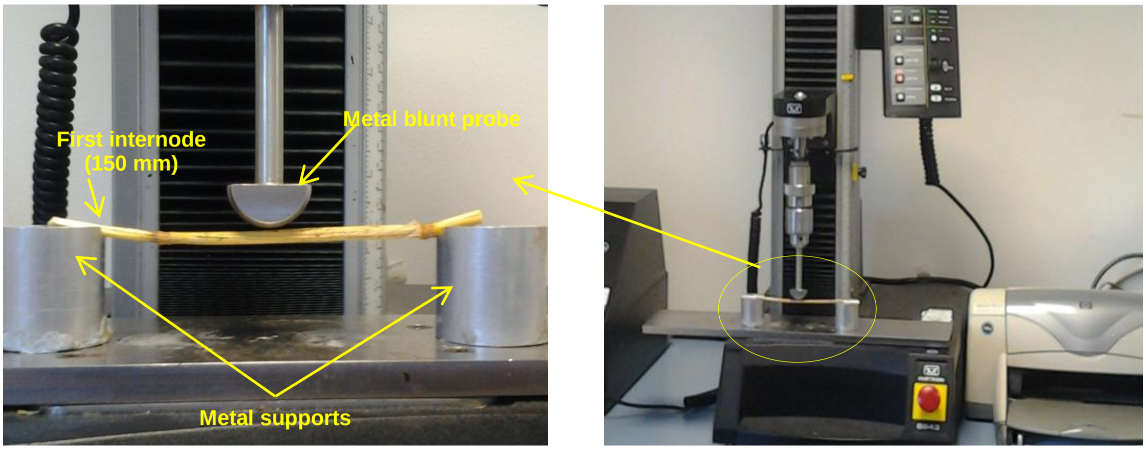


Figure 3.8. Stem bending strength measurements using an Instron machine

Stem bending moment (S) was calculated as per Crook & Ennos (1993) using Equation 3.2.

$$S=\frac{F_{max} \times L}{4} \tag{Eq. 3.2}$$

Where

F_{max} = is the maximum force that the stem can withstand before it bends,

L = is the distance between the two metal supports.

A factor of safety for the main tiller (S_{Ft}) was calculated by dividing stem bending moment over self-weight moment of the main tiller as in Equation 3.3 (Crook et al., 1994).

$$S_{Ft} = \frac{S}{S_{wt}} \tag{Eq. 3.3}$$

3.2.5.1.2 Individual plant properties

To measure the self-weight moment for a complete plant (S_{wp}), the plant (without the main tiller) in each pot was cut at a height of 150 mm from the soil surface with a pair of scissors (the remaining plant was used for anchorage moment measurement as described in section 3.2.5.3) and placed in the lodging arm, which was connected to a lodging device similar to that developed by Crook & Ennos (2000) and used by van Delden et al. (2010). The lodging arm connected to the lodging device was set at 45°, the plant was placed in the lodging arm (the 150 mm length from the centre of lodging device was filled to compensate the cut length of the plant) and the maximum torque (self-weight moment) generated by the plant recorded through an advanced torque meter (AFG-50Nm Mecmesin) that was connected to the lodging device as shown in Figure 3.9. The plant height, fresh weight, ear weight was recorded using a set of electronic KERN weigh scale and the number of tillers counted.

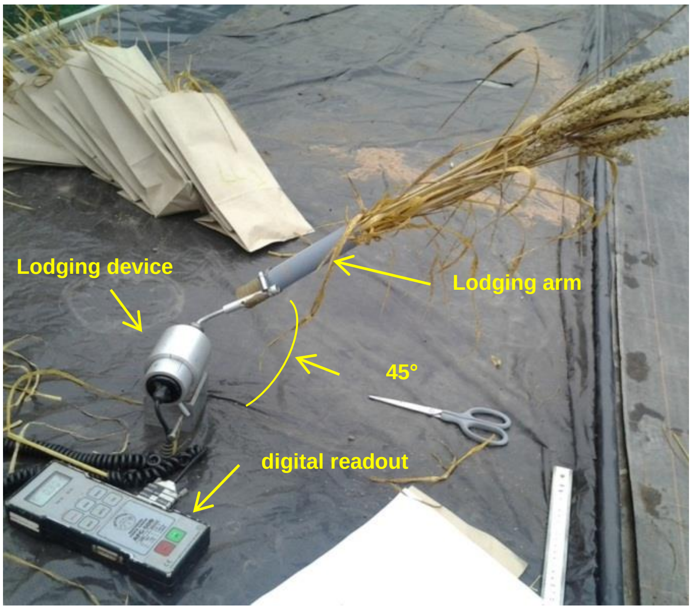


Figure 3.9. Self-weight moment measurement with a lodging device.

Plant factor of safety (S_{Fp}) was calculated by dividing plant anchorage moment (B) by the self-weight moment generated by the plant (S_{wp}), see Equation 3.4 (Oladokun & Ennos, 2006).

$$S_{Fp} = \frac{B}{S_{wp}} \qquad \text{(Eq. 3.4)}$$

Where

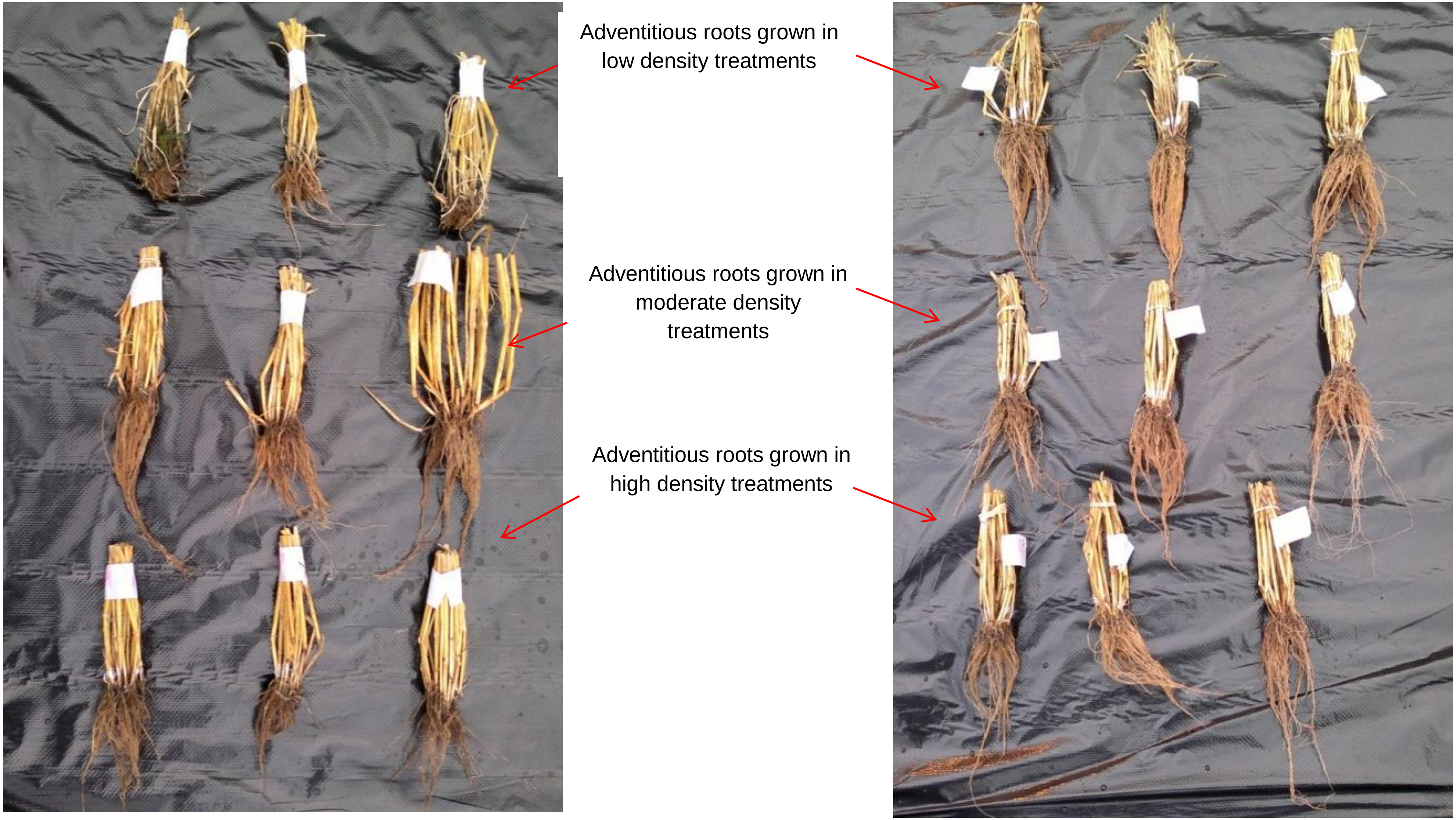
B= is plant anchorage moment.

S_{wp} = is the self-weight moment for the plant.

3.2.5.2 Adventitious root properties

Prior to the roots being excavated, the pots (including roots and soils) were submerged in water for 24 hours and were brought to saturation. They were then left for 1 hour (for the surface water to drain) before the roots in each pot were excavated with care using a hand trowel and fork.

The adventitious roots were carefully washed (Figure 3.10a and 3.10b) and stored at room temperature. Root plate diameter was measured after the roots were placed on a white sheet of paper and the section was drawn in accordance with Crook & Ennos (1993). Angle of spread was measured (to the nearest 5°) by placing the roots system on a paper and reading the maximum angle of the whole roots with a protractor (Goodman & Ennos, 1998; Berry et al., 2003a). With visual observations, the number of roots (diameter between 0.5 - 1 mm and greater than 1 mm) were counted and the total length of these roots (greater than 1 mm in diameter) measured using a ruler.



Adventitious roots grown in low density treatments

Adventitious roots grown in moderate density treatments

Adventitious roots grown in high density treatments

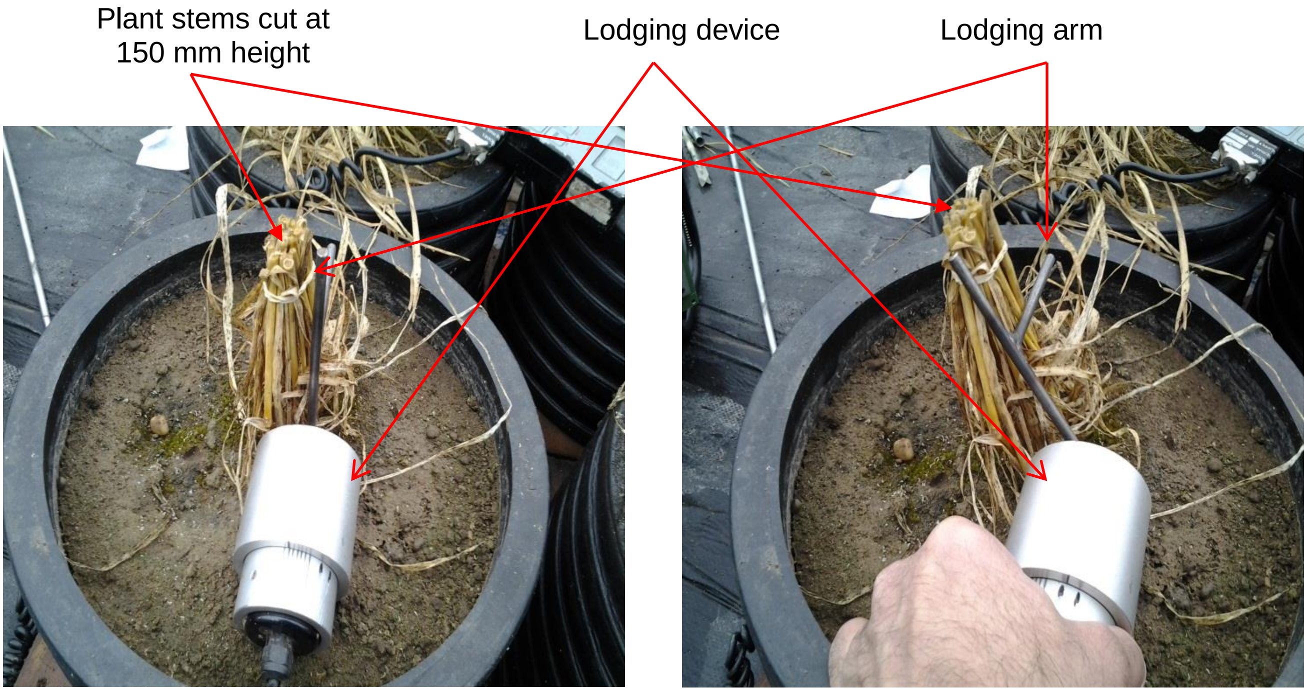
a)

b)

Figure 3.10. Examples of Adventitious roots of winter wheat (*Triticum aestivum* L. var. Cadenza.) grown in, a) sandy loam soil, b) clay loam soil.

3.2.5.3 Plant anchorage moment

To measure plant anchorage moment, at field capacity condition, the lodging device was set in the pot where the lodging arm touched the stems as shown in Figure 3.11a (which had been cut at a height of 150 mm above the soil surface to give the remaining stems more rigidity and assist in measuring the root rather than stem bending). The stems were pushed by the lodging arm to 15˚, 30˚, 45° and 60˚ (Figure 3.11b) and the maximum required torque to push the plant was recorded at each of the angle through the advanced torque meter (AFG-50Nm Mecmesin).



a) b)

Figure 3.11. Lodging arm set next to the plant, a) at vertical position, b) pushed to 45˚

3.2.6 X-ray computed tomography (CT scan)

The availability of X-ray computed technology (CT) was an interesting opportunity which allows the below ground (root and soil) part to be examined without being taking out of the soil. Therefore, due to the machine's size and resolution, in which the original pots were could not be scanned, four small-scale pots were prepared. Two samples of each of sandy loam and clay loam soil were prepared. Based on the results of the pot based experiment (already know because the CT scan test was conducted in April 2015), sandy loam and clay loam soils were compacted to 1.3 Mg m^{-3} bulk density in pots having volume 745 cm^{-3} (9.6 x 11.5 x 8.5 cm (base diameter x top diameter x height). 973.87 g of sandy loam soil and 975.58 g of clay loam soil filled in each pot to achieve 1.3 Mg m^{-3} bulk density for each soil type. On the 20th of April 2014, three seeds of winter wheat (v. Cadenza) was sown in each pot following the procedure described in section 3.2.3.

Samples were scanned (on the 9th April 2015 at the University of Nottingham, Hounsfield Facility, Sutton Bonington Campus), using a Phoenix Vtomex m 240 (GE Measurement & Control Solutions, Wunstorf, Germany). X-ray µCT scanner set at 110 kV and 180 µA, with a 0.5 mm copper filter and an image averaging of 3/1. Pixel/voxel resolution was 66 µm and each scan took 42 min to complete. The total number of image projections collected for individual samples at each X-ray CT scan was 1800 with a file size of c. 25 GB. Each sample was scanned twice; each sample was first marked and positioned in the machine for the pre lodging scan. For the post lodging scan, the plant (cut at 150 mm height previously) was pushed to the 45° inclination from the vertical and tied up to the edge of the pot with thread to keep the plant in its position through the scanning procedure (Figure 3.12).

The images were analysed using ImageJ 1.48v software to observe the changes in the soil or roots due to lodging.

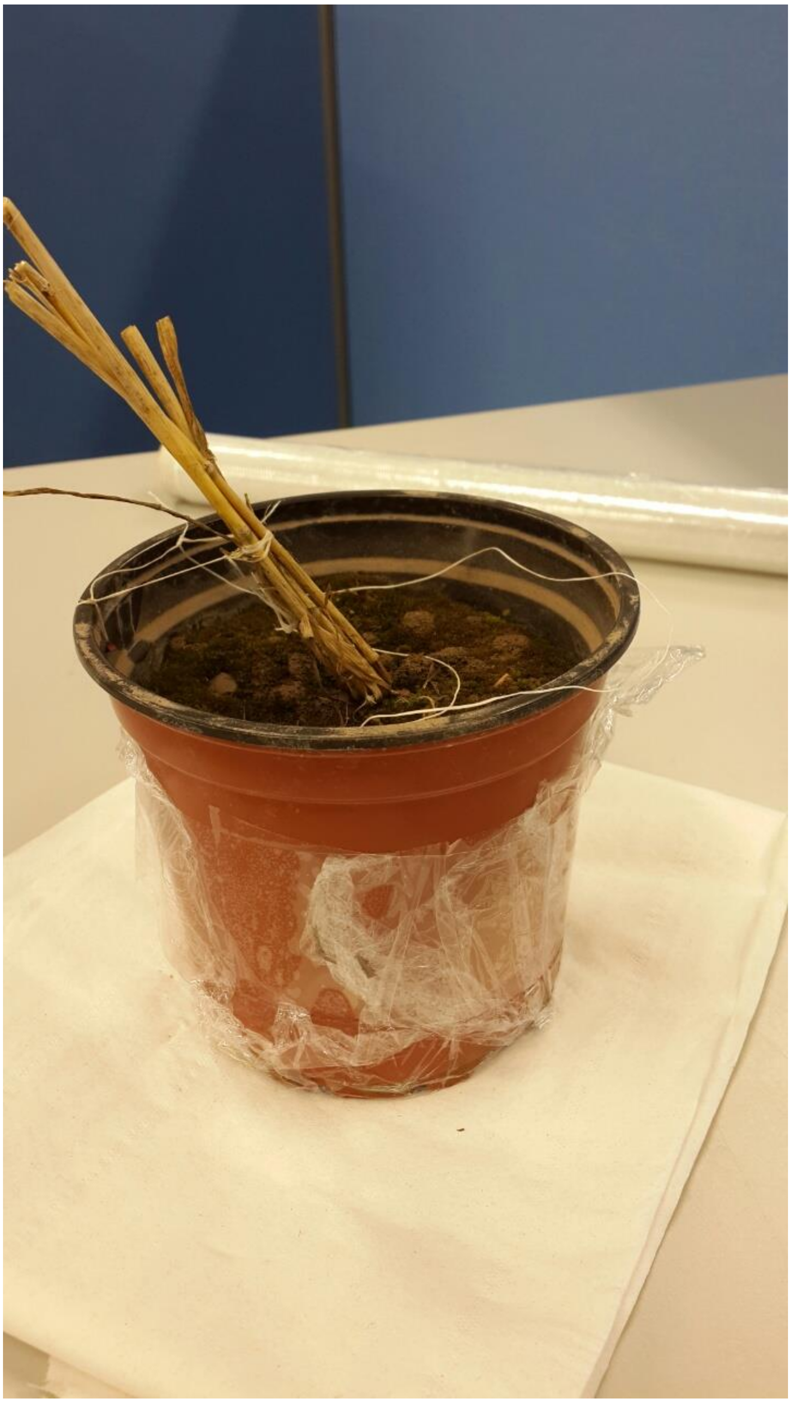


Figure 3.12. Lodged plant in pot prepared for CT scan test

3.2.7 Statistical analysis

The experimental design was a randomised complete block (RCBD) with 12 replicates. The data were analysed using Genstat 14th Edition. A two-way ANOVA test was conducted to determine the differences in the means of adventitious root properties and anchorage moment of wheat plants. Soil type and soil bulk density were considered as the main factors; soil type consisted of sandy loam and clay loam soils (2 levels), whereas soil bulk density was comprised of low (1.07 Mg m^{-3} for sandy loam, 1.13 Mg m^{-3} for clay loam soil), moderate (1.3 Mg m^{-3}) and high (1.5 Mg m^{-3}) (3 levels).

A multi factorial ANOVA test was conducted to test the differences in the means of the plant anchorage moment at the four angles of inclination (from vertical axis) in two soil types and three different bulk densities. In addition to soil type and bulk density, angle of inclination was another factor influencing plant anchorage moment with four levels 15°, 30°, 45° and 60°.

To analyse the data of soil shear strength and penetration resistance, an additional multi factorial ANOVA test was conducted to evaluate the differences between the mean values of soil shear strength and penetration resistance measured in the pots. In addition to soil type and soil bulk density, the depth of the measurements of soil shear strength and penetration resistance was considered as another factor. This was considered to have two levels; depth one ranged between 0 - 50 mm and depth two ranged from 50 - 100 mm.

Differences between mean values of the above ground properties, adventitious root properties, anchorage moment, soil shear strength and penetration resistance were evaluated using Tukey’s multi comparison test and all differences considered significant at $p \leq 0.05$.

3.3 Results

3.3.1 Soil shear strength and penetration resistance

Shear strength and penetration resistance values ranged from 16.5 ± 0.5 kPa (Figure 3.13) and 124.8 ± 6.1 kPa (Figure 3.14) in low density clay loam soil to 27.3 ± 0.5 kPa and 236.0 ± 6.1 kPa in high density sandy loam soil. At field capacity moisture content, shear strength and penetration resistance in high density treatments (1.5 Mg m^{-3}) of both sandy loam and clay loam soils were almost twice than of the shear strength and penetration resistance in the low density treatments (1.1 c, Mg m^{-3}).

The results of data analysis revealed that; soil shear strength and penetration resistance are both proportional to and increased with the increase in soil bulk density in both sandy loam and clay loam soils. The greatest values of shear strength and penetration resistance were found in high density sandy loam soil and they were significantly greater ($p < 0.001$) compared to the rest of the treatments.

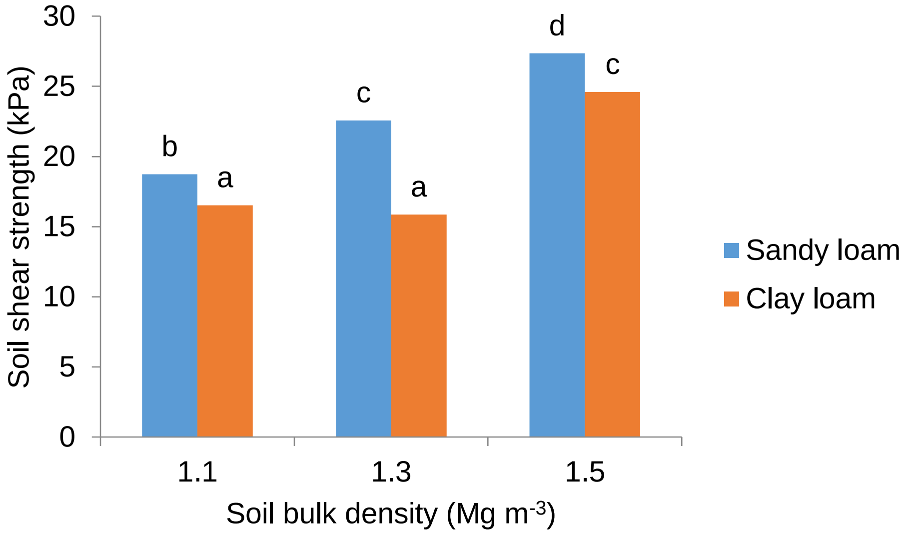


Figure 3.13. The effect of soil type and bulk density on soil shear strength (kPa) (S.E.M.) = 0.513, degree of freedom (d.f.) = 121, p = < 0.001, n = 12 for each treatment.

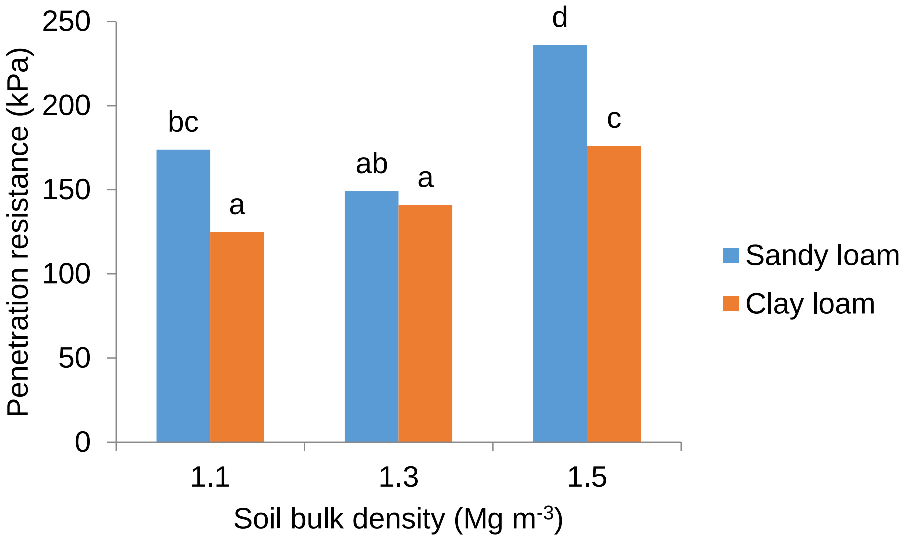


Figure 3.14. The effect of soil type and bulk density on penetration resistance (kPa) (S.E.M.) = 6.11, degree of freedom (d.f.) = 121, p = < 0.001, n = 12 for each treatment

Regardless of the soil bulk density and the depth of measurements, sandy loam soil (Table 3.3) had 16.9% higher shear strength and 20.9% higher penetration resistance compared to clay loam soil. The effect of soil bulk density on soil shear strength and penetration resistance was highly significant ($p < 0.001$). Disregarding the depth and soil types, high density treatments had 26.0% and 32.1% greater shear strength compared to the moderate and low density treatments, respectively. Similarly, increases of 29.6% and 27.5% in penetration resistance were found in high density treatments compared to the moderate and low density treatments, respectively.

Table 3.3. The effect of soil type, bulk density and depth on soil shear strength and penetration resistance.

Soil type	Bulk density	Depth (mm)	Shear strength (kPa)	Penetration resistance (kPa)
Sandy loam	1.1*	0 - 50	15.18	130.20
		50 - 100	22.31	217.40
	1.3	0 - 50	17.28	94.60
		50 - 100	27.89	203.60
	1.5	0 - 50	23.69	175.60
		50 - 100	31.02	296.30
Clay loam	1.1	0 - 50	12.64	85.00
		50 - 100	20.41	164.60
	1.3	0 - 50	12.52	97.30
		50 - 100	19.21	184.40
	1.5	0 - 50	21.69	114.20
		50 - 100	27.51	238.00
S.E.M. at (d.f. = 121)		Soil type	0.296	3.530
		Bulk density	0.363	4.320
		Depth	0.296	3.530
		Interaction	0.725	8.640
p value		Soil type	<.001	<.001
		Bulk density	<.001	<.001
		Depth	<.001	<.001
		Soil type & bulk density	<.001	<.001
		Soil type & depth	0.059	0.380
		Bulk density & depth	0.130	0.007
		Soil type, bulk density & depth	0.088	0.591

* 1.1 Mg m^{-3} is representing the un-compacted treatments and is the average value of 1.07 Mg m^{-3} for sandy loam soil and 1.13 Mg m^{-3} for clay loam soil. S.E.M. represents standard error of means, d.f. represents degree of freedom, n = 12 for each treatment.

Soil shear strength and penetration resistance were both influenced by the depth of the measurements. The mean values of soil shear strength and penetration resistance at the depth of 0 - 50 mm were generally less and followed the same trend of soil shear strength and penetration resistance as at the depth of 50 - 10 mm. At the depth of 50 - 100 mm, the high density treatments had 19.5% and 26.9% greater soil shear strength compared to the moderate and low density treatments, respectively. Likewise, penetration resistance in high density treatments was 27.3% and 28.5% greater than penetration resistance in moderate and low density treatments respectively.

3.3.2 The above ground plant properties

The effect of soil type on the above ground properties (both individual plants and the main tillers) of wheat is demonstrated in Table 3.4. Compared to sandy loam soil, clay loam soil plants had 5.2% longer stems, 14.2% greater plant fresh weight, 10.5% more number of tillers and 4.3% higher centre of gravity of the main tiller. However, sandy loam soil plants had 5.2% greater stem diameter, 15.0% stronger stems and 16.7% greater factor of safety compared to the treatments in clay loam soil. The increase in soil bulk density from 1.3 to 1.5 Mg m^{-3} had increased the stem height by 6.3%, plant fresh weight by 24.8%, plant ear weight by 25.3%, 17.9% number of tillers, 24.6% plant self-weight moment and the anchorage moment has increased by 42.9%.

It can been seen from the interaction of soil type and soil bulk density on the above ground properties of wheat that, in sandy loam soil, increasing soil bulk density from 1.03 to 1.5 Mg m^{-3} density treatments increased the height of the stem by 13.3% and the self-weight moment of the plant by 41.9%. The main tiller properties also influenced by the interaction of the soil type and bulk density, increasing soil bulk density in sandy loam soil, increased of the height of the main tiller by 12.36%, of the tiller weight by 22.2%, of the ear weight by 22.2%, of the centre of gravity by 9.3% and also increased of the self-weight moment of the main tiller by 26.4%.

Table 3.4. The effect of soil type on the above ground properties of winter wheat

		Sandy Loam			Clay loam			S.E.M. at (d.f. = 55)			*p* value		
		1.07*	1.3	1.5	1.13	1.3	1.5	Soil type	Bulk density	Interaction	Soil type	Bulk density	Interaction
Individual plant properties	Stem height (cm)	64.47^{a**}	71.00^{ab}	74.74^{b}	74.05^{b}	74.56^{b}	73.12^{b}	1.099	1.346	1.904	0.017	0.045	0.018
	Plant fresh weight (g)	47.30	71.40	78.30	71.70	78.00	80.20	3.580	4.380	6.190	0.035	0.006	0.166
	Plant ear weight (g)	32.30	52.20	52.10	47.80	54.90	55.10	2.580	3.160	4.470	0.059	0.004	0.269
	Number of tillers/plant	13.83	17.37	16.42	15.76	17.75	19.67	0.502	0.614	0.869	0.012	<.001	0.262
	Plant self-weight moment (Nm)	0.23^{a}	0.41^{b}	0.39^{b}	0.37^{b}	0.40^{b}	0.39^{b}	0.018	0.022	0.031	0.094	0.002	0.041
	Plant safety factor	2.80	2.77	3.55	1.93	2.49	2.47	0.313	0.384	0.543	0.099	0.490	0.742
	Plant anchorage moment (Nm)	0.53	1.10	1.25	0.71	1.00	0.93	0.082	0.100	0.142	0.485	0.002	0.223
Main tiller properties	Stem height (cm)	68.90^{a**}	72.96^{ab}	78.62^{b}	76.02^{ab}	75.62^{ab}	73.86^{ab}	1.022	1.252	1.770	0.253	0.111	0.005
	Tiller weight (g)	5.62^{a}	7.23^{b}	7.01^{ab}	6.77^{ab}	6.43^{ab}	5.98^{ab}	0.206	0.252	0.356	0.448	0.214	0.006
	Ear weight (g)	3.32	4.33	3.98	4.13	3.99	3.66	0.140	0.172	0.244	0.806	0.185	0.034
	Centre of gravity (cm)	49.01	49.99	54.04	53.94	54.08	51.89	0.736	0.902	1.276	0.032	0.502	0.014
	Stem diameter (mm)	4.02	4.41	4.19	4.07	4.02	3.90	0.056	0.069	0.098	0.011	0.147	0.07
	Self-weight moment	0.019^{a}	0.025^{ab}	0.026^{b}	0.025^{ab}	0.024^{ab}	0.021^{ab}	0.0009	0.0011	0.0016	0.963	0.385	0.008
	Stem bending moment (Nm)	0.19	0.23	0.21	0.19	0.18	0.16	0.010	0.012	0.017	0.034	0.616	0.323
	Safety factor	9.91	9.10	8.27	7.85	7.52	7.33	0.391	0.479	0.678	0.008	0.29	0.711

*Soil bulk density (Mg m^{-3}), ** Values in a row followed by the same letter are not significantly different at $p < 0.05$ as determined by Tukey test. S.E.M. represents standard error of means, d.f. represents degree of freedom, n = 12 for each treatment.

3.3.2.1 Plant anchorage moment

The plant anchorage moment data for all four angles showed no significant effect of the soil type on the plant anchorage moment at any of the experimental inclination angles (Figure 3.15a, 3.15b, 3.15c and 3.15d). However, the biggest variation (8.6%) between sandy loam soil and clay loam soil in plant anchorage moment was found at 45˚angle as shown in Figure 3.16. Thus, in accordance to van Delden et al. (2010) the data obtained at 45˚ were used.

Nevertheless, the anchorage moment of plants grown in sandy loam presented in Table 3.7 was 8.1% greater than the anchorage moment of plants grown in clay loam soil; this difference in plant anchorage moment was still below the significance level statistically.

Irrespective of soil type, plants grown in high bulk density soils, as indicated in Table 3.4 had greater anchorage moment and required greater forces to be pushed over; they also had greater anchorage moment (43.1%) compared to plants grown in low bulk density soils but not significantly different anchorage moment (3.6%) compared to plants grown in moderate bulk density soils.

Plant anchorage moment ranged between 0.53 Nm in low density sandy loam to 1.25 Nm (greatest) in high density sandy loam soil (Figure 3.17). In sandy loam soil, the increase in bulk density increased plant anchorage moment unlike the clay loam soil, where plant anchorage moment reduced by 7.2% when moderate density increased to high density.

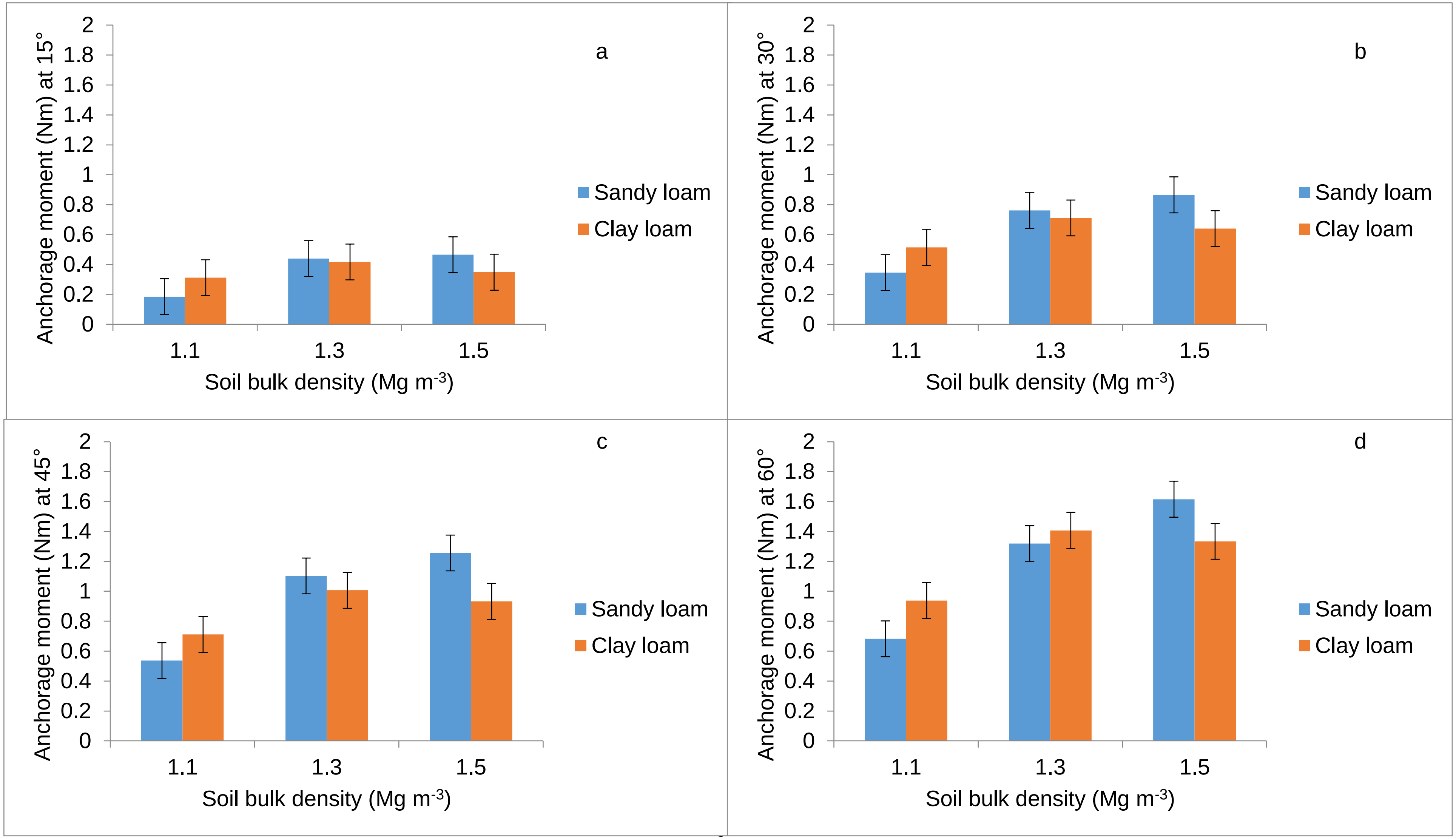


Figure 3.15. The effect of soil bulk density and soil type on plant anchorage moment (Nm), (a) at 15°, (b) at 30°, (c) at 45° and (d) at 60°. Error bars are standard error of means (S.E.M.) = 0.12, degree of freedom (d.f.) = 253, *p* = 0.978, n = 12 for each treatment.

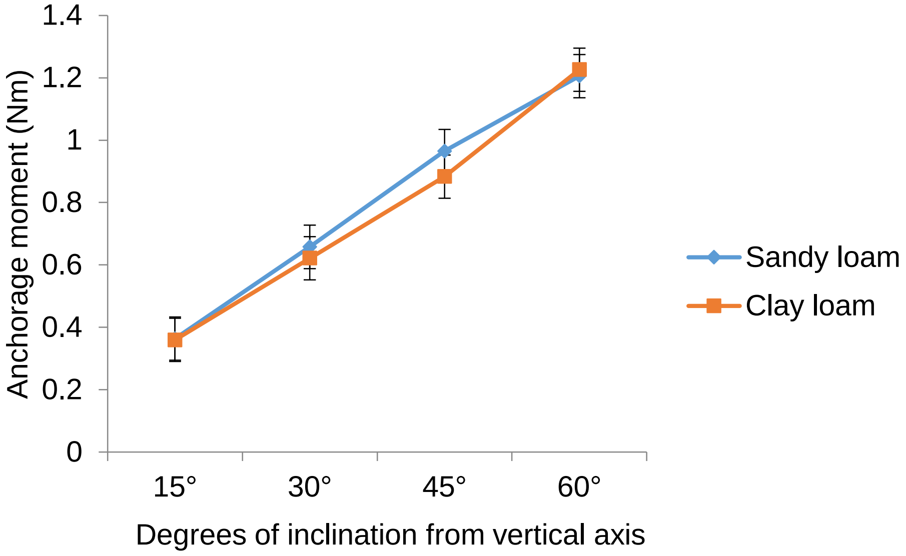


Figure 3.16. The effect of soil type on plant anchorage moment (Nm) at four angles of inclination from vertical axis, (a) at 15°, (b) at 30°, (c) at 45° and (d) at 60°. Error bars are standard error of means (S.E.M.) = 0.0693, degree of freedom (d.f.) = 253, *p* = 0.894, n = 12 for each treatment.

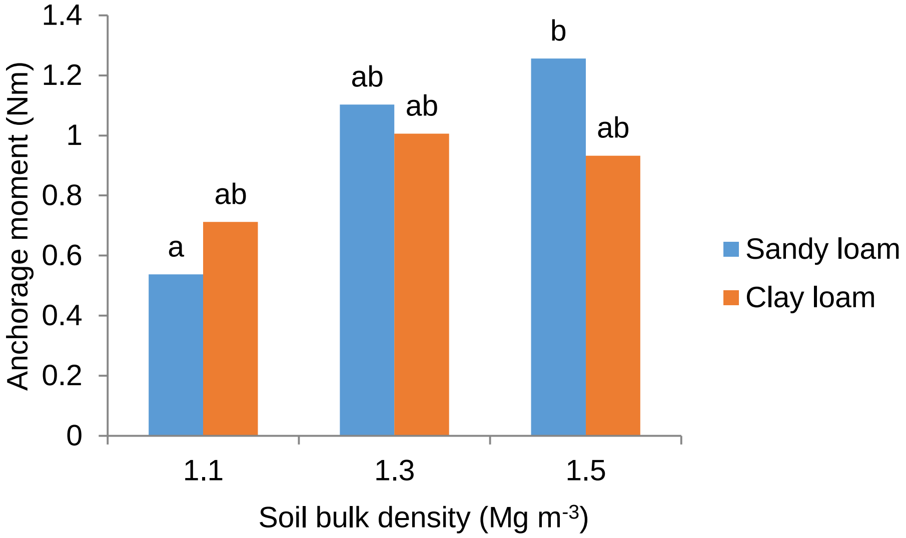


Figure 3.17. The effect of soil type and bulk density on plant anchorage moment (Nm) at 45˚, (S.E.M.) = 0.142, degree of freedom (d.f.) = 55, *p* = 0.223, n = 12 for each treatment.

3.3.3 The adventitious root properties

Unlike the results presented earlier representing the above ground properties, the results presented below for the adventitious roots properties are from the analysis of the data of 10 replications out of 12, as two replications were used for the visual evaluation of the soil structure used in this experiment.

3.3.3.1 Total length of roots (greater than 1 mm in diameter)

The results of data analysis in Table 3.5 shows that soil type significantly ($p < 0.001$) affected the total length of roots (greater than 1 mm in diameter). The total length of plants grown in sandy loam soil was 46.9% greater compared to the total length of the roots of plant grown in clay loam soil. The total length of the roots (greater than 1 mm in diameter) was significantly influenced by soil bulk density ($p < 0.001$). The total length of the roots in 1.3 Mg m^{-3} bulk density treatments surpassed the total length of the roots grown in both low and high bulk density treatments by 41.3% and 35.7%, respectively. However, the difference between high bulk density treatments and low density treatments was not significant. The greatest total length of the roots (261.1 mm) was recorded for plants grown in the moderate density sandy loam soil, which was 67.1% greater than the total length of the roots of plants grown in the low density and high density clay loam soil.

3.3.3.2 Root plate diameter

Root plate diameter was not statistically affected by soil type; the mean value of the root plate diameter in clay loam soil was only by 1.5% greater than in sandy loam soil. Plants grown in moderate bulk density soils had a significantly ($p < 0.05$) greater average root plate diameter than plants grown in low bulk density, being 14.5 % larger. Plants grown in moderate bulk density soil had root systems 10.8% greater on average than those in high bulk density soils, but the difference was not significant.

Plants grown in sandy loam soil with moderate bulk density showed the greatest root plate diameter and were significantly ($p = 0.002$) greater than those grown in low bulk density sandy loam soil by 26.3% and not significantly greater from the rest of the treatments.

3.3.3.3 Number of roots (greater than 1 mm in diameter)

The impact of soil type on the number of roots (greater than 1 mm in diameter) was highly significant ($p < 0.001$). The number of roots (greater than 1 mm in diameter) of plants grown in sandy loam soil was 58.2% higher than the number of the roots (greater than 1 mm in diameter) of plants grown in clay loam soil.

The results of data analysis indicates that the number of the roots (greater than 1 mm in diameter) was significantly influenced by soil bulk density ($p = 0.004$). The moderate bulk density treatments resulted in the highest number of roots (11.1) which was significantly greater than the number of the roots in the low and high bulk density treatments by 26.1% and 29.7%, respectively. Despite the significant effects of soil type and soil bulk density on the number of the roots (greater than 1 mm in diameter), the effect of the interaction of these two factors was statistically non significant, because of the similar pattern of the trend followed in sandy loam soil and clay loam soil with increasing soil bulk density (Figure 3.18).

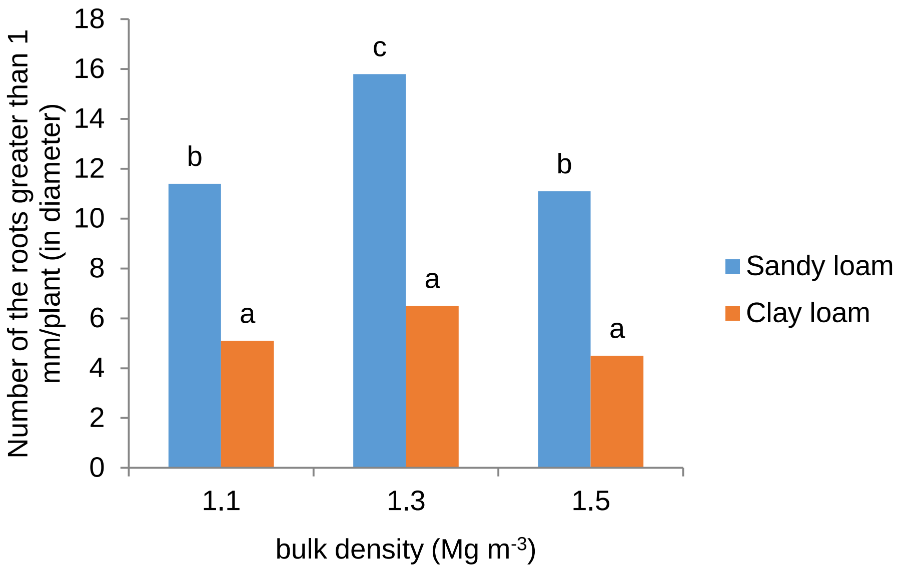


Figure 3.18. The effect of soil type and bulk density on the number of the roots (greater than 1 mm in diameter), (S.E.M.) = 1.016, degree of freedom (d.f.) = 45, *p* = 0.277, n = 10 for each treatment.

3.3.3.4 Angle of spread of the roots

The angle of spread of the roots in sandy loam soil was greater than the angle of spread of the roots in clay loam soil by an average of 25.2% (Table 3.5). Moreover, the greatest angle of spread of the roots recorded at the moderate bulk density treatments was 22.5% greater compared to the angle of spread of the roots in the high bulk density treatments and non-significantly by 13.9% compared to the low bulk density treatments.

The angle of spread of the roots of plants grown in moderate bulk density sandy loam recorded the biggest angle (81.3°) which was significantly greater (p = 0.008) from the rest of the treatments, except the angle of the roots of plants grown in high bulk density sandy loam soil (Table 3.5). The angle of spread of roots of plants grown in high bulk density clay loam soil had the lowest angle of spread of the roots and was significantly lower by 31.3%, 49.5% and 37.5% from the angle of spread of the roots of plants grown in low, moderate and high bulk density sandy loam, respectively.

3.3.3.5 Number of roots (diameter between 0.5 - 1 mm)

Soil type had no statistical effect (*p* = 0.969) on the number of roots (diameter between 0.5 - 1 mm). However, the data analysis in Table 3.5 revealed that, soil bulk density significantly affected the number of roots (diameter between 0.5 - 1 mm). Moderate bulk density treatments yielded the greatest average number of roots (diameter between 0.5 - 1 mm) which was 23.1% and 37.2% greater compared to the number of the roots in high and low density treatments, respectively. The lowest number of roots (diameter between 0.5 - 1 mm) of the plants grown in low bulk density sandy loam soil was 53.9% lower than the number of the roots (diameter between 0.5 - 1 mm) of the plants grown in moderate bulk density sandy loam, which recorded the highest number of roots (108.5) among the treatments. Moreover, the number of the roots (diameter between 0.5 - 1 mm) in sandy loam moderate bulk density was 22.7% and 38.5% significantly higher compared to the low and high bulk density clay loam soil, respectively.

Table 3.5. The effect of soil type and bulk density on the adventitious root properties of winter wheat

	Sandy Loam			Clay loam			S.E.M. at (d.f. = 45)			*p* value		
	1.07*	1.3	1.5	1.13	1.3	1.5	Soil type	Bulk density	Interaction	Soil type	Bulk density	Interaction
Total length of roots/plant (greater than 1 mm in diameter) (mm)	144.0	261.1	165.9	85.9	131.0	85.9	11.97	14.66	2.07	< 0.001	< 0.001	0.216
Root plate diameter/plant (mm)	43.7^{a**}	59.3^{b}	55.9^{b}	56.0^{b}	57.4^{b}	48.1^{ab}	1.54	1.89	2.67	0.693	0.007	0.002
Number of roots/plant (greater than 1 mm in diameter)	11.4	15.8	11.1	5.1	6.5	4.5	0.58	0.71	1.01	< 0.001	0.004	0.277
Angle of the spread of the roots/plant (°)	59.7^{b}	81.3^{c}	65.6^{bc}	59.1^{b}	56.4^{ab}	41.0^{a}	2.44	2.99	4.22	< 0.001	0.002	0.008
Number of roots/plant (diameter between 0.5 - 1 mm)	50.0^{a}	108.5^{d}	97.3^{cd}	83.8^{bc}	104.8^{cd}	66.7^{ab}	3.01	3.69	5.21	0.969	< 0.001	< 0.001

*Soil bulk density (Mg m^{-3}), ** Values in a row followed by the same letter are not significantly different at $p < 0.05$ as determined by Tukey test, S.E.M. represents standard error of means, d.f. represents degree of freedom, n = 10 for each treatment.

3.4 Discussion

3.4.1 Soil shear strength and penetration resistance

As presented in section 3.3, shear strength and penetration resistance varied across soil types regardless of soil bulk density and moisture content. It is generally accepted that clay soils have greater shear strength and penetration resistance compared to sandy soils. However, under wet conditions, particle’s size contribute to raising the required shearing force through inter-particle friction forces (Antony, 2007). Therefore, greater shear strength and penetration resistance in sandy loam soil compared to clay loam soil could be explained by two factors: the inter-particle friction forces resulting from bigger particle size in sandy loam soil are greater than those in clay loam soil (Fakhimi & Hosseinpour, 2008; Antony & Kruyt, 2009) and, secondly, moisture content in clay loam soil was 7.2% greater than the moisture content in sandy loam soil (despite the same amount of watering) which affects cohesion in between clay particles rather than friction in between sandy soil particles (Ennos, 2000).

Soil shear strength and penetration resistance are both soil bulk density dependant. The increase in soil bulk density leads to a reduction in soil porosity as a result of compressing soil particles (Hassan et al., 2007). Thus, the distance between particles diminishes, which increases the cohesion force and maximises the binding force between these particles (Topa et al., 2011). Additionally, this reduction in the distance between particles, increases the number of contact points in between soil particles (Horn et al., 1994).

However, the experiment described in this Chapter, indicated that, despite the increase in soil bulk density from low to moderate bulk density, soil shear strength reduced in clay loam soil, and penetration resistance reduced in sandy loam soil. This reduction in soil shear strength and penetration resistance (Figure 3.13 and

Figure 3.14) was likely due to the 6.0% increase in soil moisture content which affects the cohesion forces between particles in clay soil more than inter-particle friction forces in sandy soils (Ennos, 2000; Fakhimi & Hosseinpour, 2008); whereas, the effects of further increasing soil bulk density up to 1.5 Mg m^{-3} surpassed the effects of greater soil moisture content. These results are compatible with the Mohr-Coulomb's equation for soil strength as soil strength depends upon cohesion, angle of internal friction and moisture content in addition to stress.

3.4.2 The above ground properties

The main tiller properties (weight of the main tiller, ear weight, and stem diameter and stem bending moment) were negatively influenced and reduced, with increasing soil bulk density in clay loam soil, and with increasing bulk density from 1.3 Mg m^{-3} to 1.5 Mg m^{-3} in sandy loam soil. The reduction in the main tiller properties was greater in clay loam soil compared to sandy loam soil; the ability of the roots to grow in soils (in this case clay loam soil) which have micro pores smaller than the roots diameter is less or slower than in the soils (in this case sandy loam soil) that have micro pores with same or larger diameter than the roots (Hakojarvi et al., 2013).

The absence of significant differences in the ear weight of either plant or the main tiller across the two soil types used in this experiment was a good indicator of a successful nutrition and irrigation application among the treatments. Nevertheless, the variation in yield components is more likely to result from the variation in irrigation, fertilization and variety (Funk et al., 2008) in addition to the variation in climate conditions (Zhang et al., 2012) or in soil bulk density (Alameda & Villar, 2012) rather than from the variation in soil types (Cannell et al., 1984; Gales et al., 1984; Hassan et al., 2007).

Soil bulk density had a significant impact on the plant above ground properties such as stem height, plant fresh weight, number of tiller and the ear weight of the plant which were found to be significantly less in low density treatments compared to moderate density treatments in either soil types, which were in agreement with the finding of Wilhelm & Mielke (1988). However, the continuing increase in these aboveground parameters from 1.3 Mg m^{-3} to 1.5 Mg m^{-3} bulk density treatments in this study was unlike the pattern found by Wilhelm & Mielke (1988). The reason for these differences is more likely to be due to the range of soil bulk densities used in this study, which were below the range of soil bulk densities of 1.5 Mg m^{-3} highlighted by Schjonning & Rasmussen (2000) that restrict root and plant growth. Moreover, in the low density treatments in both soil types used in this experiment, the poor soil-root connections also contributed to the lower values of the plant above ground properties found in the low density treatments for either soil types compared to the values of the plant above ground properties found in the moderate and high density treatments (Wilhelm & Mielke, 1988).

The other possibility of the increase in these parameters is the increase in soil moisture content as highlighted by Jug et al. (2011) and Zhang et al. (2012). Therefore, despite the uniform irrigation system on all treatments, there was about 8% greater moisture content in clay loam soil compared to sandy loam soil due to the nature of soil type and greater water holding capacity. Moreover, the increase in the soil moisture content due to the increased soil bulk density increased the height of the stems, plant fresh weight and the number of tillers (Li et al., 2008); this increase in the above ground properties of winter wheat possibly due to the increase in the soil moisture content were similar to the results reported by Ram et al. (2013). Thus, the plants became heavier as a result of the increase in plant fresh weight, ear weight, number of tillers with the increase in soil bulk density from low to moderate density, in addition to the increase in the height of the stems. This increased the risk of stem lodging among the treatments because self-weight moment of the plants increased rapidly from low to moderate bulk density treatments as it depends upon the mentioned stem properties (Crook et al., 1994).

Safety factor against anchorage failure calculated from anchorage moment and self-weight moment was not significantly greater in treatments with high bulk density compared to low density. Greater anchorage moment of the plant with stronger stems and self-weight moment for the main tiller in sandy loam soil compared to clay loam soil resulted in greater safety factor against anchorage failure and stem failure.

The results of the data analysis indicated that the risk of stem failure or lodging in wheat is about 68% less likely to occur compared to anchorage failure or root lodging. Thereby, anchorage failure is predominant in wheat which is in agreement with the results of Crook et al*.* (1994).

Plant anchorage moment is associated with weaknesses either in the soil (low shear strength) (Ennos, 1991a; Goodman & Ennos, 1997) or in the root system (Berry et al., 2003a) and perhaps with both (Baker et al., 1998). Therefore, unlike soil bulk density, soil type as can be seen from the results presented in the Table 3.4 and Figure 3.15a, 3.15b, 3.15c and 3.15d in the result section, showed no significant effect on the plant anchorage moment. Plant anchorage moment was however affected by soil bulk density and followed a similar pattern in clay loam soil as well as in sandy loam soil. Therefore, it can be derived that the previous models of root anchorage on clay soils (Baker et al., 1998; Berry et al., 2003c; Scott et al., 2005b; Martinez-Vazquez & Sterling, 2011) could be applied to sandy soils; however, this needs to be evaluated further.

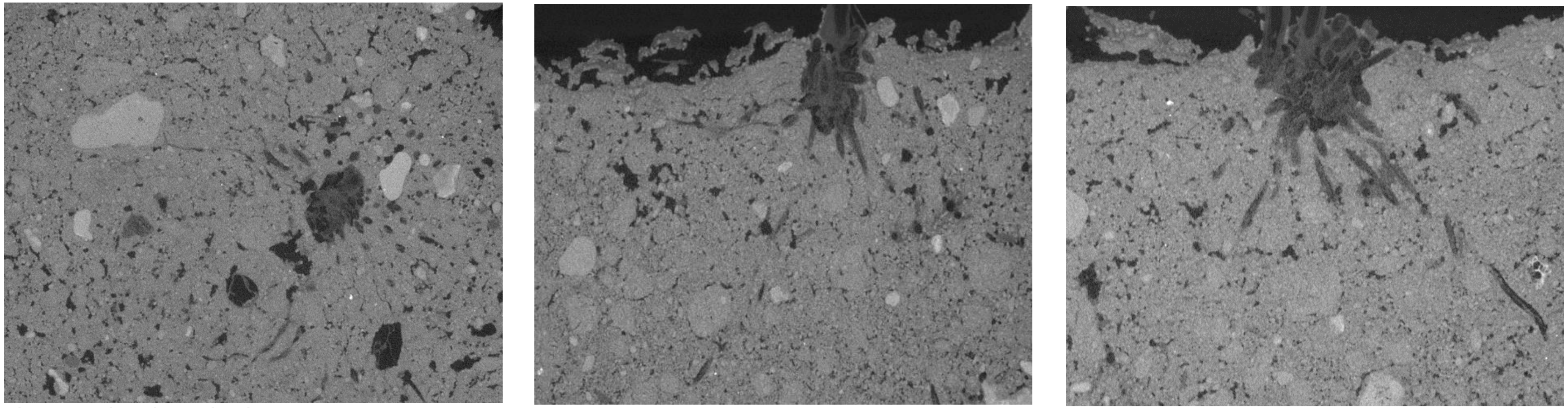
A significant increase in plant anchorage moment in moderate density treatments compared to the low density treatments could be explained by two reasons, first: a rapid increase in soil bulk density, which increased soil shear strength and penetration resistance as they increase plant anchorage moment (Crook & Ennos, 1994; Goodman & Ennos, 1999). Secondly: an increase in the measured root parameters - length, number of the roots (greater than 1 mm in diameter), angle of spread of the roots and the number of the roots (diameter between 0.5 - 1 mm) which was found due to a good root-soil connection (Berry et al., 2003a). These increases in both soil bulk density and root properties resulted in the greater plant anchorage moment in moderate density treatments compared to low density treatments in both sandy loam soil and clay loam soil; these outcomes of the plant anchorage moment are in line with the results presented by Ennos (1991) and Baker et al*.* (1998).

Furthermore, in high density treatments, despite the significant reduction in the root properties compared to the moderate density treatments in either soil types, a 6.5% increase in plant anchorage moment still occurred. This increase in plant anchorage moment was because of the further increase in soil bulk density hence, soil shear strength and penetration resistance, which compensated the reduction in the root properties. Plant anchorage moment as from these results seems to be proportional to the soil bulk density; hence, plant anchorage moment could typically be improved across various soil types by manipulating soil bulk density.

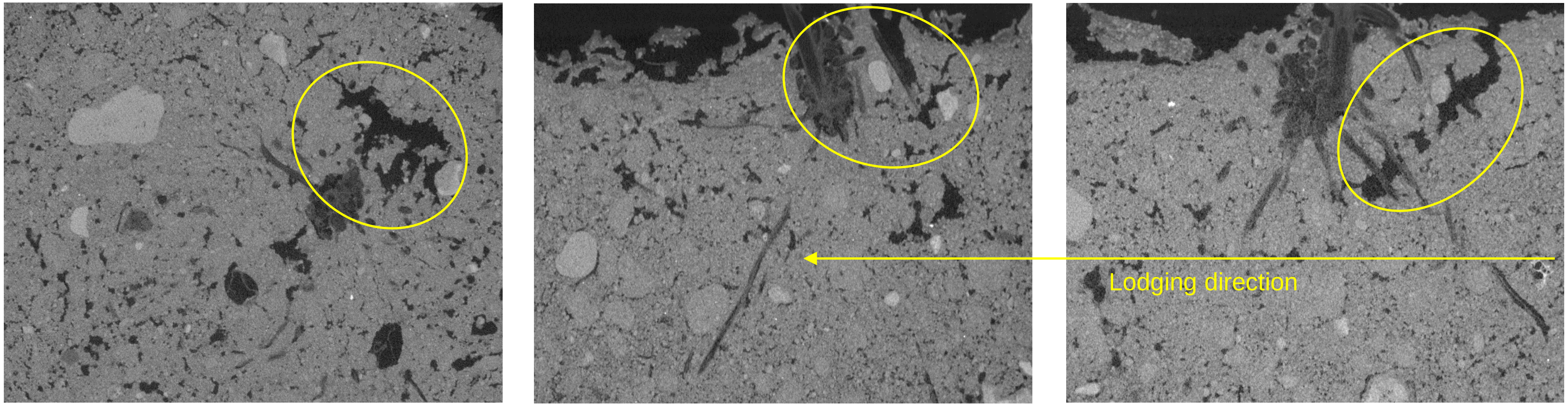
Early researchers highlighted stem failure as a predominant failure in cereals especially wheat (Pinthus & Brady, 1974; Neenan & Spencer-Smith, 1975). However, after identifying the more lodging resistance cultivars (Crook & Ennos, 1994; Navabi et al., 2006; Khakwani et al., 2010) and incorporating the dwarf gens into wheat cultivars (Kelbert et al., 2004; Shearman et al., 2005), the stems of the commonly used wheat cultivars are strong enough to resist stem failure and withstand weather conditions including wind and rain during the growing season. Thus, although the wheat cultivar Cadenza used in this study is one of the lodging susceptible cultivars (Berry et al., 2003a), during the plant anchorage tests conducted in the experiment presented in this Chapter, stem failure did not occur in either soil type nor in different bulk densities. The outcome of the results presented in section 3.3 have clearly shown that the predominant failure type in the wheat cultivar used in this study is anchorage failure due to the greater safety factor against the stem lodging than safety factor against anchorage failure. In this study, the plants were in the vertical position before they were subjected to the plant anchorage test (Figure 3.19a); the plants were pushed by the lodging arm (connected to the lodging device) to the 45˚ and failure did occur during the test as illustrated in Figure 3.19b and 3.19c in which soil failure can be clearly seen, hence, the plants did not returned to their original position (Figure 3.19d).

The results of the x-ray computed tomography (Figure 3.20, 3.21, 3.22 and 3.23) have further confirmed the anchorage failure presented in Figure 3.19. Moreover, similar to the root samples of the pot grown plant in which no damage was observed after been taking out from the soil, the photographs of the x-ray computed tomography did not show any damages in the roots. Nevertheless, soil failure represented by cracks (marked in circles) are clearly can be seen in both sandy loam and clay loam soil. Therefore, despite addressing the soil failure in this study, the mechanics of lodging due the root movement in sandy loam soil and clay loam soil at different soil bulk densities require further investigations, especially with the use of the x-ray computed tomography technique.

Figure 3.19. Artificial lodging process a) plant at vertical position before the anchorage test. b and c) plant pushed with the lodging arm to 45˚ from vertical axis and soil failure occurred. d) plant did not return to its vertical position after the anchorage test because of the soil failure.

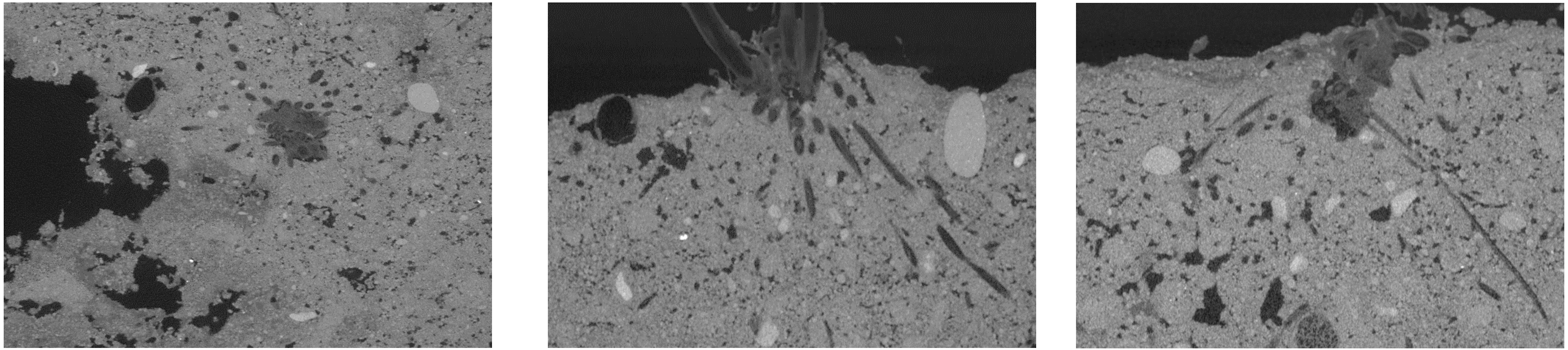


a) Pre-lodge (top view) a) Pre-lodge (right side view) a) Pre-lodge (left side view)



b) Post-lodge (top view) b) Post-lodge (right side view) b) Post-lodge (left side view)

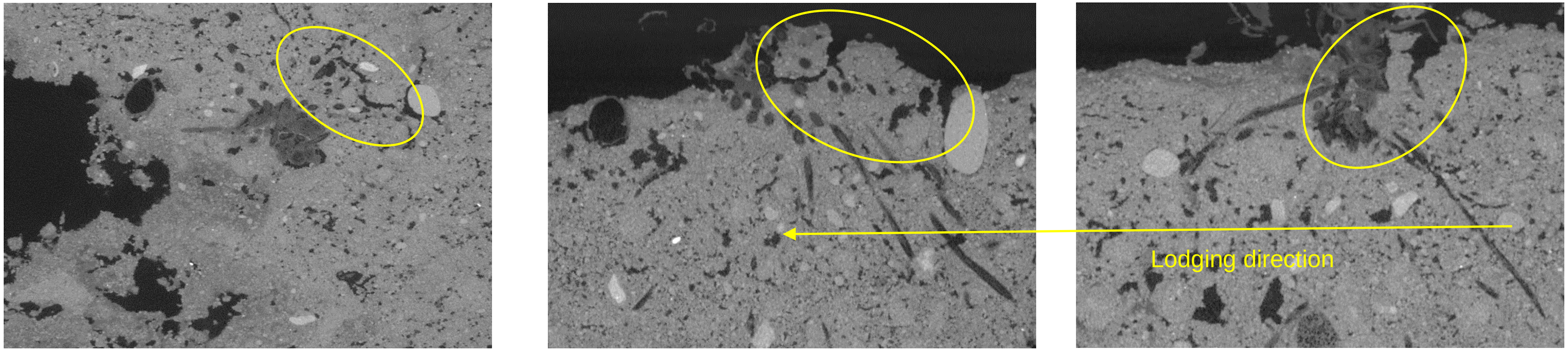
Figure 3.20. Sandy loam sample (1) of pre and post lodging test under X-ray computed tomography, the areas marked by the yellow circle indicate soil failure due to lodging.



a) Pre-lodge (top view)

a) Pre-lodge (right side view)

a) Pre-lodge (left side view)

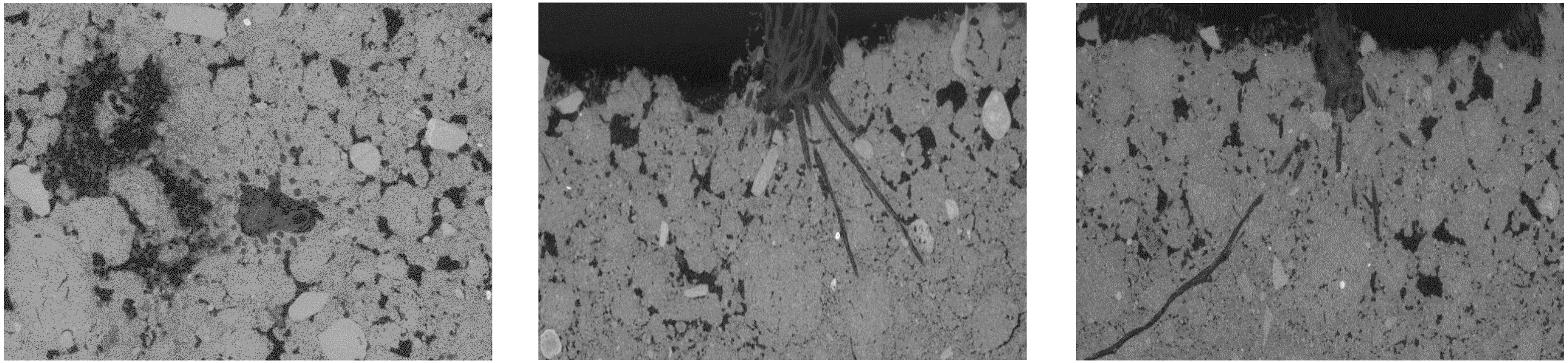


b) Post-lodge (top view)

b) Post-lodge (right side view)

b) Post-lodge (left side view)

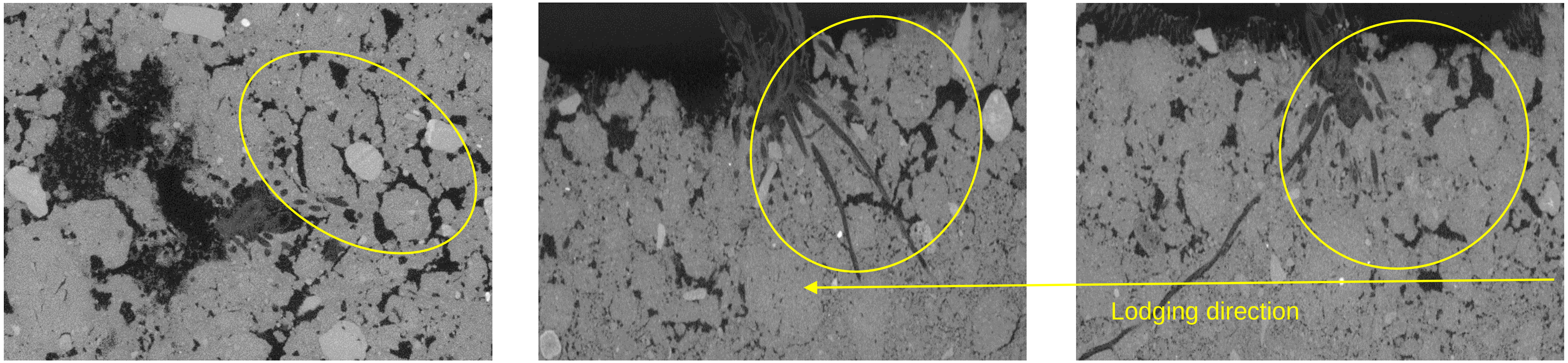
Figure 3.21. Sandy loam sample (2) of pre and post lodging test under X-ray computed tomography, the areas marked by the yellow circle indicate soil failure due to lodging.



a) Pre-lodge (top view)

a) Pre-lodge (right side view)

a) Pre-lodge (left side view)

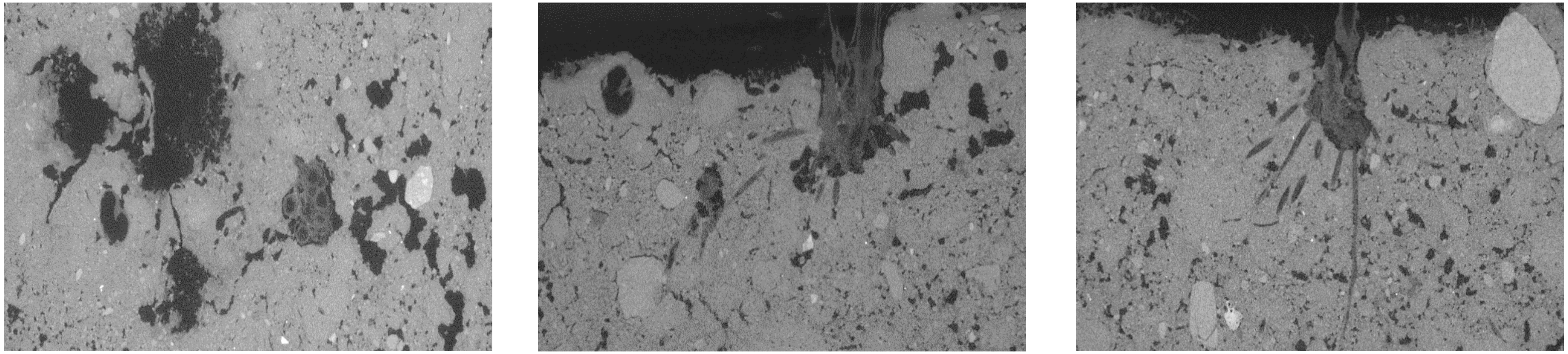


b) Post-lodge (top view)

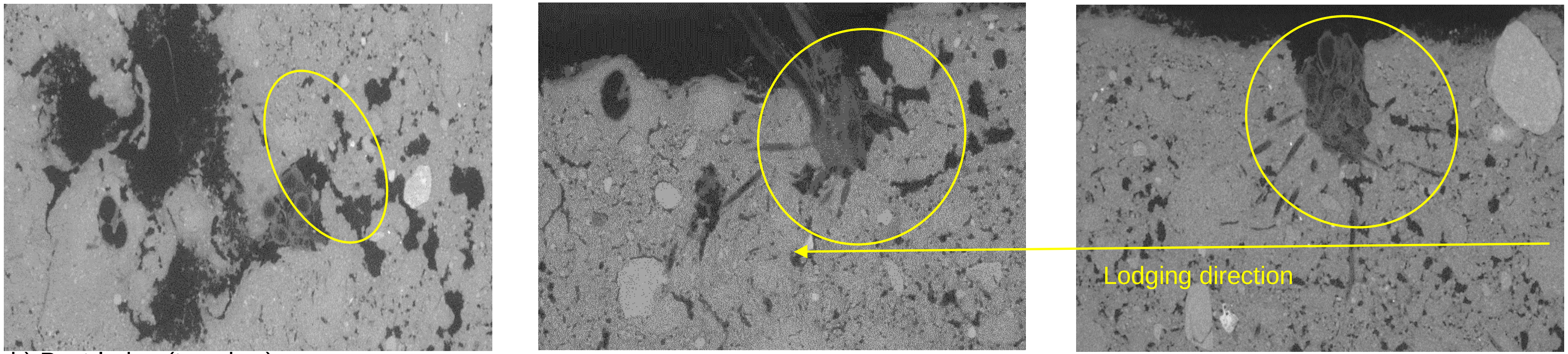
b) Post-lodge (right side view)

b) Post-lodge (left side view)

Figure 3.22. Clay loam sample (1) of pre and post lodging test under X-ray computed tomography, the areas marked by the yellow circle indicate soil failure due to lodging.



a) Pre-lodge (top view) a) Pre-lodge (right side view) a) Pre-lodge (left side view)



b) Post-lodge (top view) b) Post-lodge (right side view) b) Post-lodge (left side view)

Figure 3.23. Clay loam sample (2) of pre and post lodging test under X-ray computed tomography, the areas marked by the yellow circle indicate soil failure due to lodging.

3.4.3 The adventitious root properties

An increase in soil strength parameters (shear strength and penetration resistance) as a result of an increase soil bulk density is the major cause of restriction to root development (Holloway & Dexter, 1991; Huang et al., 2012). The total length of the roots (greater than 1 mm in diameter) associated with plant lodging or anchorage moment (Crook & Ennos, 1994) was significantly smaller in high bulk density soils (35.76%) compared to moderate bulk density soils. This reduction pattern was in agreement with the results found by Saqib et al. (2004); Hassan et al. (2007); Trukmann et al. (2008) and Bengough et al. (2011) who reported that root elongation may reduce by up to 50% when soil penetration reaches 2 MPa. In addition to soil bulk density, soil type also influenced root elongation. In the moderate and high bulk density treatments, the total length of the roots (greater than 1 mm in diameter) reduced in clay loam compared to sandy loam soil, similar to the results reported by Sposaro et al. (2008) due to insufficient pore size in clay loam soil which contains very fine particles that decreased the ability of the roots to further penetrate the soil. Thus, it can be inferred that the roots overcame the reduction in the length by producing more lateral roots with greater plate diameter which contributed to increasing anchorage moment in the top soil to reach nutrient and water sources (Hill, 1990; Ball-Coelho et al., 1998). This may explain why in this study, the roots (greater than 1 mm in diameter) of plants grown in moderate bulk density soil (1.3 Mg m^{-3}) were longer and more numerous, had greater angle of spread and greater root plate diameter compared to the plants grown in low bulk density soils. Eventually, according to the change in soil bulk density and root properties, plant anchorage moment changes, as it depends on both soil and root properties.

The increase in soil bulk density inhibits root development and reduces their ability to penetrate soil (Pietola, 2005; Aggarwal et al., 2006) as the diameter of the available pores, which allow the roots to grow through, decreases; hence the vertical elongation is restricted (Watt et al., 2006; Huang et al., 2012). Thus, increasing plant anchorage moment should not be associated with a reduction in the yield components.

Since soil bulk density can be manipulated by cultivation system, therefore, in the further investigation different cultivation practices will be applied in the field to identify the optimum soil density at which plant anchorage moment can be maximised without reducing the yield.

3.5 Conclusions

The results of this study have clearly shown that:

1. Increasing soil bulk density from 1.1 to 1.3 Mg m^{-3} increased plant anchorage moment by up to 40% resulting from an 8% increase in soil shear strength and a significant ($p < 0.001$) increase in the adventitious root properties.
2. Sandy loam had 8% greater plant anchorage moment resulting from increased soil shear strength and penetration resistance by up to 16% and 26%, respectively; and significantly ($p < 0.001$) greater adventitious root properties.
3. The results of the data analysis have shown that, winter wheat is up to 68% more prone to anchorage failure, which is more likely to be due to soil failure rather than root failure based on the results of the X-ray computed tomography.
4. Soil shear strength and penetration resistance are both proportional to the soil bulk density. In either soil type used in this study, a 26% increase in soil bulk density resulted in 32% and 27% increase in soil shear strength and penetration resistance respectively.

5. Increasing 1.1 Mg m^{-3} bulk density to 1.5 Mg m^{-3} bulk density in either soil types increased the above ground properties. However, the adventitious root properties started to reduce significantly ($p < 0.001$) with further increasing 1.3 Mg m^{-3} bulk density to 1.5 Mg m^{-3} bulk density in both sandy loam and clay loam soils.
6. For maximum anchorage moment and yield maintenance, the optimum soil bulk density was found to be ranged between 1.3 Mg m^{-3} and 1.5 Mg m^{-3} for the soil textures evaluated in this study. Further field studies need to be conducted to evaluate different cultivation systems to achieve the optimum soil bulk density, which maximises both plant anchorage moment and the harvestable yield.

Chapter 4

4. Effect of different cultivation systems on soil physical conditions and plant anchorage moment

4.1 Introduction

Based on the results from Chapter 3 in which the hypothesis of soil bulk density affecting adventitious root development and the anchorage moment of winter wheat was investigated, it is evident that soil bulk density has significant effects on the adventitious root properties and plant anchorage moment. Additionally, soil physical conditions including soil bulk density and shear strength are affected by cultivation systems (Schjonning & Rasmussen, 2000; Li et al., 2008; Benjamin & Mikha, 2010), as well as root development (Dwyer et al., 1996; Martinez et al., 2008; Sun et al., 2011). Accordingly, the studies in this Chapter, investigate the effect of cultivation systems on the adventitious root development and the anchorage moment of winter wheat both of which are soil physical conditions dependent.

Earlier studies have investigated the influence of cultivation systems on soil conditions (Wilhelm & Mielke, 1988; Schjonning & Rasmussen, 2000; Saqib et al., 2004; Scott et al., 2005b; Trukmann et al., 2008). Cultivation systems decreasing soil bulk density and shear strength was reported by Edwards et al. (1992) and Lal et al. (1994), while zero tillage resulting in no changes were addressed by Chang & Lindwall (1989) and Hill (1990). In contrast an increase in soil bulk density and shear strength has been reported due to the use of different cultivation systems (Ferreras et al., 2000); additionally, improper or continues use of the same cultivation system increases soil bulk density and shear strength and creates a hard pan layer below the cultivation depth (Schjonning & Rasmussen, 1989; Antille et al., 2008).

Due to the effect of cultivation systems on the soil physical conditions in which plant roots are develop, cultivation systems therefore affect root development too (Lipiec et al., 2003; Ali Akbar et al., 2004; Huang et al., 2012). Although the influence on the root development of cultivation systems has been well researched (Hemsath & Mazurak, 1974; Wilhelm & Mielke, 1988; Martinez et al., 2008; Bengough et al., 2011; Huang et al., 2012; Tracy et al., 2012a), the majority of studies however, focus primarily on a whole root system or the fine absorption roots critical to plant growth. Little attention has been paid to the specific adventitious (adventitious) roots of self-supported plants whose function is primarily to anchor the plant and prevent it from falling over.

Moreover, the influence of cultivation systems is further extended to include the yield of wheat (Pringle & Lark, 2007; Mufioz-Romero et al., 2010). The yield may increase or reduce with different cultivation systems depending on the depth of cultivation and loosening of soil, in addition to the developments of the root system (Gemtos et al., 2002; Jiuhao et al., 2007; Acuna et al., 2012).

To date, no studies have examined the effect of cultivation systems on the plant anchorage moment, which itself depends on both adventitious root development and soil physical conditions (Goodman & Ennos, 1998; Berry et al., 2003a; Yang et al., 2015). The studies in this Chapter thereby, focus on identifying the effect of different cultivation systems to determine the optimum soil conditions, which increase plant anchorage moment and reduce the likelihood of root lodging through a combination of enhanced soil strength and unrestricted adventitious root development without reducing the yield.

4.2 Materials and methods

4.2.1 Experiment sites and agronomy information

4.2.1.1 Large Marsh experiment (2012 - 2013)

An experiment was conducted to investigate the effect of soil tillage systems on the adventitious root properties and the anchorage moment of winter wheat; in a soil classified as sandy loam soil (Claverley series) (Smith et al., 2013) on Large Marsh field (Figure 4.1) at Harper Adams University (+52° 46' 57.58 N, -2° 25' 44.93 W) in the United Kingdom in 2012 - 2013. In the previous year, the field was drained and a winter wheat was established in a controlled traffic system (a system at which the least possible area of the field is disturbed as a result of the agricultural process and machinery loads, through running the machines on the same wheel marks), after subsoiling and ploughing to assist in the management of the homogeneity of the site (Kristof et al., 2012) .

The field was cultivated on the 6th of November 2012 using a tracked Cat Challenger MT765C with a 4 m Vaderstad Top Down to a depth of 100 and 250 mm for shallow and deep tillage treatments, respectively. On the 9th of November 2012, winter wheat (*Triticum aestivum* L. var. Duxford) was drilled using a Vaderstad Rapid drill. The experiment was established with three different tillage treatments (shallow tillage, deep tillage and zero tillage) randomised within four blocks, each block consist of 4 plots of 4 m x 84 m (width x length). The 12 plots were only the control traffic plots, chosen out of 36 plots of the field as this experiment was conducted in collaboration with control traffic and low ground pressure project running at Harper Adams University (Smith et al., 2012). Thereby, to minimise the amount of destruction and footprints in the plots, 2 m x 4 m in each plot was allocated for the sampling issues. The agronomy details applied throughout the growing stages are illustrated in Table 8.2.1 (Appendix section 8).

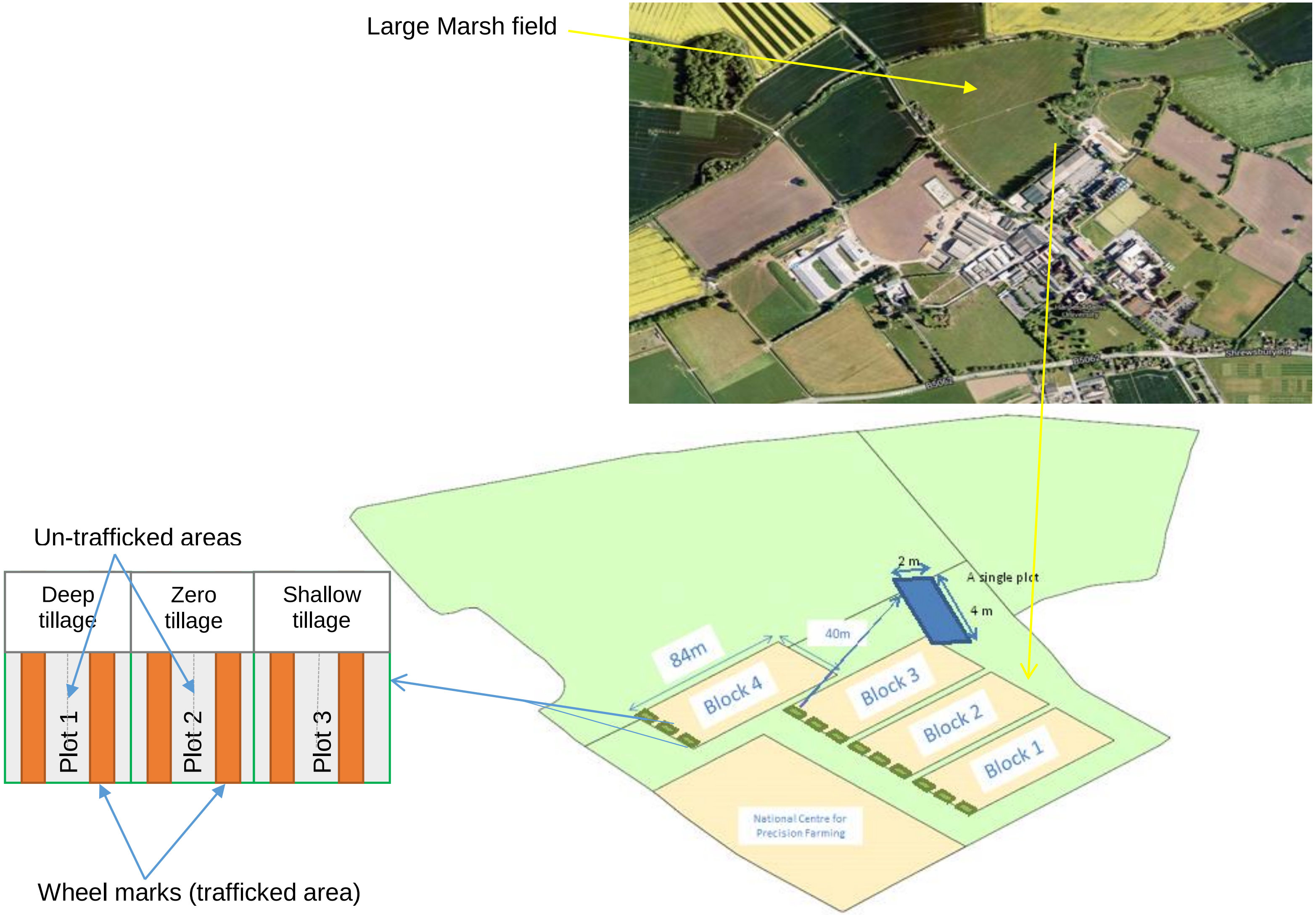


Figure 4.1. Field trail design and treatments distribution in Large Marsh field experiment 2012 - 2013.

4.2.1.2 Buttery Hill experiment (2013 - 2014)

A second experiment to look at the effect of tillage systems was conducted on Buttery Hill field at Harper Adams University (52°46'22.1"N, 2°25'41.1"W) in the United Kingdom in 2013 - 2014 on a loamy sand soil (85% sand, 6% silt and 9% clay) . The field was cultivated on the 13th of November 2013 with a range of secondary cultivation systems, namely a power harrow (PH 300), which was attached to a New Holland tractor Model T6040 (Figure 4.2).

Figure 4.2. The PH 300 power harrow with a New Holland tractor (T6040) in the cultivation process

Winter wheat (*Triticum aestivum* L. var. Duxford.) was sown using an “Accord” seed drill (Figure 4.3) on the 13th of November 2013, after harvesting of maize (*Zea mays*) crop that had been planted in the previous year.

Figure 4.3. The T6040 New Holland tractor combined with Accord seed drill in the drilling process of winter wheat (variety Duxford) on the 13th of November 2013.

In this experiment (2013 - 2014), both the power harrow (PH 300) and the Accord seed drill were set to the maximum and minimum limit of their ground pressure to create four different treatments. Thereby in combination, four tillage treatments of: high-pressure power harrow + high-pressure seed drill (H/H), high-pressure power harrow + low pressure seed drill (H/L), low pressure power harrow + high-pressure seed drill (L/H) and low pressure power harrow + low pressure seed drill (L/L) were established. The treatments were randomised over four blocks; each block contained four plots (plot for each tillage system) where each plot was 3 x 20 m (width x length).

To create low and high-pressure at which the power harrow was operated, the trap point was adjusted between the lowest and the highest positions. High pressure power harrow was achieved by placing the trap point at the lowest position (Figure 4.4a) and vice versa, for the low pressure power harrow the trap point placed on the highest position (Figure 4.4b) based on the manufacture’s recommendations.

a)
Figure 4.4 a) Trap point placed a lowest position to a achieve high pressure while harrowing

b)
Figure 4.4 b) Trap point placed a highest position to a achieve low pressure while harrowing

Figure 4.4. Trap point at power harrow, placed at Lowest and highest points to adjust the pressure of power harrow.

Changing the position of the spring trap points for the seed drill was the key factor for manipulating the pressure of the press wheel (Figure 4.5). The spring trap was placed at the highest and then at the lowest positions, the press wheel of the seed drill was lifted at each position and the pressure of 18 N and 38 N was measured using a Mecmesin force gauge at the highest and lowest positions, respectively.

The use of the four cultivation treatments resulted in a significant differences in soil shear strength, which is more associated with plant anchorage moment (Crook & Ennos, 1993; Goodman & Ennos, 1999) as demonstrated in Table 4.1. Nevertheless, no statistical variations were found in soil bulk density and penetration resistance.

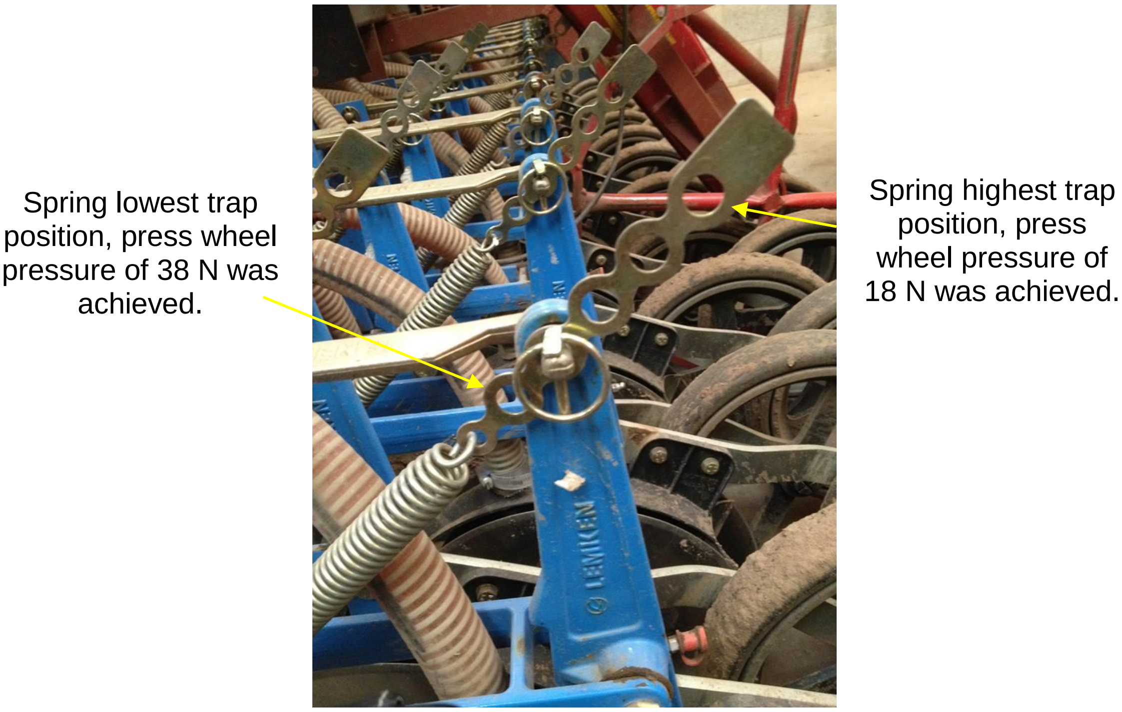


Figure 4.5. Spring trap points on the seed drill, to adjust the press wheel pressure at which high and low pressures were achieved

Table 4.1. Initial measurements of soil physical properties

Treatments	Soil bulk density (Mg m^{-3})	Soil shear strength (kPa)	Penetration resistance (kPa)
H/H	1.37	21.23^{b*}	304
H/L	1.37	22.89^{b}	293.9
L/H	1.38	17.24^{a}	225.9
L/L	1.34	16.35^{a}	245.8
S.E.M. (d.f.)	0.025 (9)	0.939 (41)	25.000 (41)
p value	0.709	<.001	0.097

H/H = high-pressure power harrow + high-pressure seed drill, H/L = high-pressure power harrow + low pressure seed drill, L/H = low pressure power harrow + high-pressure seed drill and L/L = low pressure power harrow + low pressure seed drill, * Values in a row followed by the same letter are not significantly different at $p < 0.05$ as determined by Tukey test, S.E.M. represents standard error of means, d.f. represents degree of freedom.

Rolling the field in springtime has been recommended as a lodging control method through consolidating the soil around the seeds and ensuring moisture and nutrition availability (Kopecky, 1970; Pinthus & Brady, 1974; Berry et al., 2003c). Therefore, the effect of rolling the field at springtime was also investigated. A Cambridge roller was used on the 5th of February 2014 when the plants were at tillering growing stage (GS 25 - GS 29) before stem elongation. At the time where the field was rolled, soil moisture content of 35.2%, 34.2%, 32% and 34.5% was measured in H/H, H/L, L/H and L/L treatments, respectively using a TDR moisture measure meter. The Cambridge roller (Figure 4.6) was attached to the same tractor used in the cultivation process (New Holland T6040), where two lines of rolled areas created vertical to the direction of cultivation as demonstrated in Figure 4.7. The agronomy practice on the Buttery Hill field during the growing season is illustrated in Table 8.2.2 in the Appendix section 8.

Figure 4.6. Cambridge roller, used in the Butter Hill field to create extra compaction over the treatments when the plant was at tillering growing stage (GS 25 - GS 29).

Figure 4.7. Field trial design and treatments distribution in Buttery Hill field experiment 2013 – 2014, **H/H** represents high pressure power harrow + high pressure drill, **H/L** represents high pressure power harrow + low pressure drill, **L/H** represents low pressure power harrow + high pressure drill and **L/L** represents low pressure power harrow + low pressure drill.

4.2.2 Measurements of soil physical properties and volumetric moisture content

Prior to harvesting (at grain filling stage where the ears are the heaviest and root lodging is most likely to occur), in both fields, soil bulk density was measured using a ring of 37.5 mm × 70 mm (radius × height) in the surface layer of the soil (0 - 100 mm depth). The collected samples were weighed before and after drying in the oven for at least 24 hours at 105 degrees, then soil bulk density and soil moisture content were calculated. In the Large Marsh experiment, the total of 36 soil samples was collected (three samples per each of the 12 plots) for the bulk density calculation.

In the Buttery Hill experiment, soil bulk density was measured twice. The first measurement was on the 16th of November 2013 after the cultivation process where a total of 48 samples (three samples from each plot) were collected from the field for the initial soil bulk density measurements. The second measurement was at grain filling stage about six weeks prior to harvesting when the anchorage moment was measured. The total number of samples collected for the second time was doubled compared to the initial measurement, as a rolled area was created by rolling the middle area of the plots with a Cambridge roller to investigate the effect of further soil compaction. Hence, a total of 96 soil samples (3 from the un-rolled areas and 3 from the rolled areas in each plot) were collected and was taken to the laboratory for the bulk density calculation.

At the same time as measuring plant anchorage moment, soil shear strength and penetration resistance were measured. In Large Marsh field, 72 measurements (6 in each plot) for each of soil shear strength and penetration resistance were collected.

In Buttery Hill field, 192 measurements (6 in un-rolled area and another 6 in the rolled area) were conducted for each of soil shear strength and penetration resistance measurements. The measurements of soil shear strength and penetration resistance in both fields were collected at the depth of 0 - 50 mm, the method at which shear strength and penetration resistance were measured was described earlier in section 3.2.4.

Volumetric moisture content in each field was measured using a TDR moisture measure meter when shear strength and penetration resistance measurements took place. In the Large Marsh field, the average volumetric moisture content of 30.38%, 30.01% and 27.85% recorded for zero tillage, shallow tillage and deep tillage treatments, respectively. Likewise, in the Buttery Hill field volumetric moisture content was measured in both un-rolled and rolled areas. In the un-rolled areas, the average volumetric content measured was 24.36%, 24.16%, 24.35% and 24.92% for H/H, H/L, L/H and L/L respectively; and 23%, 24.08%, 24% and 24.14% for the sequence order of the treatments respectively in the rolled areas.

4.2.3 Measurements of plant properties

The measurements of plant properties including both the above ground and root properties were carried out based on the procedures described in section 3.2.5. Plant anchorage moment was measured as previously described in section 3.2.5.3.

As regards the yield data, the data were collected both mechanically and manually in the Large Marsh field, in order to be able to calculate the reduction in the yield due to the wheel marks. The yield was recorded for each complete plot (4 m width x 84 m length) with the use of a Trimble GPS system and Ceres

8000i yield monitoring system at which were fitted on a Class dominator 85 combine harvester. In contrast, hand-harvest quadrat samples data were measured separately in-between the wheel marks and on the wheel marks (Smith et al., 2013). In the Buttery Hill fields; a Wintersteiger plot combine harvester model "Nurserymaster" with a 1.5 m cutter bar was used in each plot, thereby, separate data were collected for both rolled and non-rolled areas (Figure 4.8).

Figure 4.8. Wintersteiger combine harvester with 1.5 m cutter bar during harvesting process in the Buttery Hill field.

4.2.4 Statistical analysis

The Large Marsh experiment (2012 - 2013) was arranged in a four randomised complete block design (RCBD) and the recorded data were analysed using one way ANOVA in Genstat 14th Edition. Tillage system was considered as the main factor and had three different levels (zero tillage, shallow tillage and deep tillage treatments). A total of 72 samples was collected as tillage treatment (3) x block (4) and replication (6).

The Buttery Hill experiment (2013 - 2014) was randomised within four blocks (RCBD). The initial samples collected after cultivation and analysed using one way ANOVA in Genstat 14th Edition, with four levels of tillage treatments arranged in four blocks and three replications for each treatments, 48 samples were collected and analysed. At maturity (grain filling stage when anchorage moment was measured) and after the application of soil compaction through the rolling process, the data were analysed using two way ANOVA in Genstat 14th Edition. The experiment was composed of two factors: cultivation with four levels x rolling (2) levels randomised in (4) blocks, with six replications and a total of 196 samples collected for each variant.

The differences between the mean values of the soil physical properties and plant above ground and adventitious root properties were evaluated using Tukey's multi comparison test and all differences considered significant at $p \leq 0.05$.

4.3 Results

4.3.1 Large Marsh experiment (2012 - 2013)

4.3.1.1 Soil physical properties

The results of the data analysis in Figure 4.9 shows that tillage system significantly influenced soil bulk density. Soil bulk density was 8.2% significantly lower in deep tillage treatments compared to the soil bulk density in zero tillage treatments, but was not insignificantly greater than soil bulk density in shallow tillage treatments.

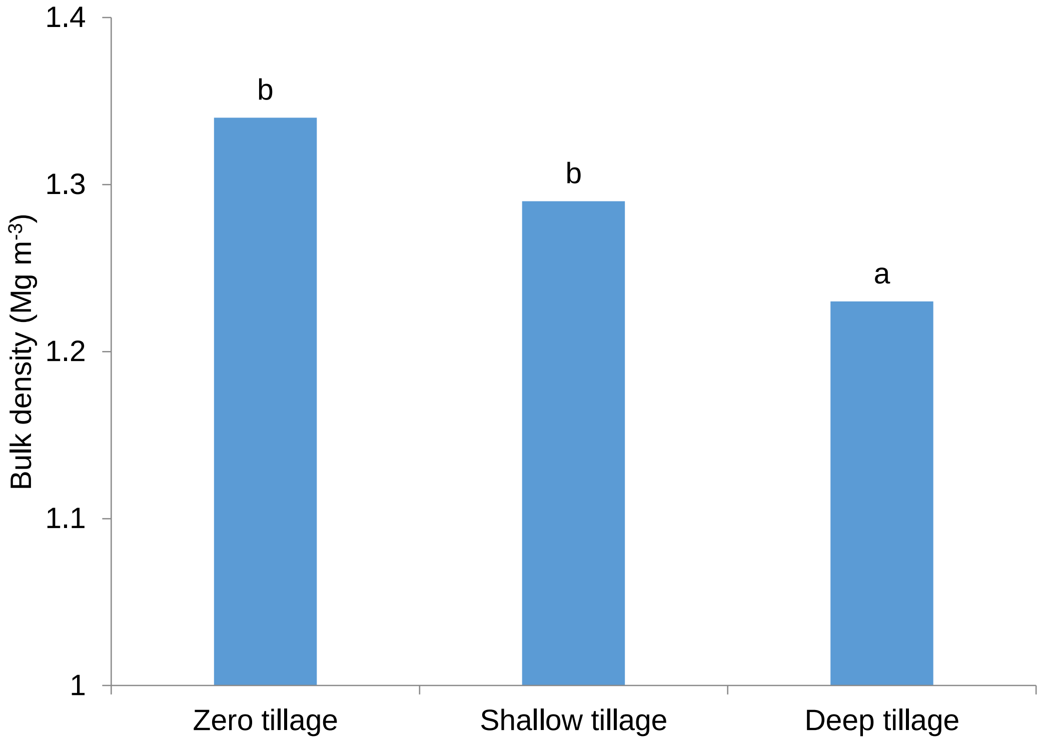


Figure 4.9. The effect of different tillage systems on soil bulk density (Mg m^{-3}). (S.E.M.) = 0.015, degree of freedom = 30, *p* = < 0.001, n = 12 for each treatment.

Furthermore, similar to the soil bulk density, among the three tillage systems, significant differences of 21.9% and 26.8% were found in soil shear strength and penetration resistance (Figure 4.10 and 4.11), respectively. Zero tillage had the greatest average of soil shear strength and penetration resistance, whereas the lowest average was found in deep tillage.

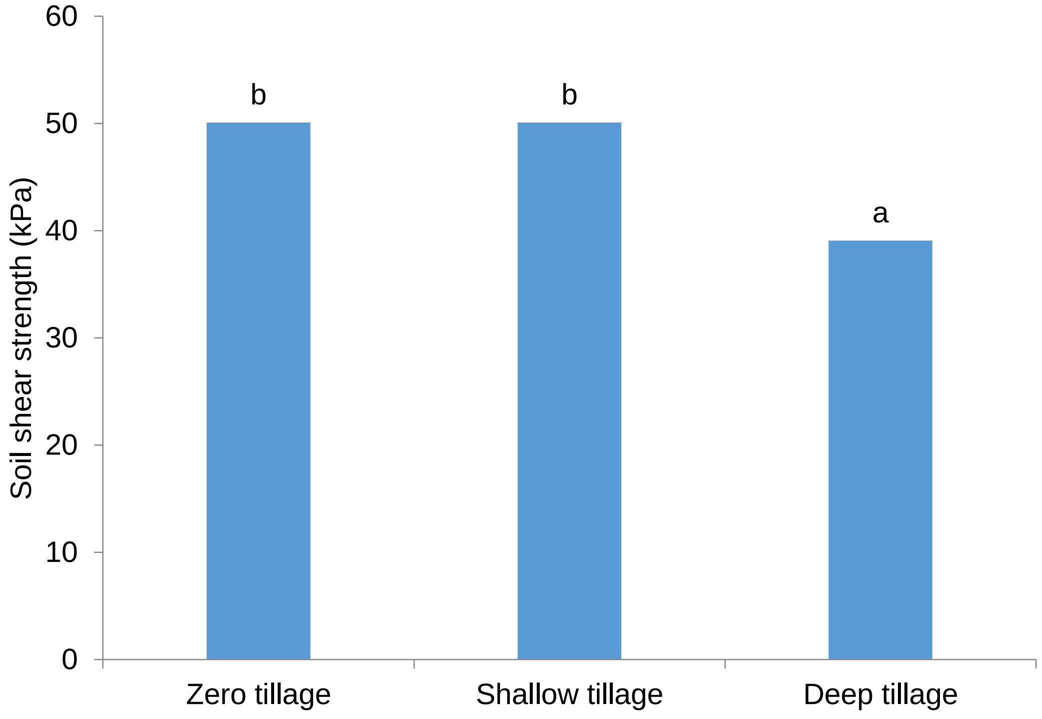


Figure 4.10. The effect of different cultivation systems on soil shear strength (kPa). (S.E.M.) = 2.49, degree of freedom = 66, *p* = 0.003, n = 24 for each treatment.

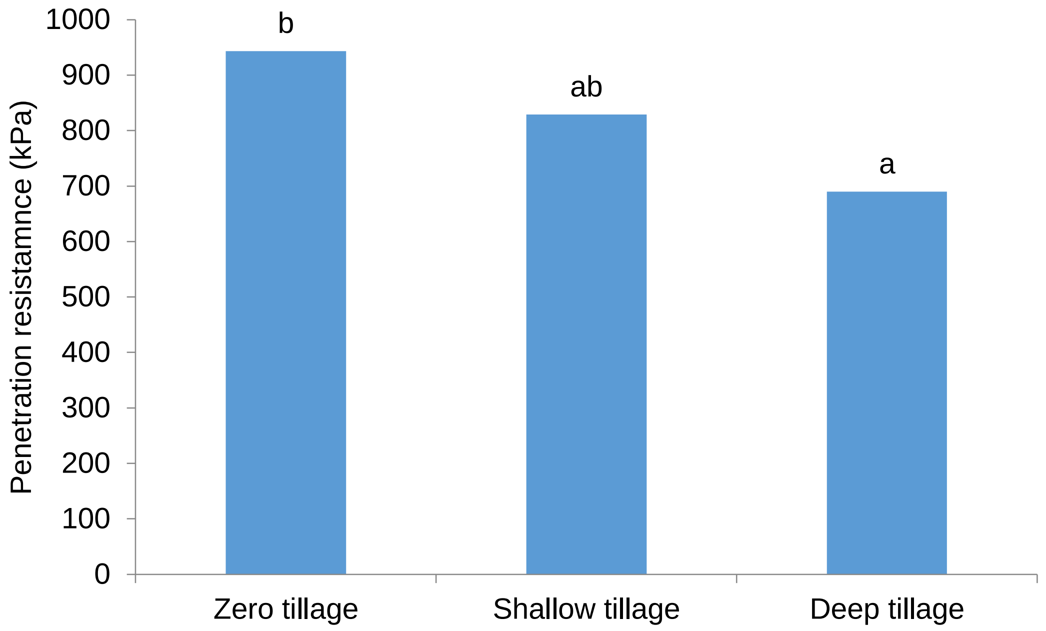


Figure 4.11. The effect of different cultivation systems on penetration resistance (kPa). (S.E.M.) = 60.4, degree of freedom = 66, *p* = 0.016, n = 24 for each treatment.

4.3.1.2 The above ground properties

Table 4.2 shows the effect of different tillage systems on the above ground properties of the main tiller as well as the number of tillers, self-weight moment and safety factor of the individual plant. The results of the data analysis revealed that the above ground properties of the main tillers: fresh weight, ear weight, main tiller diameter, self-weight moment, stem bending moment and the safety factor were not influenced by the tillage systems.

The height of the main tiller and the centre of gravity were both significantly affected and started to increase with decreasing depth of the tillage system. A 4.5% and 6.0% reduction in the height of the main tiller and centre of gravity was recorded from deep tillage system to zero tillage.

As regards an individual plants, the number of tillers per plant was found to be significantly influenced by tillage treatments and decreased with the increase of tillage intensity and soil loosening degree. Zero tillage treatments had 26.8% greater number of tillers compared to the lower number of tillers (5.46) in deep tillage treatments. Concerning the harvested yield, the data were inconsistent (Figure 4.12). Zero tillage in mechanically harvested plots, produced 16.3% and 11.3% significantly less yield compared to shallow and deep tillage, respectively. In contrast manually harvested data showed that, zero tillage had the highest yield of 10.72 t ha^{-1} collected in un-trafficked areas (between the wheel marks), but at the same time, the lowest yield of 4.34 t ha^{-1} harvested on the wheel marks in zero tillage.

Table 4.2. The effect of different tillage systems on the above ground properties of winter wheat.

		Zero tillage	Shallow tillage	Deep tillage	S.E.M. at (d.f.= 66)	*p* value
Individual plant properties	Yield (t/ha)	6.93^{a*}	8.28^{b}	7.82^{b}	0.153	<.001
	Number of tillers/plant	7.46^{b}	5.88^{a}	5.46^{a}	0.403	0.002
	Plant self-weight moment (Nm)	0.26	0.23	0.22	0.017	0.16
	Plant safety factor	2.78	2.96	2.40	0.200	0.143
Main tiller properties	Stem height (cm)	75.86^{a}	77.85^{ab}	79.46^{b}	0.905	0.023
	Tiller weight (g)	12.92	13.17	13.28	0.535	0.888
	Ear weight/tiller (g)	6.37	6.68	6.61	0.233	0.608
	Centre of gravity (cm)	50.08^{a}	52.33^{b}	53.28^{b}	0.64	0.002
	Stem diameter (mm)	4.64	4.58	4.54	0.0607	0.377
	Self-weight moment (Nm)	0.0451	0.0481	0.0494	0.00217	0.359
	Stem bending moment (Nm)	0.1515	0.1486	0.1517	0.00973	0.968
	Safety factor	3.4	3.09	3.14	0.189	0.467

* Values in a row followed by the same letter are not significantly different at $p < 0.05$ as determined by Tukey test, S.E.M. represents standard error of means, d.f. represents degree of freedom, n = 24 for each treatment.

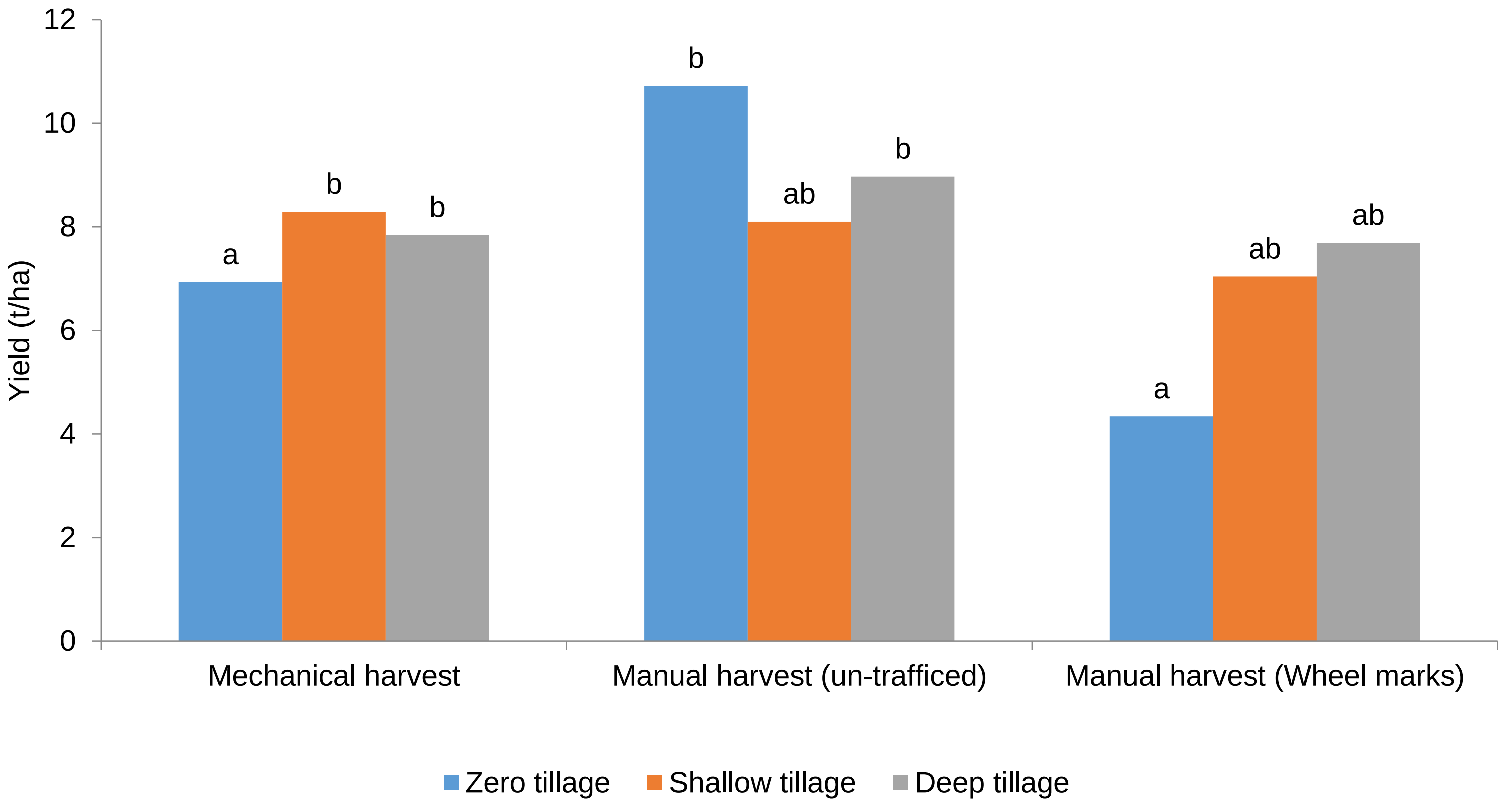


Figure 4.12. Mechanically and manually harvested yield data collected in zero, shallow and deep tillage treatments, error bars represent standard errors of means (S.E.M.), adopted from Smith et al. (2013).

4.3.1.3 The adventitious root properties

Table 4.3 shows the data analysis results in which root properties are influenced by tillage systems. Different tillage systems significantly ($p < 0.001$) influenced the mean of root plate diameter, number and total length of the roots (greater than 1 mm in diameter) and angle of spread of the roots. Differences of 18.7%, 69.4%, 58.6% and 25.6% in the mean values of the root plate diameter, number of the roots (greater than 1 mm in diameter), total length of the roots (greater than 1 mm in diameter) and the angle of spread of the roots were found between zero tillage and deep tillage systems respectively, in which greater values were recorded in the zero tillage system.

Table 4.3. The effect of different tillage systems on the root properties of winter wheat.

	Zero tillage	Shallow tillage	Deep tillage	S.E.M. at (d.f.= 66)	*p* value
Total length of the roots/plant (greater than 1 mm in diameter) (mm)	324.00^{b*}	134.00^{a}	134.04^{a}	24.300	<.001
Root plate diameter/plant (mm)	67.80^{b}	58.90^{a}	55.10^{a}	2.000	<.001
Number of the roots/plant (greater than 1 mm in diameter)	14.75^{b}	6.00^{a}	4.05^{a}	0.719	<.001
Angle of spread of the roots/plant (°)	95.20^{c}	82.50^{b}	70.80^{a}	2.710	<.001
No. of roots/plant (diameter between 0.5 - 1 mm)	60.88	54.54	53.92	3.270	0.258

* Values in a row followed by the same letter are not significantly different at $p < 0.05$ as determined by Tukey test. S.E.M. represents standard error of means, d.f. represents degree of freedom, n = 24 for each treatment.

Figure 4.13 demonstrates the significant effect of different tillage systems on the plant anchorage moment. The average anchorage moment provided by plants grown in zero tillage system was 30% greater compared to plants grown in deep tillage system. Although no correlations could be detected between the individual values, positive linear relationships were found between the mean values of plant anchorage moment and the mean values of each of soil bulk density, soil shear strength, penetration resistance, root plate diameter, number of the roots (greater than 1 mm in diameter) and the angle of spread of the roots as illustrated in Table 4.4.

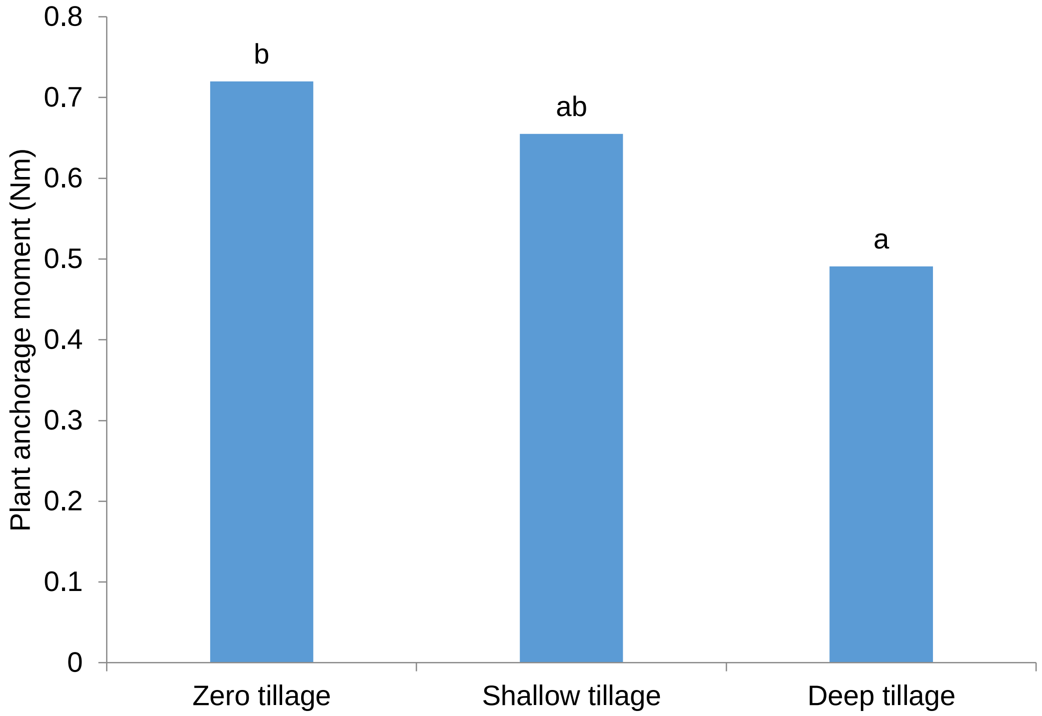


Figure 4.13. The effect of different tillage systems on the plant anchorage moment (Nm) of winter wheat. (S.E.M.) = 0.0532, degree of freedom (d.f) = 66, P = 0.01, n = 24 for each treatment.

Table 4.4. Linear relationships between the mean values (n = 3) of plant anchorage moment and soil physical properties and adventitious root properties

	R^2 values	
Soil bulk density (Mg m^{-3})	0.963	y* = 2.1033x** - 2.0842
Soil shear strength (kPa)	0.924	y = 0.0179x - 0.2075
Penetration resistance (kPa)	0.965	y = 0.915x - 0.129
Root plate diameter/plant (mm)	0.792	y = 0.0161x - 0.355
Number of the roots/plant (greater than 1 mm in diameter)	0.650	y = 0.0172x + 0.4773
Angle of spread of the roots/plant (°)	0.929	y = 0.0093x - 0.1504

* represents the anchorage moment.
** represents the property listed in the same row.

4.3.2 Buttery Hill experiment (2013 - 2014)

4.3.2.1 Soil strength properties

Table 4.5 illustrates the effect of cultivation system on the soil strength properties. Although the greatest values of soil bulk density, shear strength and penetration resistance were found in (high-pressure power harrow + drill with high-pressure) H/H treatments. However, despite setting the pressure on both the power harrow and the seed drill to the maximum and minimum limit of pressure (according to the manufacturer's recommendations), none of these values were different statistically compared to their values in the rest of the treatments. Furthermore, this non-statistical difference among the mean values of soil strength properties further extended to include the interaction of cultivation systems and rolling (soil compaction). The highest soil bulk density of 1.45 Mg m^{-3} and penetration resistance of 1121 kPa were recorded in the rolled treatments of H/H compared to the lowest bulk density of 1.35 Mg m^{-3} and penetration resistance 902 kPa in (low pressure power harrow + drill with low pressure) L/L treatments. Soil shear strength ranged between 39.88 kPa in the rolled (high-pressure power harrow + drill with low pressure) H/L to 25.12 kPa in the un-rolled L/L treatments. Unlike soil cultivation, rolling the soil significantly increased soil bulk density (Figure 4.14) and soil shear strength (Figure 4.15) by about 4% and 30%, respectively.

Table 4.5. The effect of rolling and cultivation system on soil strength properties

Rolling	Cultivation	Soil bulk density (Mg m^{-3})	Shear strength (kPa)	Penetration resistance (kPa)
Un-rolled	H/H	1.38	27.73	1001.67
	H/L	1.38	28.65	1069.00
	H/H	1.37	25.13	996.75
	L/L	1.35	25.12	902.00
Rolled	H/H	1.45	38.29	1121.58
	H/L	1.41	39.88	973.00
	L/H	1.43	37.77	963.83
	L/L	1.42	36.86	1026.92
S.E.M. at (d.f. = 181)	Rolling	0.007	1.011	45.255
	Cultivation	0.015	1.011	64.000
	Interaction	0.013 (85)	1.430	90.510
p value	Rolling	<.001	<.001	0.651
	Cultivation	0.221	0.091	0.708
	Interaction	0.514	0.905	0.523

H/H represents high-pressure power harrow + drill with high-pressure, H/L represents high-pressure power harrow + drill with low pressure, L/H represents low pressure power harrow + drill with high-pressure and L/L represents low pressure power harrow + drill with low pressure. S.E.M. represents standard error of means, d.f. represents degree of freedom.

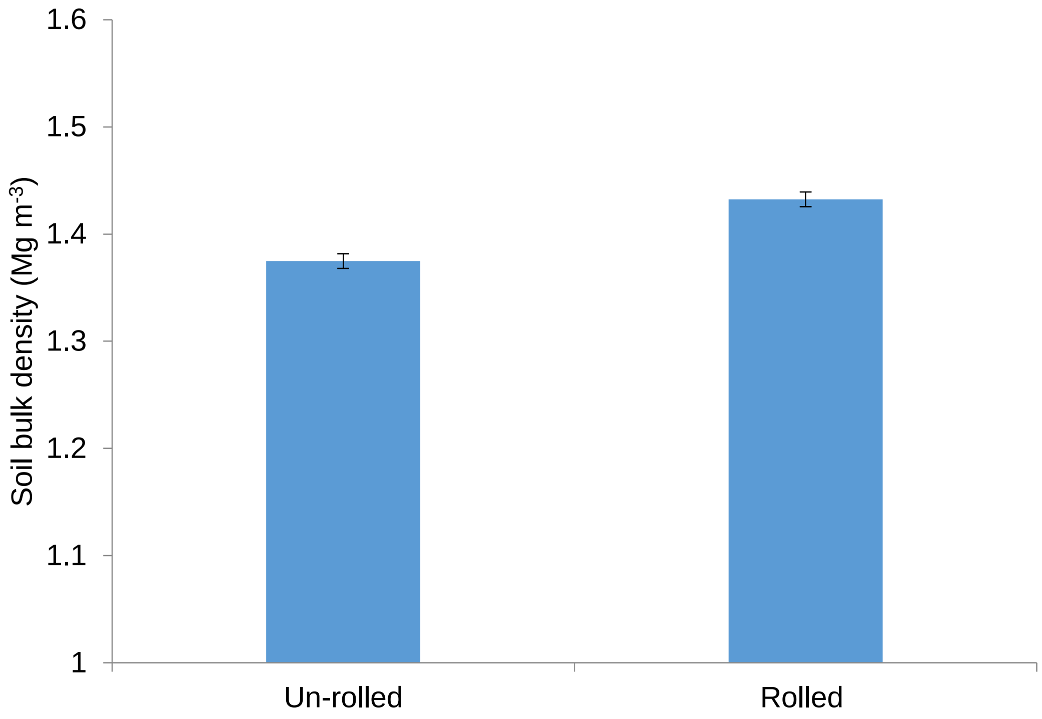


Figure 4.14. The effect of rolling on soil bulk density. Error bars represent standard error of means (S.E.M.) = 0.00683, degree of freedom (d.f) = 85, p = < 0.001, n = 24 for each treatment.

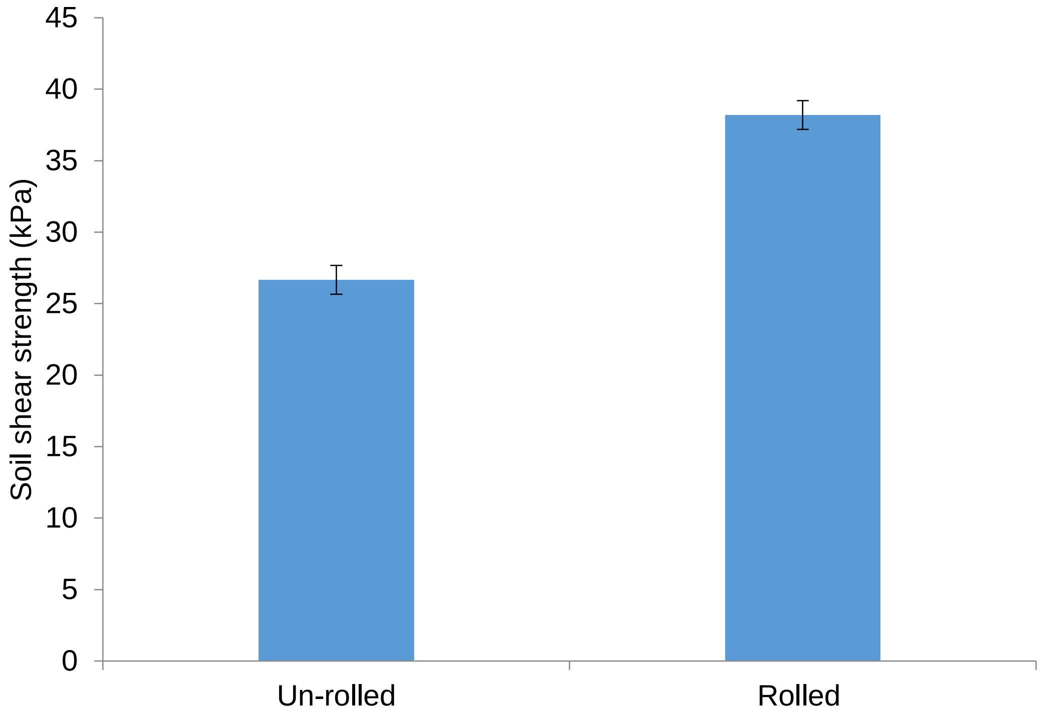


Figure 4.15. The effect of rolling on soil shear strength. Error bars represent standard error of means (S.E.M.) = 1.011, degree of freedom (d.f) = 181, *p* = < 0.001, n = 48 for each treatment

4.3.2.2 The above ground properties

The effect of cultivation system on the above ground properties of plant is shown in Table 4.6. No statistical variations were observed in the above ground properties of the plants including both the main tiller properties and the whole plant properties. Moreover, the interaction of cultivation system and rolling had no significant influence on the above ground properties. This was despite some significant differences due to rolling the soil in the mean values of self-weight moment of the plant, number of tillers, fresh weight and the ear weight of the main tillers. A 14.3% reduction in the self-weight moment of plant, up to 10.0% in the number of tillers, 5.5% and 12.0% in the fresh weight and the ear weight of the main tiller was observed based on the results of data analysis.

Similar to the above ground properties, no significant differences were found in the yield data due to the effect of cultivation system. The average yield ranged between the highest of 6.74 t ha^{-1} in the rolled H/L and the lowest yield of 6.09 t ha^{-1} in the un-rolled H/H.

Table 4.6. The effect of rolling cultivation system on the above ground properties of winter wheat

		Individual plant properties				Main tiller properties							
Rolling	Cultivation	Yield (t/h)	Number of tillers/plant	Plant self-weight moment (Nm)	Plant safety factor	Stem height (cm)	Tiller weight (g)	Ear weight/tiller (g)	Centre of gravity (cm)	Stem diameter (mm)	Stem bending moment (Nm)	Self-weight moment (Nm)	Safety factor
Un-rolled	H/H	6.09	4.38	0.10	3.00	87.43	11.10	6.515	61.13	4.63	0.138	0.046	3.17
	H/L	6.44	4.63	0.10	3.29	87.19	10.34	5.958	60.36	4.48	0.130	0.042	3.12
	H/H	6.30	4.50	0.10	2.90	88.40	11.49	6.494	60.30	4.56	0.127	0.044	2.89
	L/L	6.25	4.33	0.09	3.18	88.08	11.08	6.457	60.13	4.68	0.147	0.047	3.23
Rolled	H/H	6.11	4.04	0.08	2.96	88.05	10.64	5.425	58.42	4.58	0.140	0.045	3.18
	H/L	6.74	3.79	0.08	2.92	87.87	9.83	5.367	59.93	4.62	0.126	0.042	2.99
	H/H	6.15	4.04	0.08	3.00	88.41	10.61	5.818	60.30	4.70	0.145	0.049	3.03
	L/L	6.48	4.13	0.09	2.87	87.61	10.48	5.733	59.66	4.52	0.125	0.043	2.89
S.E.M. at (d.f. = 181)	Rolling	0.093 (21)	0.0942	0.0030	0.0930	0.3440	0.2160	0.1300	0.3640	0.0410	0.0040	0.0010	0.0840
	Cultivation	0.132 (21)	0.1332	0.0040	0.1310	0.4870	0.3060	0.1850	0.5150	0.0580	0.0050	0.0010	0.1190
	Interaction	0.187 (21)	0.1884	0.0060	0.1860	0.6890	0.4330	0.2610	0.7280	0.0820	0.0080	0.0020	0.1680
p value	Rolling	0.462	<.001	0.002	0.242	0.665	0.046	<.001	0.081	0.775	0.849	0.932	0.52
	Cultivation	0.085	0.986	0.935	0.86	0.622	0.132	0.239	0.887	0.811	0.536	0.189	0.636
	Interaction	0.625	0.382	0.82	0.548	0.814	0.962	0.785	0.241	0.194	0.076	0.304	0.533

H/H represents high-pressure power harrow + drill with high-pressure, H/L represents high-pressure power harrow + drill with low pressure, L/H represents low pressure power harrow + drill with high-pressure and L/L represents low pressure power harrow + drill with low pressure. S.E.M. represents standard error of means, d.f. represents degree of freedom.

4.3.2.3 The anchorage moment and adventitious root properties

The outcome of the data analysis demonstrated in Table 4.7 shows that plant anchorage moment and adventitious root properties were not statistically influenced by cultivation systems, neither by its interaction with soil rolling. Nevertheless, regardless of cultivation treatments, Figure 4.16 shows an 18.0% reduction in plant anchorage moment due to soil rolling, in general, all adventitious root properties were significantly greater in the un-rolled treatments compared to the rolled ones. Due to the soil rolling, the mean values of the root plate diameter, number of roots (diameter between 0.5 - 1 mm) and the number of roots (greater than 1 mm in diameter) were reduced by 9.0%, 16.0% and 16.3%, respectively. Similarly, the total length of the roots (greater than 1 mm in diameter) and the angle of spread of the root decreased up to 14.0% and 6.5%, respectively. This reduction in the adventitious roots properties was accompanied by an increase in soil penetration resistance and shear strengths about 3.0% and 43.0% respectively, due to rolling the soil when the plant was at the stage of early tillering (GS 25 - GS 29). Similar to the results from the Large Marsh experiment, positive linear relationships were found (Table 4.8) between the mean values of plant anchorage moment and the mean values of each of soil bulk density, angle of spread of the roots and the number and total length of the roots (greater than 1 mm in diameter).

Table 4.7. The effect of rolling and cultivation system on anchorage moment and adventitious root properties of winter wheat

Rolling	Cultivation	Anchorage moment (N.m)	Total length of the roots/plant (greater than 1 mm in diameter) (mm)	Root plate diameter/plant (mm)	Number of roots/plant (greater than 1 mm in diameter)	Angle of spread of the roots/plant (°)	Number of roots/plant (diameter between 0.5 - 1 mm) (mm)
Un-rolled	H/H	0.290	111.80	52.25	5.83	87.30	51.50
	H/L	0.308	129.20	54.04	7.00	96.50	51.50
	H/H	0.286	128.20	55.50	7.08	95.30	48.70
	L/L	0.289	130.40	53.71	6.79	91.80	48.20
Rolled	H/H	0.236	97.50	48.75	5.29	84.20	40.90
	H/L	0.237	119.50	47.04	6.17	85.90	39.30
	H/H	0.242	98.00	49.04	5.17	85.40	42.40
	L/L	0.242	111.20	51.33	5.71	91.10	45.00
S.E.M. at (d.f. = 181)	Rolling	0.0110	6.040	1.128	0.301	2.070	1.470
	Cultivation	0.0160	8.540	1.596	0.426	2.930	2.080
	Interaction	0.0230	12.080	2.257	0.603	4.140	2.940
p value	Rolling	0.001	0.033	0.003	0.011	0.039	<.001
	Cultivation	0.976	0.371	0.708	0.396	0.48	0.975
	Interaction	0.933	0.851	0.686	0.695	0.547	0.412

H/H represents high-pressure power harrow + drill with high-pressure, H/L represents high-pressure power harrow + drill with low pressure, L/H represents low pressure power harrow + drill with high-pressure and L/L represents low pressure power harrow + drill with low pressure. S.E.M. represents standard error of means, d.f. represents degree of freedom.

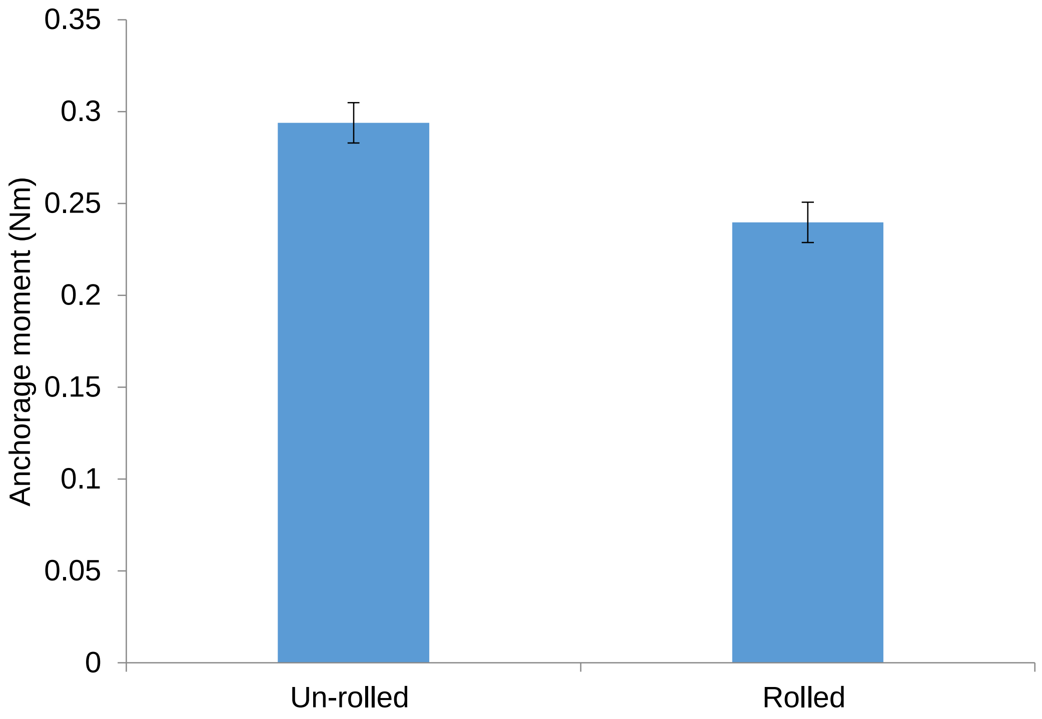


Figure 4.16. The effect of rolling on the plant anchorage moment (Nm). Error bars represent standard error means (S.E.M.) = 0.011, degree of freedom (d.f) = 181, *p* = 0.001, n = 48 for each treatment

Table 4.8. Linear relationships between the mean values (n = 4) of plant anchorage moment and soil bulk density and adventitious root properties

	R^2 values	
Soil bulk density (Mg m^{-3})	0.597	y* = 0.0006x** + 0.2459
Angle of spread of the roots/plant (°)	0.510	y = 0.0016x + 0.1243
Total length of the roots/plant (greater than 1 mm in diameter)	0.816	y = 0.0006x + 0.1961
Number of the roots/plant (greater than 1 mm in diameter)	0.610	y = 0.0172x + 0.4773

* represents the anchorage moment.
** represents the property listed in the same row.

4.4 Discussion

4.4.1 Soil properties

Different tillage practices create various soil conditions, with lower soil bulk densities resulting from deeper and more intense tillage systems (Guclu Yavuzcan et al., 2002; Hou et al., 2012). In the Large Marsh experiment (2012 - 2013), greater manipulation and loosening soil in deep tillage systems because of soil agitation and deformation due to the deeper cultivation resulted in greater soil aeration and porosity which reduced the solid ratio in comparison to the pores, could explain the lower soil bulk density in deep and shallow tillage systems compared to less disturbed soil in zero tillage treatments (Iqbal et al., 2005; Alaoui et al., 2011; Pravin et al., 2013; Schjonning & Thomsen, 2013).

Penetration resistance is proportional to soil shear strength and both decrease with the increase of soil manipulation and loosening caused by the deeper tillage systems (Schjonning & Rasmussen, 1989; Hamza & Anderson, 2005; Osunbitan et al., 2005). Soils with high bulk density tend to have a higher numbers of pores with small diameter which increase water suction with greater adhesion forces due to the less water available at the same potential compared to soils with lower bulk density, hence, greater penetration resistance and shear strength (Zhang et al., 2001).

In contrast, the results obtained in Buttery Hill experiment (2013 - 2014) did not follow the same trend as observed in the Large Marsh experiment. The difference between high and low pressures applied to the power harrow and the seed drill during the cultivation and seedling process, was not enough to create different soil conditions. Additionally, soil settlement during the growing season could explain the small non-statistical variations found in soil physical properties (Celik et al., 2011; Oyelade & Aduba, 2012).

The only significant factor that affected the soil physical properties was rolling the soil with the Cambridge roller in springtime; as the soil physical properties were increased due to rolling of the soil (Hakansson & Lipiec, 2000; Kaliyan et al., 2013). Additionally, 16%, 17%, 19% and 18% reduction in the soil moisture contents in H/H, H/L, L/H and L/L treatments also attributed in increasing the values of soil shear strength and penetration resistance measured at maturity compared to the initial measured values. Furthermore, the 4% increase in soil bulk density due to soil rolling in springtime resulted in a 30% increase in soil shear strength, which was in agreement with the earlier finding of Godwin (1974).

4.4.2 The above ground properties

The non-significant results due to the effect of different tillage systems found in the above ground properties of the plant in both Large Marsh (2012 - 2013) and Buttery Hill (2013 - 2014) experiments agreed with the results reported by Jug et al. (2011) and Zhang et al. (2012). The above ground properties of wheat plant are less likely to be influenced by tillage systems compared to other environmental conditions, as irrigation and the uniform application of fertilizers among the treatments (Funk et al., 2008).

However, in the Large Marsh experiment (2012 - 2013), some variations were observed in the height of the tiller, centre of gravity and the number of tillers per plant. The height of the main tiller and centre of gravity reduced with increasing tillage depth; this is in agreement with the results presented by Li et al. (2008) where the height of plants reduced as the seed placed closer to the soil surface and exposed to cooler condition as a result of zero tillage compared to deep tillage.

In contrast, the 8.3% greater moisture content (hence greater root development), 16% less plant number m^{-2} (Smith et al., 2013) and less sowing depth in zero tillage compared to deep tillage, along with greater soil bulk density resulted in greater number of tillers per plant (HGCA, 2008; Rieger et al., 2008; Huang et al., 2012; Guan et al., 2015).

In the Large Marsh experiment (2012 - 2013), yield data varied from one tillage treatment to another. The mechanically harvested yield in zero tillage treatments was significantly less ($p < 0.001$) compared to shallow and deep tillage treatments. The reduction in the height of the plant and in the centre of gravity which might decrease the capacity of the canopies for the photosynthetic process was attributed to the yield reduction (Peng et al., 2014). Similar reduction pattern was also reported by Hajabbasi & Hemmat (2000); Gemtos et al. (2002) and Huang et al. (2012).

The treatments in the Buttery Hill experiment (2013 - 2014), showed no differences in the harvested yield. The non-significant differences between the treatments were expected, as the above ground properties showed no statistical variations due to the cultivation effect, similar to the yield data.

Although the two experiments were conducted in two different locations, over two years and soil types, the experiments can still be distinguished based on the one fundamental base, which is control traffic system. By comparing the mean value of the yield of any of the cultivation system in the controlled traffic experiment with the grand mean of the yield data from the non-controlled traffic experiment, zero tillage, shallow tillage and deep tillage had 9%, 23% and 19% greater yield, respectively. There was 17% difference between the grand mean yields of the two experiments, with the highest yield in the controlled traffic experiment.

Increasing the harvestable yield of winter wheat is the major objective of researchers; therefore, the increased yield in the controlled traffic experiment highlights the importance of control traffic practice. Nevertheless, the zero tillage system was the most efficient tillage practice in turns of maximising plant anchorage moment. However, it did not result in the highest yield data. The yield reduction in the zero tillage system (mechanically harvested) compared to shallow and deep tillage system seemed to be due to the soil compaction caused by the wheels, as the highest yield collected was in the zero tillage system (manually harvested) in non-trafficked areas between the wheel marks where the wheel marks were avoided.

Thus, increasing the potential yield with the use of zero tillage system requires further studies to reduce the effect of wheel marks. In the Buttery Hill experiment (2013 - 2014), the less variations among soil physical properties due to tillage treatments explain the non-significant differences in the yield data (Grandy et al., 2006; Rieger et al., 2008; Soane et al., 2012).

4.4.3 The adventitious root properties

The mean values of the root parameters in the Large Marsh experiment (2012 - 2013), increased with decreasing the soil tillage intensity from the deep tillage to the zero tillage system. As discussed by Alameda & Villar (2012), the growth of the rooting system depends upon the strength of the soil in which the roots are grown. The results of the root growth in the current study were in agreement with the finding of Hemsath & Mazurak (1974), Scott et al. (2005b) and Munoz-Romero et al. (2010) who reported an improvement in root growth development with the increase in limited soil bulk density up to 1.5 Mg m^{-3}. However, this pattern of root growth development was in contrast to the results presented by other researchers such as Saqib et al. (2004); Hassan et al. (2007); Trukmann et al. (2008) and Bengough et al. (2011), who reported up to 50% reduction in the root development with excessive soil conditions when penetration resistance is greater than 2 MPa. This could be explained by the maximum mean values of, both, soil bulk density and penetration resistance created by zero tillage, which were less than the critical limit of 1.5 Mg m^{-3} reported by Schjonning & Rasmussen (2000).

The mean of soil bulk density (1.34 Mg m^{-3}) achieved by the zero tillage system had 8.3% greater soil moisture content compared to the deep tillage system, which provided sufficient moisture content to the root system and prevented possible drought stress (Whalley et al., 2006). In addition, it had a better root-soil connection compared to the deep tillage system, which results in greater nutrient uptake and lateral root growth (Hemsath & Mazurak, 1974; Gartner, 1994).

Accordingly, in the Buttery Hill experiment (2013 - 2014), the non-significant variations in the adventitious root properties, found to be due to the similar soil conditions, resulted from the different tillage practices. Nevertheless, a significant reduction in the adventitious root properties occurred because of rolling the soil, hence, increasing soil strength properties (Bengough & Mullins, 1990; Pringle & Lark, 2007; Chen & Weil, 2011).

Plant anchorage moment depends upon both soil strength and adventitious root properties (Crook et al., 1994; Goodman & Ennos, 1999). Hence, increases in soil strength properties together with the increase in the root parameters in the Large Marsh experiment (2012 - 2013), along with the positive linear relationships found between them are the main reasons of increasing plant anchorage moment (Berry et al., 2003a; Sposaro et al., 2008). In contrast, despite increasing soil physical properties in the Buttery Hill experiment (2013 - 2014) with further rolling of the soil, the plant anchorage moment was reduced. Although both soil shear strength and adventitious properties are associated with plant anchorage (Crook & Ennos, 1993; Goodman & Ennos, 1999; Peng et al., 2014), however, the reduction in the adventitious root properties due to the rolling in springtime could not be compensated for the increase in soil bulk density. Furthermore, a 4% increase in soil bulk density due to rolling in springtime resulted in a 30% increase in soil shear strength which is in agreement with the results of Godwin (1974). The increase in shear strength had significantly ($p < 0.001$) decreased the adventitious root properties, which explains the reduced plant anchorage moment. Therefore, even though rolling in springtime before GS 39 has been reported to minimise the incidence of lodging (Kopecky, 1970; Pinthus & Brady, 1974; Berry et al., 2003c). It is clear that further studies are needed to identify the optimum plant growth stage at which the soil can be rolled with a minimised effect on the adventitious root development.

The predominance of stem failure or anchorage failure in wheat cultivars is debatable among researchers. It can be derived from the results of Large Marsh experiment (2012 - 2013) that, root lodging is predominant in winter wheat. This is in agreement with the finding of Berry et al. (2003a); Peng et al. (2014); Rademacher (2009) and Wang J Fau - Zhu et al., 2012) who reported that the strength of the stems of commonly used cultivars is enough to resist stem lodging. Therefore, lodging is more likely to be due to anchorage failure. However, the results are in contrast to the finding of Neenan and Spencer-Smith (1975) and Pinthus and Brady (1974) who addressed stem failure as predominant in winter wheat.

4.5 Conclusions

The main findings of this Chapter can be concluded as:

1. The zero tillage system applied under a controlled traffic conditions resulted in a 31% and 9% greater plant anchorage moment compared to deep tillage system and shallow tillage system, respectively.
2. Tillage system had significant effects (p <.001) on soil physical conditions, the adventitious root development and resulting plant anchorage moment. The greater the depth of the tillage system, the less the values of soil physical properties (soil bulk density, soil shear strength and penetration resistance), and adventitious root properties, and consequently, plant anchorage moment.
3. Zero tillage system had the average yield of 6.9 t ha^{-1} which was 16.3% and 11.3% less compared to the shallow tillage and deep tillage systems,

respectively. Moreover, from the manual harvesting data collected in between the wheel marks (tramlines), the highest yield of 10.7 t ha^{-1} was collected in zero tillage treatments. Nevertheless, in zero tillage system conducted under controlled traffic conditions, the wheel marks caused 35.3% reduction in the yield. Therefore, to embrace the use of zero tillage system as an optimum tillage practice in terms of both plant anchorage moment and the harvestable yield, further studies are needed to reduce the effects of wheel marks.

4. Rolling the soil during springtime at growth stage GS 25 – GS 29 resulted in an 18.4% reduction in plant anchorage moment caused by a significant reduction in adventitious root properties.
5. Despite the initial significant difference in soil shear strength, the use of power harrow with the seed drill both set to the maximum and the minimum pressure points (manufacture's recommendations) caused no differences in soil physical conditions, adventitious root development or plant anchorage moment by the end of the season due to the soil settlement.

Chapter 5

Effect of moisture content at early growing stages on the adventitious root properties and plant anchorage moment of winter wheat

5.1 Introduction

Plant root development is dependent upon many factors, one of which is water availability during the growing season. Wheat (*Triticum aestivum*) root systems consist of the fine absorption roots, which are important in turns of providing the plant with the necessary water and nutrients for survival (Grando & Ceccarelli, 1995; Hoad et al., 2001); and the adventitious roots (adventitious), whose function is to anchor the plant and resist lodging (Ennos, 1991a; Korndorfer et al., 2008; Ortiz & Balkcom, 2012).

In most of cereal crops including wheat, adventitious root development extends from the three-leaf stage, GS 12, to the beginning of booting at GS 39 (Newman & Moser, 1988; Crook et al., 1994; HGCA, 2008). These growing stages are the most sensitive stages in which the adventitious roots are affected if the plant experiences drought stress or waterlogging (Gales et al., 1984; Carr, 1989; Gorny, 1992). The duration of the drought stress is less important than the growth stage at which drought stress occurs (Tischler et al., 1989; Guedira et al., 1997; Izzi et al., 2008). Consequently, with variations due to the cultivars susceptibility to drought stress (Dickin & Wright, 2008), the effect of drought stress on root development may last until sufficient water becomes available (Yang et al., 2006). However, drought stress beyond booting stage GS 39, may not influence the root characteristics assuming they are already fully developed (Izzi et al., 2008).

In cereals, such as wheat, the effect of soil moisture content on the fine absorption root characteristics associated with plant growth and potential yield is well documented (Liu et al., 2004; Izzi et al., 2008; Shi et al., 2014). Nevertheless, studies of the effect of soil moisture content on adventitious root development at early growing stages until GS 39 are scarce.

Nowadays, climate change and global warming are becoming more problematic and unpredictable around the world, so drought stress or waterlogging is the major factor limiting crop production and affecting root development (Adda et al., 2005; Ma et al., 2013). For the future, the weather in the United Kingdom is predicted to be wetter in winter seasons and drought stressed in summer seasons because of high expected rainfall in winter time unlike in summer period (Hulme & Dessai, 2008).

Similar to the root properties, the above ground properties of wheat are also sensitive to soil moisture content (Blum, 2005; Aminzadeh, 2010). Most of the studies have been conducted on growth stages from GS 39 to maturity at which the above ground characteristics are most sensitive to the moisture content and the yield is constrained (Al-Khatib & Paulsen, 1984; Stone & Nicolas, 1995; Zhang et al., 2014).

The moisture resistant or sensitive wheat cultivars have also been identified (Stone & Nicolas, 1994, 1995; Dickin & Wright, 2008; Chen et al., 2012; Li et al., 2013). The effect of moisture content on the above ground biomass and the height of wheat plants have been considered (Blum, 2005; Nouri-Ganbalani et al., 2009; Shi et al., 2014), and the yield and its components were also researched (Cannell et al., 1984; Dickin & Wright, 2008; Zhang et al., 2015).

Earlier studies have been conducted on plants grown in soil types ranging from clay (Liu et al., 2004) to sand soils (Labdelli et al., 2014), as the water holding capacity is different from one soil type to another, affecting the plant responses (Cannell et al., 1984; Gales et al., 1984). Additionally, moisture content affects the physical properties of soil including soil shear strength, which in turn then affects root development, as discussed in section 2.3.1 and section 2.4.3.

In this study, the effect of different moisture content enforced at critical times up to GS 39, on the adventitious root development of winter wheat grown in pots filled with either sandy loam soil or clay loam soil was investigated. Therefore, the risk of root lodging at late growing stages, when the ears are heaviest and plants are more likely to root lodge, can be predicted based on the amount of rainfall in springtime. Thus wheat growers can determine the optimum spring management practices such as the application of nitrogen and plant growth regulator to minimise lodging later in the season.

5.2 Materials and methods

5.2.1 Soil texture and pot preparations

Winter wheat plants were grown in pots filled with either sandy loam soil or clay loam soil. The soils and the pots used in this experiment are the same ones (sandy loam and clay loam) used in the first experiment in Chapter 3 and described in section 3.2.1 and Appendix 8. 1. A total of 48 pots were prepared (soil type = 2 x irrigation rates = 3 x blocks (replicated = 8)). The pots were randomly placed on two benches in a polytunnel experimental unit at Harper Adams University.

5.2.2 Soil bulk density and shear strength

To minimise the effect of soil bulk density and based on the results presented previously in Chapter 3 in which the best adventitious root development was taken place, the soils in the pots were compacted to 1.3 Mg m^{-3} at which applied to all the treatments. Hence, a uniform and comparable soil bulk density was achieved as illustrated in section 3.2.2. Soil shear strength was measured at the depth of 0 - 50 mm using a shear vane following the method explained in section 3.2.4.

5.2.3 Sowing and fertilizer

Each pot was sown with three seeds of winter wheat (*Triticum aestivum* L. var. Cadenza) on 21th of March 2014. Similarly to the process previously described in section 3.2.3, the established plants were thinned after 2 - 3 weeks to one plant per pot.

No soil analyses were conducted as soil analyses are recommended to be performed once every three to four years (Walworth, 2008; Hunnings et al., 2011). More details on soil chemical and nutrient analysis results, fertiliser applications can be found in Table 3.1, and section 3.2.3.

5.2.4 Identifying available water and volumetric moisture content at field capacity condition for sandy loam and clay loam soil used in this experiment

To determine the amount of water and percentage volumetric water content at field capacity for each soil type, in addition to the main 48 pots, one pot from sandy loam soil and another one from clay loam soil was prepared prior to the experiment. To bring the soils in the pots to saturation, each pot was weighed with and without its soil, using a digital weighing balance (Soehnle Professional 30 kg max.). The pots (including the soil) were submerged in water for 24 hours. After the pots were fully saturated, they were taken out of the water, the weight and the volumetric moisture content measured using a theta probe (HH2 Moisture Metre AT delta-t devices Cambridge - England). The data were recorded at 1 hour intervals for the first 8 hours, then at 24 and 48 hours at which point the soils had ceased to lose weight and could be said to be at field capacity (when water drainage due to the gravity was stopped) as illustrated in Figure 5. 1.

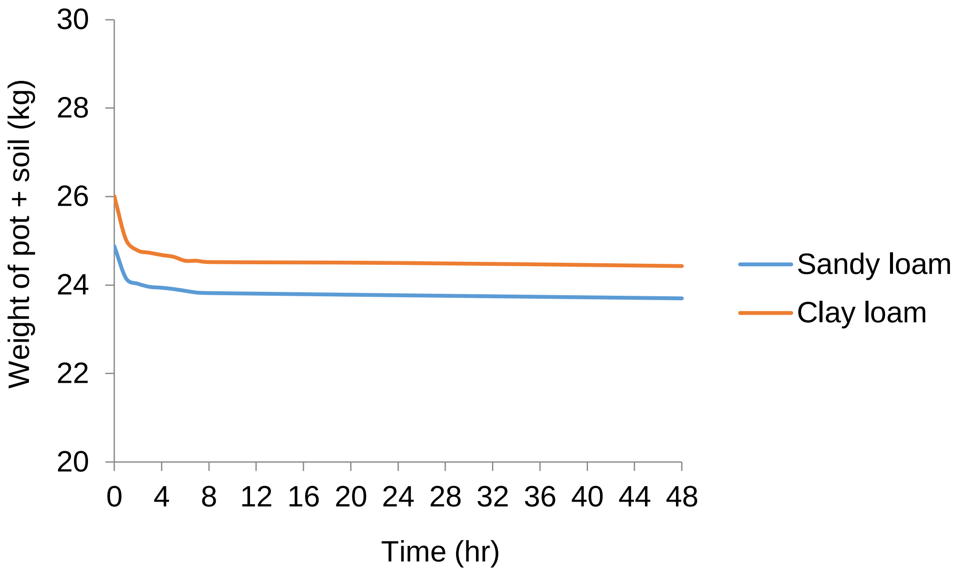


Figure 5.1. Reduction in the weight of soils from saturation to field capacity after 48 hours.

5.2.5 Treatments distribution and watering

At the beginning of the experiment (seed planting) and to assure seed germination, both clay loam and sandy loam treatments were watered equally to keep all of the treatments at field capacity condition until two leaves of the plants were developed (growing stage GS 12). From seed drilling to GS 12, the pots were weighed every 2 - 3 days and as required. The required amount of water per each pot was determined based on the initial weight of the pots (dry soil + pot) (see Table 8.2.3 in Appendix 8.2) and the weight of the pots at field capacity (see Table 8.2.4 in Appendix 8.2) (Newman & Moser, 1988; Izzi et al., 2008).

From the growing stage GS 12 to GS 39, to avoid any miscalculation of the weight of the pots because of the continuous increase in the weight of the plants during the growing season, the available water content of the treatments was determined based on the volumetric water measurements using the Theta Probe device.

The experiment comprised three treatments for each soil type (total of six).

Three irrigation treatments were investigated: well irrigated, kept between 85% - 100% of field capacity until GS 39 (booting stage); normally irrigated, kept irrigated to maintain the moisture content between 65% - 85% of field capacity until GS 39 where most of the adventitious roots are developed (Newman & Moser, 1988; Beltrano et al., 2006); and for the water stressed treatments, the VWC% was kept between 50% - 65% of the field capacity until GS 39.

Table 5.1. Volumetric water content (%) of the treatments at different levels compared to field capacity condition

	Volumetric Water Content (%) at			
	Field capacity	85% of field capacity	65% of field capacity	50% of field capacity
Clay loam soil	42.5	36.1	27.6	21.2
Sandy loam soil	35.8	30.4	23.2	17.9

After GS 39, all treatments were kept watered to maintain their moisture content at about 65% - 85% (average of 75%) of field capacity (normally irrigated) because the adventitious roots should be fully developed by GS 39 and would not be influenced by moisture content.

Based on the differences in the volumetric water content recorded in each measurement compared to the initial volumetric content of each treatment (see Table 8.2.5 in Appendix 8.2), the required amount of water was calculated using Equation 5.1. Accordingly, for each 1% reduction in the volumetric water content, 132.5 g of water was added to the treatments in clay loam soil and 134.6 g of water was added to the treatments in sandy loam soil.

$$\text{Required amount of water (ml)} = \frac{available\ water\ at\ field\ capacity\ (ml) \times 1\%}{Volumetric\ water\ content\ at\ field\ capacity\ (\%)} \quad \text{...(Eq. 5.1)}$$

5.2.6 Measurements of plant properties

All plant property measurements were conducted following the same techniques and methodologies applied and explained in section 3.2.5. As regards the measurements of the plant anchorage moment, the plants were pushed to a 45° from the vertical axis with the lodging arm of the lodging device as previously described in section 3.2.5.3.

5.2.7 Statistical analysis

The experimental treatments were randomised over 8 blocks (replicates) and the collected data analysed using a two way ANOVA in Genstat 14th Edition (VSN International ltd.) (RCBD 2 x 3 factorial ANOVA). The effect of three levels of moisture content (in relation to field capacity) on the winter wheat (*Triticum aestivum* L. var. Cadenza) grown in either sandy loam or clay loam soil was investigated. Tukey's multi comparison test was conducted to evaluate the mean values of all measured properties, differences considered significant at $p \leq 0.05$.

5.3 Results

5.3.1 The above ground properties

5.3.1.1 Main tiller properties

Table 5.2 shows the effect of soil type and moisture content on the main tiller properties of wheat plant. In general, soil types did not statistically affect the above ground properties measured in this study. However, the fresh weight of the main tillers grown in clay loam soil was significantly (up to 10.0%) less compared to sandy loam soil. Conversely, the centre of gravity of plants grown in clay loam soil was significantly (9.0%) higher. Moreover, in clay loam soil, the greater height of the plants, ear weight and the centre of gravity resulted in 15.0% less safety factor compared to the plants grown in sandy loam soil, so more vulnerable plants and a greater risk of stem lodging is suggested.

Table 5.2. The effect of soil type and moisture content on the main tiller properties of winter wheat

Soil type	Moisture content	Stem height (cm)	Tiller weight (g)	Ear weight/tiller (g)	Centre of gravity (cm)	Stem diameter (mm)	Self-weight moment (Nm)	Stem bending moment (Nm)	Safety factor
Sandy Loam	85% - 100% of F.C. *	79.950	9.960	5.220	50.950	4.492	0.035	0.188	5.370
	65% - 85% of F.C.	84.210	11.110	5.980	54.740	4.513	0.042	0.241	5.690
	55% - 65% of F.C.	81.300	11.210	5.310	49.160	5.112	0.038	0.302	7.930
Clay loam	85% - 100% of F.C.	82.440	10.140	5.980	56.070	4.650	0.039	0.240	6.060
	65% - 85% of F.C.	83.650	9.210	5.380	57.550	4.435	0.036	0.191	5.150
	55% - 65% of F.C.	84.280	9.800	5.560	56.650	4.393	0.038	0.208	5.300
S.E.M. at (d.f. = 35)	Soil type	0.7890	0.3050	0.1690	0.6570	0.1066	0.0011	0.0162	0.3870
	Moisture content	0.9660	0.3740	0.2080	0.8040	0.1306	0.0013	0.0198	0.4740
	Interaction	1.366	0.529	0.293	1.137	0.1847	0.0019	0.028	0.670
p value	Soil type	0.152	0.021	0.563	<.001	0.166	0.767	0.185	0.140
	Moisture content	0.147	0.671	0.701	0.017	0.321	0.583	0.261	0.192
	Interaction	0.384	0.135	0.079	0.136	0.061	0.07	0.039	0.056

*F.C. represents field capacity. S.E.M. represents standard errors of mean, d.f. represents degree of freedom, n = 8 for each treatment.

The main tiller properties in general were not influenced by the moisture content, the values of the main tiller properties of plants in normally irrigated treatments (65% - 85% of field capacity) were not statistically greater compared to the water stressed treatments and those kept well watered at field capacity. The centre of gravity of the stressed treatments was 5.7% significantly less compared to the normally watered treatments. Similarly, the effect of the interaction of soil type and moisture content was found to be not significant on the main tiller properties. Apart from the stem bending moment at which the lowest value of 0.188 Nm was recorded for the plants grown in sandy loam soil and watered to the level of 85% - 100% of field capacity compared to the greatest value of 0.302 Nm for water stressed plants grown in sandy loam soil.

5.3.1.2 The above ground plant properties

The effect of soil type and moisture content on the above ground properties of winter wheat is demonstrated in Table 5.3. The soil type had no significant effect on the above ground properties. However, this does not include the height of the tillers and the self-weight moment generated by the plant. Irrespective of moisture content, plants grown in clay loam soil were significantly 3.4% taller and generated about 15% greater self-weight moment compared to the plants grown in sandy loam soil. Although the differences did not reach the significance level, the 11.5% greater number of tillers, up to 11.0% heavier ear weight and more than 4.0% greater fresh weight in clay loam soil contributed to the greater self-weight moment generated by plants grown in clay loam soil compared to sandy loam soil.

Regardless of the effect of soil type, moisture content significantly influenced the height of the tillers. Generally, the above ground properties in normally watered treatments recorded greater average values compared to the well watered and the water stressed treatments. Nevertheless, the height of the tillers of plants in normally watered treatments were 5.3% greater compared the height of tillers in the well watered treatments. Significant differences were also found in the height of the plant tillers due to the interaction of soil type and moisture content treatments. The height of the tillers ranged between 74.1 cm for well watered plants grown in sandy loam soil, which was significantly less compared to 79.8 cm recorded in water stressed plants grown in clay loam soil. No significant differences were found between the rest of the treatments as a result of the effect of soil type and moisture content rates.

Table 5.3. The effect of soil type and moisture content on the plant above ground properties of winter wheat

Soil type	Moisture content	Stem height (cm)	Plant fresh weight (g)	Plant ear weight (g)	Number of tillers/plant	Plant self-weight moment (Nm)	Plant safety factor
Sandy Loam	85% - 100% of F.C. *	74.14^{a**}	103.80	72.90	17.00	0.47	4.86
	65% - 85% of F.C.	79.84^{b}	115.40	83.20	17.25	0.56	3.26
	55% - 65% of F.C.	75.27^{ab}	98.90	70.20	13.87	0.38	3.82
Clay loam	85% - 100% of F.C.	77.33^{ab}	112.60	76.30	17.62	0.49	3.36
	65% - 85% of F.C.	78.53^{ab}	125.20	90.70	18.88	0.60	2.54
	55% - 65% of F.C.	79.88^{b}	117.10	87.40	17.88	0.58	2.08
S.E.M. at (d.f. = 35)	Soil type	0.668	5.52	4.19	0.826	0.0263	0.345
	Moisture content	0.818	6.76	5.13	1.012	0.0322	0.422
	Interaction	1.157	9.56	7.25	1.431	0.0455	0.579
p value	Soil type	0.028	0.125	0.123	0.083	0.027	0.010
	Moisture content	0.019	0.347	0.237	0.311	0.051	0.086
	Interaction	0.039	0.865	0.625	0.487	0.122	0.677

*F.C. is field capacity. S.E.M. represents standard error of means, d.f. represents degree of freedom, n = 8 for each treatment, ** Values in a row followed by the same letter are not significantly different at $p < 0.05$ as determined by Tukey test.

5.3.2 Plant anchorage moment and soil shear strength

Plant anchorage moment and soil shear strength as influenced by soil type and moisture content are shown in Table 5.4. Regardless of moisture content, plants grown in sandy loam soil had a 17.0% greater anchorage moment than the plants grown in clay loam soil. The effect of moisture content was also found to be significant on the plant anchorage moment. Irrespective of the effects of soil type, the treatments which were watered to 85% - 100% of field capacity had 24.0% greater anchorage moment compared to the water stressed (55% - 65% of field capacity) treatments. In both soil types, plant anchorage moment decreased with decreased the rate of moisture content from 100% - 85% to 65% - 55% of field capacity. Thereby, the highest plant anchorage moment value of 1.85 Nm was recorded in well watered (85% - 100% of field capacity) plants grown in sandy loam soil which was 35% significantly greater compared to the water stressed plants grown in clay loam soil (Figure 5.2).

Similar to the plant anchorage moment, soil shear strength irrespective of moisture content, was also influenced by soil type. Soil shear strength in sandy loam soil was 19.7% greater compared to shear strength in clay loam soil. In general, at all moisture content rates in sandy loam soil, soil shear strength found to be greater in comparison with soil shear strength in clay loam soil. The greatest shear strength of 24.64 kPa was recorded in the well watered treatments in sandy loam soil compared to 19.22 kPa in water stressed treatments grown in clay loam soil (Figure 5.3).

Table 5.4. The effect of soil type and moisture content on plant anchorage moment and soil shear strength

Soil type	Moisture content	Plant anchorage moment (Nm)	Soil shear strength (kPa)
Sandy Loam	85% - 100% of F.C.*	1.849	24.640
	65% - 85% of F.C.	1.670	22.070
	55% - 65% of F.C	1.366	23.080
Clay loam	85% - 100% of F.C.	1.509	16.710
	65% - 85% of F.C.	1.470	20.060
	55% - 65% of F.C	1.190	19.220
S.E.M. at (d.f. = 35)	Soil type	0.0752	0.5630
	Moisture content	0.0920	0.6900
	Interaction	0.1302	0.9750
p value	Soil type	0.031	<.001
	Moisture content	0.012	0.874
	Interaction	0.795	0.014

*F.C. is field capacity. S.E.M. represents standard error of means, d.f. represents degree of freedom, n = 8 for each treatment.

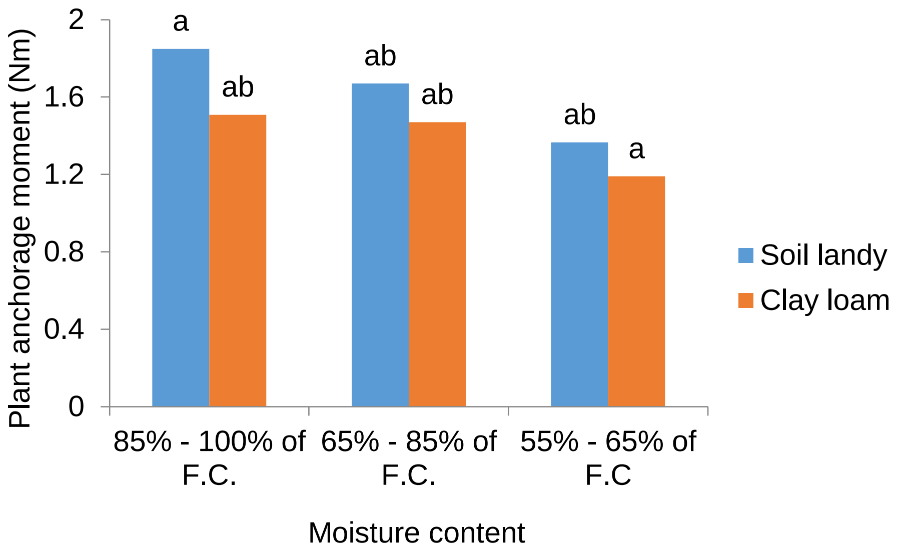


Figure 5.2. The effect of soil type and moisture content on the plant anchorage moment (Nm). F.C. is field capacity, Error bars are standard error of means (S.E.M.) = 0.1302, degree of freedom (d.f.) = 35, *p* = 0.795, n = 8 for each treatment.

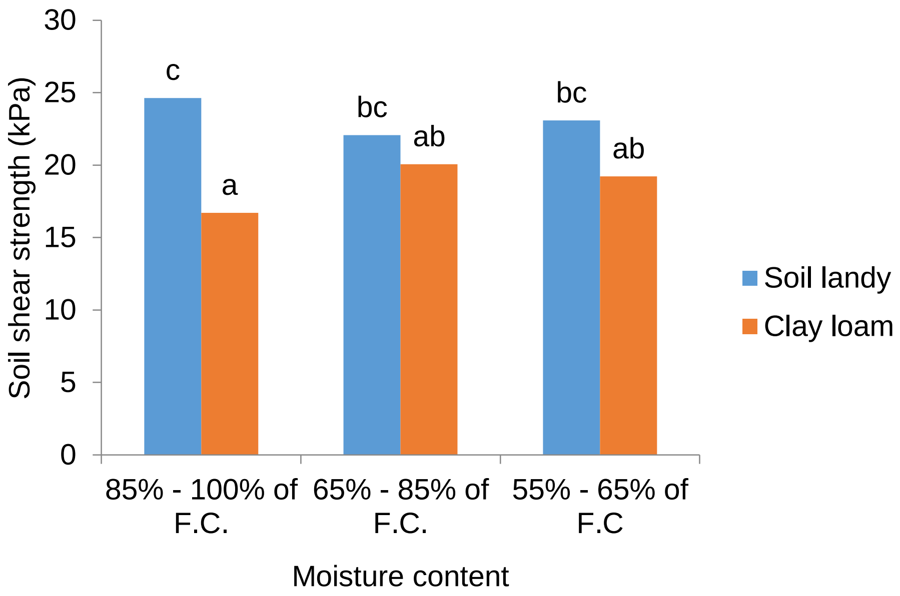


Figure 5.3. The effect of soil type and moisture content on soil shear strength (kPa). F.C. is field capacity, Error bars are standard error of means (S.E.M.) = 0.975, degree of freedom (d.f.) = 35, *p* = 0.014, n = 8 for each treatment.

5.3.3. The adventitious root properties

Table 5.5 demonstrates the effect of soil type and moisture content on the adventitious root properties of winter wheat. The plants grown in sandy loam soil had 7.7% greater total length of the roots (greater than 1 mm in diameter), 13.0% greater number of roots (greater than 1 mm in diameter) and 5.0% greater angle of the roots than the plant grown in clay loam soil. Nevertheless, the root plate diameter and the number of the roots (diameter between 0.5 - 1 mm) were 4.6% and 9.6% greater, respectively, in clay loam soil. The moisture content influenced the root plate diameter and the number of the roots (diameter between 0.5 - 1 mm). Regardless of soil type, the well watered plants had greatest root plate diameter of 7.28 cm and 153.8 number of roots (diameter between 0.5 - 1 mm), which were 9.8% and 23.5% greater compared to the water stressed plants. Furthermore, the normally watered plants grown in clay loam soil had the greatest number of roots (diameter between 0.5 - 1 mm) of 162.4 compared to the rest of treatments, which was statistically 31.0% greater compared to the number of the roots (diameter between 0.5 - 1 mm) of the water stressed plants grown in sandy loam soil.

Table 5.5. The effect of soil type and moisture content on the adventitious root properties of winter wheat

Soil type	Moisture content	Total length of the roots/plant (greater than 1 mm in diameter) (mm)	Root plate diameter/plant (mm)	Number of the roots/plant (greater than 1 mm in diameter)	Angle of spread of the roots/plant (°)	Number of the roots/plant (diameter between 0.5 - 1 mm)
Sandy Loam	85% - 100% of F.C.*	279.0	67.0	13.9	86.4	144.1
	65% - 85% of F.C.	278.0	74.1	13.1	85.8	145.1
	55% - 65% of F.C.	197.0	63.2	8.5	71.8	112.2
Clay loam	85% - 100% of F.C.	245.0	74.9	10.9	78.9	158.0
	65% - 85% of F.C.	234.0	71.4	10.6	75.4	162.4
	55% - 65% of F.C.	219.0	68.0	9.9	77.6	122.9
S.E.M. at (d.f. = 35)	Soil type	19.500	1.580	0.877	2.670	5.920
	Moisture content	23.800	1.940	1.074	3.270	7.250
	Interaction	33.700	2.740	1.518	4.620	10.250
p value	Soil type	0.509	0.151	0.275	0.296	0.105
	Moisture content	0.229	0.037	0.093	0.218	0.002
	Interaction	0.584	0.153	0.301	0.186	0.949

*F.C. is field capacity. S.E.M. represents standard error of means, d.f. represents degree of freedom, n = 8 for each treatment.

5.4 Discussion

5.4.1 Soil shear strength and plant anchorage moment

Soil shear strength is an important factor in determining the physical soil conditions (Fredlund et al., 1996). It changes from one soil type to another because of the change in the cohesion forces and the angle of the internal friction between soil particles, which in turn vary due to the available amount of moisture in the soil (John et al., 1986; Ayers, 1987; Tekinsoy et al., 2004). It was reported that clay soils have greater soil shear strength compared to sandy soils (Lee et al., 2003; Kim & Borden, 2011). However, under wet conditions, sandy soils have greater shear strength than clay soils (Havaee et al., 2015).

In this experiment and for all treatments, the greater values of soil shear strength measurements in sandy loam soil compared to clay loam soil is more likely to be due to the greater soil moisture content in clay loam soil, because the measurements were taken when the soils were at field capacity conditions, in which the plant anchorage moment was measured. Although soil bulk density was uniform in both soil types and the measurements were taken at field capacity conditions, clay loam soil had 15.7% greater moisture content (see Table 5.1). Thereby, it was reported that the greater internal angle of friction in between the particles of sandy loam soil (Fakhimi & Hosseinpour, 2008; Antony & Kruyt, 2009) was less affected by increased soil moisture content compared to the cohesion forces in between clay loam soil particles (Ennos, 2000; Antony, 2007). Hence, greater shear strength in sandy loam soil was observed at field capacity moisture content.

Likewise, the pattern of soil shear strength was followed by plant anchorage moment. Plant anchorage moment depends on the soil shear strength (Crook & Ennos, 1994; Berry et al., 2003a; Scott et al., 2005b; Sposaro et al., 2010), the greater the soil shear strength the greater plant anchorage moment (Ennos, 1991a; Goodman & Ennos, 1999). Hence, the greater soil shear strength in sandy loam soil caused greater plant anchorage moment compared to the clay loam soil. Plant anchorage moment not only depends on soil shear strength, but also on the adventitious root development (Ennos, 2000; Berry et al., 2006; Martinez-Vazquez & Sterling, 2011; Yang et al., 2015) which in turn are affected by the amount of the available water during the growing stages (Tischler et al., 1989; Guedira et al., 1997).

Plant anchorage strength, therefore, was found to be less in the water stressed treatments compared to the well watered treatments (85% - 100% of field capacity). This reduction in the plant anchorage moment in the stressed treatments was caused by the decreased adventitious root properties due to the reduced available water during the growing stages at which adventitious root development took place (Yang & Zhang, 2006; Dickin & Wright, 2008). Consequently, in either soil type, the values of plant anchorage moment started to decrease from the well watered treatments to the stressed treatments by 25.0% due to the reduction in the adventitious root properties, hence, producing weaker plants and increasing the risk of root lodging (Day & Intalap, 1970).

Therefore, to avoid or minimise the risk of root lodging in wet summer following a dry winter, wheat growers should consider an optimum springtime management practice, which includes the application of plant growth regulator and a low rate of nitrogen application (Tomm et al., 2001; Sterling et al., 2003; Shekoofa, 2008; Rademacher, 2009).

5.4.2 Plant properties

The available amount of water affects the above ground properties (Cannell et al., 1984; Liu et al., 2006). Most importantly, the effect of the soil moisture content depends on the growth stage of the plant (Leyshon & Sheard, 1974; Gorny, 1992; Zhang et al., 2014).

The non-significant effects of moisture content on the above ground properties, was due to the applying the same amount of water to the treatments from GS 39 to the maturity, which is in agreement with the results of Gales et al. (1984) and Beltrano et al. (2006). Additionally, it was reported that the above ground properties are more likely to be affected if drought stress occurring from jointing growth stage to maturity (Day & Intalap, 1970; Hassan et al., 1987; Liu et al., 2006). Nevertheless, the lower available water in water stressed treatments resulted in shorter tillers and lower centre of gravity, in agreement with the finding of Hassan et al. (1987); Miazek et al. (2001) and Gupta et al. (2001).

Similar to the above ground plant properties, root development was also affected by the moisture content or the available amount of water in the soil (Malik et al., 2002; Izzi et al., 2008). The root properties are most affected during the early growing stages until GS 39 (Newman & Moser, 1988; Adda et al., 2005; Yang et al., 2006). The reduced adventitious root properties due to the decreased moisture could be explained by the increase in soil shear strength that restrained root development (John et al., 1986; Ayers, 1987); which is in agreement with the results of Liu et al. (2004); Sahnoune et al. (2004) and Labdelli et al. (2014).

Moreover, drought stress affects soil physical conditions (Evans et al., 1996; Fan & Su, 2008; Quraishi & Mouazen, 2013), which in turn affects root development (Martinez et al., 2008; Fan & Chen, 2010; Bengough et al., 2011; Huang et al., 2012). Although no differences were detected in soil shear strength in between moisture content treatments, because the measurements were taken when the plant anchorage moment was measured and hence the soils were all at field capacity condition. However, during the water stress period, soil shear strength was assumed to be greater in the stressed treatments because the less the moisture content the greater the soil shear strength (Ayers, 1987; Manuwa, 2012), which was associated with limiting root development (Bengough & Mullins, 1990; Tracy et al., 2012b; Mathias et al., 2013).

As one of the main roots functions is to anchor the plants (Fakhimi & Hosseinpour, 2008; Martinez-Vazquez & Sterling, 2011), plants with reduced adventitious root properties are more exposed to root lodging (Ennos, 1991a; Goodman & Ennos, 1999; Berry et al., 2004; Yang et al., 2015). This is evident in this study as the risk of root lodging is 23% greater in the water stressed plants due to the lower adventitious root properties.

5.5 Conclusions

1. Wheat plants subjected to less available moisture content in early growing stages until the beginning of booting stage (GS 39) are estimated to be 25% more prone to anchorage failure at grain filling stages in a wet summer compared to well-watered plants.
2. The reduction in the adventitious root properties reached up to 20% due to the reduced moisture content to 55% - 65% of field capacity. Consequently, the likelihood of anchorage failure is higher as shown by the 28% decrease in the safety factor against root lodging.
3. The likelihood of anchorage failure is up to 8% higher in plants grown in clay loam soil than the plants grown in sandy loam soil, due to the reduced safety factor resulted from greater values of the above ground properties.
4. Reducing the amount of water to 55% - 65% of field capacity applied from GS 12 to GS 39 reduced the above ground properties by up to 10% including the number of tillers, plant ear weight, plant fresh weight, stem height and consequently the plant self-weight moment.

Chapter 6

6. General Discussion

The aim of this project was to determine the effect of soil physical conditions on the anchorage and the yield of wheat, and it had been split out to three main objectives. The first objective, the effect of soil bulk density on the adventitious root properties and the anchorage moment of winter wheat grown in sandy loam and clay loam soil was dealt with through conducting the experiment described in Chapter 3.

The effect of soil bulk density on the fine absorption roots is well researched with high soil density restraining root development (Schjonning & Rasmussen, 2000; Saqib et al., 2004; Huang et al., 2012). Until now, little attention has been paid to the adventitious roots, which anchor the plant and resist lodging, it was therefore hypothesised that similar to the fine absorption roots, adventitious roots will be influenced by soil bulk density.

The effect of three soil bulk densities of 1.1, 1.3 and 1.5 Mg m^{-3} (were selected to reflect those represent field conditions with various cultivation systems) on plant anchorage moment, soil shear strength and penetration resistance was investigated, and the results indicated significant effects of soil bulk density on the adventitious root properties, thereby plant anchorage moment.

Increasing soil bulk density from 1.1 Mg m^{-3} to 1.3 Mg m^{-3} increased adventitious root properties associated with anchorage moment as well as soil shear strength and penetration resistance, accordingly, plant anchorage moment in both sandy loam and clay loam soils. Although soil shear strength and penetration resistance continuously increased with further increasing soil bulk density from 1.3 Mg m^{-3} to 1.5 Mg m^{-3} in both soil types, adventitious root properties however, began to reduce with increased soil bulk density (Bengough & Mullins, 1990; Reichert et al., 2009; Huang et al., 2012).

Plant anchorage moment, consequently, rapidly increased with an increased soil bulk density from 1.3 Mg m^{-3} to 1.5 Mg m^{-3} as anchorage moment depends on soil physical properties namely shear strength and adventitious root properties (Crook & Ennos, 1993; Goodman & Ennos, 1999; Berry et al., 2003c; Yang et al., 2015).

The results of the continuous increase in soil shear strength and penetration resistance with the increasing soil bulk density from 1.1 Mg m^{-3} to 1.5 Mg m^{-3} are in agreement with the finding of Benjamin & Cruse (1987) and Manuwa (2012) who reported that, at a given soil moisture content, the greater the soil bulk density the greater the soil shear strength and penetration resistance. Therefore, soil shear strength and penetration resistance are proportional to soil bulk density.

Thus, despite the significant reduction in the adventitious root properties with increasing soil bulk density from 1.3 Mg m^{-3} to 1.5 Mg m^{-3}, plant anchorage moment remained greater at 1.5 Mg m^{-3} compared to the plant anchorage moment at 1.3 Mg m^{-3} soil density. This means that the reduced root properties were compensated by an increased shear strength and penetration resistance. It can be derived that, the greater plant anchorage moment at 1.5 Mg m^{-3} resulted from the greater soil strength properties rather than adventitious root properties. Nevertheless, due to the less adventitious root development the plants grown at 1.5 Mg m^{-3} soil density were expected to be more vulnerable and prone to root lodge compared to the plants grown in

1.3 Mg m^{-3} soil densities.

Regardless of soil bulk density, adventitious roots were also influenced by soil type. Sandy loam and clay loam soil at each bulk density showed similar effects on the adventitious root properties, but to a different extent. The water holding capacity and porosity (size and number of pores) are different between sandy loam and clay loam soil, unlike sandy loam soil, the pore number in clay loam soil is greater but with smaller size and diameter (Fakhimi & Hosseinpour, 2008; Topa et al., 2011). Consequently, compared to the sandy loam soil, the decreased size of the pores in clay loam soil at 1.5 Mg m^{-3} caused greater reduction in the adventitious root properties, which could not be compensated by the increase in soil shear strength and penetration resistance. Thereby, the plants grown at 1.5 Mg m^{-3} in clay loam soil were 8% less anchored compared to the plant grown at 1.3 Mg m^{-3}.

Moreover, through studying the above ground plant properties associated with lodging, the predominance of stem failure and anchorage failure was also addressed in this project. The type of lodging (stem lodging and root lodging) depends upon the environmental conditions, soil physical conditions and the growing stage of the plant at which lodging occurs (Baker et al., 1998; Goodman & Ennos, 1999; Berry et al., 2003c). As expected, the outcome of the experiments indicated that the values of safety factor against stem lodging in general were greater than the values of safety factor against root lodging or anchorage failure. Thereby, root lodging or anchorage failure is more likely to occur.

It can also be considered that stem failure results from the anchorage failure. According to Crook & Ennos (1993), plants generate a self-weight moment which causes stem failure when the stems are no longer in the vertical position; in some other words, the greater the inclination angle from the vertical the greater the self-weight moment generated by the plant.

Therefore, if no anchorage failure occurs due to the robust and well established plant, the stems remain in their vertical position (with more or less variations) at which the minimum self-weight moment is generated, hence minimised risk of stem failure. Accordingly, this conclusion is in agreement with the finding of Crook & Ennos (1993); Navabi et al. (2006) and Khakwani et al. (2010) who addressed anchorage failure as more likely in wheat plants.

The first objective of the project was explored through the glasshouse experiment in which the effect of soil bulk density on the adventitious root properties and plant anchorage moment was evident. However, in order for these results to be validated in a practicable method in which the wheat growers can manipulate soil physical conditions, two field experiments were conducted to determine the effect of different cultivation systems on soil physical conditions and the anchorage moment of wheat. The two experiments were conducted, one under control traffic condition in which the effect of three tillage systems (zero tillage, shallow tillage and deep tillage system) was evaluated on the soil physical conditions, adventitious root properties and plant anchorage moment of wheat. Variation in soil physical conditions depends on the type of soil tillage system; the greater the soil loosening the less the soil bulk density, shear strength and penetration resistance (Benjamin & Cruse, 1987; Arvidsson, 1998; Hou et al., 2012). The values of soil physical properties were significantly decreased with the increase in tillage depth from zero tillage to deep tillage system. Zero tillage systems due to the less soil agitation had greatest soil bulk density of 1.34 Mg m^{-3} compared to the lowest soil bulk density of 1.23 Mg m^{-3} in deep tillage at 25 cm with the biggest soil agitation.

The variation in soil physical conditions due to tillage system affects root development (Braim et al., 1992; Aggarwal et al., 2006; Wang et al., 2014a). The greatest adventitious root properties were recorded in zero tillage treatments and reduced with the decreasing soil bulk density, shear strength and penetration resistance in shallow and deep tillage systems. Increased root properties due to increasing soil bulk density up to 1.5 Mg m^{-3} was reported by Hemsath & Mazurak (1974) and Scott et al. (2005b), whereas bulk density more than 1.5 Mg m^{-3} limits root growth (Schjonning & Rasmussen, 2000; Bengough et al., 2011). Moreover, plant anchorage moment was positively correlated with soil physical conditions and adventitious root properties (demonstrated in Chapter 4). Accordingly, zero tillage had greater plant anchorage moment by 9% and 32% compared to shallow tillage and deep tillage systems, respectively.

However, the effect of four tillage system (Chapter 4) on the soil physical conditions conducted under non-controlled traffic condition was found to be non-significant. Therefore, no-statistical variations were found in the adventitious root properties and thereby plant anchorage moment across the four tillage systems.

Nevertheless, soil bulk density, shear strength and penetration resistance increased with recompacting the soil in springtime. Hence, plant anchorage moment diminished due to reduced adventitious root properties in compacted treatments compared to non-compacted ones. These outcomes further confirm the dependence of plant anchorage moment on the physical conditions of soil and the adventitious root development.

Maintaining high yield is central to cereal growing, hence lodging is an always risk. Moreover, variation in the obtained yield of wheat has been related to the tillage system (Holloway & Dexter, 1991; Tao & Ren, 2004; Kankanen et al., 2011).

An increase in the crop yield was reported with zero tillage system (Ball-Coelho et al., 1998; Ishaq et al., 2001; Hassan et al., 2007; Machado et al., 2008; Huang et al., 2012; Ram et al., 2013). However, under traffic controlled condition, despite the increased adventitious root properties, soil bulk density and soil moisture content in zero tillage system, the yield found to be less by 16% and 11% compared to shallow and deep tillage systems respectively.

The reduced yield in the zero tillage system in comparison to the conventional tillage was also observed by Lyon et al. (1998) and Kosutic et al. (2005), however in this study, one third reduction in the yield was caused by the wheel marks in the zero tillage system under controlled traffic condition (see Figure 4.12).

Accordingly, the variation in the yield due to the use of different tillage systems was caused by different physical soil conditions and plant properties. Hence, in the second experiment conducted under non-controlled traffic conditions, the non-statistical differences in the soil physical conditions and plant properties explain the similarity in the harvested yield from the four tillage systems.

Due to the significant influence of soil moisture content on both soil physical conditions and plant properties associated with lodging (Kim & Borden, 2011; Siddig et al., 2013), another experiment was conducted in which the effect of soil moisture content on the adventitious root properties and the anchorage moment of winter wheat was investigated. Based on the assessment of the effect of three soil moisture contents (85% - 100%, 65% - 85% and 55% - 65% of field capacity) on soil shear strength and adventitious root properties of winter wheat growing in either sandy loam or clay loam soil, the risk of root lodging or anchorage failure was predicted. Soil moisture content showed a significant effect on the adventitious root properties at early growing stages when the adventitious roots development is taking place (HGCA, 2008).

Unlike the above ground properties, adventitious root properties associated with plant anchorage moment, rapidly decreased with reduced soil moisture content from 85% - 100% to 55% - 65% (Yang et al., 2006; Izzi et al., 2008; Whitmore & Whalley, 2009). Nevertheless, the measurements of soil shear strength was conducted at field capacity condition for both soil types which explain the non-statistical differences due to the soil moisture content. However, the variation in the water holding capacity between the soil types due to the nature of each soil resulted in different soil shear strength (Kim & Borden, 2011; Havaee et al., 2015). Subsequently, the plants grown in both soil types and received less amount of water (55% - 65% of field capacity) at early growing stages were up to 25% more root lodging or anchorage failure susceptible.

Thus, the overall objectives of this project have been investigated through the studies presented in Chapter 3, 4 and Chapter 5 in which the results indicated that unlike the harvested yield, the maximum anchorage of wheat against root lodging was achieved under zero tillage system. Soil rolling at wheat growth stage GS 25 - 29 significantly decreased adventitious root properties and thereby plant anchorage moment by 18%. Additionally, in relation to moisture content, a reduced moisture content at early growing stage (root development stages) increased the risk of root lodging at late growing season (grain filling stage where lodging is more likely to occur).

Therefore, since the above ground properties of the plant associated with lodging have been extensively researched; this project opens a new research approach for further optimising the yield in relation to the plant anchorage moment through manipulating soil physical conditions with cultivation systems. Moreover, taking into account the soil moisture content (precipitation) at early growing stages, proper management practices are required in springtime to reduce the risk of lodging in wheat at maturity.

Chapter 7

7. Conclusions

A series of studies was conducted to investigate the hypothesis that the anchorage moment of wheat can be optimised through manipulating soil physical conditions. For this work, soil physical conditions, adventitious root development and plant anchorage moment were investigated in both a glasshouse experiment and field scale (controlled and un-controlled traffic) studies, evaluating the effects of zero tillage, shallow tillage and deep tillage and also a range of secondary cultivation systems, respectively. The following conclusions were drawn:

1. It has been possible to enhance the development of the adventitious roots and the resulting plant anchorage moment of wheat using a zero tillage system in the controlled traffic conditions:
    a. A zero tillage system with a bulk density of 1.34 Mg m^{-3} resulted in the maximum plant anchorage moment of 0.72 Nm, in relation to the improved adventitious root development.
    b. The plants grown under the zero tillage system were 31% and 9% more resistant to root lodging compared to the plants grown under deep and shallow tillage systems, respectively.
    c. The plants grown under the zero tillage system had greater adventitious root development (18% increase in root plate diameter, 70% increase in the number of the roots (greater than 1 mm in diameter), 25% increase in the angle of spread of the roots and 58% increase in the total length of the roots (greater than 1 mm in diameter)) compared to the deep tillage system.

   d. Zero tillage system resulted in a 13% increase in root plate diameter, a 59% increase in the number of the roots (greater than 1 mm in diameter), a 13% increase in the angle of spread of the roots and a 58% increase in the total length of the roots (greater than 1 mm in diameter) compared to the shallow tillage system.
   e. Under the zero tillage conditions the soil bulk density was 8% greater than the 1.23 Mg m^{-3} in the deep tillage, and resulted in a higher soil shear strength and penetration resistance of 22% and 27%, respectively.
   f. Zero tillage system had the average yield of 6.9 t ha^{-1}, which was 16 % and 11% less compared to the shallow tillage and deep tillage systems, respectively.
2. The use of the secondary cultivation systems had a limited potential to manipulate soil physical conditions:
   a. The use of a combination of power harrow and seed drill in the non-controlled traffic condition had no significant effects on the soil physical conditions. Thereby, no differences in the adventitious root development and plant anchorage moment were observed.
   b. There is an evidence that rolling the soil in springtime at growth stage GS 25 - GS 29 will reduce the plant anchorage moment up to 18% due to the increasing soil bulk density from 1.37 to 1.43 Mg m^{-3}, 30% increase in the soil shear strength and a significant ($p < 0.001$) reduction in the adventitious root properties.
3. At field capacity moisture content, in the pot-based study, the effects of soil type and bulk density on the soil physical conditions, adventitious root development and the resulting plant anchorage moment were found to be significant:

   a. Increasing soil bulk density from 1.1 to 1.3 Mg m^{-3}, increased plant anchorage moment by up to 40% which resulted from an 8% increase in the soil shear strength and a significant ($p < 0.001$) increase in the adventitious root properties.
   b. At field capacity moisture content, sandy loam had an 8% greater plant anchorage moment due to the 16% and 26% greater soil shear strength and penetration resistance, respectively; and significantly ($p < 0.001$) greater adventitious root properties.

4. It has been possible to minimise root lodging in wheat at grain filling stages based on the available amount of soil moisture content at leaf emergence stages:
   a. Wheat plants subjected to less available moisture content in early growing stages until the beginning of booting stage (GS 39) are 25% more prone to root lodge compared to the well-watered plants.
   b. The reduction in the adventitious root properties reached up to 20% due to the reduced moisture content to 55% - 65% of field capacity. Consequently, the likelihood of anchorage failure is higher as shown by the 30% decrease in the safety factor.
5. Winter wheat is up to 68% more prone to anchorage failure than steam failure and is more likely to be due to soil failure rather than root failure as observed from the X-ray computed tomography.
6. A novel method of root movement observation using the X-ray computed tomography has been employed in this study. It is recommended this method is further used to evaluate the mechanics of anchorage failure.

Recommendations for further studies

1. To embrace the use of zero tillage system as an optimum tillage practice in turns of both plant anchorage strength and the harvestable yield, further studies need to be conducted to minimise the effects of the wheel marks. Zero tillage system had the average yield of 6.9 t ha^{-1}, which was 16 % and 11% less compared to shallow tillage and deep tillage systems, respectively. Moreover, from the manual harvesting data collected in between the wheel marks (tramlines), the highest yield of 10.7 t ha^{-1} was obtained in zero tillage treatments. Nevertheless, in zero tillage system conducted under controlled traffic conditions, the wheel marks caused 35.3% reduction in the yield.
2. Identify the optimum growth stages for rolling the soil after drilling in springtime, which causes less damage to the adventitious root properties, hence a maximised plant anchorage, and maintaining yield.
3. Improve the forecast of the lodging risk at grain filling stages based upon management decisions in springtime (the application of plant growth regulator and nitrogen) in relation to the adventitious root development.
4. The availability of X-ray CT scan technique should be considered in studies that are more theoretical to investigate:
    a. The mechanics of anchorage failure (root lodging/soil failure) in a range of soil types (pure sand to pure clay).
    b. Predicting the cone-root diameter in relation to the adventitious root development due to its significant effect on the plant anchorage moment.
    c. Modelling more accurately the contribution of adventitious root development on soil plate diameter.

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Appendix 8

8.1 Effects of distance apart, depth and soil type on *in situ* shear strength measurements

8.1.1 Objectives

1. To determine the minimum distances between two single shear strength measurements.
2. To determine the dimensions of the pots used in the experiments presented in Chapter 3 and Chapter 5.

8.1.2 Methodology

In situ soil shear strength measurements were conducted at Harper Adams University located at (Latitude 52.772863, Longitude -2.434845) at depth of 5 and 10 cm in Four Gate and Large Marsh fields. The soil textures used in these measurements were; sandy soil at Four Gate field, sandy loam and clay loam soils at Large Marsh field. Prior to the shear strength measurements, soil moisture content was measured using a Field Scout TDR 100, Spectrum Inc. Technologies and the average moisture content recorded were 20.1%, 31.59% and 35.59% for sandy, sandy loam and clay loam soil, respectively.

The shear vane tests were performed at two depths of 5 and 10 cm. The measurement started with pushing down the shear vane in to the soil to the depth of 5 cm then rotated clockwise as demonstrated in Figure 3. 4, torque was applied and the maximum value recorded; in the same position, the shear vane was then further pushed down in to the soil to the second depth of 10 cm and the same process repeated. The maximum shear strength (kPa) indicated on the torque meter was recorded for each depth in accordance to procedure described by Sposaro et al. (2008).

The vane shear was moved from the starting point to the second distance 4 cm apart then 6, 8 and 10 cm (Figure 8. 1), the measurement process was repeated at each point and data were recorded.

A multi factorial ANOVA test was conducted in Genstat 14th Edition to determine the statistical differences between the treatments. The main factors were soil type (3 levels), distance apart (5 levels) and the depth of the measurements (2 levels), with 20 replicates for each treatments, the total number of the measurements was 600 measurements.

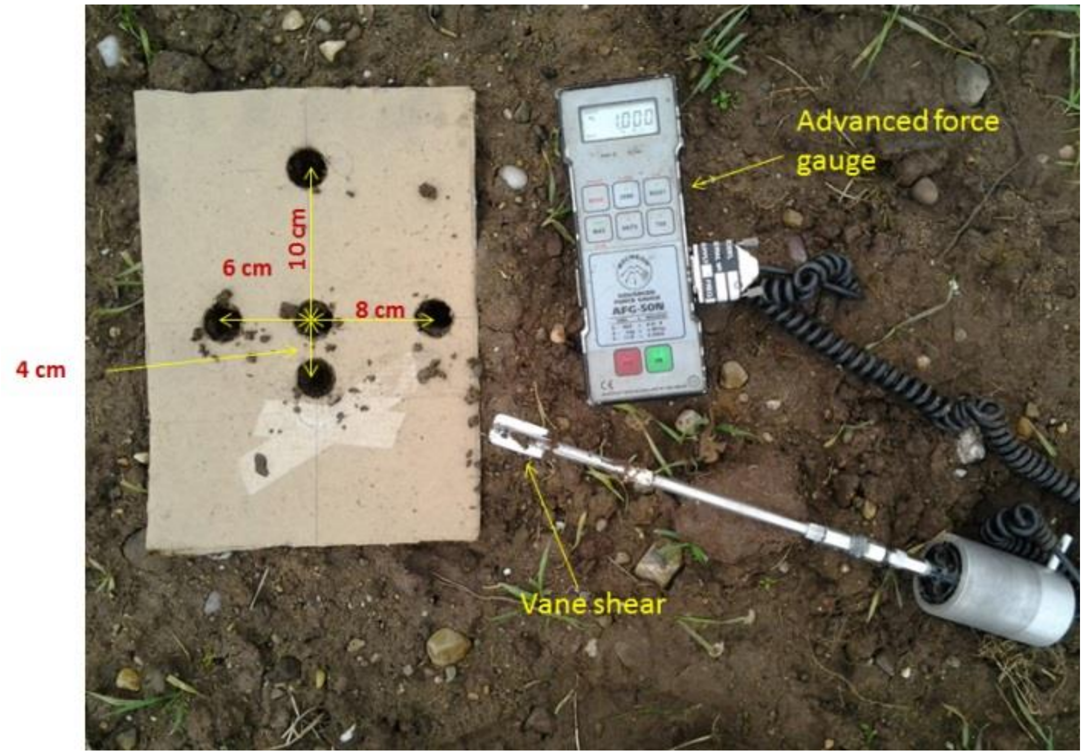


Figure 8.1. *In situ* shear strength measurements at five different points and two depths in each point

8.1.3 Results and discussion

The results of the statistical analysis revealed that distance apart significantly affected the measurements of soil shear strength (*p* <0.001). The values of shear strength measured at both 4 and 6 cm apart were significantly different from those measured at the start point (Figure 8. 2); shear strength at 4 and 6 cm apart were significantly lower than those measured at the start point by 21.3% and 12.6%, respectively. Non-significant differences were also observed between those values measured at 6 and 8 cm apart compared with those measured at the start point. The presence of significant differences in this case indicates a measurement interfering in those distances at which shear strength was measured, this interference is caused by the vane shear blade as disturbs the soil horizontally more than vertically during rotating and taking measurements. Thus, shear measurements should be avoided at these distances.

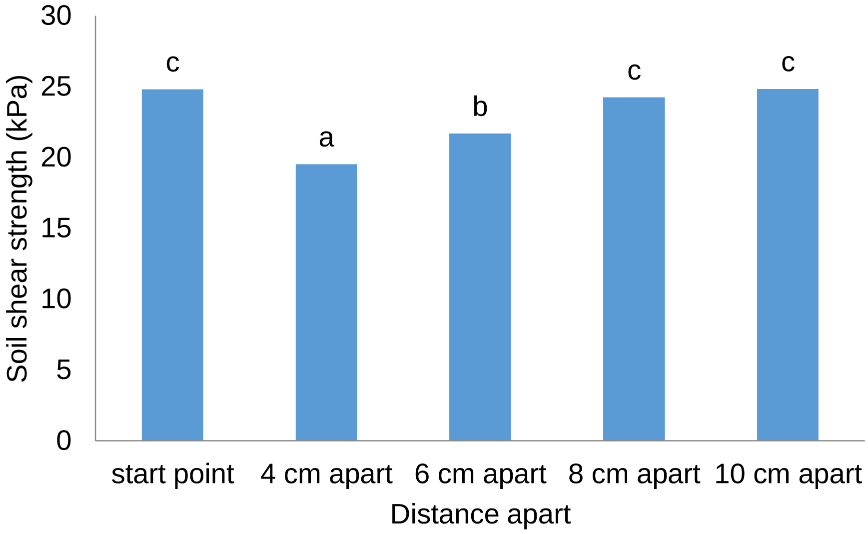


Figure 8.2. The effect of distance apart on *in situ* shear strength measurements
Error bars represents standard error of means (S.E.M.) = 0.470,
degree of freedom (d.f.) = 570, *p* = < 0.001

Moreover, soil type also statically influenced the value of shear strength (Figure 8. 3). Shear strength in sandy soil was significantly lower by 15.7% compared to sandy loam soil and by 25.2% lower than shear strength in clay loam soil. Regardless of moisture content, bulk density and soil compaction, shear strength depends on the soil type and its clay content (Dolinar, 2004; Dolinar & Trauner, 2007) and increase with the increase in the clay percentage of the soil (Khalilmoghadam et al., 2009).

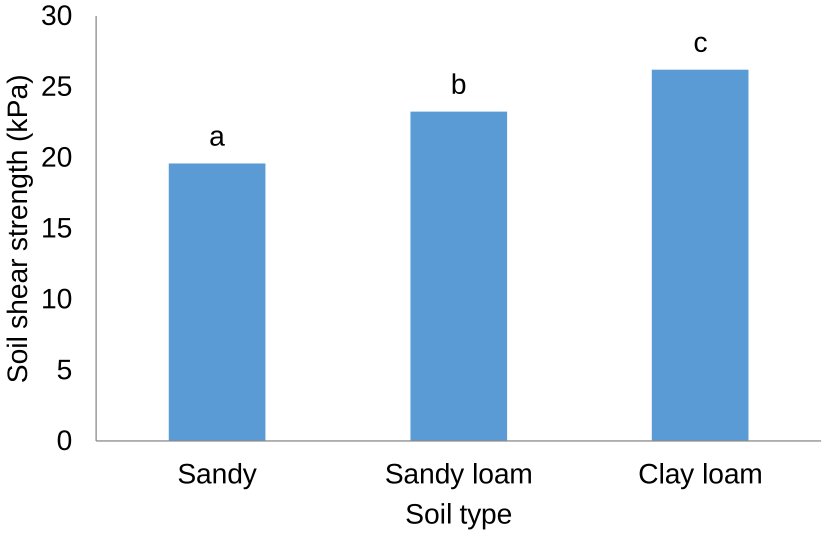


Figure 8.3. The effect of soil type on *in situ* soil shear strength measurement
Error bars represents standard error of means (S.E.M.) = 0.364,
degree of freedom (d.f.) = 570, p = < 0.001

Disregards of soil type and the distances apart the measurements, the average value of shear strength measured at the depth of 10 cm was 70% greater compared to the average shear strength value measured at the depth of 5 cm as illustrated in Figure 8. 4. These results were in agreement with results of Bachmann et al. (2006), who reported a greater soil shear strength in the bottom layers of soil compared to the surface layers as a results of soil settlement, compaction and the soil weight of the upper layers, these components incorporate in the increase in soil shear strength with the increase in the soil depth (Bachmann et al., 2006).

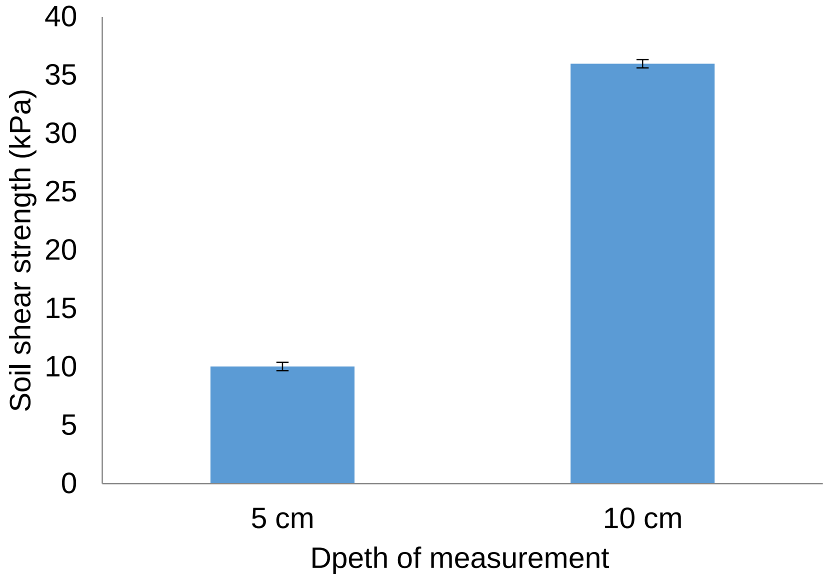


Figure 8.4. The effect of depth on *in situ* soil shear strength measurement
Error bars represents standard error of means (S.E.M.) = 0.297,
degree of freedom (d.f.) = 570, p = < 0.001

The interaction of the effect of soil type and the depth was illustrated in Figure 8. 5. Soil type and the depth of the measurements should be taken into account when soil shear strength is measured (Zhao et al., 2009; Arvidsson & Keller, 2011).

In sandy soil at the depth of 5 cm shear strength was significantly different and lower than those in sandy loam and clay loam soil by 25.2% and 47.4%, respectively; also the difference between sandy loam and clay loam soil itself was significant and less by 29.7% in sandy loam soil. All these three measurements at depth of 5 cm were significantly different from the values measured at the depth of 10 cm in the three soil types. At the depth of 10 cm, sandy soil had 13.3% less shear strength compared to sandy loam soil and 17.5% less compared to clay loam soil.

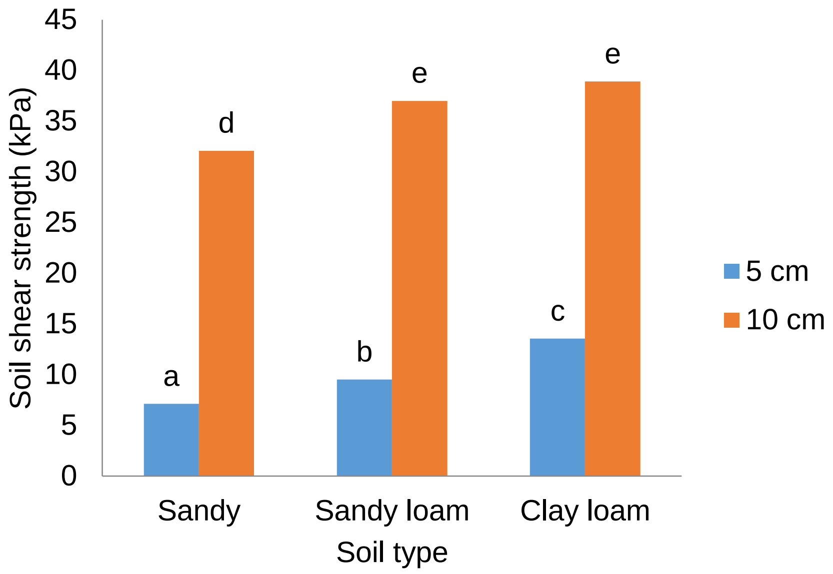


Figure 8.5. The effect of soil type and depth on *in situ* shear strength measurements
Error bars represents standard error of means (S.E.M.) = 0.727,
degree of freedom (d.f.) = 570, p = 0.031

8.1.4 Conclusions

1. The distance apart between the points of *in situ* shear strength measurements significantly affects its values.
2. The value of the measured shear strength increase with the increase in the depth.
3. The depth did not influence the measurements values at the same point.
4. Shear strength varied with soil type. Shear strength showed greater values in clay loam soil than sandy loam and sandy soil used in this investigation.

   Therefore, the distance between measurement points should not be less than 8 cm to avoid any possible interfering of the measurements.

8.2 Agronomy details

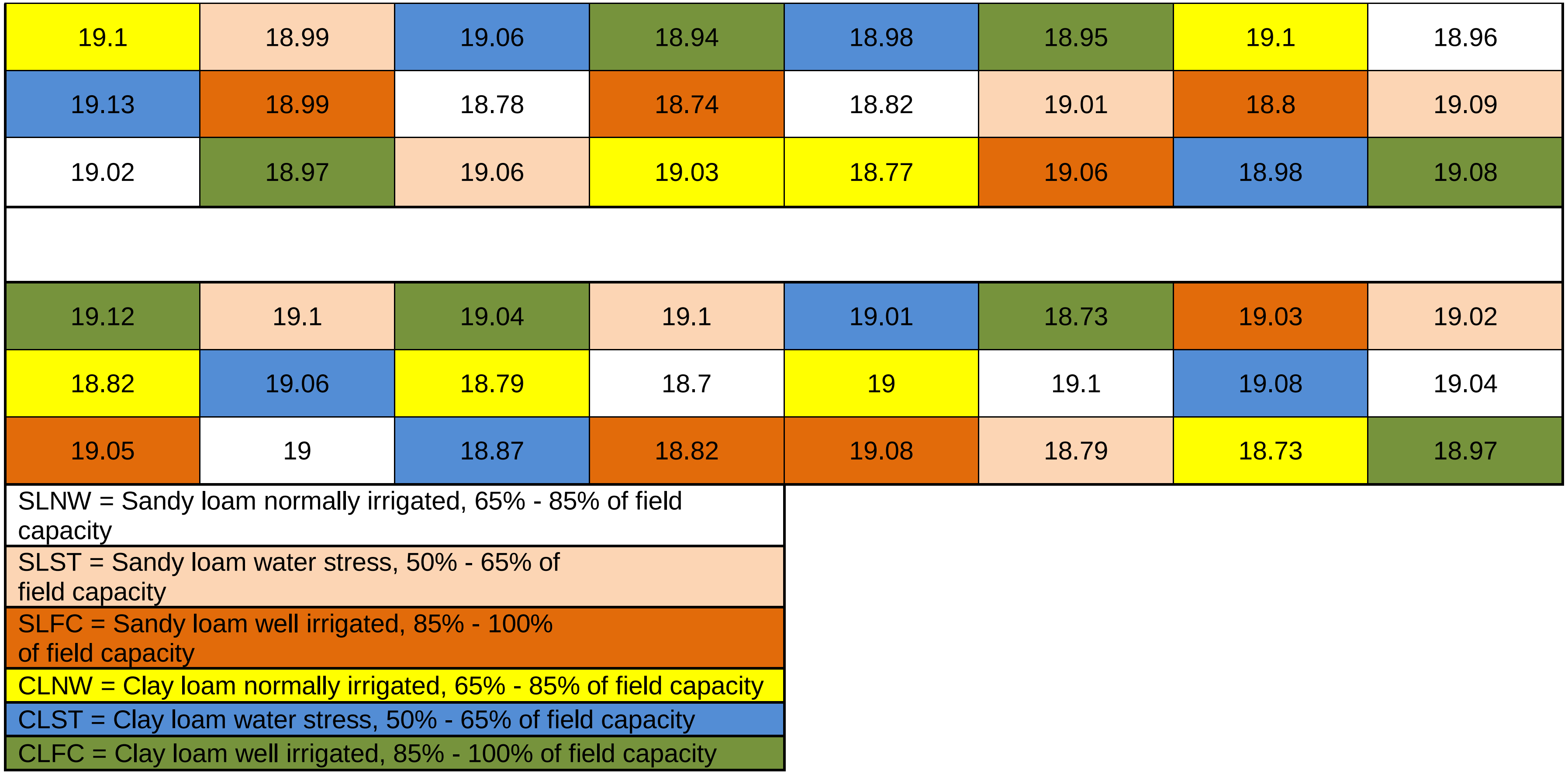
Table 8.2.1. Agronomy practice details on Large Marsh field in 2012 – 2013

Date of action	Type of action	Product name	Amount / 3.12 ha (area of the study field)
06 Nov. 2012	Ploughing	Tracked Cat Challenger MT765C ,Vaderstad TopDwon	25 cm deep tillage, 10 cm shallow tillage
09 Nov. 2013	Seeding	Duxford C2 Jockey, Vaderstad Rapid drill	561.60 kg
07 Jan. 2013	Spray	Slug pellets, Sluxx	15.60 kg
05 Mar. 2013	Fertilizer	Fertilizers, Top Crop 26N 37SO3	461.76 kg
02 May 2013	Spray	Chemicals, Cherokee cyproconazolechlorothaloNSpropiconazol	3.12 L
	Spray	Herbicide, Starane XL fluroxypyr+florasul	3.12 L
	Spray	Fungicides, Chord boscalid + epoxiconazole	3.12 L
	Spray	Herbicide, PresiteSxmetsulfuron-methyl + thifensulfuron	156.00 g
	Spray	Fungicides, Justice proquinazid	0.31 L
	Spray	Growth Regulators, Tempo trinexapac-ethyl	0.31 L
07 May 2013	Fertilizer	Fertilizers, GrowhowNitram 34.5%	680.16 kg
20 May 2013	Fertilizer	Fertilizers, GrowhowNitram 34.5%	680.16 kg
25 May 2013	Spray	Trace Element, Sedema Manganese Sulphate	15.60 kg
	Spray	Adjuvant, Activator 90	0.15 L
03 Jun. 2013	Spray	Fungicides, Vertisanpenthiopyrad	2.34 L
	Spray	Fungicides, ProsaroProthioconazale+Tebuco	2.34 L
24 Jun. 2013	Spray	Fungicides, ProsaroProthioconazale+Tebuco	1.87 L
12 Aug. 2013	Spray	Herbicide, Azural (glyphosate)	9.36 L

Table 8.2.2. Agronomy practice on the Buttery Hill field during the growing season 2013 - 2014.

Date of action	Type of action	Product name and rate per hectare
28.10.2014	subsoiled	
13. 11. 2014	ploughing	New Holland T 6040 + Dowdeswell power harrow PH 300 (adjusted to low and high pressure based on the manufacturer’s recommendations)
13. 11. 2014	seeding	Duxford C2 Jockey + Accord seed drill 160 kg/ha
27.03.2014	fertiliser	60 kg N as sulphur N
07.04.2014	T 0	Cherokee (1 L/ha) Chlormoquat (1 L/ha) Manganese
16.04.2014	fertiliser	60 kg N as ammonium nitrate
27.04.2014	T 1	Ignite (1 L/ha) Bravo 500 (1 L/ha) Agrovista 3See (1 L/ha) Moddus (0.1 L/ha)
28.04.2014	fertiliser	60 kg N as ammonium nitrate
19.05.2014	T 2	Aviator (1 L/ha) Bravo 500 (1 L/ha)
16.06.2014	T 3	Proline 275 (0.35 L/ha) Folicur (0.5 L/ha) Amistar (0.3 L/ha)

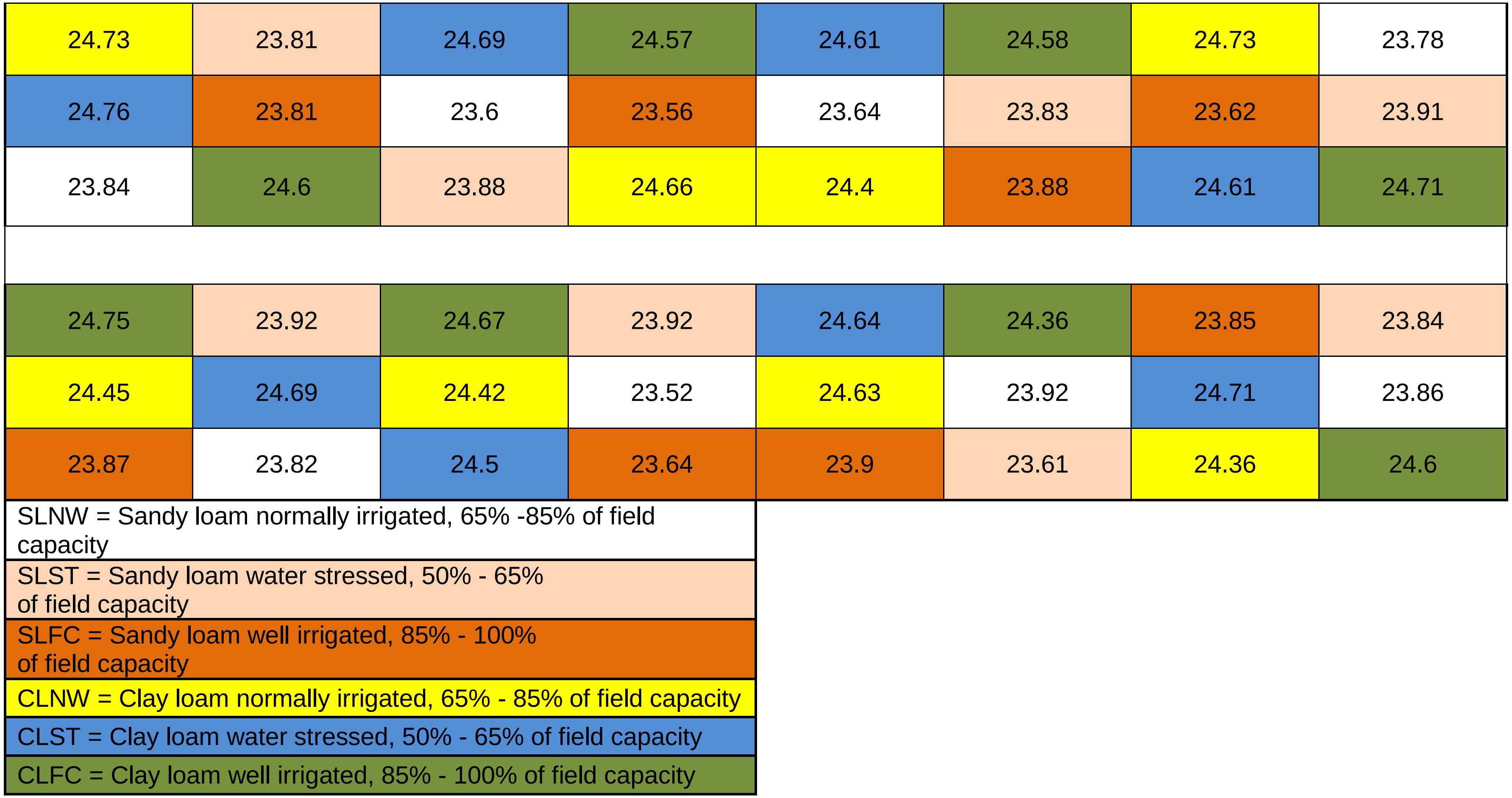
Table 8.2.3 Treatments distribution in 8 blocks over two benches and the weight of the pots + soil (kg) at dry condition.



19.1	18.99	19.06	18.94	18.98	18.95	19.1	18.96
19.13	18.99	18.78	18.74	18.82	19.01	18.8	19.09
19.02	18.97	19.06	19.03	18.77	19.06	18.98	19.08
19.12	19.1	19.04	19.1	19.01	18.73	19.03	19.02
18.82	19.06	18.79	18.7	19	19.1	19.08	19.04
19.05	19	18.87	18.82	19.08	18.79	18.73	18.97

SLNW = Sandy loam normally irrigated, 65% - 85% of field capacity
SLST = Sandy loam water stress, 50% - 65% of field capacity
SLFC = Sandy loam well irrigated, 85% - 100% of field capacity
CLNW = Clay loam normally irrigated, 65% - 85% of field capacity
CLST = Clay loam water stress, 50% - 65% of field capacity
CLFC = Clay loam well irrigated, 85% - 100% of field capacity

Table 8.2.4. Treatments distribution and the weight of the pots + soil (kg) at field capacity condition.



24.73	23.81	24.69	24.57	24.61	24.58	24.73	23.78
24.76	23.81	23.6	23.56	23.64	23.83	23.62	23.91
23.84	24.6	23.88	24.66	24.4	23.88	24.61	24.71
24.75	23.92	24.67	23.92	24.64	24.36	23.85	23.84
24.45	24.69	24.42	23.52	24.63	23.92	24.71	23.86
23.87	23.82	24.5	23.64	23.9	23.61	24.36	24.6

SLNW = Sandy loam normally irrigated, 65% -85% of field capacity

SLST = Sandy loam water stressed, 50% - 65% of field capacity

SLFC = Sandy loam well irrigated, 85% - 100% of field capacity

CLNW = Clay loam normally irrigated, 65% - 85% of field capacity

CLST = Clay loam water stressed, 50% - 65% of field capacity

CLFC = Clay loam well irrigated, 85% - 100% of field capacity

Table 8.2.5. The maximum limit of volumetric moisture content (%) of each treatment

36.12	23.27	27.62	42.5	27.62	42.5	36.12	30.43
27.62	35.8	30.43	35.8	30.43	23.27	35.8	23.27
30.43	42.5	23.27	36.12	36.12	35.8	27.62	42.5
42.5	23.27	42.5	23.27	27.62	42.5	35.8	23.27
36.12	27.62	36.12	30.43	36.12	30.43	27.62	30.43
35.8	30.43	27.62	35.8	35.8	23.27	36.12	42.5

SLNW = Sandy loam normally irrigated, 65% - 85% of field capacity

SLST = Sandy loam water stress, 50% - 65% of field capacity

SLFC = Sandy loam well irrigated, 85% - 100% of field capacity

CLNW = Clay loam normally irrigated, 65% - 85% of field capacity

CLST = Clay loam water stress, 50% - 65% of field capacity

CLFC = Clay loam well irrigated, 85% - 100% of field capacity