Identification of optimum seedbed preparation and establishment using soil structural visualisation

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Abstract

A key aspect of the condition of soil as a medium for growing plants is the soil physical environment under which germination, growth and establishment occur. Crucially this affects factors such as water content, oxygen availability and soil strength. The dynamics of soil physical properties, and in particular soil structure, of a range of soils and how they relate to plant establishment are considered in this thesis. By engineering a variety of seedbeds and contrasting soil structures using different cultivation techniques, from intensive (plough) to reduced (disc) strategies, significant differences in the physical properties of the soils in terms of volumetric water content, soil strength and bulk density and interactions with plant establishment were identified. A model for Soil Quality of Establishment (SQE) was developed to predict plant establishment based upon soil bulk density and cultivation practices which significantly accounted for c. 50% of the variation occurring across contrasting soil types and environmental conditions. It was hypothesized from this that the precise porous architecture (i.e. soil structure) plays a crucial role in plant establishment given soil bulk density was a significant factor in the SQE model. Utilizing X-ray Computed Tomography (CT) both at a macro (c.300μm) and meso (c.65μm) scale soil structure (in terms of: porosity, pore area and perimeter, elongation, nearest neighbour distance, ECD and pore distribution) were determined in a quantitative manner. Results showed significant decreases in plant populations with associated increases in the soil porosity, with strong links to the pore size, roughness and spatial distribution (accounting for soil-seed contact, water storage / flow and ease of plant / root movement within the soil). Preferred porosity conditions for establishment and yield occurred between 12 - 20 % porosity (at the meso scale). SQE prediction was significantly improved with the addition of structural properties accounting for c. 70 % variation in crop establishment across soil texture and seasonal variation. The further 30 % variation in crop establishment may be explained by unforeseen circumstances such as disease and weather but equally this may also be related to crop genetics, soil chemistry and or the biological activities within the soil.

CONTENTS

Chapter 2: Using selected soil physical properties of seedbeds to predict crop establishment 78

Chapter 3: Effect of seedbed cultivation and soil macro structure on the establishment of winter wheat (*Triticum aestivum*) 90

DEDICATION

This work is dedicated to my parents and grandparents without whom I would not have achieved so much, and to my bride to be Nicola for all the love, support and understanding.

"It is not how much you do, but how much love you put in the doing."

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And finally I have one last thing to say……………………………**'42'**

List of Tables

List of Figures

Chapter 1: General Introduction

1.1 Rationale

Seedbed preparation is crucial for the growth of seedlings, plant establishment and the final yield of crops. As such, a great deal of consideration is needed to determine the most suitable conditions for crop growth. An important aspect of this is the physical characteristics of the seedbed such as soil strength, bulk density, water content, aggregate size distribution, water retention, aggregate stability, temperature, oxygen and nutrient availability. The soil-plant system is extremely complex and previous work has shown the importance of soil physical properties in determining germination, crop establishment and yield (Awadhwal and Thierstein, 1985; Jakobsen and Dexter, 1987; Juma, 1993; Guérif et al., 1999; Aubertot et al., 1999; Dexter, 2004). However, no studies to date have concentrated on the direct effect of cultivation equipment on the changes to soil structure as a determinate of crop establishment and crop growth.

Cultivation prepares soil for seeding by assisting the decomposition of organic matter, aeration of the soil, weed control, drainage and most importantly seedbed preparation. Whether cultivation of the soil improves its condition for seed germination, establishment and yield has been debated, and in many cases it has been shown that excess cultivation can have detrimental effects on establishment (Arshard et al., 1999; Ball et al., 1994; Ball-Coelho et al., 1998; Berntsen and Berre, 2002; Czyz, 2004; Díaz-Zorita et al., 2004; Scott et al., 2005; Servadio et al., 2005; Unger, 1979; Vos and Kooistra, 1994).

Seedbed practices are therefore key as cultivation implements impose varying degrees of alterations to both the surface soil and sub-soil. As such it is crucial to determine the best practice for seedbed preparation to maximise crop establishment and yield.

This research aims to understand these complex interactions by looking at how specific soil physical properties, in particular soil structure, affects crop establishment using image analysis (Ringrose-Voase, 1987; Commins et al., 1991; Glasbey et al., 1991; McBratney et al., 1992; Kokko et al., 1993; Heijs et al., 1996; Vogel and Roth, 2001; Pierret at al., 2002; Mooney et al., 2007). This research evaluates the effectiveness of using image analysis of soil structure in the assessment of seedbed preparation for cereal crop production, particularly focusing on the use of winter wheat (*Triticum aestivum*). Key issues include; the characterisation of the soil physical properties of the prepared seedbeds; the characterisation of the porous architecture induced by cultivation practices at a variety of spatial resolutions; linking the physical and structural condition of soil to crop establishment and yield; and the differences between soil texture and the response of cultivation to soil structure and establishment.

1.2 Literature review

A seedbed is defined as a loose shallow surface layer, tilled during seedbed preparation with a basal layer underneath which is untilled and usually firm (Håkansson et al, 2002). A seedbed is required to provide a medium for germination, root growth, emergence and establishment (Arvidsson et al, 2000), as such this covers a wide range of determinate factors.

The following sections define seedbed attributes, consider the effect of seeding on establishment (Section 1.2.4), describe the seedbed structural effects on establishment in relation to soil strength (Section 1.2.3.4), aggregate size variation (Section 1.2.3.7), stability and crusting (Section 1.2.3.8), discuss the need for and types of cultivation and the effect these have on establishment (Section 1.2.5; 1.2.6), describe the use of soil structural visualisation in this context and hypothesise the optimum seedbed condition (Section 1.2.7). This thesis focuses on the structural attributes of soil in the determination of best seedbed development practices, therefore chemical and biological factors are not considered here as this was not the aim of this research, but their influence is noted in the development of soil structure and the interactions they produce under field conditions.

1.2.1 Seedbed dynamics

The interactions between soil properties and plant root systems are vitally important for a number of considerations ranging from the formation of soil structure, rhizosphere biochemistry, root zone development, seedbed quality and germination.

The key mechanisms associated with soil structural development and plant establishment are listed in *Figure 1.1*; their interactions creates the vital differences between what can be determined as a 'good' or 'bad' seedbed in terms of maximum yield potential.

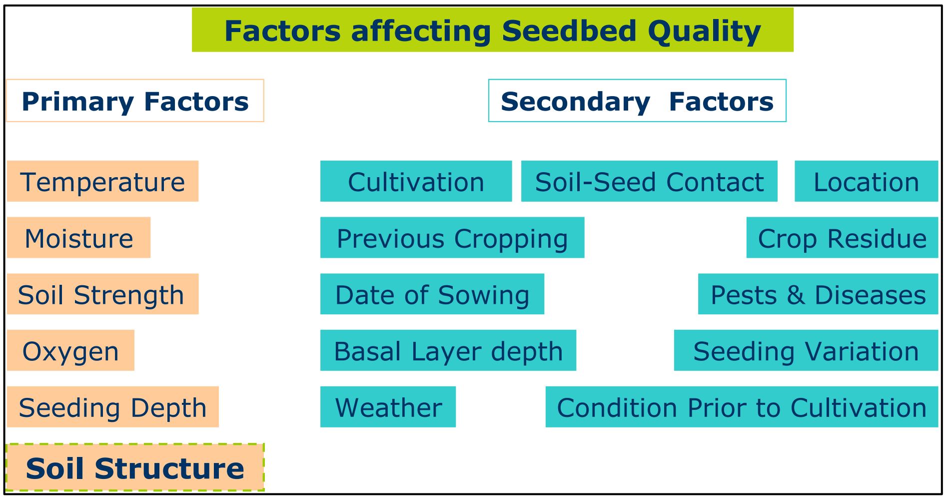


Figure 1.1: Key mechanisms associated with seedbed preparation and soil-plant interactions. We hypothesise soil structure should also be included as a primary influencing factor in plant establishment.

Seedbed quality is affected by a variety of biological, physical and chemical influences that are directly or indirectly related to the management practices. These can be defined as either primary or secondary factors (Figure 1.1). Primary factors consist of limiting conditions such as temperature, soil water content, shear strength, penetration resistance, oxygen diffusion rates and the depth of seeding. Secondary factors consist of broader aspects such as soil-seed contact, cultivation type, date of sowing, location, previous cropping, pests and disease, weather conditions, crop residues, row spacing, seeding rates, seed variety, basal layer relative to seed, soil condition prior to cultivation (Håkansson and Polgàr, 1984, McWilliam, 1998, Davies, B.D. (pers. comm.), Håkansson et al., 2002, Blake et al., 2003, Lipiec and Hatano, 2003, Licht et al., 2004).

1.2.2 Plant establishment

An established plant is defined as a seedling which is sufficiently intact to have the expectation of reaching maturity (Bradbeer, 1988). **Germination** of a seedling is initiated by the presence of water and a sufficient medium which provides warmth (optimum 20-25^{o}C) and oxygen diffusion creating aerobic conditions. A seedling is reliant upon stored food within the embryo of a seed until such time as root (radicle) and shoot (plumule) development occurs (Soffe, 2003). **Emergence** describes post germination growth and development at a point in which root and shoot development is no longer reliant upon stored food but is in fact autotrophic, often associated with the emergence above ground level. Milthorpe and Moorby (1974) found a wheat seedling does not become independent of seed reserves for nutrients until the third leaf begins to emerge. **Establishment** is achieved once a vegetative state occurs, this is when cellular division promotes leaf and stem extension. Establishment rates are a measure of surviving plants either in late autumn or in spring. **Spring Establishment** accounts for the plants which do not survive the winter i.e. winter kill. Higher susceptibility to winter kill occurs within some species and / or regions of the United Kingdom (such as Scotland – due to heavy frosts etc.). Final yields are a measure of the yield achieved at harvest time once crops have developed to maturity.

1.2.3 Effects of the seedbed environment on plant establishment

The seedbed environment, determined by strength, water content, temperature, aerobic conditions, organic matter and cereal residues play a crucial role in the determination of plant health and ultimately yield.

1.2.3.1 Soil water content and potential

Soil water potential is the pressure at which water in soil is held and is directly related to the soil structural and textural conditions of a particular soil. Pardo et al. (2000) found the spatial distribution of roots and plant water uptake was strongly affected by soil structural conditions and by the weather conditions which persist at the time. Soil water content plays a key role in the development of seedlings, as they are required to reach 35-45% of grain dry weight before germination will occur (Blake et al., 2003).

Soil water potential is also responsible for a number of potential yield consequences with problems occurring from a well drained soil resulting in drought, and the opposite, of a poorly drained soil resulting in very high saturation levels. Both cause wilting damage to crops and a loss in overall yields. Optimum soil water retention (also referred to as the available water capacity) is the water held between field capacity (following 48 hours drainage from saturation -15 kPa) and permanent wilting point (-1.5 MPa) (Russell, 1973; Fitzpatrick, 1986)(Figure 1.2). Low soil water potentials act as a signal inducer within the plants resulting in the stunting of growth (Passioura, 2002) and reduction in yield, and continued decreases in water potentials result in the permanent wilting point being passed at which crops will fail.

The ability of soil to transmit water is dependent upon the interlink between pore arrangement, size and geometry i.e. structure (Connolly, 1998). These interlinks, as Connolly (1998) states, can be classed by the size of pores which range from 0.2µm to 10mm or more in diameter. Pores sized between 0.2-30µm are important for storing water and uptake by plants whereas pores sized between 30-300µm are important for infiltration but do not retain water for use by plants. The soil water retention characteristic is measured using a water release curve, determined by the loss in water content (on a drying curve) from a particular pore size range at degrees of pressure (suction) on a sand, clay or pressure membrane table (Figure 1.2).

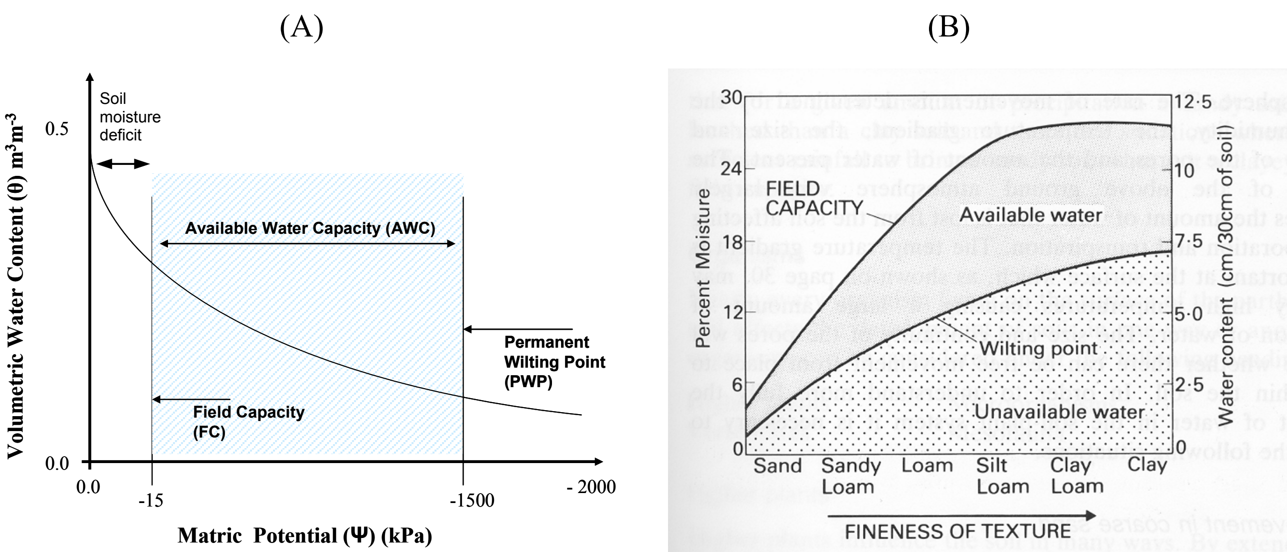


Figure 1.2: Soil water retention curve (a) showing the relationship with matric potential and holding capacity. (b) General soil water content relationships with soil texture (Figure from Fitzpatrick, 1986).

Soil water content conditions of the soil also affect (Arvidsson et al, 2004; Munkholm and Schjønning, 2004) the appropriate time for particular cultivation equipment and drilling. Soil types have a 'friable range', outside of this cultivation is ineffective or damaging to the soil structure. Both dry and saturated soils can result in damage to soil horizons as a result of structurally induced changes resulting in a loss of productivity and yields.

1.2.3.2 Soil temperature

Soil temperature, the ability to retain heat, as with soil water content, is directly related to soil texture and weather conditions. Plant growth or germination is therefore restricted to an optimum temperature range. However optimal temperature for germination is species dependent (McWilliam, 1998). Optimum temperature ranges for most crops are within 20-25 ^{o}C (Blake et al., 2003), however, germination will start at temperatures of 5 ^{o}C (Fitzpatrick, 1986) but will cease when temperatures are excessively high resulting in loss of water. Optimum germination temperatures for Triticum *aestivum* have been determined to be between 15-31 ^{o}C (Mayer & Poljakoff-Mayber, 1989). Licht and Al-Kaisi (2004) found that changes in soil temperature due to tillage was highly dependent on air temperature throughout the day and that the maximum soil temperature was reached at the times of maximum air temperature, at around 12:00-16:00h.

1.2.3.3 Soil texture

Blake et al. (2003) reported texture accounted for 11.6% of variation in autumn establishment and 4.9% for spring establishment. They also suggested sandy soils had better establishment than other soils (90% opposed to 65% in loam and clay textured soils), due to friability over wide ranges of water contents, good soil/seed contacts and lower soil strengths. Blake et al. (2003) also suggested soil stability as a result of texture is a key factor. This was also determined by Wakindiki & Ben-Hur (2002) who found soil texture was very influential upon soil stability, and thus crusting potentials, infiltration rates and erosion. They determined this was a result of both texture and chemical composition, of the minerals which make up the texture, with an increasing stability in soils with ≥20% clay and those with a higher proportion of kaolinite.

1.2.3.4 Soil strength

The effect of soil strength and penetration resistance on establishment, both in terms of the development of root systems and the emergence to establishment of crops has been well researched (e.g. Gregory, 2006). A number of publications have suggested optimum conditions for establishment, Jakobsen and Dexter (1987) found for wheat that soil strength must be: <3.0MPa for germination, <2.3MPa for root elongation, <1.7MPa for coleoptiles and <0.8MPa for emergence. Nasr and Selles (1995) provided a guideline of <1.5-1.4MPa for soil strength and penetration resistance limitations on establishment. Pardo et al. (2000) found that soil strength >3MPa became a limitation to root development and establishment of chickpea, whereas Bengough & Mullins (1990) stated that root growth is hindered at levels above 1MPa and is non-existent at 5MPa.

Shear strength can be determined using a shear vane which records lower values compared to penetration resistance due to shallower assessment between 0 and 80 mm. Schjønning and Rasmussen (2000) found shear strength was no higher than 95kPa (silt loam) across direct drilled and mouldboard ploughed soils of silt loam, sandy loam and a sand. Ball et al. (1997) found soil shear strength was increased by up to three times under wheeled traffic than zero-traffic.

1.2.3.5 Bulk density

Dense soils and the associated high strength limits root growth due to the restriction of large mechanical resistance and reduced oxygen supply (Gregory, 2006). Bowen (1981) stated root impedance within soils occurs between 1.55 to 1.85 Mg m^{-3} depending upon soil texture. Other studies also suggest both high and low bulk density can result in reduced crop establishment (Masle and Passioura, 1987). Nasr and Sellers (1995) found the most rapid and complete emergence was achieved with densities <1.2 Mg m^{-3}.

Table 1.1: Typical bulk density and porosity values for selected agricultural soils. (Soffe, 2003)

Bulk Density (Mg m^{-3})	Porosity (%)	Description
0.5 - 0.8	>70	Loose, uncompacted topsoils. Peats and organic soils.
~ 1.0	60-65	Permanent pasture, woodland soils, well structured.
~ 1.5	45	Compacted, root penetration difficult.
~ 2.0	25	Dense, no root growth.

Heavy cultivation equipment or multiple pass management has been linked with severe compaction resulting in high mechanical resistance within soils (Soane et al., 1982; Wu et al., 1997; Alakukku, 1996). Munkholm et al. (2003) identified no till systems severely increased bulk density and resistance of soils over a three year period, due to the passing of drill equipment. Tullberg (1990) estimated over 30% of agricultural soil is damaged by the tyres of machinery even in zero tillage systems.

Ball et al. (1997) found bulk density was 15 % less in soils under conventional and reduced systems than short term zero tillage, but that there was no significant difference between conventional and reduced tillage.

1.2.3.6 Oxygen diffusion

Oxygen diffusion in soil is crucial for seed development and good health in established crops. During germination if insufficient oxygen supply reaches the seed, resulting in anaerobic conditions, this can generate toxic conditions for germinating seedlings (Bradbeer, 1988). Similarly, during wet periods soil can readily become saturated, expelling air from pores, again resulting in anaerobic conditions within a seedbed (Brady & Weil, 1996). This can be detrimental both at germination and once the crop is established. Limiting oxygen supply to roots may damage them permanently thus limiting further plant growth or possibly leading to plant death. Singh and Singh (2003) observed 11 % mortality in seedling under waterlogged conditions during germination. Blackwell and Wells (1983) found that levels of oxygen diffusion rates < 121 ng cm^{-2} min^{-1} resulted in a reduction in root elongation while levels < 7.8 ng cm^{-2} min^{-1} caused root growth to cease. They also noted that reduced oxygen supply resulted in a thickening of root diameter.

1.2.3.7 Aggregate size

The soil aggregate size distribution either directly or indirectly effects establishment, and the development of root systems, through restrictions to aeration and water content within the soil. Murungu et al. (2003) found finer aggregate sizes (<1 mm) generally led to a greater final emergence and better seedling growth, due to increased soil/seed contact, compared with larger aggregates. Less than 4 mm was found to be the optimum aggregate size for establishment by both Nasr and Selles (1995) and Håkansson and Polgàr (1984). Russell (1973) observed that 1-5 mm size aggregates with at least 15 % <250 µm was preferable for establishment, whilst Håkansson et al. (2002) found that at least 50 % aggregates at <5 mm was optimum for establishment and root development.

1.2.3.8 Soil stability and crusting

Soil stability is crucial for a seedbed. Unstable seedbeds in terms of aggregates can lead to surface capping or crusting. Crusts form when soil particles are aligned due to stability breakdown, which results in the reduction of macroporosity and an alignment of homogeneous and less connected macropores parallel to the soil surface (Davies et al., 2001; Rousseva et al., 2002). Crusting can result from a number of factors such as low organic matter content, texture, heavy rain both pre and post cultivation and heavy machinery (Wiseman et al., 1993). Crusting can be severely detrimental, preventing water and air movements in soil and notably in crop germination and emergence if the cap formed before emergence (Rathore et al., 1983; Morrison et al., 1988; Vandervaere et al., 1997; Davies et al., 2001; Awadhwal & Thierstein, 1985). Surface runoff and patchy emergence is also likely as a result of crusting (Robinson & Phillips, 2001). Crust formation is strongly affected by tillage. Usón and Poch (2000) found reduced tillage practices caused thicker and more complex crusting than conventional tillage. Some studies have looked at the possibility of preventing crust formation or increased crusting (such as the addition of gypsum to the soil surface) with some moderate success (van der Watt & Claassens, 1990).

1.2.3.9 Soil organic matter

Soil organic matter plays a vital role in soil stability by binding mineral particles into aggregates (Tisdall and Oades, 1982). Soil organic matter is also a contributor to soil fertility providing sources of nutrients for crops such as nitrogen, phosphorus and sulphur. Intensively farmed soils have, in recent years, become difficult to manage due to falling organic matter contents within the soils (Soffe, 2003). No till management systems have more stable aggregates and increased soil organic matter in comparison to conventional tillage practices (Bronick and Lal, 2005). Similarly, Larney et al. (1997) found 2.2 Mg ha^{-1} less organic matter within conventionally tilled soils compared with less intensive cultivation after a 16 year study.

Soils which suffer long-term degradation under intensive agriculture, due to losses in soil organic matter levels as it is broken down and taken up by soil fauna and flora (Sommerfeldt and Chang, 1985) have severe negative effects on soil organism regeneration abilities, resulting in less developed, finer and weaker aggregates, as well as reduced pore sizes (Kay, 1990). Susceptibility to soil physical degradation is therefore increased allowing for erosion and surface crusting. Watts et al. (2001) observed agricultural soils with high soil quality and SOM should be strong when wet and weak when dry. This allows for the soil to resist structural collapse (i.e. crusting) in wet soil conditions, while weaker soil conditions in the dry allow for reduced soil resistance and improved root penetration and soil workability. However, the loss in organic matter as a result of cultivation can degrade a soil to the point at which it becomes the opposite, strong when dry and weak when wet, resulting in severe structural collapse and increased resistance (Tisdall and Oades 1982; Davies 1985).

1.2.3.10 Crop residue

In 1992, EU legislation (Statutory Instruments No. 1366 – The crop residue (burning) regulations, ISBN 0110343662) banned the burning of crop residues due to environmental damage. Crop residues have a significant effect on the seedbed environment and crop growth. Surface residues interfere with cultivation equipment and seed drills often resulting in poor drill penetration, seed placement and establishment stand (Siemens & Wilkins, 2006). Studies have shown a link between reduced soil seed contact needed for good establishment and surface crop residues resulting in decreased populations (Bordovsky et al., 1998). Surface residue breakdown produces toxins which can also be detrimental to crop growth (Harper, 1985). However, longer coleoptiles have been shown to improve seedling emergence in areas of high surface residue (Rebetzke et al., 2005). In the same study, Rebetzke et al. (2005) also found that high surface residue can result in a delay in 1st leaf emergence within the crop. Large amounts of surface residue increase soil macroporosity in near surface zones (Dao, 1996). Surface residue can also prevent soil crusting by protecting the surface from heavy rain drops as well a reduction of surface evaporation (Awadhwal & Thierstein, 1985; Børresen, 1999).

1.2.4 Effects of seeding on establishment

The development and hindrance to crop establishment is significantly affected by the ability of accurate and sufficient drilling of seeds. Factors such as the date of sowing, seeding rate, previous crop, seed variety and depth of seeding (influenced by the degree and type of cultivation) all contribute to the environment in which a seedling has to develop.

1.2.4.1 Sowing date

Traditionally winter wheat is sown between September and November in the UK, however many studies have shown a direct link with delayed sowing and reduced crop establishment. McLeod et al. (1992) observed plant populations decreased by 40-60 % with a delay from early September to the end of October. Blake et al. (2003), showed establishment decreased from around 70 % in September to early October sowings to 60 % in late October and less then 50 % in November and later. Delayed sowing may be associated with the inability to adequately prepare the seedbed for seeding due to adverse weather conditions such as heavy rainfall. Decreased establishment is also strongly linked with decreasing soil and air temperatures. Establishment decreases rapidly when soil temperatures at 100 mm fall below 8 °C (Blake et al., 2003). An increase in seeding rate is required at later sowing dates to allow for reduced establishment. However, some studies have shown this does not fully compensate yield losses in late seeding (McKenzie et al, 2007).

1.2.4.2 Seeding rate

Seeding rate is the number or weight of seeds drilled per metre square, this is determined by field conditions (i.e. soil type) and the time of year. Establishment percentages drop off rapidly at higher seed rates. Increased seed rates lead to higher competition between plants, thus reducing establishment percentage. Reduced seeding rates allows for greater radiation interception, canopy nitrogen and green area per plant; which results in increased grain number per plant (Whaley et al., 2000). Spink et al. (2000) found optimum seeding rates for winter wheat in September of 62 plants per m^{-2}. However, later sowing dates required higher seeding rates with optimum numbers increasing to 93 and 139 plants per m^{-2} in October and November respectively (Spink et al., 2000). Reduced plant populations are also adept at compensatory responses through increased tillering, particularly wheat, with lower plant density resulting in similar ear numbers (Lithourgidis et al., 2006).

1.2.4.3 Previous cropping

Previous cropping can be beneficial or detrimental to crop growth and establishment. The use of high nutrient capture crops prior to the present crop can result in reduced nutrient availability within the soil (Shepherd & Lord, 1996), which will affect the crop once seed reserves have been exhausted. Previous or continued cropping, of the same species, can also lead to disease pressures from soil borne diseases such as *Gaeumannomyces graminis var. tritici* (take-all), which affects wheat roots. Blake et al. (2003) reported the establishment of wheat following oats was 79%, potatoes, set-aside and peas was 66-72% and wheat, rape and beans was 54-60%. Previous crops can also affect the soil structure such a clover which rapidly enhances the pore space of the soil (Holtham et al., 2007; Papadoupoulos et al., 2006). The equipment used in seedbed preparation and harvest of the previous crop can also have severe impact upon establishment as a result of soil structural damage.

1.2.4.4 Seed variety

The requirements of seeds from a seedbed and the conditions under which they are placed vary between genotypes. Seed varieties are chosen based upon either spring or winter variety, the latest possible sowing date and disease resistance. This is to prevent severe frost damage to crops and diseases etc. more resilient varieties provide the best chance of establishment. Blake et al. (2003) stated that incorrect variety choice may have minimal effect on establishment but equally this may lead to a 10% reduction in establishment.

1.2.4.5 Seeding depth

Sowing depth is critical for seed germination both in terms of distance to soil surface, available nutrients and water content. The depth of sowing is dependent upon seed size and availability of soil water content (Soffe, 2003). In general, sowing aims to be deep enough to ensure good coverage and quick emergence but not sufficiently deep to prevent full shoot penetration to the surface. If seeds are sown too shallow this may prevent adequate water uptake; the smaller the seed, the shallower the sowing due to reduced seed reserves (Soffe, 2003). Seeding depth can be difficult to control and is dependent on the pre-sowing cultivations, if the soil is too unconsolidated this will lead to deep sowing, if too dense then the seeds may not be adequately covered (which may result in loss due to pest damage). Kirby (1993) observed significant decreases in emergence and establishment times with an increase in seeding depth as well as reduced crop stands. The prolonged emergence also has implications toward crop health. Kirby (1993) noted the best establishment in wheat was observed at sowing depths around 68 mm with good establishment occurring in ranges between 23-83 mm. Other studies have suggested 15-40 mm for wheat (Håkansson and Polgár, 1984) and 35-40 mm for barley and oats (Håkansson et al., 2002). Bouaziz and Hicks (1990) identified that a depth of 158 mm could be achieved before failure to emerge would occur in wheat seedlings. Bouaziz and Hicks (1990) further suggest that crop stand was not totally dependent upon seeding depth but also effected by other factors such as seedbed strength / resistance, coleoptile length, soil water content and lack of oxygen.

1.2.5 Cultivation

Cultivation can be performed in many different ways from intensive applications to reduced, and even zero tillage (drilling only). The range of equipment available for these operations is vast e.g. plough, disc, spring tine, power harrow, Cambridge rollers and many more. This section will concentrate on a selection of these apparatus.

1.2.5.1 Effect of cultivation

Cultivation must be performed within the ‘friable range’ of the soil type to avoid damaging the soil i.e. not during or after heavy rainfall, as this would result in compaction and soil smearing. Excessive cultivation can also damage biological activity in soil. Cultivation processes generally have the following effects; loosening, consolidating, breaking, mixing, levelling and inverting. Each of these can have beneficial and detrimental effects upon the seedbed environment for establishment. **Loose** soil is needed for drilling and reduced soil resistance needed for adequate germination, and emergence as well as root penetration. However, loose soil can also result in seeds being drilled too deep and reduced soil contact, preventing 100% emergence and adequate nutrient and water uptake. **Consolidation** is needed in cases where the soil is too loose. However, this can also result in surface and subsoil compaction effects which can prevent emergence and root development. **Breaking** (performed on large dried out clods) is needed for improved soil seed contact but, can also result in surface compaction and ponding. **Mixing** provides a source of nutrients, biological habitats and appropriate fertilizer addition to the soil. However, this can result in increased disease, aeration and reduced soil seed contact. **Levelling** is needed in some crops for harvest requirements and uniform growth but, can result in increased soil strength, resistance and surface ponding. **Inverting,** often performed by ploughing, is needed for the burial of crop residue and increasing soil seed contact. However this can lead to subsoil smearing or slaking resulting in plough pans and solute movement issues.

1.2.5.2 Cultivation equipment

1.2.5.2.1 Plough

The plough comes in a variety of classes. For the purpose of this thesis the term plough refers to a mouldboard plough (Figure 1.3). The plough consists of a series of mouldboards, forward rake points, vertical plates and tail pieces attached via a leg to the coulter frame. The mouldboards are passed through the soil at a depth at of around 300 mm depending upon the speed of cultivation and soil type. The plough inverts the soil while loosening, leaving ridges and furrows across the field. Good ploughing, with level and uniform furrows, can only be achieved if all plough components are aligned parallel to each other (Soffe, 2003).

1.2.5.2.2 Disc harrow

The disc harrow consists of two to four adjustable axles each with a number of concave discs mounted along its length (Figure 1.3). Axles are angled for forwards motion with front axle discs cutting and throwing soil outwards while rear axle discs throw soil inwards (Soffe, 2003). Discs are passed through the soil roughly at around 150 mm depth depending upon speed of cultivation and the soil type. No inversion of the soil takes place, thus a mixing of soil and surface residue occurs. Discs are suited to breaking up large clods.

1.2.5.2.3 Power harrow

Often used as a form of secondary cultivation, power harrows consist of vertical spiked pairs of tines each driven by a series of gears which drives or is driven by adjacent gears which results in neighbouring sets of tines contrarotating (Soffe, 2003). The movement of the tines is faster than the forward motion of the tractor allowing for a pulverising action upon the soil (Figure 1.3). Power harrows produce fine tilth seedbeds which are level and compact. They also do not bring up subsoil or residue, working only at depth of around 120mm.

1.2.5.2.4 Tine

Tined cultivators fall into three groups; deep, medium or shallow working (Davies et al., 2001). Tines can also come in different shapes with different angles from straight to curved and either fixed (rigid) or moving (spring) with front boards or crumblers attached to mounted sections. For the purpose of this thesis only shallow working tines (more specifically the spring tine) are considered as deep and medium tines are often associated with drainage and subsoil work as opposed to seedbed preparation. The spring tine (Figure 1.4) is a curved tine which is able to vibrate (due to its shape) as the machine passes forwards. Usually set at a depth between 100-150mm, although adjustable to the needs of the field or conditions, the spring tine shatters and breaks clods producing a loose soil with smaller clods. The spring tine is also effective at weed removal.

Figure 1.3: Cultivation equipment; Mouldboard plough attached to tractor (a) and soil surface inversion (b); Disc harrow (c) and the cultivation effect upon the soil (d); Power harrow in action (e) and the effect upon the soil surface with uniform compact (f) and level seedbeds (g).

1.2.5.2.5 Drill

Although not technically a cultivation tool, the drill is responsible for seeding of the prepared seedbed. The drill does not perform cultivation but does create soil disturbance at drill depth usually between 20 and 80mm where the soil is firstly pushed aside in a drill channel created by multiple drill shoots which feed from a grain store at a set drilling rate, this is then covered over by rear consolidators immediately behind the seed shoot (Figure 1.4).

1.2.5.2.6 Cambridge roller

Used as consolidators or soil compactors, when the soil is too loose or heavily clodded, post drilling to achieve greater seed-soil contact and or level surfaces. Cambridge rollers are made up of ribbed cast iron wheels on an axle (Figure 1.4), the ribbed point of contact with the soil results in disintegrating and compaction of the soil (Soffe, 2003). Extra weight can be added to the roller if required.

1.2.6 Effect of cultivation on establishment

Cultivation creates a soil structure which enables crop establishment and the growth of crops. However, cultivation can cause issues within the soil environment which are not conducive to crop establishment and growth such as compaction, crusting, ponding, soil degradation and nutrient loss.

Figure 1.4: Cultivation equipment; Spring tine both in action (a) and the effect upon the soil surface(b) and the shape of the forward facing tine with curved spring action (c); Drilling and the effect upon the soil (d) and seeding groves (e & f); Cambridge roller and the compaction / consolidation effects upon the soil (g & h).

1.2.6.1 Compaction

Trafficking by wheeled operations is common to all forms of tillage systems, even zero tillage (Tullberg, 1990). Compaction of the seedbed environment and indeed, at depth, is the result of excessive cultivation, heavy tillage machinery and residual effects of harvest machinery. Kay (1990) also states conventional heavy machinery causes the collapse and loss of macropore structure and the breakdown of aggregation as a result of compacted soil. This has further implications as Pagliai et al. (2003) found decreased porosity caused by tillage was strongly correlated with an increase in soil resistance and decreased hydraulic conductivity. Increased mechanical impedance of the soil either by surface compaction or at depth (subsoil) has a direct influence on plant growth both in terms of emergence, yield and root development (Hassan et al., 2007). Stirzaker et al. (1996) observed decreased root length, diameter and total explored volume with severe increases in soil resistance. Reduction in crop establishment and yield is associated with excessive mechanical impedance (Lipiec et al., 1991). Arvidsson (1998) found a link between soil organic matter in reducing the effects of compaction on barley yield where SOM levels were above 50 g kg^{-1}, however SOM levels below 30 g kg^{-1} did not reduce the effect of compaction resulting in an 11 % decrease in yield. Arvidsson (1998) further states that soils with high organic matter in field conditions are able to counteract some of the negative effects of compaction which emphasises the need for recompaction of loosened soil to attain maximum yield.

Gysi et al. (1999) observed differing responses to soil compaction and reduced soil quality aspects under different water contents of the soil. Wet soil was more susceptible to partial loads, whereas dry soils were more susceptible to compaction under full loads. Therefore, timing of tillage in relation to soil water content and texture is crucial (‘friable range’) (Håkansson and Lipiec, 2000). O’Sullivan (1992) observed under uniaxial compaction, a susceptibility to clod formation as a result of compaction, which would require increased cultivation the following season, suggesting the benefit of reduced ground pressure was essential in particular conditions. Horn et al. (1995) describes the formation of dense platy aggregates as a response to excessive compaction from repeated wheeling which resulted in pronounced horizontal flux of water, and reduced vertical flux, which may cause both severe erosion and impede gas exchange.

Tillage-induced subsoil compaction may be alleviated through the use of periodic chiselling, deep ploughing, the addition of organic matter and the inclusion of deep-rooted crops in crop rotations (Hassan et al., 2007). Hamza and Anderson (2005) suggest other methods of compression prevention or remediation; 1) reduced pressure by decreasing axle load or increased contact area of wheels to the soil; 2) working soils at optimum water content; 3) reduced number of passes of machinery; 4) specific traffic routes within fields – controlled traffic; 5) increasing soil organic matter; 6) removal of soil compaction through deep ripping along with an aggregating agent; 7) crop rotations with strong / deep tap roots; 8) appropriate management for soil / crop systems to resist harmful external stresses. Other approaches of soil protection for excessive degradation include the use of single pass or agricultural machines which carry out multiple operations simultaneously and the use of low-pressure tyres in decreasing soil compaction.

1.2.6.2 Soil degradation and nutrient loss

Cultivation can cause severe nutrient loss through soil degradation as well as erosion by wind and water. Soil degradation affects crop growth and yield as a result of decreased rooting depth, available water and nutrient reserves. In a study of the effects of soil degradation on maize grain yield, Lal and Singh (1998) found a decreased yield of between 14 to 39 % due to soil erosion. The loss of soil minerals or nutrients may also be caused by the removal of crops at harvest (Addiscott and Dexter, 1994). Crops absorb soil nutrients during growth and incorporate them into plant biomass, and thus this nutrient store is lost upon removal of the crop. MacDonald et al. (1989) found 68 % of the nitrogen was recovered within the crop grain in winter wheat.

Soil minerals or nutrients may be lost due to leaching as a result of cultivation. This is caused by runoff, either as a direct result of cultivation, such as plough pan formation resulting in heavy leaching of soil minerals from the soil, or as an indirect effect of cultivation angles and slope. Tillage does not have a direct effect on the precipitation, sorption or desorption mechanisms of soil minerals but cultivation alters the nature and area of soil surfaces within the soil, via which these processes take place (Addiscott and Thomas, 2000). Malo et al. (2005) found significant observable decreases in phosphorous, potassium, pH, total carbon, organic carbon and total nitrogen in an 80 year study of cultivation impacts on soil nutrients compared with non-cultivated soils.

Tillage operations should create a surface roughness and porosity to encourage movement of water into the soil matrix, which will prevent surface runoff and preferential flow removing soil nutrients. Addiscott and Thomas (2000) suggest solutions to nutrient loss caused by tillage with the use of inversion tillage interruptions of minimal tilled soil to reduce run-off risks and applications of secondary tillage to create uniform aggregated seedbeds and increased sorption areas within the soil.

1.2.7 Examination of soil structure

1.2.7.1 Soil structure

As a soil develops, mineral particles of sand, silt and clay mix together with organic matter creating aggregates and soil structure. Soil structure is defined as the degree and type of aggregation and the nature and distribution of pores and pore space (Fitzpatrick, 1986). Soil structure can also be described as the degree of stability in aggregates (Bronick & Lal, 2005). Tillage systems have a major role in the development and maintenance of soil structure by modifying the size, shape and stability of the soil aggregates in the preparation of seedbeds (Soffe, 2003; Carter, 2004). Soil structure is therefore crucial to crop establishment, growth and yield as soil structure is directly associated with many of the soil physical properties of the soil. Gerhardt (1997) states soil structure is the determinate for the accessibility of air, water and nutrients needed for crop growth. Gerhardt (1997) observed that the ease of root and shoot movement through the soil is determined by soil structural arrangement as well as for drainage and the resistance to soil degradation and compaction.

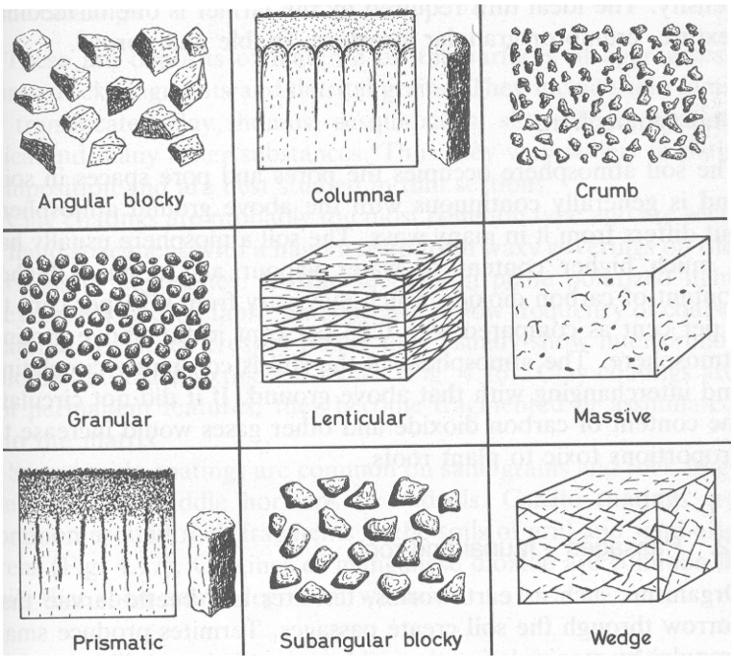


Figure 1.5: Representation of the main soil structure units / aggregates (Figure from Fitzpatrick, 1986).

Soil structure can be characterised by the shape of aggregates; such as blocky, columnar, crumb, granular, massive etc. (Fitzpatrick, 1986) (Figure 1.5); or by their size done in hierarchical order; microstructure (< 2 µm diameter), microaggregates (2-250 µm) and macroaggregates (> 250 µm) (Tisdall and Oades, 1982). Different physical, chemical and biological factors result in the stabilisation of the differing sizes (Dexter, 1988) these being; humic acid and inorganic ions for microstructure, microbial materials such as polysaccharides, hyphal fragments and bacterial cells or colonies in microaggregates, and a combination of plant roots and fungi / fauna in stabilised macroaggregates (Carter et al., 1999; Carter, 2004; Degens, 1997; Lavelle et al., 1997; Schjonning et al., 2002). Structure sizes may also be determined through the combination of lower hierarchical sizes or the fragmentation of higher hierarchical orders (Dexter, 1988) via processes such as wet-dry cycles. Soil texture is also a determining factor in the development of soil structure (aggregation); very sandy soils typically remain loose and unaggregated, clay dominated soils aggregate well, whilst silty or sandy soils form less stable aggregates (Bronick & Lal, 2005; Shepherd, 2002). Dexter (1988) states that for a soil structure to have desirable hydraulic and mechanical properties, and therefore provide adequate medium for crop production, it is necessary for each of the hierarchical structures to be well developed and stable against water and mechanical stress. Favourable soil structure and high aggregate stability are important in improving soil fertility, increasing agronomic productivity, enhancing porosity and decreasing erodability (Bronick & Lal, 2005).

1.2.7.2 Quantification of soil structure

Soil structure until recently was mainly assessed in a qualitative manner through the assessment of size, shape and stability either in the field or using soil thin sections (micromorphology). In recent decades, the use of image analysis to define and quantify soil structure (Ringrose-Voase and Bullock, 1984; Ringrose-Voase, 1987; Ringrose-Voase, 1996; Vogel, 1997; Horgan, 1998; Lipiec et al., 2006) has increased rapidly, in part due to the advances in technology such as digital cameras, higher resolution, faster computers and processors, digital image capturing, higher storage capacity and advances in X-ray Computed Tomography (see section 2.7.3). Improved software and digital image processing procedures have also aided the enhancement in image analysis and the quantification of soil porosity (Murphy et al., 1977; Moran et al., 1989; McBratney et al., 1992; Jogerius, 1972; Terrible & Fitzpatrick, 1992;

Marcelino et al., 2007; Protz & Van den Bygaart, 1998; Ringrose-Voase & Bullock, 1984).

Image analysis of soils provides quantifiable data concerning the pore space (Terrible & Fitzpatrick, 1992; Protz et at., 1992) and has been widely used in a variety of soil assessments such as; biological activities in relation to soil porous architecture (Nunan et al., 2001, 2003; Harris et al., 2002; Lamandé et al., 2003); the movement or distribution of fluids and preferential flows within soil through pore space (Deeks et al., 1999; Mooney, 2004; Morris & Mooney, 2004; Pagliai and Vignozzi, 2003); the assessment of pore connectivity (Vogel, 1997); determination of soil fractal parameters (Pachepsky et al., 1996; Giménez et al., 1997); the effects of tillage applications on the soil environment and possible soil degradation such as compaction (Pagliai et al., 2004; Hubert et al., 2007; VandenBygaart et al., 1999; Douglas & Koppi, 1997; Fox et al., 2004) and agricultural management such as organic farming (Kooistra, 1991; Papadoupoulos et al., 2006) or the effects of structure and crops e.g. cereal lodging (Mooney et al., 2007) and roots (Van Noordwijk et al., 1993; Pagliai & De Nobili, 1993; Bengough et al., 2001). However, Bui (1991) importantly states that accurate and quality image analysis is highly dependent upon the quality and resolution of the initial image acquired and on the contrast achievable in processing.

1.2.7.3 Using X-ray Computed Tomography to examine soil structure

X-ray Computed Tomography (CT) is a non-destructive and non-invasive method that can be used for rapid imaging of soil structure and enable quantitative measurements of the soil pore network (Figure 1.6). After the development of X-ray CT systems in medical sciences based upon principles presented by Houndsfield (1973), the application of the technique to other scientific fields followed with the first results of X-ray CT in soil science reported by Petrovic et al. (1982) who used X-ray CT to assess the relationship between bulk soil density and X-ray attenuation. Hainsworth and Aylmore (1983) followed this by assessing root-related water absorption processes using X-ray CT.

The theory behind the use of X-ray CT has been covered previously in a number of reviews e.g. Van Geet et al., 2000. Simply, a beam of X-ray radiation passes through a sample or material, which then experiences progressive attenuation due to interactions with constituent atoms (Taina et al., 2008). Beam attenuation is the result of three mechanisms; incoherent scatter, coherent scatter and photoelectric absorption (Simons et al., 1997). Incoherent scatter is affected by the density of the material scanning, coherent scatter is the redirection of X-ray photons without loss in energy and photoelectric absorption is the result of photon absorption within an atom and the ejection of an electron (Simons et al, 1997; Taina et al., 2008; Ketcham, 2005). Houndsfield units (HU) describe X-ray attenuation of specific volumes or elements such as solid, mineral, air and water, for example a value of 0 would represent water and air (at standard temperature and pressure) (Taina et al., 2008). X-ray CT projections attained through reconstructions are made of integrations of attenuation coefficients, the most common of these being the filtered back-projection algorithm (Kak and Slaney, 1988). X-ray CT image stacks can be differentiated into their respective densities using segmentation techniques such as image thresholding using histogram attenuations to create binary images which can be quantitatively analysed based upon pixel (2-D) or voxel (3-D) arrangements (Figure 1.6).

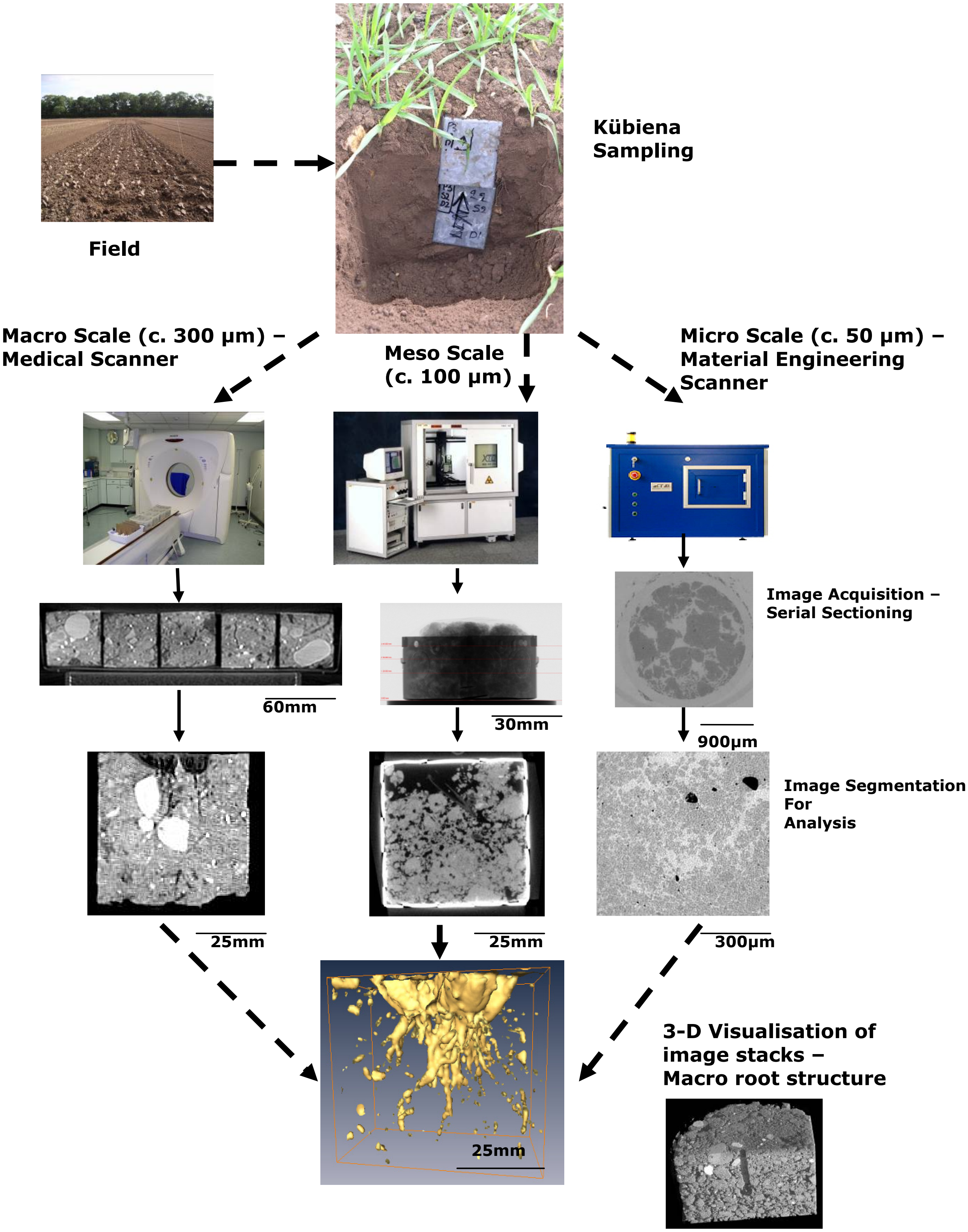


Figure 1.6: X-ray Computed Tomography scales of resolution and image acquisition through to analysis and 3-D visualisation applications for quantifying soil structure.

The use of X-ray CT has allowed soil structural conditions and the subsequent effects of this upon soil function to be assessed both in 2-D and 3-D where previously this would have not been possible, with the exception of thin section or resin impregnated soil. X-ray CT has been performed in many aspects of soil science for example; Perret et al. (1999) used X-ray CT to determine tortuosity, hydraulic radius, numerical density and connectivity of pore networks in undisturbed soil cores and further went on (Perret et al., 2002) to assess macropore size, distribution, length, branching and connectivity from mathematical morphology parameters. Anderson et al. (1992) showed X-ray CT imaging data could be correlated with standard measurements of solute breakthrough but gave a level of detail not previously attained. Heijs et al. (1996) took this a step further assessing preferential flow patterns within soil, determining that macropore networks strongly correlate to flow regimes. Flow regimes using X-ray CT have also be mapped in 3-D. Mooney (2002) quantified water infiltration using repeated scans after an infiltration period, producing a 3-D map of pore space and water movement.

X-ray CT has similarly been used to investigate the biological interactions with soil. Johnson et al. (2004) used X-ray CT to track the movement and final position of a clover root weevil larvae in real time whilst Nunan et al. (2006) investigated the microbial habitat structure within soil using synchrotron X-ray CT. Nunan et al. (2006) was able to resolve 3-D architecture of microaggregates directly relevant to the scales of microorganisms finding that the habitats to which fungi, bacteria and other microbiota live and function is highly heterogeneous. Other studies have focused upon flora effects or more specifically plant roots such as Heeraman et al. (1997) who assessed in-situ plant roots in 3-D, determining plant root length was higher within X-ray CT samples than using conventional destructive measurements, but that fine root detection was highly dependent upon the resolution and noise from the soil matrix. Other non-invasive studies of roots within soil (Gregory et al., 2003; Perret et al., 2007) disagreed with Heeraman et al. (1997) stating that X-ray CT underestimates root length dynamic compared with destructive techniques.

The use of X-ray CT to assess the soil environment has also been widely used within agriculture, for example; Olsen and Børresen (1997) utilised X-ray CT to measure soil properties following cultivation concluding that conventional tillage (ploughing) results in compaction and reduced macroporosity at depth in comparison to reduced tillage. Similar results were also recorded by Langmaack et al. (2002) who found conventional tillage reduced soil porous architecture in terms of total pore length, volume, tortuosity and continuity, compared with conservation tillage. However, increased surface crop residue associated with reduced tillage strategies has been found to significantly increase cracking and porosity near decaying residue (De Gryze et al., 2006) which may account for some of the differences observed by Olsen & Børresen (1997) and Langmaack et al. (2002). In a comparison of no till systems versus conventional farming practice, Gantzer and Anderson (2002) observed conventional tillage had significantly increased measurements of macropore number, area, perimeter, circularity and fractal dimension compared to no till systems. Other studies have shown the effects of soil compaction, as a result of management practices, on soil properties and crops such as Lipiec and Hatano (2003) who reported significant relationships with root growth and solute flow and Mooney et al. (2006) who used X-ray CT to illustrate the effect of soil structure on the propensity of cereal root systems to fail. Mooney et al. (2006) identified that subterranean stem rotation was the major mechanism causing plants to fail and that an increase in surface bulk density post establishment was needed to resist root failure.

1.3 Research aim and objectives

The overall aim of this project was to investigate and quantify the effect of soil physical properties, in particular soil structure, over a period of time, induced by selected cultivation practices (intensive to reduced techniques), on crop growth and establishment. The over arching hypothesis is:

"Soil structure significantly affects crop establishment, growth and ultimately yield?"

To address this question three sub-aims have been developed:

1. To identify the optimum soil physical condition for seed germination and crop growth.

2. To understand the effect of consolidation processes post drilling on the changes to the soil porous architecture.

3. To develop a greater understanding of soil quality produced by cultivation with the aim towards reduced cultivation strategies.

1.4 Thesis structure

Chapter 1 has provided an overview of the subject area covered in this thesis and introduced the rationale behind the research conducted with the research aims and objectives. **Chapter 1A** provides an overview of two preliminary experiments conducted to inform the main investigative chapters. **Chapter 2** assesses the effects of primary, secondary and tertiary cultivation practices on selected soil physical properties of a range of seedbeds as they evolve and develops a model of their effects on crop establishment. This has been published in *Soil and Tillage Research* (Atkinson et al. 2007. **97**: 218-228.) and hence is included in 'paper format'. **Chapter 3** assesses the affects of primary, secondary and tertiary cultivation practices on the soil macro structure using X-ray CT and models the relationships between macro structure, soil physical properties and crop establishment. This research is under review for publication in *Soil and Tillage Research* (Atkinson et al. 2008. XXXXXXX) and is included in 'paper format'. **Chapter 4** assesses the effect of primary, secondary and tertiary cultivation practices upon the meso structure of the soil using resin impregnated soil blocks and image analysis, and models the effects of data from this scale on crop establishment. **Chapter 5** describes the comparison between two soil types and the effects of minimal and secondary cultivation on crop establishment and selected soil physical properties. **Chapter 6** assesses the effect of minimal and secondary cultivation on soil meso structure across two soil types using X-ray CT, and the effect on crop establishment. **Chapter 7** provides a general discussion of the key findings reported within each chapter. **Chapter 8** gives the major conclusions from all of the research conducted.

Chapter 1A: Method Development

This chapter provides an overview of two preliminary experiments conducted prior to the main investigative chapters. These experiments, one glasshouse trial and one small field trial, were designed to perfect the sampling and imaging methodologies and provide an insight into the nature of the root-soil interactions so as to allow informed decisions in the later experimentation. As such they were not designed to provide statistical based conclusions but to guide the design for the field experiments. Experiments helped to determine optimum sampling periods in terms of examining both soil changes and root-soil interactions by looking at the structural deviations and how these changed over the evolution of the plant growth cycle.

1A.1 The effect of soil structure upon establishment (Glasshouse)

The aim of the initial experiment was to determine if manipulated soil structural / quality variations affect the establishment of crops. The investigation included treatments which were: soil texture (loamy sand, sandy loam, clay loam); soil structure (field aggregate size distribution (representation of bulk soil conditions) and fine (< 2mm) aggregates (i.e. large aggregates removed)); soil strength (medium to high, low to medium (defined later)). The experiment was performed in a controlled glasshouse environment.

1A.1.1 Sample Preparation

Soil samples were collected from the topsoil of both the Newport series (loamy sand) and Worcester series (clay loam) at the University of Nottingham experimental farm, Bunny, Nottinghamshire, UK (52.52^{o}N, 1.07^{o}W). A further soil sample was collected from the topsoil of the Dunnington Heath series (sandy loam) at the University of Nottingham experimental farm, Sutton Bonington, Leicestershire, UK (52.5^{o}N, 1.3^{o}W). Samples were prepared in columns 75 mm diameter by 160 mm height; the soil was wetted and maintained at field capacity and then uniformly packed (between 1.0 and 1.5 g cm^{-3} depending on treatment and soil texture) into each column with the desired treatment application. Treatments consisted of soil texture, aggregate variations of <2mm fine and field size distribution and soil strengths, low (0-25 kPa) and medium/high (50-80 kPa) as well as two cereal crops Hordeum *vulgare* - barley (cv. Optic) and Brassica *napus* - oil seed rape (cv. Recital). Each treatment was replicated three times and distributed in a random pattern under a natural light emitter (Figure 1A.1).

Figure 1A.1: Images of packed columns in a random distribution (a). b) Oil seed rape within a clay loam at 28 days post seeding. c) Barley within a clay loam at 28 days post seeding.

Soil strength treatments were produced using a standard soil compaction rammer complying with BS1377 (1975) (2.5 kg of 50 mm diameter and 300 mm drop) and a small disc 8 mm thick. The soil was packed into each column and was then compacted to the desired soil strength by hitting the disc at the surface a calculated number of times (Figure 1A.2). The weight was dropped from a height of 300 mm and was repeated in quick succession when more than one hit was required. Soil strength was then determined with the use of a Pilcon Hand Vane tester 0 – 200 kPa. Compaction to strength ratios were calculated for each soil texture. Soil strengths of 0 – 25 kPa were created from one hit and strengths of 50 – 80 kPa were created from eight hits.

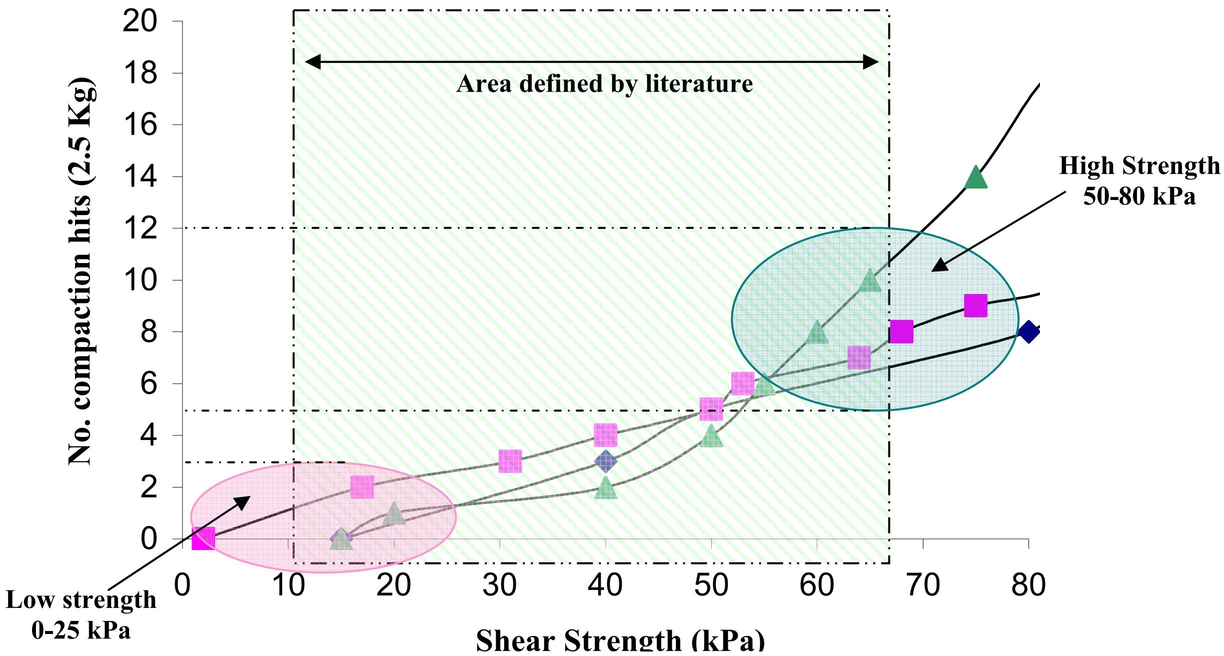


Figure 1A.2: Diagram showing the method of soil shear strength calculation from compaction of the three soil types (clay loam =▲; sandy loam = ■; loamy sand = ◊) used within the glasshouse experiment. Highlighted area shows region of values recorded within literature (Schjønning and Rasmussen, 2000). Circular highlights show regions of high (50-80 kPa) and low (0-25 kPa) soil strength used within this experiment.

Soil volumetric water content was monitored throughout the experiment using a Delta-T theta probe (type ML2X), within one of the three replicates due to the disturbance caused on insertion of the probe, to maintain consistent water contents. Measurements showed clay loam soils volumetric water content of roughly around 40 % water content and the sandy loam and loamy sand at around 30 % water content. Excessive ponding occurred within high strength soils often showing a wet soil surface but dry base. No difference in response to crop was measured in response to water content.

1A.1.2 Sampling

Samples were harvested at growth stages 14 for oil seed rape and 22 for barley due to the speed of germination and growth of the different species. At each harvest measurements of crop development were recorded including fresh weight (weight of freshly cut crop), dry weight (weight after 24 hours at a temperature of 105ºC), main shoot height, number of tillers (barley), number of leaves and the maximum / minimum leaf area. Soil strength was recorded upon harvest using a Pilcon hand vane. Soil cores 52 mm diameter by 70 mm depth were removed from 1 of each replicate and taken from the soil surface. The cores were then impregnated using an epoxy resin mix and photographed under ultra violet light (see chapter 4 sections 4.2.3; 4.2.4 for method details). Images were then processed using the software AnalySIS ®.

1A.1.3 Results

1A.1.3.1 Crop measurements

Differences between the two crop types and the conditions of the soil (Table 1A.1) became apparent almost immediately with excessive ponding occurring within highly compacted soils. Compaction severely hindered emergence of oil seed rape (OSR) increasing the time to germinate and to reach growth stage 14 by c. 7 days (P = 0.004). A slight increase in the time to emergence and development was also seen within the barley although this was not significantly different (c. 2 days). No significant difference in fresh or dry weight was observed within OSR as a result of treatments applied. A soil type and aggregate interactions was observed with field aggregates having higher dry weight within the sandy soils but the opposite within a clay loam with higher dry weights occurring under finer (< 2mm) aggregates. Barley fresh weight and dry weight was significantly affected by soil type (P = 0.002; 0.003) and aggregate size (P = 0.003; 0.028), with higher fresh and dry weights occurring in the clay loam soil and with columns containing field aggregates (Table 1A.1). The sandy loam soil had a slightly higher barley fresh and dry weight compared to the loamy sand. Main shoot height and the number of leaves of both crop species was not significantly affected by soil treatments and was roughly c. 40 cm with c. 7 leaves within the barley and c.13 cm and c. 4 leaves within the OSR (Table 1A.1). Leaf area within the barley was significantly affected by soil type, aggregate size and soil strength, with the smallest leaf area occurring within the loamy sand (P <0.001), finer aggregates (P = 0.004) and high soil strength (P = 0.012) and the largest leaf area occurring within the clay loam (P < 0.001), field aggregates

Table 1A.1: Mean crop variation as a result of treatment conditions. OSR = oil seed rape. Bulk = field aggregates representing bulk soil condition. Fine = sieved soil < 2 mm in diameter with large aggregates removed.

Experimental Design				Fresh Weight (g)	s.e.d	Dry Weight (g)	s.e.d	Height Main Shoot (cm)	s.e.d	No.Tillers	s.e.d	No.of Leaves	s.e.d	Max. Leaf Area (mm^2)	s.e.d	Min. Leaf Area (mm^2)	s.e.d
Clay Loam	Barley	Bulk	High Strength	4.72	0.99	0.80	0.23	45.30	2.48	2	0	8	1	157.45	7.02	35.73	2.43
			Low Strength	5.53	0.58	0.98	0.08	49.67	1.20	2	1	8	1	200.11	31.97	41.31	6.43
		Fine (< 2mm)	High Strength	2.84	1.79	0.54	0.45	43.17	12.60	2	0	7	1	96.23	51.24	23.61	10.33
			Low Strength	3.72	0.96	0.61	0.23	44.27	7.97	2	1	7	1	136.53	24.12	33.87	1.74
	OSR	Bulk	High Strength	3.28	0.39	0.43	0.09	12.70	2.17	0	0	4	1	102.32	13.21	8.89	1.38
			Low Strength	3.06	0.20	0.32	0.05	12.70	1.77	0	0	4	0	92.42	0.97	7.76	0.07
		Fine (< 2mm)	High Strength	3.31	0.96	0.72	0.37	12.47	2.29	0	0	4	0	85.25	20.02	7.63	1.21
			Low Strength	3.37	1.12	0.63	0.42	13.37	1.75	0	0	4	0	82.53	21.50	7.52	1.32
Loamy Sand	Barley	Bulk	High Strength	4.00	1.31	0.64	0.44	48.90	8.17	2	0	8	1	87.16	17.37	24.07	3.69
			Low Strength	2.73	1.00	0.35	0.22	38.60	3.50	2	1	7	1	92.32	34.93	24.37	5.87
		Fine (< 2mm)	High Strength	1.93	0.48	0.14	0.13	35.57	5.15	2	0	7	1	68.11	12.68	20.53	3.61
			Low Strength	2.06	0.52	0.16	0.04	35.00	4.43	2	0	7	1	76.74	18.57	22.86	2.26
	OSR	Bulk	High Strength	3.44	0.54	0.50	0.06	13.10	0.85	0	0	5	1	94.58	18.22	8.61	1.06
			Low Strength	2.87	1.16	0.33	0.15	12.87	4.03	0	0	4	1	88.99	35.44	8.17	2.03
		Fine (< 2mm)	High Strength	3.29	0.12	0.53	0.23	12.77	2.10	0	0	4	1	87.98	9.43	7.99	0.93
			Low Strength	2.39	0.76	0.24	0.13	11.47	3.54	0	0	4	1	68.21	20.46	6.97	0.89
Sandy Loam	Barley	Bulk	High Strength	3.18	0.44	0.43	0.13	39.93	4.71	2	0	8	1	105.66	5.63	28.42	3.21
			Low Strength	2.78	0.75	0.33	0.25	40.23	6.90	2	0	7	1	94.13	27.58	25.82	6.04
		Fine (< 2mm)	High Strength	2.80	1.39	0.39	0.56	44.07	11.23	2	0	7	2	65.98	12.34	19.17	0.88
			Low Strength	3.02	0.27	0.35	0.18	36.27	2.25	2	0	8	0	112.02	7.81	29.33	1.40
	OSR	Bulk	High Strength	4.06	0.89	0.59	0.26	14.90	1.61	0	0	4	1	116.66	5.53	9.43	0.29
			Low Strength	3.45	0.18	0.44	0.03	14.23	1.90	0	0	4	0	99.85	10.61	8.36	0.62
		Fine (< 2mm)	High Strength	3.38	0.72	0.38	0.11	13.30	1.84	0	0	4	0	98.79	22.07	8.17	1.09
			Low Strength	3.46	0.48	0.47	0.14	13.73	1.84	0	0	4	0	103.07	14.50	8.48	0.45

(*P* = 0.001) and low soil strength (*P* = 0.014) conditions (Table 1A.1). OSR was affected differently to barley with the smallest leaf area occurring as a result of finer aggregates (*P* = 0.049) and the largest leaf area as a result of soil type (*P* = 0.040) in particular sandy loam then clay loam and finally loamy sand (Table 1A.1). Soil strength increased by harvest in all treatments, especially under the OSR crop which suggests barley roots perhaps reduce the effect of compaction increase over time whilst OSR does not (Figure 1A.3).

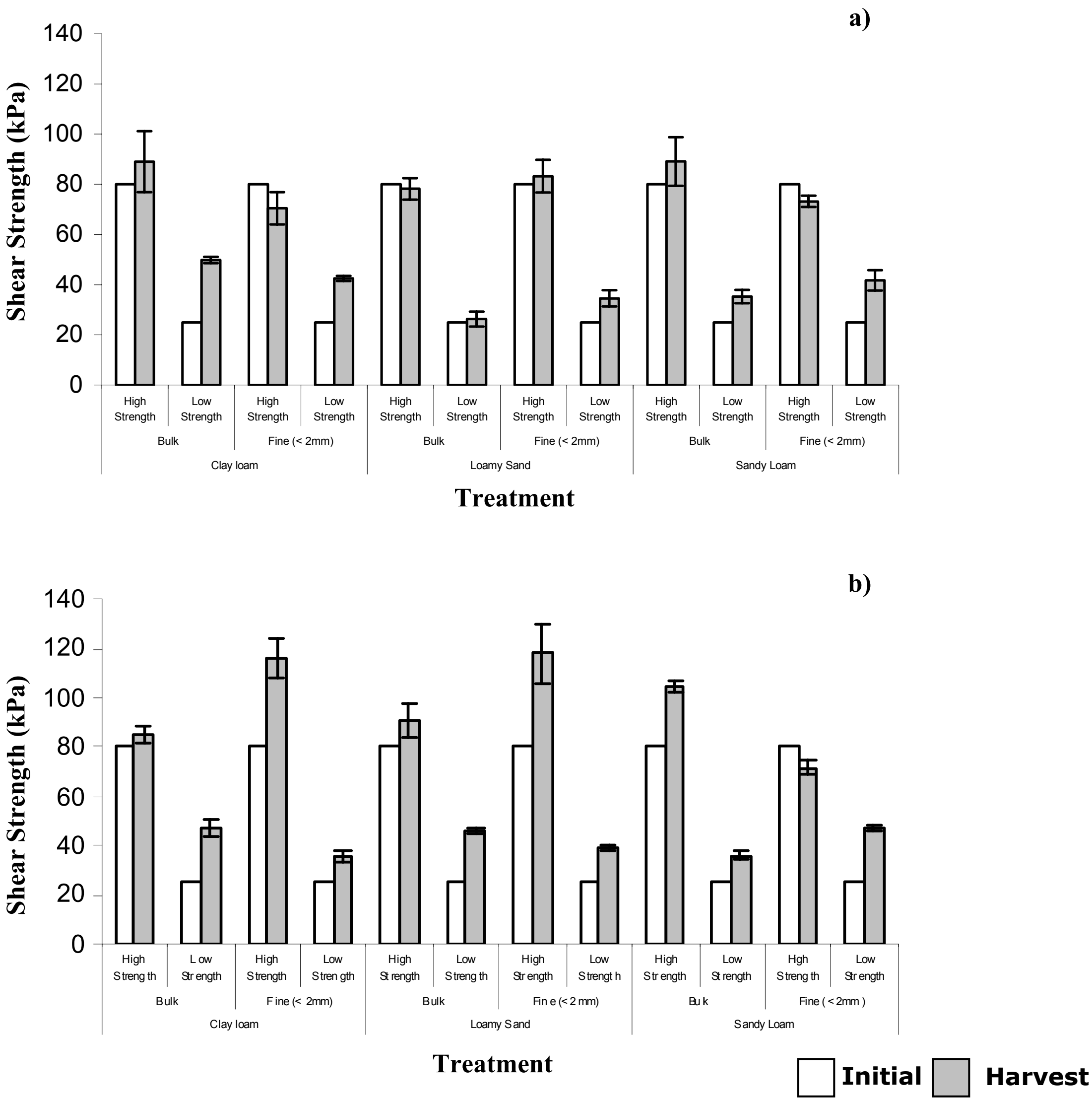


Figure 1A.3: Shear strength condition changes over time in response to crop a) barley and b) oil seed rape.

1A.1.3.2 Soil structure

Quantified soil structure from image analysis (Figure 1A.4) showed significantly different responses from the different soil textures ($P < 0.001$) with the clay loam having generally higher porosity and structural conditions (c. 12 %) than the sandy soils (c. 10 %). Soil type and aggregates similarly affected the pore space with generally higher pore space associated with field aggregates in all soils except loamy sand which had greater pore space under finer aggregates (due to loamy sand aggregating poorly). Lower soil strength resulted in greater pore space, whilst high strength was responsible for increased pore elongation and nearest neighbour distances (defined in chapter 4 section 4.2.5). Due to the experimental design it was not appropriate to statistically measure the interaction between crop and soil, however it can be seen from Figure 1A.5 that the addition of crops to the soil increased (in most cases) soil porosity under high strength soils (perhaps due to un-differentiation between air and root material), whilst in low soil strength either through soil collapse or the aggregation of soil by plant root material a reduction in porosity was observed, these relationships also varied between soil texture.

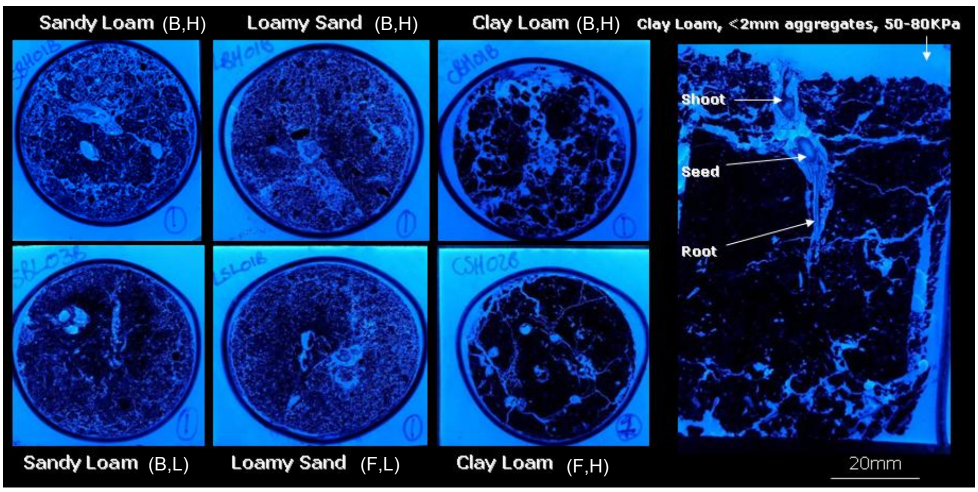


Figure 1A.4: Image selection of barley cores and soil texture / structure differences. B = field aggregates; F = < 2mm aggregates; H = high strength (50-80 kPa); L = low strength (0-25 kPa).

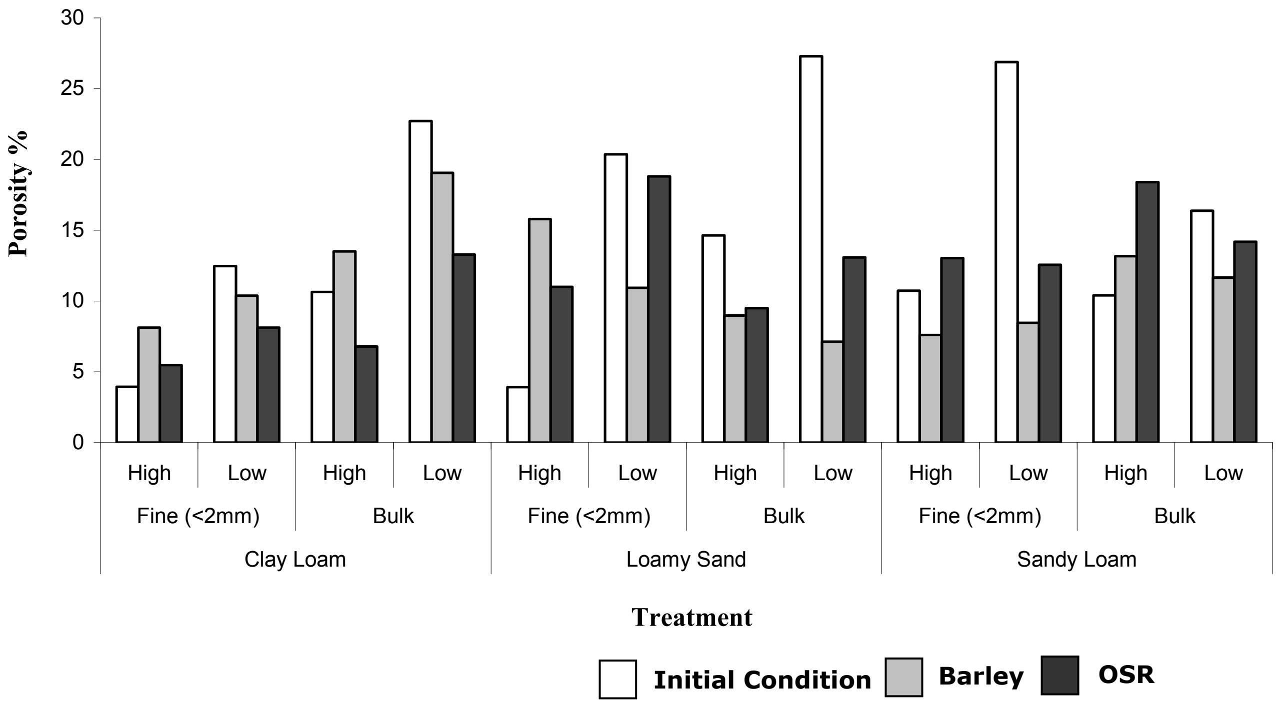


Figure 1A.5: Porosity variation between treatment and crop type. High = High strength (50-8 kPa); Low = Low strength (0-25 kPa); Fine = < 2mm aggregates; Bulk = Field aggregates representative of bulk soil condition.

1A.1.4 Summary

- ❖ Crop development response and establishment can be limited by the physical condition of the soil. Links with soil structure were established both in response to crops and in the establishment of crops in terms of porosity and structural behaviour of the soil.

- ❖ Aggregate size and soil strength play an important role in the establishment and development of the two crops used in this experiment. Low soil strength was preferable for small seeds such as OSR, while high strength was a hindrance to both but to a lesser extent in barley. Field (un-sieved) aggregates opposed to finer (< 2 mm sieved) aggregates provided the most suitable environment for establishment, perhaps due to advantages in the soil structural environment as a result of variation in storage, flow and ease of movement for nutrients, water and roots.

- Soil texture can be a limiting factor on the speed of germination and crop establishment / development, which was fastest within the clay loam soil. This may be related to nutrient availability within the soil, and or water/heat retention (both relating to structural arrangement in relationship to soil-seed contact).

1A.2 Barley establishment under four spring cultivations (Field Trial)

A small scale field trial experiment designed to introduce field sampling techniques and small scale management practices in the preparation of seedbeds and establishment was set up in March 2005. The field trial was sown with spring barley (optic). The aim of this investigation was to examine the effect of a small range of cultivation techniques in the preparation of a spring seedbed and monitor the evolution of the seedbeds both physically and structurally.

1A.2.1 Field site and experimental design

A field experiment was established at the University of Nottingham experimental farm, Sutton Bonington, Leicestershire, UK (52.5^{o}N, 1.3^{o}W). The soil was a sandy loam of the Dunnington Heath series (FAO class; Stagno-Gleyic Luvisol) (Table 1A.2). (As used in the previous glasshouse trial)

Table 1A.2: Selected soil properties of the Dunnington Heath (FAO class: Stagno-Gleyic Luvisol).

**Percentage on a mass basis, measured using hydrometer method (Rowell, 1994).*

FAO Class	Sand (>50 µm) (%)*	Silt (2-50 µm) (%)*	Clay (<2 µm) (%)*	Saturated hydraulic Conductivity (cm s^{-1})	Bulk Density (g cm^{-3})	Organic Matter (%)	pH
Stagno-Gleyic Luvisol (Dunnington Heath)	66.4	18.0	15.6	1.86×10^{-3}	1.51	4.88	6.47

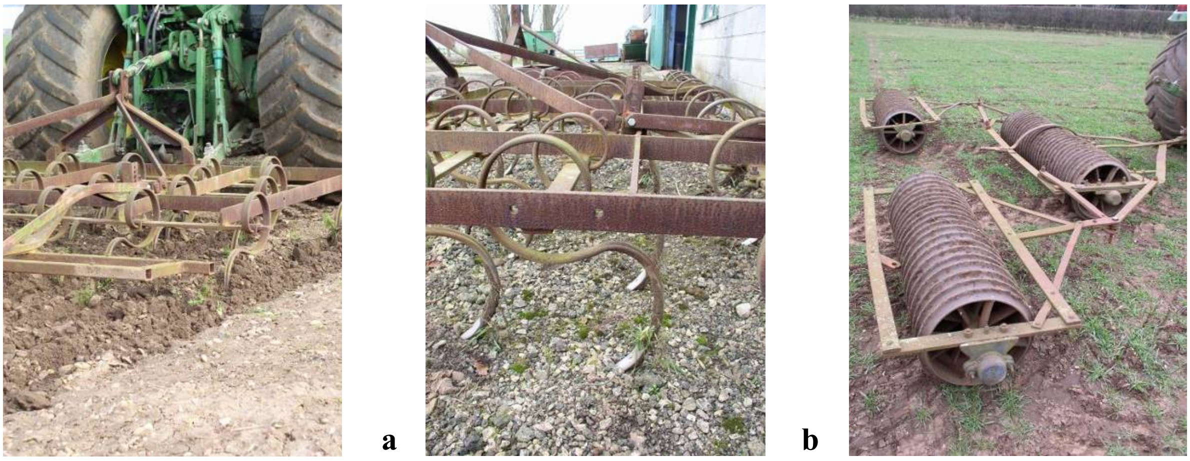
The site had received winter cultivation ready for spring drilling; this consisted of ploughing to 25cm, power harrowing to 12cm and rolling at surface. The beds were left to age over the winter months and further cultivations were performed in early March. These were an unaltered soil directly drilled from its wintered condition, spring tine (to break-up surface crusting) (Figure 1A.6) to a depth of 15-18cm and then drilled, and then finally the same combinations with post drill rolling (Figure 1A.6) giving a total of four seedbeds; 12m by 12m in size with 2m centres for trafficking (total cultivated area assessed 10m by 10m per treatment). No replicate plots were used in this initial experiment.

Treatment 1 – Wintered (W)

Treatment 2 – Wintered + Rolled (WR)

Treatment 3 – Spring Tine + Rolled (STR)

Treatment 4 – Spring Tine (ST)



a b c

Figure 1A.6: Spring tine cultivation in the creating of a seedbed (a) & tine shape (b) and rolling equipment (c) used in the preparation of the spring seedbeds.

Four sampling regimes informed from the previous experiment and included; before cultivation, after further cultivation and drilling, emergence and establishment (totalling four destructive sampling periods) or roughly equal to four week / monthly periods. This allowed for quantitative analysis of the variation and effects of the cultivation techniques, drilling and establishment upon soil structure and the soil structural affects upon root growth, establishment and yield. Sampling consisted of both destructive soil cores (3 x 0-80 mm and 1 x 80-160 mm depths) and bulk density samples as well as non-destructive methods (recording in field measurements of soil volumetric water content, soil strength, and penetration resistance) (see chapter 2 for detail concerning soil physical property measurement). Establishment/yield estimates were calculated from grid counts performed every five days from five grids per treatment in a random placement; this was performed on an undisturbed division of each plot, non-destructive measurements were also recorded at this period. Soil cores were impregnated using an epoxy resin (see chapter 4 section 4.2.3 for detailed method) and scanned using a Philips Mx8000 IDT whole-body X-ray Computed Tomography (CT) scanner (see chapter 3 section 3.3.4 for method detail).

1A.2.2 Results

1A.2.2.1 Seedbed physical condition

Spring tined application resulted in soil loosening reducing the soil penetration resistance (Figure 1A.7), shear strength and soil bulk density (Table 1A.3). Wintered treatments were harder than spring tined but did not appear to differ with an application of rolling with similar responses in strength, water and establishment (Table 1A.3). Rolled application within spring tined treatments resulted in an increase in soil strength (but reduced overall compared with wintered until establishment). Volumetric water contents within the soil did not deviate between wintered and rolled treatments but was reduced within spring tined (Table 1A.3). Establishment as a result of seedbed preparation showed dramatic increases in crop establishment when a spring tine was applied compared with wintered applications. This was again improved with the addition of rolling post drilling within spring tined application (Table 1A.3).

1A.2.2.2 Seedbed macro structure

Seedbed macro structure was determined from X-ray CT of impregnated soil cores at a resolution of 586 µm pixel^{-1} in time sequences (Figure 1A.8). Soil macro porosity at the surface (0 – 80 mm) was roughly equal prior to cultivation in all seedbeds c. 5.5 % (Figure 1A.9). Tillage in all treatments increased porosity although this was much reduced within the wintered treatments (c. 8 %) compared with a large increase in porosity within the spring tined treatments (c. 13 %) (the larger increase associated with spring tined and rolled) (Figure 1A.9).

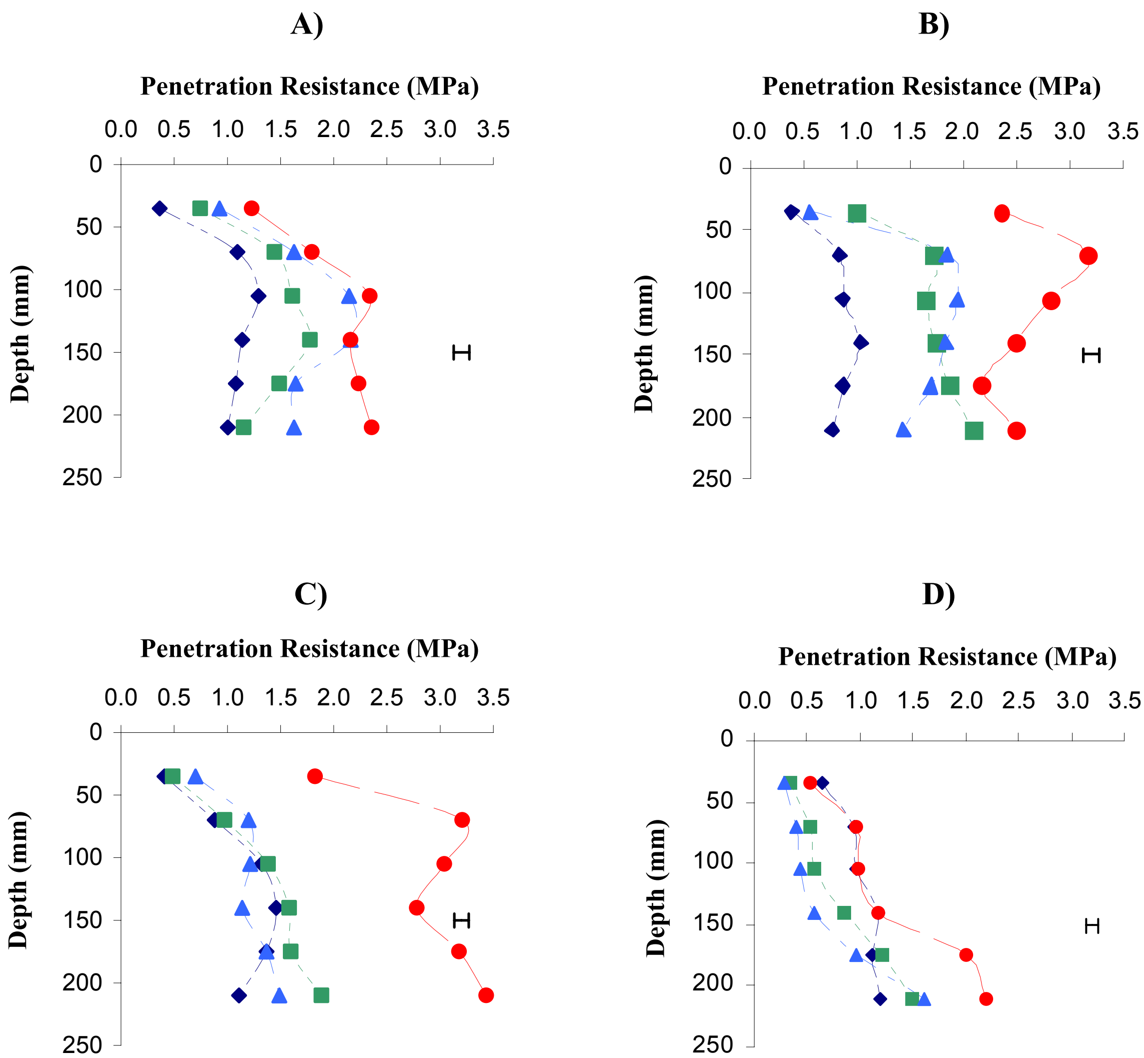


Figure 1A.7: Penetration resistance variation over the evolution of the seedbeds (prior to cultivation = ◊; after cultivation = ■; emergence = ▲; establishment = ●). A) wintered, B) wintered and rolled, C) spring tine and rolled and D) spring tine. Error bar depicts s.e.d.

Table 1A.3: Seedbed evolution and the effect of cultivation.

(W)	**Growth Stage**			
Physical Measurement	Prior to Cultivation	After Cultivation	Emergence	Establishment
Bulk Density (g $cm^{-3)}$	1.18 (± 0.03)	1.16 (± 0.03)	1.11 (± 0.01)	1.27 (± 0.05)
Shear Strength (KPa)	43.8 (± 10)	74 (± 7.5)	94.8 (± 4)	116.8 (± 7)
Water Content ($m^3m^{-3)}$	0.38 (± 0.02)	0.23 (± 0.02)	0.25 (± 0.01)	0.17 (± 0.01)
Establishment Counts (final)				15 (± 3)

(WR)	**Growth Stage**			
Physical Measurement	Prior to Cultivation	After Cultivation	Emergence	Establishment
Bulk Density (g $cm^{-3)}$	1.09 (± 0.13)	1.16 (± 0.05)	1.14 (± 0.06)	1.22 (± 0.01)
Shear Strength (KPa)	42.8 (± 2)	70.2 (± 3.5)	83.6 (± 7.5)	115.6 (± 2)
Water Content ($m^3m^{-3)}$	0.38 (± 0.01)	0.26 (± 0.02)	0.24 (± 0.02)	0.11 (± 0.02)
Establishment Counts (final)				14 (± 4)

(STR)	**Growth Stage**			
Physical Measurement	Prior to Cultivation	After Cultivation	Emergence	Establishment
Bulk Density (g $cm^{-3)}$	1.27 (± 0.05)	1.15 (± 0.02)	1.21 (± 0.04)	1.10 (± 0.06)
Shear Strength (KPa)	48.2 (± 3)	31.6 (± 3)	50.8 (± 4.5)	115.8 (± 8)
Water Content ($m^3m^{-3)}$	0.34 (± 0.04)	0.21 (± 0.01)	0.18 (± 0.03)	0.10 (± 0.01)
Establishment Counts (final)				67 (± 3)

(ST)	**Growth Stage**			
Physical Measurement	Prior to Cultivation	After Cultivation	Emergence	Establishment
Bulk Density (g $cm^{-3)}$	1.05 (± 0.01)	1.10 (± 0.03)	1.10 (± 0.07)	1.10 (± 0.12)
Shear Strength (KPa)	49.4 (± 3.5)	11.2 (± 1)	18.6 (± 2)	48.2 (± 9)
Water Content ($m^3m^{-3)}$	0.33 (± 0.01)	0.15 (± 0.02)	0.05 (± 0.02)	0.07 (± 0.01)
Establishment Counts (final)				57 (± 3.5)

Porosity within the treatments remained roughly at these levels throughout the experiment but with a gradual increases of c. 4 % within the wintered and rolled treatment and c. 3 % in both spring tined treatments (Figure 1A.9). Porosity at depth (80 – 160 mm) was generally higher overall with c. 10 % prior to cultivation, this remained within the wintered treatments but the use of spring tine created an increase in macro porosity at depth from around 10 % to between 18-20 % (Figure 1A.9). This remained high throughout the experiment, but was overall lower within spring tined and rolled compared with spring tined alone. Similar results were also observed in pore size (Figure 1A.10).

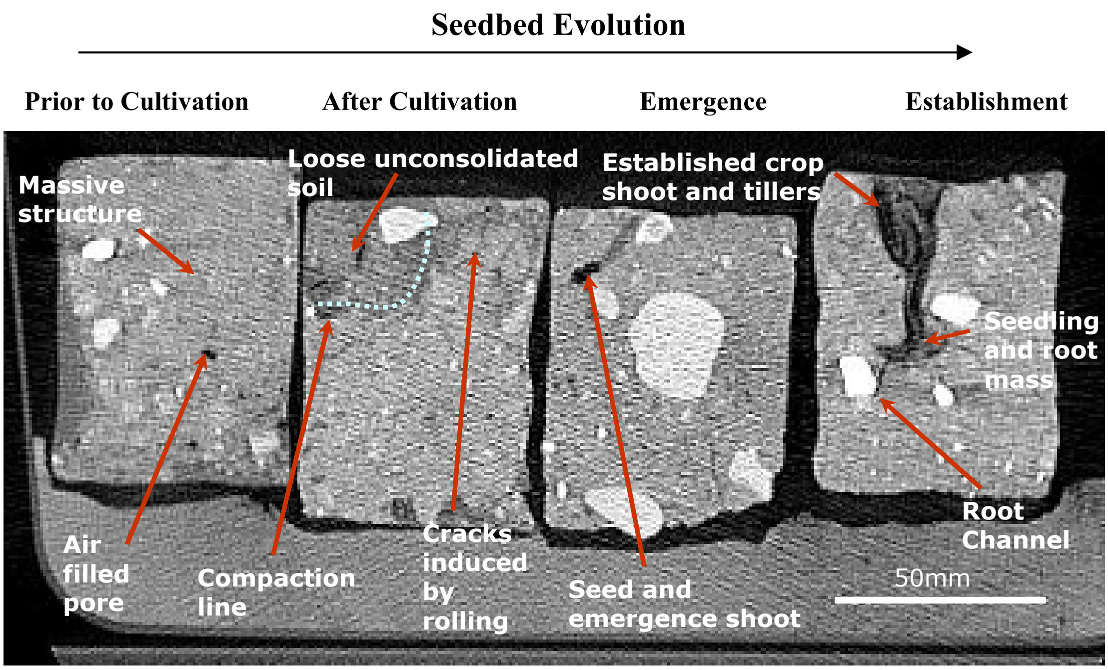


Figure 1A.8: An example of macro CT scan showing the evolution in seedbed soil structure of a spring tine and rolled treatment from prior to cultivation (left) through to establishment (right).

1A.2.2.3 Seedbed meso structure

Seedbed meso structure was determined from impregnated soil cores and imaging under ultra violet light at a resolution of 66 µm pixel^{-1} and processed using image analysis software to provide quantified soil structural data (Figure 1A.11). Soil porosity at both depths was consistent with the effects observed within macro structural analyses with the exception of increased overall porosity due to improved resolution of finer pore space (Table 1A.4). Average pore size as a result was also reduced due to higher numbers of finer pores, but also remained consistent with the cultivation effects observed in macro structure (Table 1A.4).

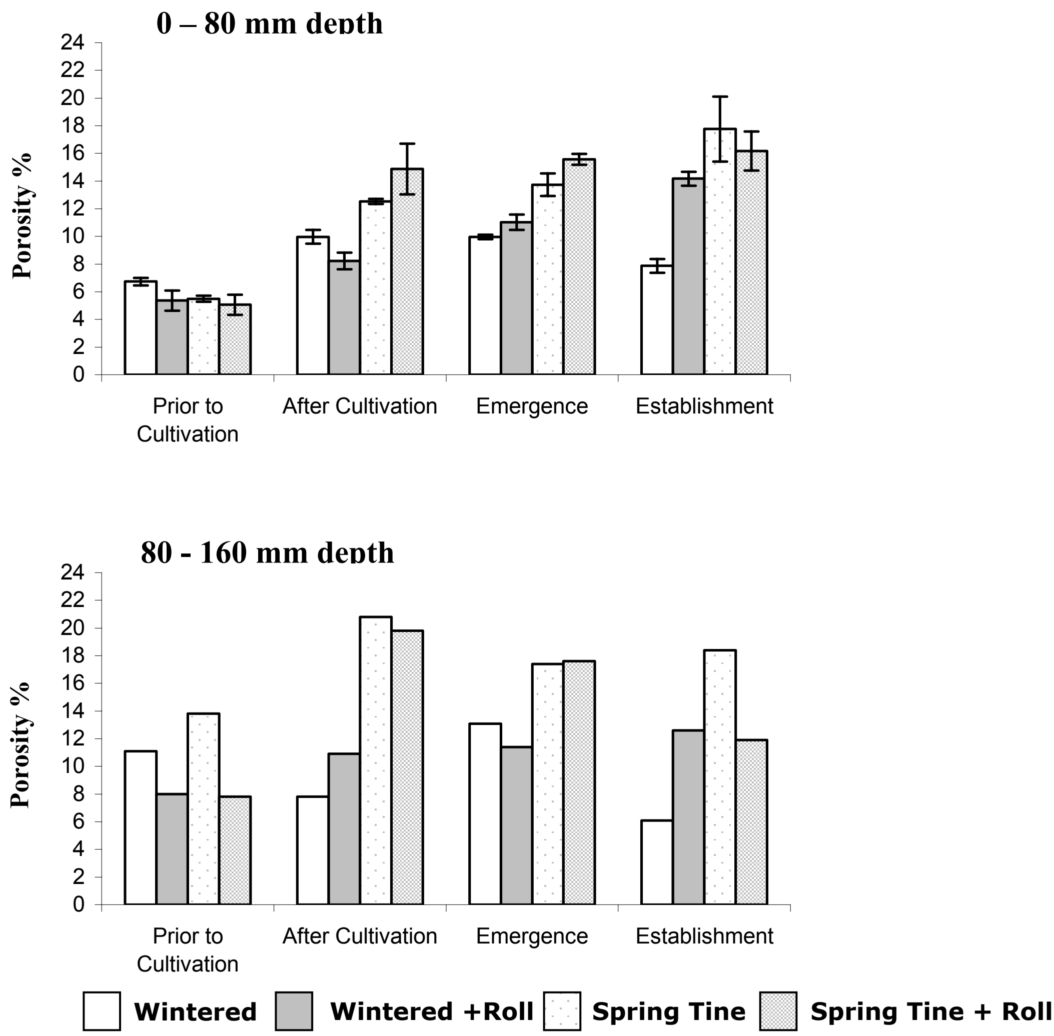


Figure 1A.9: Macro porosity variation over time as a result of cultivation differences. (80-160 mm no error bar as unreplicated)

The pore shape and distribution of pores was also measured at this scale showing overall larger diameter pores within wintered treatments but increased sphericity compared with spring tined treatments which showed greater pore elongation (Table 1A.4). The distribution of pores within the soil also showed a reduction in the nearest neighbour distance as a result of spring tine cultivations showing an increase in the number of finer pores created by this cultivation, this was slightly increased again with the addition of rolling (Table 1A.4). This was also true of pore perimeter, which also showed a reduction in pore perimeter in treatments which were rolled (Table 1A.4).

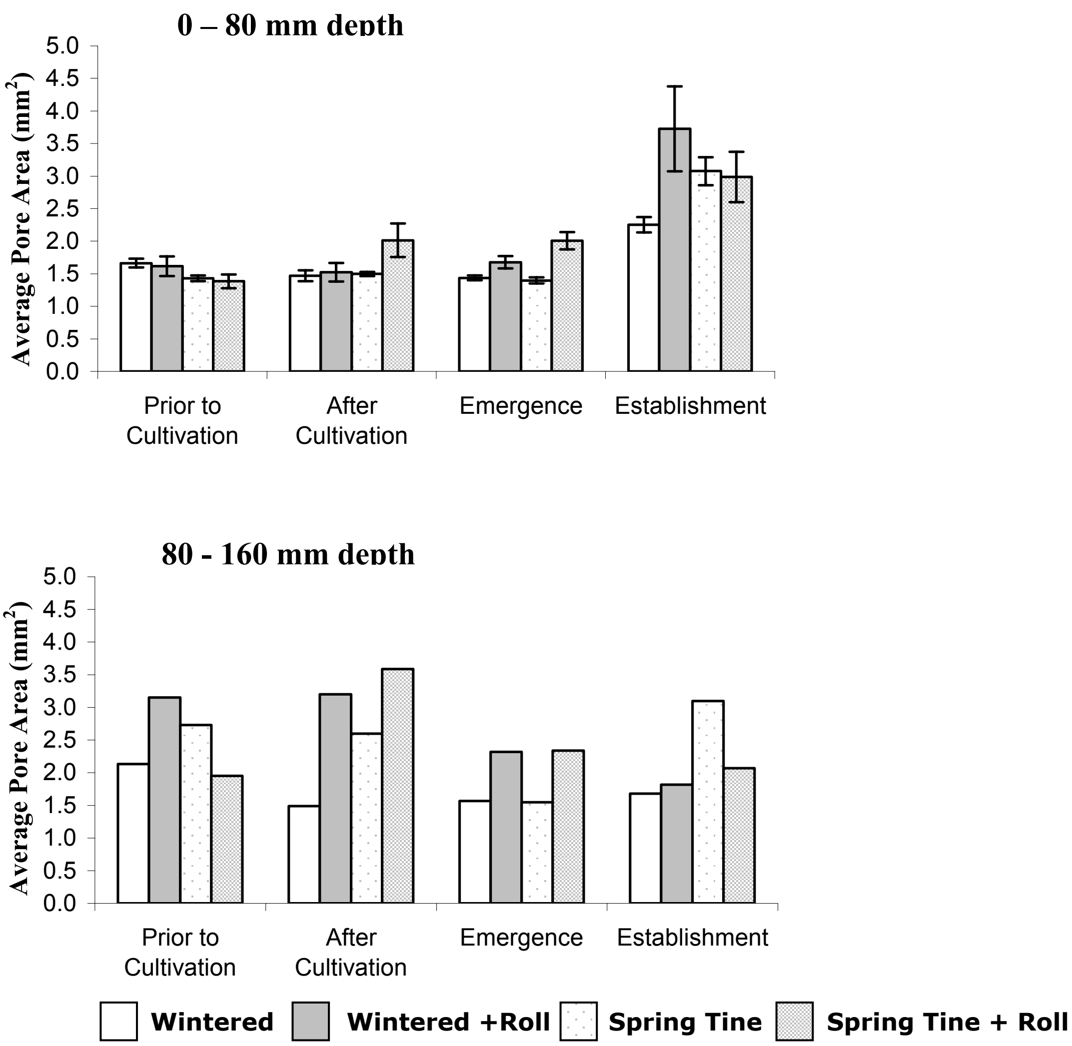


Figure 1A.10: Macro pore area variation over time as a result of cultivation differences. (80-160 mm no error bar as unreplicated)

Table 1A.4: Mean variation in meso structure between cultivation treatments at 0 – 80 mm depth.

Porosity %

	Wintered	s.e.d	Wintered + Rolled	s.e.d	Spring Tine	s.e.d	Spring Tine + Rolled	s.e.d
Prior to Cultivation	26.4	2.720	16.5	2.450	22.4	1.520	18.2	4.120
After Cultivation	24.4	1.790	20.0	1.820	38.5	1.140	23.9	1.090
Emergence	22.6	3.660	20.8	3.150	29.0	0.100	19.8	0.650
Establishment	26.5	1.730	20.4	2.640	26.6	2.720	24.7	0.650

Area (mm^2)

	Wintered	s.e.d	Wintered + Rolled	s.e.d	Spring Tine	s.e.d	Spring Tine + Rolled	s.e.d
Prior to Cultivation	0.33	0.078	0.27	0.041	0.25	0.010	0.23	0.075
After Cultivation	0.34	0.055	0.32	0.078	0.44	0.021	0.26	0.060
Emergence	0.23	0.021	0.19	0.045	0.19	0.014	0.13	0.024
Establishment	0.20	0.030	0.16	0.014	0.15	0.017	0.17	0.014

ECD (mm)

	Wintered	s.e.d	Wintered + Rolled	s.e.d	Spring Tine	s.e.d	Spring Tine + Rolled	s.e.d
Prior to Cultivation	0.33	0.011	0.26	0.033	0.28	0.021	0.26	0.026
After Cultivation	0.31	0.024	0.30	0.017	0.25	0.009	0.26	0.014
Emergence	0.26	0.020	0.24	0.034	0.28	0.009	0.23	0.026
Establishment	0.25	0.002	0.23	0.005	0.24	0.004	0.23	0.023

Elongation

	Wintered	s.e.d	Wintered + Rolled	s.e.d	Spring Tine	s.e.d	Spring Tine + Rolled	s.e.d
Prior to Cultivation	1.74	0.032	1.65	0.092	1.66	0.043	1.59	0.065
After Cultivation	1.74	0.022	1.76	0.018	1.66	0.022	1.70	0.031
Emergence	1.65	0.049	1.66	0.087	1.78	0.009	1.59	0.048
Establishment	1.71	0.021	1.62	0.041	1.74	0.013	1.65	0.057

Sphericity

	Wintered	s.e.d	Wintered + Rolled	s.e.d	Spring Tine	s.e.d	Spring Tine + Rolled	s.e.d
Prior to Cultivation	0.29	0.012	0.27	0.008	0.28	0.003	0.29	0.007
After Cultivation	0.27	0.010	0.29	0.003	0.28	0.006	0.28	0.005
Emergence	0.28	0.012	0.27	0.010	0.26	0.001	0.30	0.011
Establishment	0.27	0.016	0.28	0.008	0.27	0.002	0.28	0.003

Nearest Neighbour Distance (mm)

	Wintered	s.e.d	Wintered + Rolled	s.e.d	Spring Tine	s.e.d	Spring Tine + Rolled	s.e.d
Prior to Cultivation	0.55	0.022	0.58	0.032	0.51	0.020	0.53	0.005
After Cultivation	0.55	0.043	0.57	0.027	0.48	0.005	0.50	0.030
Emergence	0.49	0.013	0.45	0.043	0.42	0.012	0.42	0.036
Establishment	0.42	0.009	0.43	0.030	0.40	0.003	0.42	0.025

Perimeter (mm)

	Wintered	s.e.d	Wintered + Rolled	s.e.d	Spring Tine	s.e.d	Spring Tine + Rolled	s.e.d
Prior to Cultivation	2.32	0.191	1.80	0.333	2.03	0.095	1.95	0.568
After Cultivation	2.19	0.038	2.31	0.326	3.52	0.237	2.01	0.270
Emergence	2.11	0.263	1.86	0.396	2.13	0.070	1.30	0.128
Establishment	1.88	0.193	1.76	0.053	1.61	0.158	1.71	0.095

Spring Tine Wintered

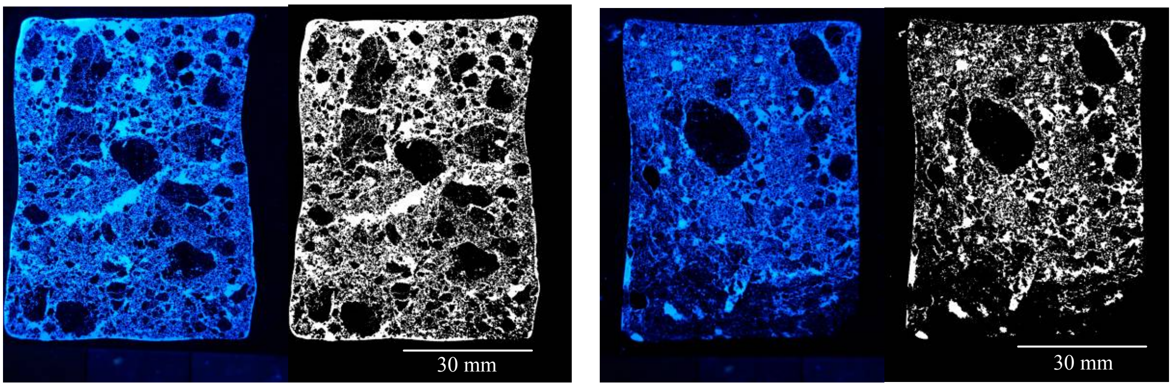


Figure 1A.11: Imaging and binary quantification of impregnated soil blocks after cultivation. left: spring tine treatment. right: wintered treatment. White = pore space.

1A.2.3 Summary conclusion

- ❖ Soil structural visualisation was an effective tool for the assessment of structural changes induced by cultivation technique and provided previously undefined data on the environment under which crop establishment must occur as a result of management techniques applied.

- ❖ Soil porosity was significantly increased under spring tined treatments, accounting for the greater loosening of the soil. This was then reduced under rolling accounting for the consolidation affect of rolling.

- ❖ Soil structure properties (i.e. porosity) at the surface were reduced compared to at depth within the wintered treatments. This was mostly uniform within spring tined treatments. Cultivation therefore will affect the seedbed behaviour as a result of structural change both at surface and at shallow depth i.e. 0 – 160 mm, therefore the need for shallow surface depth sampling is not required as this is not dissimilar to a depth of 0 – 80 mm.

- ❖ Wintered conditions were not conducive to crop establishment due to hard seedbed structures, pertaining to reduced porosity and high soil strength. Therefore a need for cultivation at this period appears to be prudent for adequate seed drilling and optimum seedbed conditions for establishment.

Chapter 2:

Using selected soil physical properties of seedbeds to predict crop establishment

This chapter assesses the effect of primary, secondary and tertiary cultivation practices on selected soil physical properties of a range of seedbeds as they evolve and develops a model of their effects on crop establishment. This chapter has been published in *Soil and Tillage Research* (Atkinson et al. 2007. **97**: 218-228) as such it is included in published 'paper format'.

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Using selected soil physical properties of seedbeds to predict crop establishment

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Abstract

Seedbed preparation can involve a wide range of tillage methods from intensive to reduced cultivation systems. The state or quality of the soil to which these tillage methods are applied for cereal crop management is not easily determined and excessive cultivations are often used. Seedbed preparation is crucial for crop establishment, growth and ultimately yield. A key aspect of the soil condition is the soil physical environment under which germination, growth and establishment occur. Crucially this affects factors such as temperature, water content, oxygen availability, soil strength and ultimately the performance of a seedbed. The dynamics of soil physical properties of a range of seedbeds and how they relate to crop establishment are considered in this paper. Significant interactions between cultivation techniques, physical properties of the seedbed in terms of penetration resistance, shear strength, volumetric water content and bulk density and the interaction with crop establishment were identified. A soil quality of establishment (SQE) model was developed for the prediction of crop establishment based upon soil bulk density and cultivation practices. The SQE significantly accounted for ca. 50% of the variation occurring and successfully predicted crop establishment to a standard error of around 20 plants per m^{-2} across contrasting soil types and environmental conditions.

Keywords: Soil quality; Tillage; Soil physical properties; Seedbed; Establishment

1. Introduction

Seedbed preparation is crucial for crop establishment, growth and ultimately, yield. Typically the aims of cultivation are to incorporate crop residue, bury weeds and loosen soil to allow appropriate soil–seed contact, easy flow of nutrients, air and water and unimpeded root penetration and crop growth (Hermawan and Bomke, 1997; Bengough et al., 2006). The use of tillage to prepare seedbeds and the subsequent benefits are well documented. However the amount of tillage and best practice in terms of optimum soil physical properties specifically for the establishment period has received less attention in comparison.

The influence of a seedbed can vary greatly in terms of soil aggregation and subsequent porosity. This soil arrangement therefore has direct impacts on soil temperature, water content, oxygen availability and strength, all of which have the potential to affect the performance of the seedbed and its ability to provide an adequate environment for crop establishment. In a review Braunack and Dexter (1989), state in summary of previous work conducted in soil aggregation that beds of aggregates will exhibit differing physical and chemical properties depending on the size of the

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aggregates, thus influencing the suitability of a seedbed for germination, emergence and root development, by influencing factors such as intra- and inter-aggregate aeration. Schjønning and Rasmussen, 2000, found that cultivation methods can have large impacts on surface soil layers, altering both strength and pore dynamics (air and water filled), which can restrict plant growth. The relationship between soil physical properties and the plant root systems are vitally important in this process since these are directly effective of seedbed quality (Awadhwal and Thierstein, 1985; Aubertot et al., 1999; Dexter, 2004).

Crop establishment is the key to successful yields (Blake et al., 2003). Different crops, however, require different soil physical properties for successful establishment. Excessive compaction and soil resistance can result in detrimental effects on root growth and development, which may lead to root behaviour and characteristics changing to accommodate increased strength (Bingham and Bengough, 2003; Clark et al., 2003). Jakobsen and Dexter (1987) found while modelling soil function for Triticum aestivum L. that soil strength for crop development were not affected at; <3.0 MPa for germination, <2.3 MPa for root elongation, <1.7 MPa for coleoptile growth and <0.8 MPa for emergence. In a review by Bengough and Mullins (1990) they discuss hindrance to growth at levels >1 MPa and non-existent growth at 5 MPa. Plant growth is also affected by the soil physical environment created by cultivation, Dexter (1986), stated that root behaviour is dependent upon pore space, with large pore spaces resulting in deflection and contact with compacted sub-layers. Kvasnikov (1928), states that maximum yields in wheat, barley and oats are achieved with seedbeds of 1–2 and 2–3 mm size aggregates. Håkansson et al. (2002) found rolling after drilling cereals resulted in improved final emergence by 4% and improved yields by 2%. The spatial distribution of roots and plant water uptake is strongly affected by soil physical conditions (Pardo et al., 2000). Recent studies have shown a link between effective stress and soil strength in relation to reduced impedance of roots in unstructured soils at matric potentials > 250 kPa (Whalley et al., 2005).

While several studies have sought to develop indices to measure soil quality (e.g. Pagliai et al., 2003), very few studies, with the exception of the least limiting water range (LLWR), (Da Silva et al., 1994; Leão et al., 2006) and soil condition index (SCI), (Tapela and Colvin, 2002), have attempted to combine soil physical properties into an index of soil quality related to crop establishment. However, these methods are time consuming, often requiring more complex measurements, hence a quick assessment using fewer soil physical properties and a consistent prediction of crop establishment would be advantageous. This has not previously been developed and this paper seeks to address this research gap.

The objectives of this research were: (i) to identify changes in soil physical properties in a range of evolving seedbeds created by a variety of cultivation methods, (ii) to determine the effect of soil physical properties on crop establishment and (iii) to develop a model to predict crop establishment based on soil physical properties. It was hoped that any such model would be applicable at estimating complicated functions of soils from simple measurements.

2. Materials and methods

2.1. Field site and experimental design

A field experiment was established in 2005 at the University of Nottingham experimental farm, Sutton Bonington, Leicestershire, UK (52.5°N, 1.3°W). The soil was a sandy loam of the Dunnington Heath series (FAO class; Stagno-Gleyic Luvisol) (Table 1). The field was in a rotation of winter oats, winter wheat, sugar beet, winter wheat, with the current experiment in winter wheat following winter oats. The experimental design was a 2 x 2 x 2 factorial, arranged in a split plot with three replicate blocks. Primary cultivations (plough or disc) were arranged on the main plots, which were divided into four sub-plots on which the

Table 1
Selected soil properties of the Dunnington Heath (FAO class: Stagno-Gleyic Luvisol) and Worcester (FAO class: Argillic Pelosol) series

FAO class	Sand (>50 mm) (%)[a]	Silt (2–50 mm) (%)[a]	Clay (<2 mm) (%)[a]	Saturated hydraulic conductivity (cm s 1)	Bulk density (g cm 3)	Organic matter (%)	pH
Stagno-Gleyic Luvisol	66.4	18.0	15.6	1.86×10^{-3}	1.51	4.88	6..5
Argillic Pelosol	31.1	34.5	34.4	6.31×10^{-5}	1.40	5.49	6..9

[a] Percentage by mass, measured using hydrometer method (Rowell, 1994).

other treatments were factorally combined and allocated at random; secondary cultivation (± power harrow) and tertiary cultivation (± rolling) with Cambridge rollers post-drilling. Previous cultivations for 2 years had been performed by a single pass heavy disc cultivator incorporating a levelling board and roller (Vaderstad Carrier Super CR500). The experiment comprised of 24 plots that were 24 m x 2.5 m wide, in sets of 8 plots in 3 blocks with 12 m discards between blocks. Plots were drilled using a Nordsten drill with winter wheat (T. aestivum) cv. Robigus at a rate of 250 seeds per m^2 on 27 September 2005. Cultivations were performed the day before drilling for primary cultivations and the day of drilling for secondary cultivations and rolling.

Soil quality of establishment (SQE) validation sampling was conducted at the University of Nottingham experimental farm, Sutton Bonington, Leicestershire, UK (52.5°N, 1.3°W), in an adjacent field to the previous year and Bunny, Nottinghamshire, UK (52.52°N, 1.07°W). The soils were a sandy loam of the Dunnington Heath series (FAO class; Stagno-Gleyic Luvisol) at Sutton Bonington and a clay loam of the Worcester series (FAO class; Argillic Pelosol) at Bunny (Table 1). Both sites were drilled with winter wheat (T. aestivum) cv. Einstein at a rate of 300 seeds per m^2 on 4 October 2006.

2.2. Measurement of soil physical characteristics

Soil physical measurements were taken prior to cultivation and at weekly intervals until early November where the crop had exceeded a 'well emerged' stage, noted by successive plant counts recording the same or approximate value. Further measurements were taken at the end of November (pre-winter establishment) and at spring establishment in early March (2006) to account for any over winter plant losses. The soil physical properties of the seedbed were evaluated by measurements of soil shear strength, penetration resistance, water content and bulk density, as well as crop establishment. Bulk density measurements were recorded at five key stages; prior to cultivation, after cultivation, emergence, pre-winter establishment and spring establishment. All measurements were conducted within the centre 1 m of each plot, leaving a 0.75 m distance from the passage of any wheeled traffic.

Volumetric water content (VWC) of the upper 60 mm of soil was measured using a Delta-T Theta probe (type ML2X) with three replicates for each plot. Field measurements were calibrated using gravimetric and bulk density data. A Findlay/Irvine Ltd. 'Bush' cone soil penetrometer was used to assess penetration resistance with three replicates per plot at intervals of 35 mm to a depth of 210 mm. Measurements were recorded in MPa. Measurements of soil shear strength were taken using a Pilcon 120 kPa hand vane, at a depth of 50 mm, replicated three times per plot. Bulk density measurements were made using undisturbed 230 mm^3 cores from the topsoil to a depth of 52 mm, replicated three times per plot, following oven drying for a period of 24 h at 105°C.

Physical measurements were recorded on each sampling date within a reasonable proximity of each other. Crop establishment was assessed using one 1.2 m x 0.6 m quadrat per plot placed randomly at the time of cultivation to prevent bias.

2.3. Statistical analysis

The statistical software package GenStat™ v.8.1 was used to analyse all data using analysis of variance (ANOVA) to test for significant differences between treatments and to calculate standard errors of difference (S.E.D.). Primary cultivation formed the main plots, secondary and tertiary cultivation were factorially combined and randomised on the sub-plots. Multiple linear regressions were used to produce a model to predict establishment utiising the soil physical measurements and cultivation treatments as parameters. A backwards step-wise approach was used to determine the minimum adequate model.

3. Results

3.1. Prior to cultivation (- 6 days)

Soil physical data was collected 6 days prior to cultivation to provide a base-line measurement. No significant variation was recorded for volumetric water content and bulk density. However, differences were found in the strength of the soil, which varied slightly between main plots for shear strength ($P < 0.05$) and between sub-plots for penetration resistance ($P < 0.01$). In response, an assessment was performed to determine if the significant differences had any underlying cause likely to affect the results over the experimental period. Shear strength showed at -6 days the main plots due to be disc cultivated had slightly higher shear strength. However, these differences did not persist after cultivation. At -6 days the plots that were to receive no secondary cultivation had slightly higher penetration resistances, i.e. 3.51 MPa versus 3.24 MPa. Primary cultivation appeared to eradicate any significant influence occurring prior to cultivation within plough plots but underlying differences remained within Block 2 on the disc plots, most likely due to a clay layer at depth becoming shallower within the block.

3.2. Penetration resistance

Disced plots had greater penetration resistance than ploughed plots ($P < 0.01$). Power harrowing increased penetration resistance of seedbeds by 0.2–0.5 MPa ($P < 0.00\ 1$), while rolling increased penetration resistance at cultivation and became increasingly important with seedbed age ($P < 0.001$). Penetration resistance at depth was increased by secondary cultivation ($P < 0.00\ 1$). Rolling in combination with secondary cultivation also produced greater penetration resistance ($P < 0.05$) (Fig. 1).

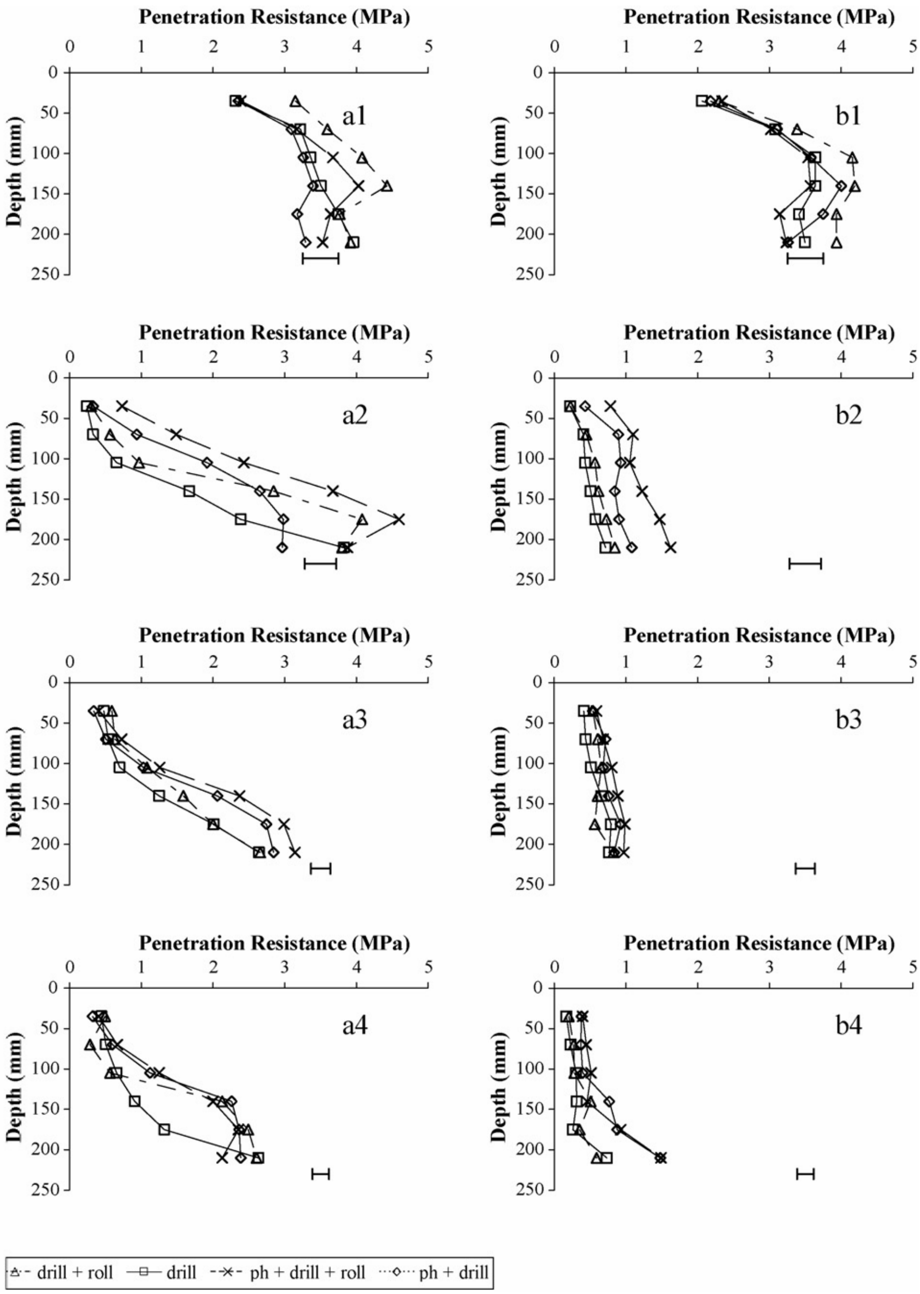

Fig. 1. Penetration resistance (MPa) with depth, showing the differences in soil penetration resistance between (a) disc treatments and (b) plough treatments; (1) prior to cultivation, (2) after cultivation, (3) emergence and (4) pre-winter establishment. Bars depict S.E.D., 143 d.f.

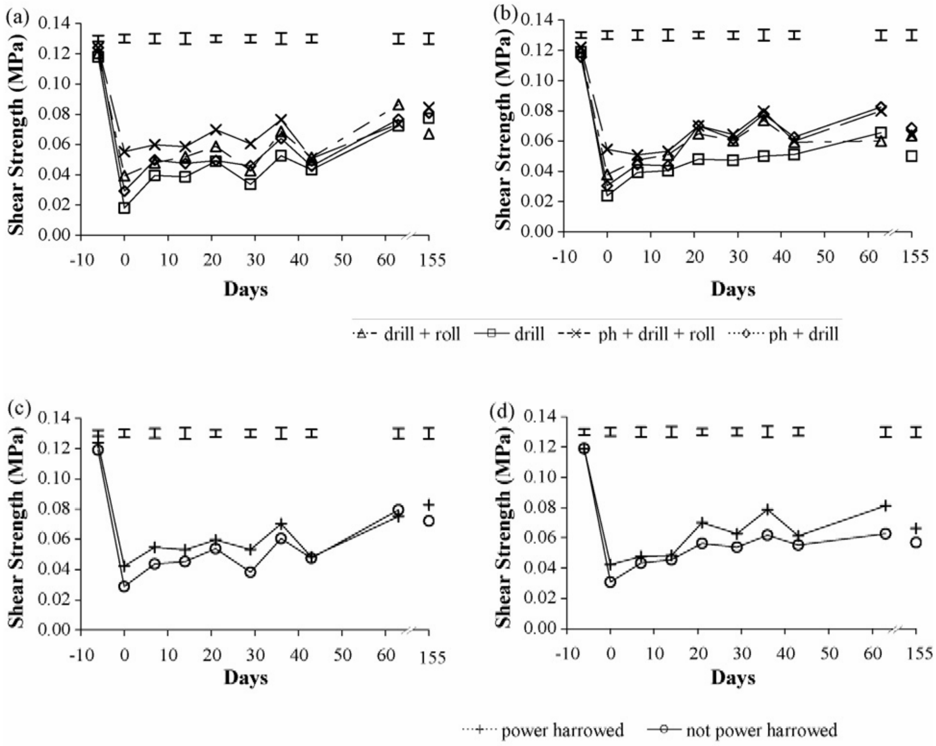

Fig. 2. Soil shear strength variation over time: (a) disc treatments, (b) plough treatments, (c) effect of power harrowed cultivation on disc plots and (d) effect of power harrowed cultivation on ploughed plots. Date of cultivation taken as 0 days. Bars depict S.E.D., 23 d.f.

At cultivation, discing created a much stronger seedbed (2.1 MPa) than ploughing (0.7 MPa). There was also a highly significant ($P < 0.001$) interaction between primary cultivation and depth, with increasing penetration resistance at 10.5 cm depth in disced plots (>1 MPa), while penetration resistance remained <1 MPa until 21 cm depth in ploughed plots. Primary treatments also had a significant ($P < 0.01$) interaction with rolling. In disc treatments, rolling increased penetration resistance by 0.8 MPa and in ploughed treatments by 0.2 MPa. Secondary cultivation and rolling both increased penetration resistance ($P < 0.001$). Penetration resistance of ploughed treatments remained ca. 1 MPa lower than disced throughout the experiment ($P < 0.001$) (Fig. 1). Penetration resistance of power harrowed plots generally remained ca. 0.2 MPa greater than those that were not power harrowed ($P < 0.001$).

3.3. Shear strength

Soil shear strength was not significantly affected by primary cultivation, except at 21 and 29 days when ploughed treatments had significantly ($P < 0.05$) greater shear strength than disced plots. At cultivation, power harrowing and rolling increased soil shear strength ($P < 0.001$) by 0.02 MPa (Fig. 2). As the seedbeds aged, plots that had received secondary cultivation developed greater shear strength than those not power harrowed ($P < 0.01$, Fig. 2). The increase in soil shear strength caused by rolling persisted until 36 days after cultivation.

3.4. Volumetric water content

Greater soil water contents were recorded within disced compared to ploughed plots (typically >3–5%) from 28 to 63 days. Although not significant at 155 days, this trend continued post-winter with a difference of >4.4% in disced plots (Fig. 3). Secondary cultivation had the greatest effect on soil water content with a significant increase recorded from cultivation through to spring establishment ($P < 0.01$). Rolling showed no significant influence on soil water content with a mean difference between treatments of <2% (Fig. 3).

A significant interaction between primary and secondary cultivation was observed at 21 days ($P < 0.05$) and 63 days ($P < 0.01$). Similar patterns were recorded on both dates with ploughing (14.7% and

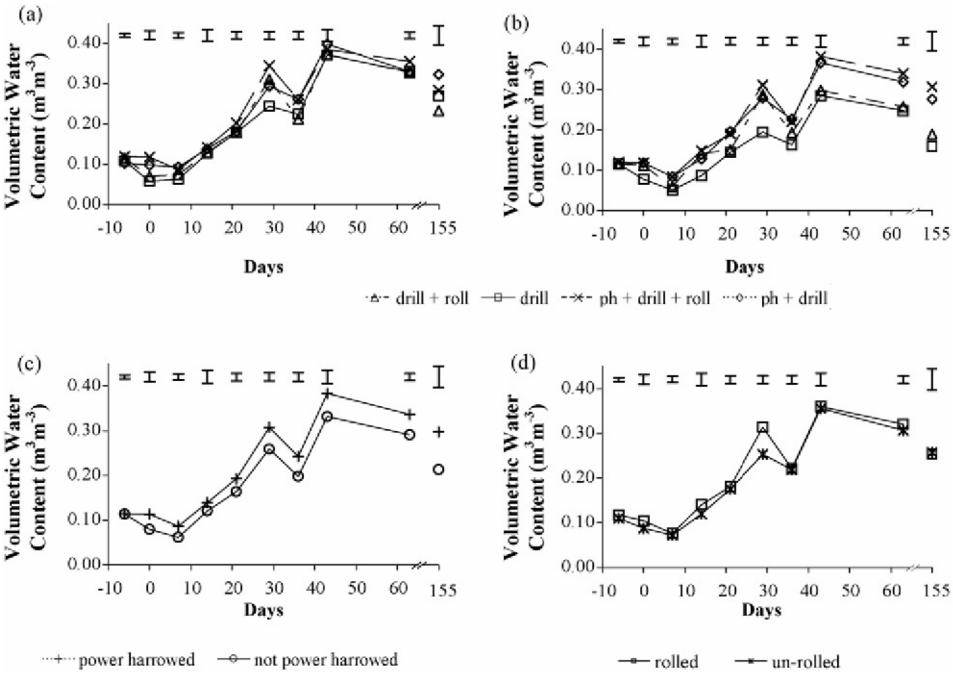

Fig. 3. Soil water content variation over time: (a) disc treatments, (b) plough treatments, (c) effect of power harrowing, (d) effect of rolling. Date of cultivation taken as 0 days. Bars depict S.E.D., 23 d.f.

29.1%) producing reduced water contents than discing (17.9% and 33.5%) and secondary cultivation leading to an increased water content by up to 1.5% within disc treatments and 7.6% within plough treatments.

3.5. Bulk density

Primary cultivation did not significantly affect bulk density but power harrowing increased bulk density by 0.1 g cm^{-3} ($P < 0.001$) and rolling by 0.08 g cm^{-3} ($P < 0.01$, Fig. 4). With increasing seedbed age, disc treatments had significantly higher bulk density ($P < 0.05$) than plough treatments (1.33–1.26 g cm^{-3}) after emergence. Secondary cultivation increased bulk density from 1.23 to 1.35 g cm^{-3} after emergence ($P < 0.00$ 1). Rolling had no effect on surface bulk density post 7 days (Fig. 4).

3.6. Crop establishment

Initial emergence occurred between 7 and 14 days, with the first recorded measurements taken 14 days after drilling. At this point, emergence was significantly higher ($P < 0.05$) within ploughed (192.9 per m^{-2}) compared to disced (156.5 per m^{-2}) treatments. Disc treatments 'caught up' (Fig. 5) over time but the differences were significant ($P < 0.05$) again at the spring establishment count, with 35.6 more plants per m^{-2} within ploughed treatments.

Treatments receiving secondary cultivation had a mean establishment of 204 plants m^{-2} compared to 145 plants per m^{-2} at 14 days ($P < 0.001$) (Fig. 5). However over time, differences between treatments declined and at final establishment power harrow plots had only 15 plants per m^{-2} more than those that were not power harrowed ($P < 0.05$). Rolling increased establishment by 20 plants per m m^{-2} at day 14 ($P < 0.05$) but, by 21 days rolling had no significant influence on crop establishment (Fig. 5). Therefore rolling affected time of emergence but not final plant number.

3.6.1. Soil physical properties and establishment

An increase in penetration resistance (0–70 mm) had a negative relationship ($P < 0.05$) with establishment prior to cultivation but was positively related ($P < 0.05$) after cultivation. Therefore there was a negative relationship between resistance of the soil and establishment as the soil became increasingly compact (>3 MPa), or increasingly loose (<0.5 MPa). Volumetric water content (VWC) had a non-significant relationship with crop establishment, except at initial cultivation when establishment was positively correlated ($P < 0.05$) with increased VWC. Shear strength

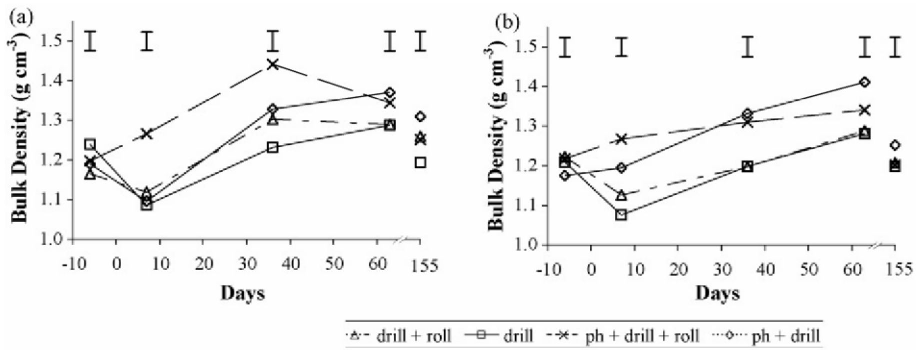

Fig. 4. Soilbulkdensityvariationovertime: (a) disc treatments and (b) plough treatments. Date of cultivation taken as0days. Bars depict S.E.D., 23 d.f.

had a positive relationship ($P < 0.05$) with establishment after 21 days post-cultivation; this was particularly strong at 29 days. Bulk density showed a positive relationship ($P < 0.05$) with establishment after cultivation but was not significant after this period.

3.7. Soil quality of establishment (SQE)

Soil quality affects establishment and growth of crops in terms of strength, resistance, water content and density. The interaction between soil physical properties and crop establishment illustrate a wide variety of relationships although it is unlikely soil quality could be simply explained by a single relationship. Using multiple linear regression a model for explaining the variation in soil quality and predicting establishment was developed, using data up to and including 14 days after cultivation. This was chosen based upon computational limits and number of days to emergence. The model was designed to assess seedbed quality once created, and predict establishment, i.e. soil quality of establishment (SQE) using averaged plot values for penetration resistance (0–70 mm depth), shear strength (50 mm depth), water content (50 mm) and bulk density

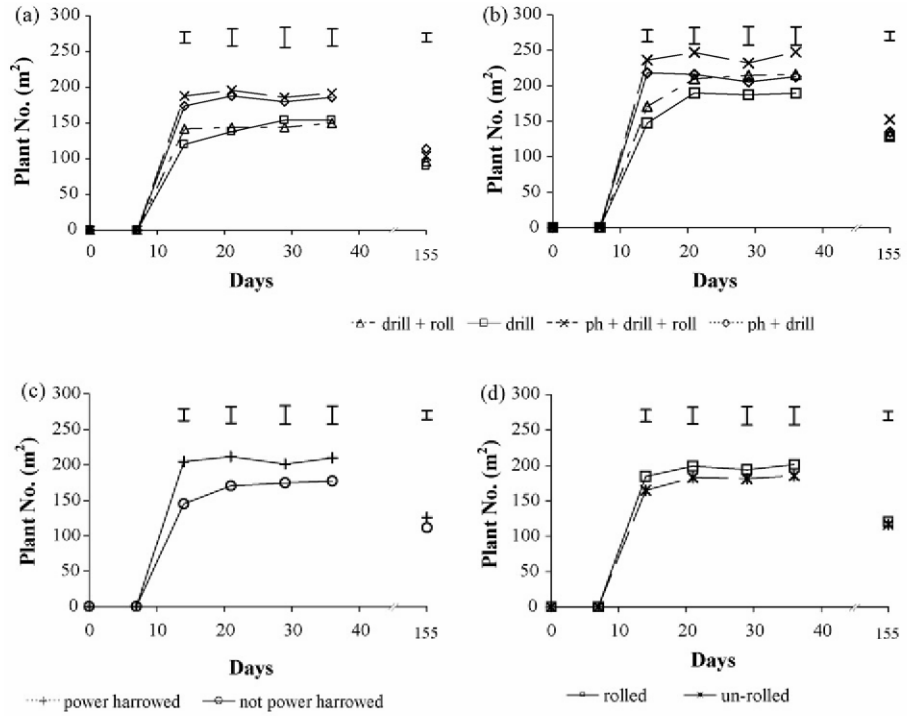

Fig. 5. Plant no. per m^2 over time within (a) disc treatments, (b) plough treatments, (c) effect of power harrowing and (d) effect of rolling. Bars depict S.E.D., 23 d.f.

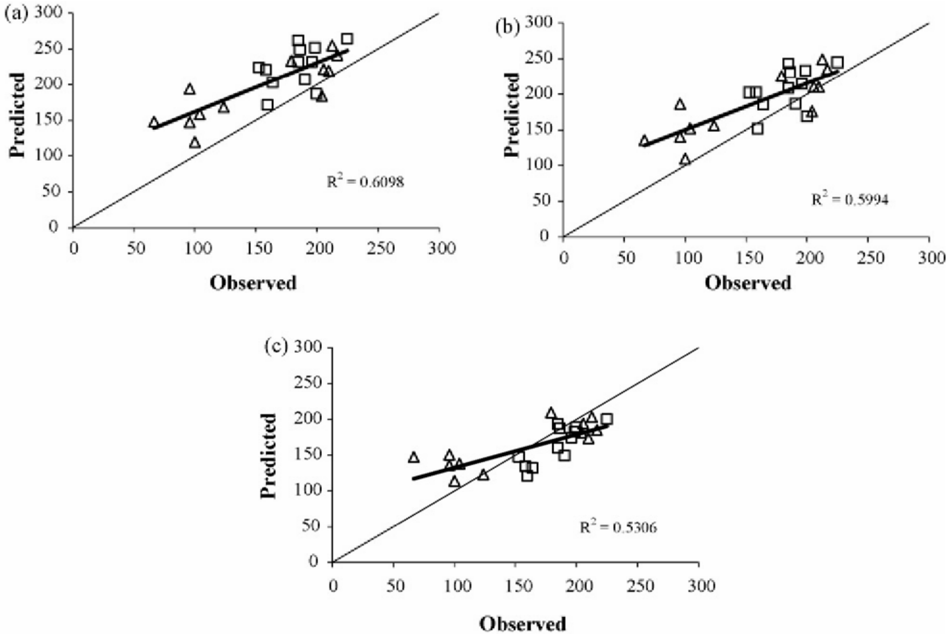

Fig. 6. Validation of modelled relationships between soil physical properties and crop establishment. Validation was conducted over two soil types a clay loam (Δ) and sandy loam (□) as well as different environmental conditions to the data in which the model was created. The three models created, (a) Eq. (1), (b) Eq. (2) and (c) Eq. (3), account for varying degrees of variation, with the determined best fit model as (c) due to a reduced over prediction.

(0–52 mm). It became apparent early in model development that cultivation technique had a strong influence on crop establishment that was not entirely explained by the soil physical properties measured. Therefore numerical values were assigned to the cultivation techniques as follows; disc =0, plough = 1, secondary (no = 0, yes = 1), rolled (no = 0, yes = 1). The lower the value, the less intensive the cultivation.

Backwards stepwise regression was used to find the optimal model (Eq. (1)) where P = primary, S = secondary, R = rolled, PR = penetration resistance prior to cultivation, WC = water content, SS = shear strength at cultivation and BD = bulk density at 7 days. Regression analysis was significant ($P < 0.001$), accounting for 71.1% of variation with an estimated error of ca. 18.5 within the fitted data.

$$SQE = 427 + 34.8P + 52.2S + 71.2R - 50.6PR + 120WC - 1761SS - 102BD \quad (1)$$

The SQE was validated against a small sub-set of data collected in the 2006–2007 season. Samples were collected from experiments using disc treatments, ±power harrowing and ±rolling and across two soil types (Dunnington Heath series – sandy loam and Worcester series – clay loam). Regression analysis performed on the validation sub-set gave a good fit which was significant ($P < 0.001$) accounting for 59.2% of variation with a standard error of ca. 25.7 (Fig. 6a). However the model slightly 'over predicted' establishment in the validation, possibly as a result of a change in the moisture regime at cultivation, which was generally higher within the validation sub-set by ca. 10%. This suggests the model may be over parameterised and that the moisture conditions of the soil are accounted for in the other factors such as soil strength and bulk density. It was unlikely that temperature conditions between the two seasons caused this as this remained roughly constant at 13 °C during the time periods from cultivation to final establishment in both years.

A second model was therefore developed using the same principle as before but removing all water content data from the analysis, producing the same model as in Eq. (1) but without water content at cultivation (Eq. (2)). Regression analysis was significant ($P < 0.001$) accounting for 70.6% of variation with an estimated error of ca. 18.6 within the fitted data.

$$SQE = 418 + 37.1P + 54.1S + 70.6R - 50.3PR - 1692SS - 89.2BD \quad (2)$$

Regression analysis performed on the validation sub-set gave a good fit which was significant ($P < 0.001$) accounting for 58.1% of variation with a standard error of ca. 25.1 (Fig. 6b). The previous model's over prediction was significantly reduced and a comparison of 1:1 line of identity, which accounts for model variation from a perfect 1:1 line where greater than 0 is regarded as a good fit, showed a change from -0.23 R^2 in Eq. (1) to a value of 0.23 R^2. There was still a slight over prediction within this model. It was also unclear why the model should choose factors prior to cultivation as the values are from 0 to 70 mm depth and thus should have been eradicated at cultivation.

A third model was subsequently developed using the same principles but removing 'prior to cultivation' data from the analysis. This resulted in the selection of cultivation techniques and bulk density at 7 days only (Eq. (3)). Regression analysis was significant ($P < 0.001$) accounting for 55.6% of variation with an estimated error of ca. 20.6 within the fitted data.

$$SQE = 303 + 49.6P + 48.1S + 28R - 150BD \qquad (3)$$

Regression analysis performed on the validation sub-set gave the best fit of all models which was significant ($P < 0.001$) accounting for 50.9 % of variation with a standard error of ca. 20.4 (Fig. 6c). A comparison of 1:1 line of identity showed a change from -0.23 R^2 in Eq. (1) and 0.23 R^2 in Eq. (2) to 0.52 R^2 in Eq. (3).

4. Discussion

The examined soil physical properties were significantly modified by contrasting cultivation technique. Discing produced compact seedbeds with observed increases in penetration resistance and bulk density, in comparison to ploughed treatments. Comia et al. (1994) similarly found reduced penetration resistance within ploughed treatments while, Filipovic et al. (2006) also found conventional tillage reduced bulk density. Discing produced finer aggregate development which resulted in higher observed volumetric water content in the top soil layer due to smaller pore development near the surface and subsequently greater water retention. Crop emergence was more favourable within ploughed treatments despite the compact seedbed and the assumption of increased soil–seed contact associated with discing, possibly due to reduced surface crop residues. Addae et al. (1991) also found emergence rates delayed (up to 0.5 days) under minimal tillage compared with conventional tillage. Other studies have shown a link between reduced soil–seed contact and surface crop residues resulting in decreased populations of dryland and irrigated wheat (Bordovsky et al., 1998). However, differences in the number of emerged plants diminished with time, ploughing therefore affected rate of emergence rather than final plant number.

Secondary cultivation (power harrowing) resulted in increased penetration resistance, shear strength and bulk density due to surface compaction. Secondary cultivation also increased volumetric water content and crop establishment throughout the experiment, due to the creation of a fine aggregated seedbed allowing increased water storage and soil–seed contact. Rolling increased consolidation resulting in higher shear strength and penetration resistance, which was higher in conjunction with discing as a result of initial shallower cultivation. Rolling produced an increased crop emergence rate, due to initial consolidation. However, over time rolling was responsible for soil surface hardening which is detrimental to plant growth (Pagliai et al., 2003).

The interaction between soil physical properties and crop establishment illustrated reduced emergence both in high strength and low bulk density soil conditions. Masle and Passioura (1987) also noted soil mechanical resistance adversely affects the growth of wheat in both compacted and loose soil. Other studies have suggested a loose soil can result in deep sowing and reduced seedling emergence especially with small grain cultivars (Hãkansson et al., 2002). Similar observations were found with the effect of bulk density on crop establishment, where lower bulk density values were less responsive to crop establishment, due to reduced soil seed contact and increased lag time for imbition of water vapour to seeds (Bordovsky et al., 1998; Wuest, 2002). Other researchers have recorded that increased bulk density resulted in reduced emergence, with the fastest and more complete emergence achieved with bulk densities <1.2 g cm^{-3} (Nasr and Selles, 1995).

The SQE performed well on the contrasting soil types and under different environmental conditions, accounting for over 50% of the variation in establishment with relatively low standard errors with respect to the natural variability of the conditions. The initial model slightly 'over predicted' establishment in the validation data, possibly because of a change in moisture regime at cultivation, which was generally higher within the validation sub-set by ca. 10%, with no difference in mean temperature across seasons. As shown, there was a strong relationship between water content at cultivation and establishment which the model will account for. However, one may argue this model may be over parameterised, as water content is closely related to cultivation technique (particularly power harrowing) and strongly correlated with soil strength and bulk density.

Table 2
Selected statistical variation between SQE model(s) in the validation sub-set

	Model 1	Model 2	Model 3
Significance (95% confidence limit)	<0.001	<0.001	<0.001
% Variation accounted	59.2	58.1	50.9
Estimated standard error	25.7	25.1	20.4
1:1 line of identity (R^2	- 0.23	0.23	0.52
Slope	0.69 (S.E. 0.117)	0.66 (S.E. 0.114)	0.46 (S.E. 0.093)
Intercept	92.95 (S.E. 20.31)	84.28 (S.E. 19.82)	86.15 (S.E. 16.01)
Average observed population (per m^2)	167	167	167
Average predicted population (per m^2)	208	194	164
Mean % deviation	1.02	0.67	-0.09

The second model had a better fit however, the over prediction was also considerable. Using parameters ‘prior to cultivation’, at 0–70 mm depth, created increased variability. If the model was used at other locations which have not used the same previous year cultivation techniques as performed at the used field sites, added variability may also be entered into the model. Subsequent removal of ‘prior to cultivation’ data resulted in the best fit model (Eq. (3)). Although accounting for less variation in both the fitted and validation data sets, this model does not suffer from the over prediction observed in the previous models (Table 2). It is interesting to note the model selects only bulk density and cultivation technique as not only is bulk density correlated with soil strength and water content, but it is also an indicator of soil structural condition. This suggests the cultivation technique applied and the soil structure created by these techniques have the greatest effect on crop establishment.

5. Conclusions

The soil quality of establishment (SQE) models were successful in explaining how variation in soil physical properties affect crop establishment. Each model accounted for ca. 50% or more of the total variation in winter wheat establishment. Over parameterisation led to an ‘over prediction’ within the initial two models from the validation data, as a direct result of soil water content and ‘prior to cultivation’ measurements. Removing these from the model prevented over prediction highlighting that bulk density (in conjunction with cultivation technique) accounted for the best fit model prediction of crop establishment.

It is possible the model could be improved by including other measurements such as soil temperature, oxygen diffusion rate, etc. and other cultivation techniques. However, as bulk density is an indicator of soil structure, it could also be anticipated that a greater understanding of the soil porous architecture through measurements of properties such as porosity and pore size distribution might yield further information regarding crop establishment. It must also be noted not all factors can be controlled, such as disease, weather, etc. which can also effect the variability of crop establishment and growth. Ultimately it is important that any model of establishment should be linked closely with cultivation methods and in line with the appropriate management directives for soil protection.

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Chapter 3:

Effect of seedbed cultivation and soil macro structure on the establishment of winter wheat (*Triticum aestivum*)

This chapter assesses the affect of primary, secondary and tertiary cultivation practices on the soil macro structure using X-ray CT and models the relationships between macro structure, soil physical properties and crop establishment. This chapter is under review for publication in *Soil and Tillage Research* (Atkinson et al., 2008) and is included in unpublished 'paper format'.

3.1 Abstract

Soil physical properties affect the establishment of crops; these properties are influenced by cultivation incurred during seedbed preparation and vary greatly depending upon the intensity of applications. However, there is little quantified data concerning the influence of cultivation upon the precise soil structural arrangement and the effects of this on crop establishment. The dynamics of soil macro structure properties on a range of seedbeds and how they relate to crop establishment are considered in this paper. Significant interactions between cultivation techniques, soil physical properties, the soil macropore structure of the seedbed and the interaction with crop establishment were identified. The relationship between soil structure and crop establishment was highly significant, with increased pore space reducing final establishment numbers. An improvement to a previously developed model (soil quality of establishment (SQE)) was developed following the addition of soil macro structure properties, accounting for improved predictability of between ca. 6 - 19 % of

the variation accounted across soil types, environmental conditions and image resolution changes.

Keywords: Soil quality; Tillage; Soil structure; Seedbed; Establishment.

3.2 Introduction

Cultivation practices have a large influence on the soil physical properties of seedbeds and the subsequent establishment of crops. Such management regularly affects soil strength, water content, temperature, nutrient and oxygen availability, all of which affect the performance of a seedbed. The physical properties of soil can be translated as measures of the structural conditions created by cultivation. However, the influence that cultivation and its subsequent effect on crop establishment have on soil structure has rarely been quantified. We hypothesise that by exploring the structural arrangement of a seedbed, in terms of its porous architecture, the effect on crop establishment may be better understood.

The quantification of soil structure provides a greater understanding of the soil physical environment. The most common way of visualising soil structure at present is by the use of X-ray Computed Tomography (CT) which enables the rapid observation of soil structure in two and three dimensions (Vogel and Roth, 1998; Perret et al., 1999; Young et al., 2001). X-ray CT can be performed at a variety of scales, typically ranging from 5 μm to 500 μm, on undisturbed soil cores of varying size depending upon the scanner type. X-ray CT is now a widely used and accepted tool for determining soil structural conditions, such as fluid dynamics through soil, changes in pore dynamics and morphological changes under cultivation (Mooney, 2002; De Gryze et al., 2006; Rachman et al., 2005).

Jégou et al. (2002) used medical X-ray CT for quantifying the impact of soil compaction on earthworm burrow systems. This enabled them to determine that compaction contributed to the fragmentation of burrow systems with reduced continuity; which prior to this technique would not have been possible to determine non-destructively. Langmaack et al. (2002) found that conventional tillage reduced soil porous architecture in terms of total pore length, volume, tortuosity and continuity, compared with conservation tillage. Mooney et al. (2006) used X-ray CT to illustrate the effect of soil structure on the propensity of a cereal root system to fail. They identified that subterranean stem rotation was the major mechanism causing plants to fail and that an increase in surface bulk density post establishment (e.g. by rolling) was needed to resist root failure. Gantzer and Anderson (2002), using X-ray CT, showed conventional tillage created significantly higher macroporosity (11 %) compared to no till systems (5 %).

Previously Atkinson et al. (2007) developed a soil quality of establishment model (SQE) which successfully predicted crop establishment, across two seasons and soil types, based on cultivation method and the soil physical properties. Here we hypothesised that the addition of quantified soil structural data would provide a greater understanding of how the porous architecture affects crop establishment.

Previous studies using soil structural imaging to examine the effects of agricultural practices have tended to concentrate on compaction and its effects on soil function and crop growth. Very few have concentrated on quantifying the impact of cultivation on the soil structural environment and its subsequent effect on crop establishment. The objectives of this paper were (i) to identify changes in soil macro structural properties in a range of evolving seedbeds created by different cultivation methods, (ii) to determine the effect of soil macro structure on crop establishment and links with physical properties and (iii) to develop a model to predict crop establishment based on soil physical properties and macro structural elements.

3.3 Materials and methods

3.3.1 Field site and experimental design

A field experiment was established in 2005 at the University of Nottingham, Sutton Bonington, Leicestershire, UK (52.5^{o}N, 1.3^{o}W). The soil was a sandy loam from the Dunnington Heath series (FAO class; Stagno-Gleyic Luvisol) (Table 3.1). The field was in a rotation of winter oats, winter wheat, sugar beet, winter wheat, with the current experiment in winter wheat following winter oats. The experimental design was a 2 x 3 factorial, arranged in a split plot with three replicate blocks. Primary cultivations (plough or disc) were arranged on the main plots, which were divided into three sub-plots on which secondary applications were factorally combined and allocated at random; either power harrowing (SN), rolling (NR) (Cambridge rollers post-drilling) or combined applications of both power harrowing and rolling (SR). Previous cultivations for two years had been performed by a single pass heavy disc cultivator incorporating a levelling board and roller (Vaderstad Carrier Super CR500). The experiment comprised of 24 plots that were 24 x 2.5 m wide, in sets of 8 plots in 3 blocks with 12 metre discards between blocks. Plots were drilled using a Nordsten drill with winter wheat (*Triticum aestivum*) cv. Robigus at a rate of 250 seeds per m^2 on 27th September 2005. Cultivations were performed the day before drilling for primary cultivations and the day of drilling for secondary cultivations and rolling.

Sampling for model validation was conducted at the University of Nottingham, Sutton Bonington, Leicestershire, UK (52.5^{o}N, 1.3^{o}W), in an adjacent field to the previous year, and at Bunny, Nottinghamshire, UK (52.52^{o}N, 1.07^{o}W). The soils were a sandy loam from the Dunnington Heath series (FAO class; Stagno-Gleyic Luvisol) at Sutton Bonington and a clay loam from the Worcester series (FAO class; Argillic Pelosol) at Bunny (Table 3.1; Figure 3.1). Both sites were drilled with winter wheat (*Triticum aestivum*) cv. Einstein at a rate of 300 seeds per m^2 in early October 2006.

Table 3.1: Selected soil properties of the Dunnington Heath (FAO class: Stagno-Gleyic Luvisol) and Worcester (FAO class: Argillic Pelosol) series. [a]Percentage by mass, measured using hydrometer method (Rowell, 1994).

FAO Class	Sand (>50 µm) (%)*	Silt (2-50 µm) (%)*	Clay (<2 µm) (%)*	Saturated hydraulic Conductivity (cm s^{-1})	Bulk Density (g cm^{-3})	Organic Matter (%)	pH
Stagno-Gleyic Luvisol (Dunnington Heath)	66.4	18.0	15.6	1.86×10^{-3}	1.51	4.88	6.5
Argillic Pelosol (Worcester)	31.1	34.5	34.4	6.31×10^{-5}	1.40	5.49	6.9

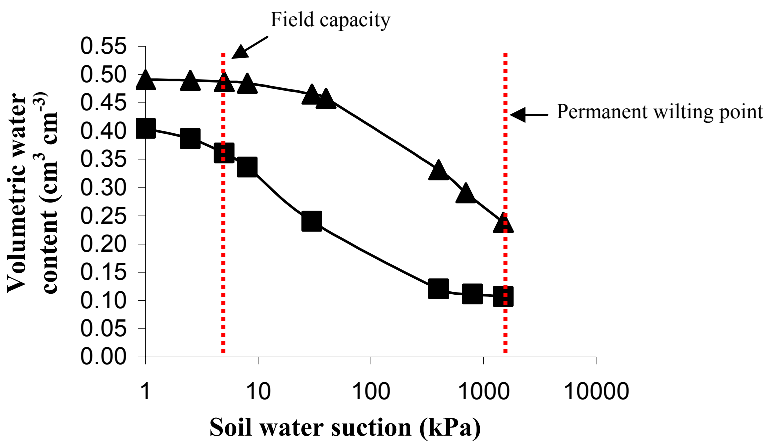


Figure 3.1: Water release curve for the two soil textures (Table 3.1), data fitted to the Van Genuchten-Maulem (1980) model. Clay Loam = ▲; Sandy loam = ■. Data courtesy of Morris (2004).

3.3.2 Soil structure sampling

Soil samples were collected by sampling the top 70 mm of the soil profile with Kubiena tins (70 x 70 x 50 mm) from a shallow pit within the centre 1 m of each plot leaving a 0.75 m distance from all wheeled traffic in randomised locations and replicated twice. The orientation was marked and the sample carefully removed from the soil by excavating around the container. Samples were then wrapped in cling film to prevent water loss and damage. Samples were taken at key stages of seedbed evolution; prior to cultivation, after cultivation, emergence, establishment and spring establishment.

3.3.3 Resin impregnation of undisturbed soil cores

Soil cores were air dried for a maximum of 7 days to reduce the moisture content; however, samples were not dried sufficiently as to allow shrinkage or structural damage. A mixture of the following impregnation components was then prepared in sequence; Crystic resin (Crystic 17449, Aeropia Ltd, UK), catalyst (Organic peroxide '0' – Methyl Ethyl Ketone Peroxide, ScottBader, UK), acetone (Laboratory Reagent Grade, Fisher Scientific, UK), accelerator 'G' (Aeropia Ltd, UK) and fluorescent dye (Uvitex OB, CIBA Inca., UK). Impregnation of samples was performed using a thinned resin solution, achieved by a 1.5:1 ratio of acetone to resin. This was reduced to a 1:1 ratio, 0.5:1 ratio in subsequent top-ups if required. Catalyst was used in a 100:1 ratio of resin to catalyst. Accelerator was used in a 100:0.2 ratio of resin to accelerator. Within each mix of the above ratios ca. 0.5 g of optical brightener was dissolved. Resin mixture was poured gently on to the samples and allowed to infiltrate into the pore space. A 10 mm head was left above samples prior to placing under a low vacuum to evacuate air (no observable change in soil structure occurred as a result of this process). Extra solution was added to samples if the resin mixture level fell below the soil surface. Samples were air cured until solid (2-3 weeks), then cured at 40 ºC for a further two weeks.

3.3.4 X-ray Computed Tomography

Resin impregnated soil blocks were scanned using a Philips Mx8000 IDT whole-body X-ray Computed Tomography (CT) scanner at the Queens Medical Centre (QMC), Nottingham, UK. The samples were scanned using a spiral scan routine. Exposure limits of 140Kv and 201mAs were applied to increments of -0.8 mm, giving slice thicknesses of 0.8 mm at an output device resolution of 512 x 512 pixels, and spatial resolution (voxel) of 0.46 x 0.46 x 0.46 mm, in a rotation time of 0.75 seconds. The field of view was set at 447 mm to allow for maximum image size. Data from each scan was recorded on a magnetic tape and converted to ARC / NEMA (DICOM) format for processing.

3.3.5 Image analysis of soil structure characteristics

Image stacks (a collection of images) acquired at scanning were 512 x 512 x 660 pixels (330 MB) in size. Each frame within this was 512 x 512 pixels which provided a spatial resolution of 824 µm $pixel^{-1}$. CT images were re-sized for each sequence of images, and converted to the TIFF format using public domain software ImageJ (Vs. 1.35p, National Institutes of Health, USA, http://rsb.info.nih.gov/ij/). Image sequences varied between samples due to edge effects, however, for consistency 30 images (maximum number of continuous images across all samples) taken from the centre of each sequence was used. Image manipulation was performed in ImageJ to isolate pore space. This involved resizing each sample (30 images per sample) to a size of 56.82 x 56.82 mm. A series of imaging filters were evaluated from which the median and sharpen filter produced the best results. Images were then binarised by manual adjustments of a threshold (Hounsfield units – HU), due to inconsistency in automated threshold algorithms used in ImageJ; this was performed individually for each sample (c. 1300-1600). Binary images (stacks) were then subjected to a close function (dilation and erosion) consisting of two iterations and eight pixels. Morphological analysis was performed on the binary images created (Figure 3.2) using ImageJ, this included the following measurements; pore count, total pore area, average pore size, total image porosity and pore size distribution. Plant material was included as pore space due to issues with density differentiation between air and root.

3.3.6 Statistical analysis

The statistical software package GenStat^{TM} v.8.1 was used to analyse all data using an analysis of variance (ANOVA) to test for significant differences between treatments and to calculate standard errors of difference between mean (S.E.D).

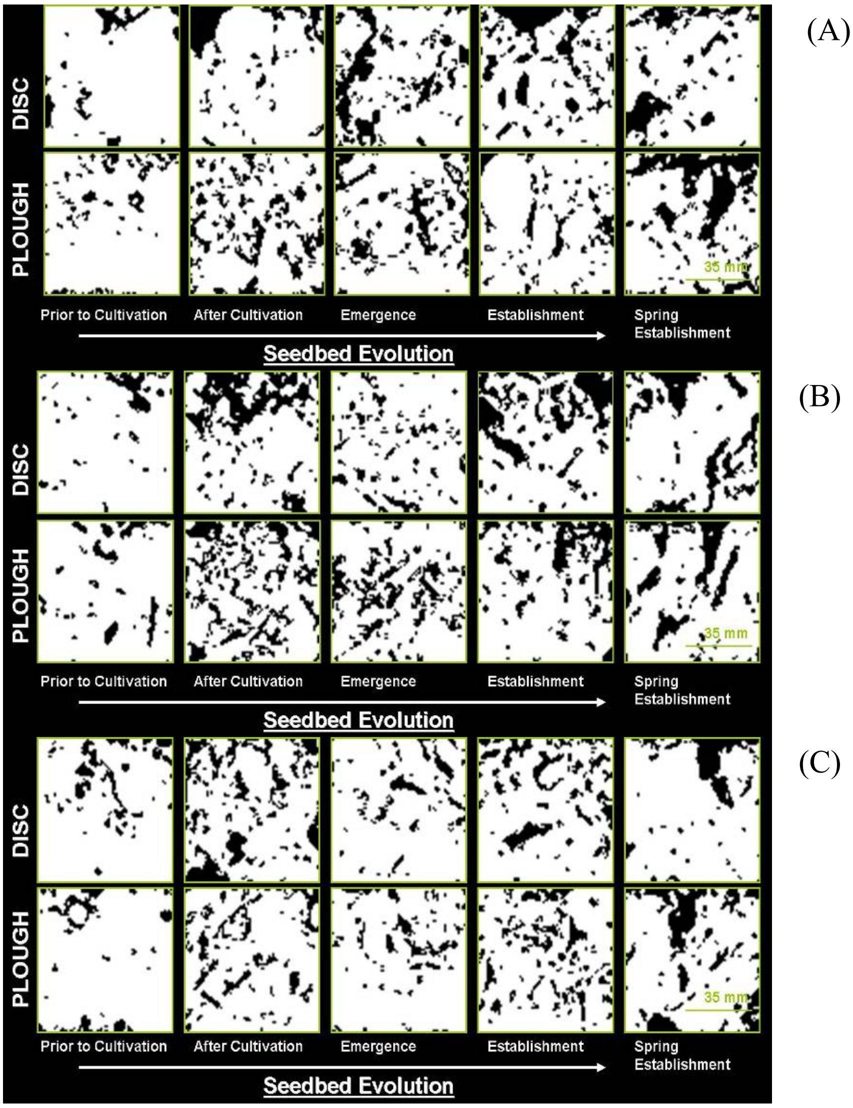


Figure 3.2: Morphological analysis of seedbed evolutionary changes between primary treatments are shown. A) Primary and rolled. B) Primary and power harrowed. C) Primary, power harrowed and rolled.

3.4 Results

3.4.1 Macro porosity

Soil macro porosity was not significantly different between plots prior to cultivation with natural variability between 9-12 % (Table 3.2). Evolution in macro porosity showed the greatest increase ($P < 0.001$) after cultivation by ca. 10 %, this decreased with the age of the seedbed and by spring establishment macro porosity was ca. 5-6 % greater than prior to cultivation (Figure 3.3). Interactions over time with primary cultivation, although not significant, showed increased macro porosity (4 %) within disc treatments compared to plough, this decreased by emergence to within ca. 1 %, and increased again with plant development by establishment to ca. 4 % (Figure 3.2). Over seedbed evolution, secondary cultivations showed clear increased macro porosity (ca. 3-4 %) initially after cultivation within treatments which received rolling. However, after 7 days this trend was reversed and treatments that received rolling had ca. 2-4 % less porosity than power harrowed treatments (Figure 3.3). Significant interactions occurred over time between primary and secondary cultivations ($P < 0.05$), after cultivation, disc treatments, which included rolling, increased macro porosity, but within ploughed treatments this was only true of non-power harrowed plots (Figure 3.3). At emergence, a reverse pattern was observed in both plough and disc treatments with rolling reducing macro porosity (Figure 3.3). At establishment, the largest macro porosity occurred within the disc and rolled treatment (ca. 23 %) and the lowest in the ploughed plots (ca. 14 %) ($P < 0.05$) (Figure 3.3). Spring establishment again reduced macro porosity as a result of rolling, and ploughed treatments which received power harrowing were ca. 3 % less than non-power harrowed treatment ($P < 0.01$) (Figure 3.3).

3.4.2 Macroscale average pore size (mm^2)

Average pore size was not significantly different prior to cultivation with natural variability between ca. 10-15 mm^2 (Table 3.2). As seedbeds evolved, average pore size as a result of primary cultivation was consistently higher within disc treatments compared to ploughed ($P < 0.05$) (Figure 3.3). The greatest increases in average pore size ($P < 0.01$) occurred after cultivation by ca. 5 mm^2, this decreased with seedbed age and at emergence it was roughly similar to the value prior to cultivation (11.5-12 mm^2), this increased again by establishment (ca. 15 mm^2) and spring establishment (ca. 14 mm^2). Initially after cultivation, large increases in average pore size were seen within rolled treatments (ca. 18 mm^2) compared with unrolled (ca. 12 mm^2), however this was reversed as the seedbed evolved with rolled treatments having reduced average pore size compared with unrolled (ca. 5-7 mm^2) (Figure 3.3). The interactions between primary and secondary application showed significant interactions ($P < 0.01$) whereby an increase in cultivation intensity i.e. rolled through to combined, led to a general decrease in average pore size within disc treatments but an increase within ploughed treatments.

Table 3.2: Mean macro structure variation of evolving seedbeds under different cultivation. Images representative of Plough, Power Harrow and Rolled treatment, black represents pore space.

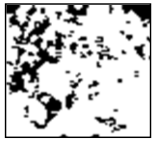
Prior to Cultivation

(- 6 Days)

Treatment	Primary	Secondary	Rolled	Porosity (%)	s.e.d	Average Pore Size (mm^2)	s.e.d	PSD_{cu}	s.e.d
DDR	Disc	N	Y	7.69	0.711	9.61	1.235	11.02	3.268
DPD	Disc	Y	N	13.03	2.628	15.36	4.308	16.97	3.377
DPDR	Disc	Y	Y	12.25	1.819	13.31	1.994	15.24	2.811
PDR	Plough	N	Y	12.54	1.284	10.86	1.056	11.40	1.025
PPD	Plough	Y	N	9.18	1.592	8.37	0.820	12.88	2.591
PPDR	Plough	Y	Y	14.02	1.351	12.45	1.170	12.33	1.229

After Cultivation

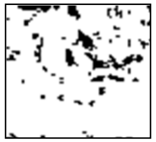
(+ 7 Days)



Treatment	Primary	Secondary	Rolled	Porosity (%)	s.e.d	Average Pore Size (mm^2)	s.e.d	PSD_{cu}	s.e.d
DDR	Disc	N	Y	25.14	3.243	22.14	3.740	26.46	2.918
DPD	Disc	Y	N	19.99	1.703	14.69	2.034	23.84	6.431
DPDR	Disc	Y	Y	26.55	3.116	24.79	5.151	30.59	4.250
PDR	Plough	N	Y	22.19	1.838	16.23	2.678	18.69	5.060
PPD	Plough	Y	N	18.07	2.081	10.59	1.159	15.11	3.415
PPDR	Plough	Y	Y	18.16	2.799	12.02	2.250	15.48	2.976

Emergence

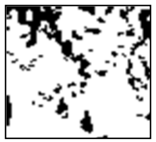
(+ 36 Days)



Treatment	Primary	Secondary	Rolled	Porosity (%)	s.e.d	Average Pore Size (mm^2)	s.e.d	PSD_{cu}	s.e.d
DDR	Disc	N	Y	17.45	1.888	12.16	1.464	16.45	3.109
DPD	Disc	Y	N	20.01	2.646	14.70	2.796	19.84	7.040
DPDR	Disc	Y	Y	18.67	2.469	11.55	1.495	15.04	2.054
PDR	Plough	N	Y	18.45	0.835	11.49	0.886	13.10	1.101
PPD	Plough	Y	N	20.10	1.605	11.89	1.210	19.03	3.206
PPDR	Plough	Y	Y	14.44	1.684	9.73	1.268	11.97	1.939

Establishment

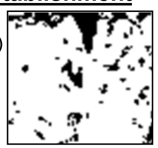
(+ 63 Days)



Treatment	Primary	Secondary	Rolled	Porosity (%)	s.e.d	Average Pore Size (mm^2)	s.e.d	PSD_{cu}	s.e.d
DDR	Disc	N	Y	22.75	0.722	20.68	1.394	30.69	5.539
DPD	Disc	Y	N	22.72	1.355	20.35	1.417	33.25	6.070
DPDR	Disc	Y	Y	17.53	1.195	15.34	1.330	17.98	2.524
PDR	Plough	N	Y	14.65	1.578	9.19	0.892	10.09	0.561
PPD	Plough	Y	N	18.68	0.955	11.44	0.946	20.84	3.098
PPDR	Plough	Y	Y	17.77	0.703	11.83	0.643	14.33	1.410

Spring Establishment

(+ 155 Days)



Treatment	Primary	Secondary	Rolled	Porosity (%)	s.e.d	Average Pore Size (mm^2)	s.e.d	PSD_{cu}	s.e.d
DDR	Disc	N	Y	14.35	1.108	13.79	0.928	19.25	1.383
DPD	Disc	Y	N	20.36	2.543	18.51	2.962	19.93	4.610
DPDR	Disc	Y	Y	12.32	0.976	10.90	0.525	16.79	2.782
PDR	Plough	N	Y	17.72	2.540	14.88	2.141	37.18	8.326
PPD	Plough	Y	N	15.22	0.560	11.90	0.800	21.67	2.271
PPDR	Plough	Y	Y	15.53	0.960	13.75	0.960	22.78	3.367

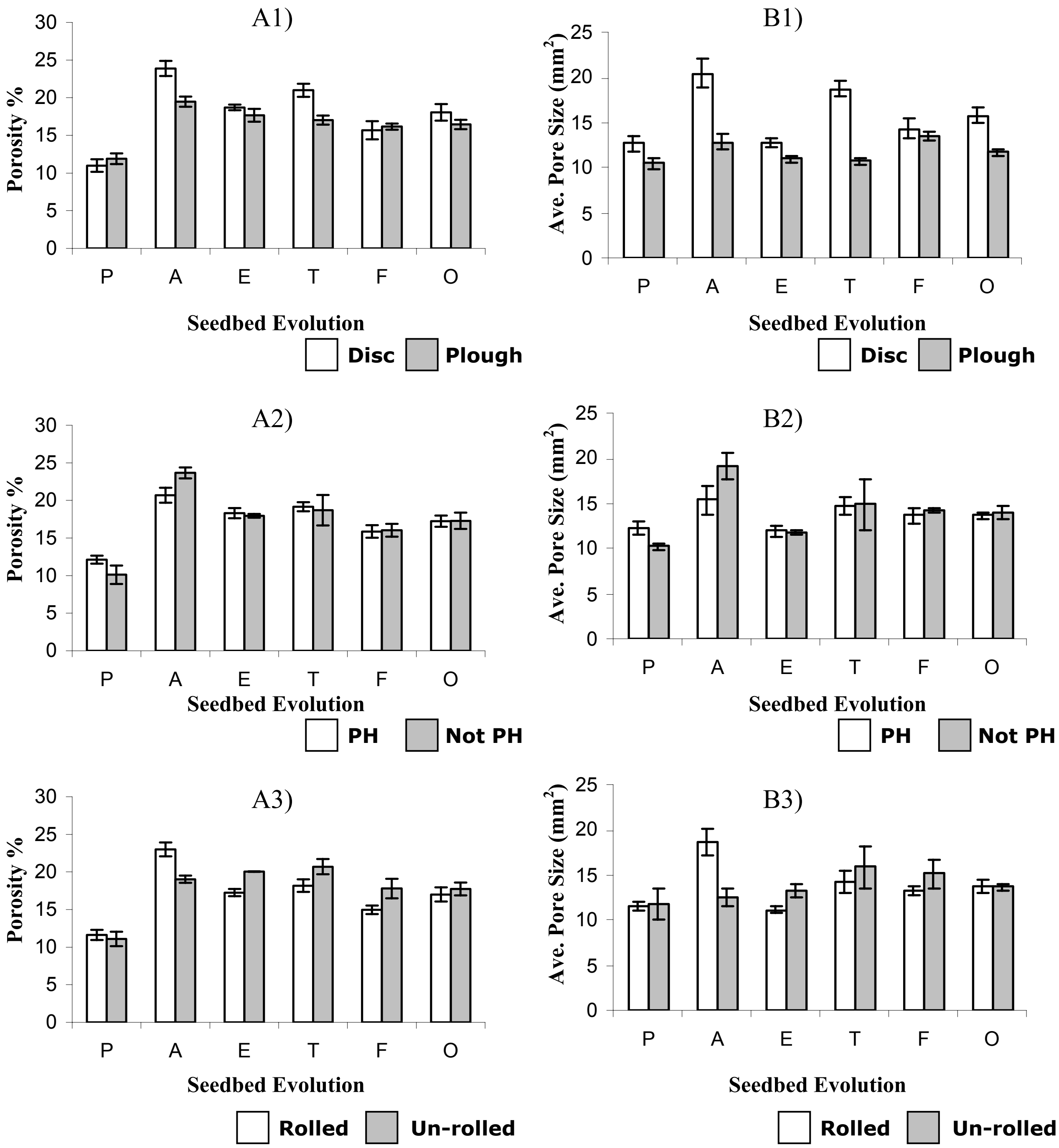


Figure 3.3: Changes in soil macro structure of A) porosity and B) average pore size mm^2, due to cultivation influences 1) primary cultivation. 2) power harrowing (PH). 3) rolling. Figures show mean variation at each time series evolution of the seedbeds, P = prior to cultivation, A = after cultivation, E = Emergence, T = establishment, F = spring establishment, and O = mean variation across the time series. Error bars in s.e.d

3.4.3 Macroscale pore size distributions (PSD)

Cultivation resulted in an overall increase in total pore area which is described by the PSD (Figure 3.4; 3.5). Ploughed treatments were normally distributed between 0.5 and 3 mm^2 $\log_{10}$, however, rolling resulted in an increased pore size, particularly where power harrowing was not applied. The same was not true of disced treatments following cultivation with all treatments resulting in larger pore sizes. Power harrowing produced a more uniform pore size distribution, while rolling considerably increased pore size. Pore area was greatly reduced as the seedbed evolved, however, the difference between primary cultivation remained the same with disc treatments generally having a greater total pore area and larger pore size. Power harrowed treatments within disc applications remained similar to results after cultivation, however, ploughing increased the number of larger pores. The application of power harrowing and rolling resulted in a decrease in total pore area. Around winter (Figure 3.4; 3.5) and spring establishment pore area and total number of larger pores increased slightly possibly in response to crop growth.

3.4.3.1 Pore size distribution - coefficient of uniformity (PSD_{cu})

The coefficient of uniformity (Kézdi, 1974) can be used to numerically illustrate the differences in distributions where large and small pores co-exist. This provides a ratio of the size of pores at a 10 % and 60 % total porosity of the sample (or distribution), the larger the ratio the greater the number of larger pores (Eq. (1)).

$$PSD_{CU} = \frac{d_{60}}{d_{10}} \qquad (1)$$

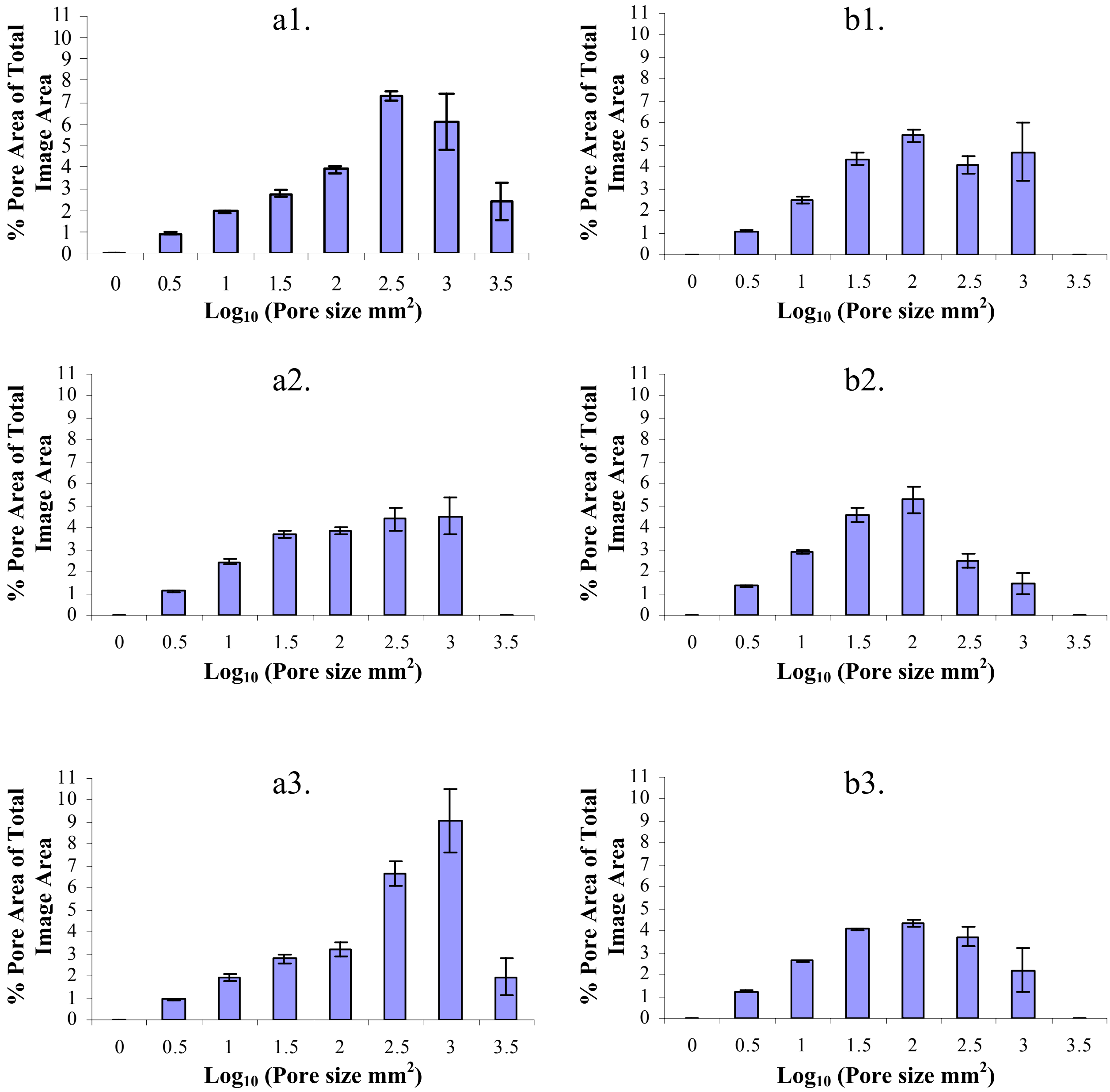


*Figure 3.4: Pore size distribution **after cultivation a**. Disc treatment. **b**. Plough treatment, with either 1) drill and roll. 2) power harrow and drill. 3) power harrow, drill and roll. From 0-70mm soil depth at the macroscale, expressed as percentage of total image area. Error bars in s.e.d.*

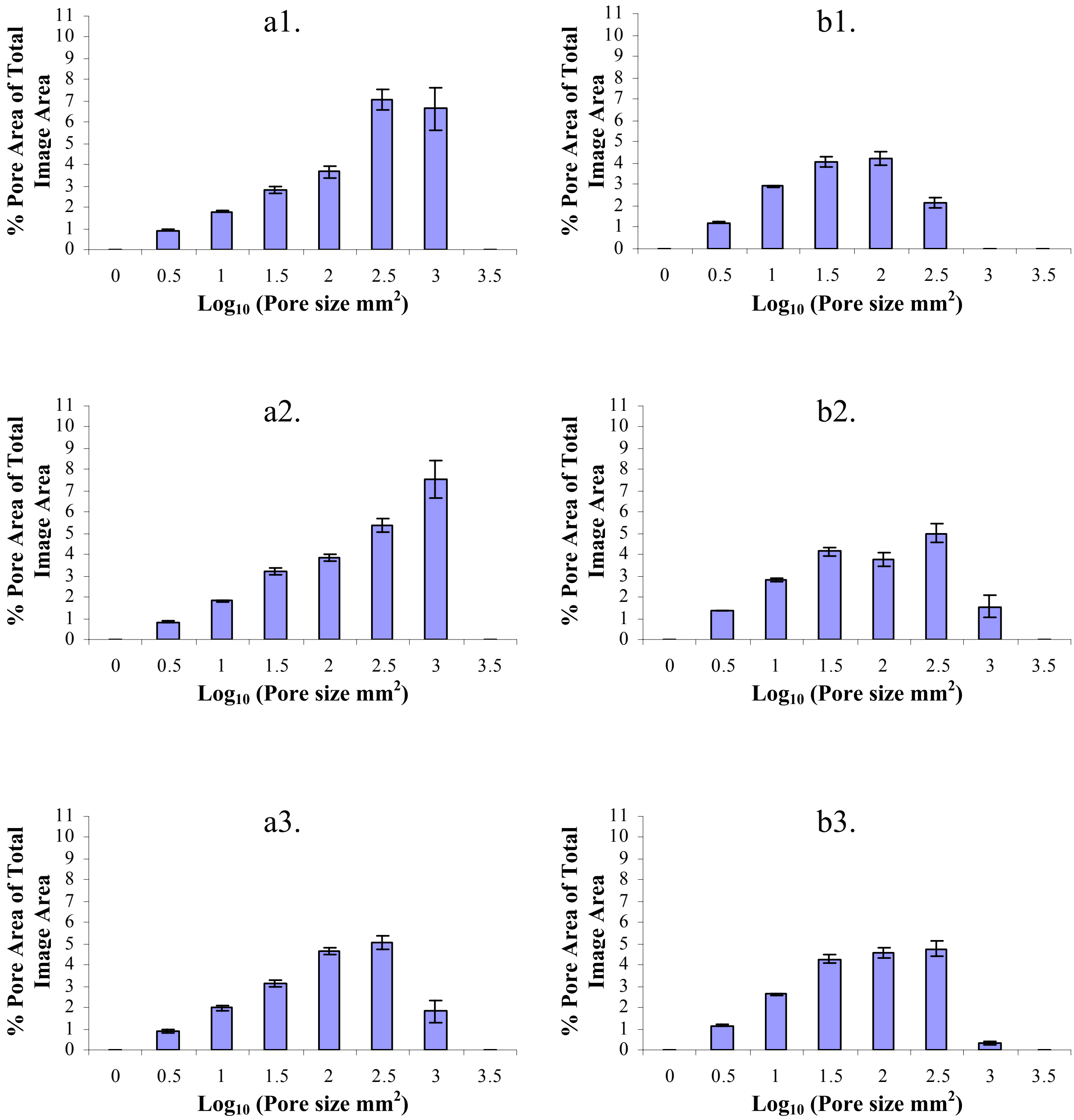


Figure 3.5: Pore size distribution at ***establishment a****. Disc treatment.* ***b****. Plough treatment, with either 1) drill and roll. 2) power harrow and drill. 3) power harrow, drill and roll. From 0-70mm soil depth at the macroscale, expressed as percentage of total image area. Error bars in s.e.d.*

No significant differences in PSD_{cu} were observed prior to cultivation with a mean ratio of 13.3 (Table 3.2). After cultivation there were no significant differences, as a result of large heterogeneity in porosity within the data, however trends in PSD_{cu} followed previous observations recorded for average pore size (Figure 3.6). Significant ($P < 0.001$) changes in the PSD_{cu} occurred over time as a result of cultivation. Over the evolution of the seedbeds, PSD_{cu} as a result of primary cultivation was significant ($P < 0.05$) with the mean difference higher with disc (ca. 21) than plough (ca. 17). There were highly significant ($P < 0.01$) differences between secondary cultivations once the seedbed had aged and crop establishment had occurred, with the largest ratio occurring within the power harrowed treatment (ca. 27 - 21), then rolled (ca. 28 - 20) and finally combined (power harrowed and rolled) (ca. 19 - 16) (Figure 3.6). Interactions between primary and secondary applications was significant with increased seedbed age ($P < 0.01$), accounting for larger ratios within ploughed treatments with rolling 37 and 23 in combination with power harrowing. However, under disc treatments, power harrowing had the largest ratio (ca. 20), then rolled (ca. 19) and combined (ca. 17). (Figure 3.6)

3.4.4 Soil structural relationships

The soil structural measurements derived by image analysis correlated strongly with the influence of soil strength changes, with direct correlations with penetration resistance and shear strength and soil macro structure porosity, pore size and PSD_{cu}. Over the evolution of the seedbed, the impact of increased soil strength resulted in a decrease in the measured structural properties of the soil. However, there were also significant correlations with cultivation at particular time periods, especially after

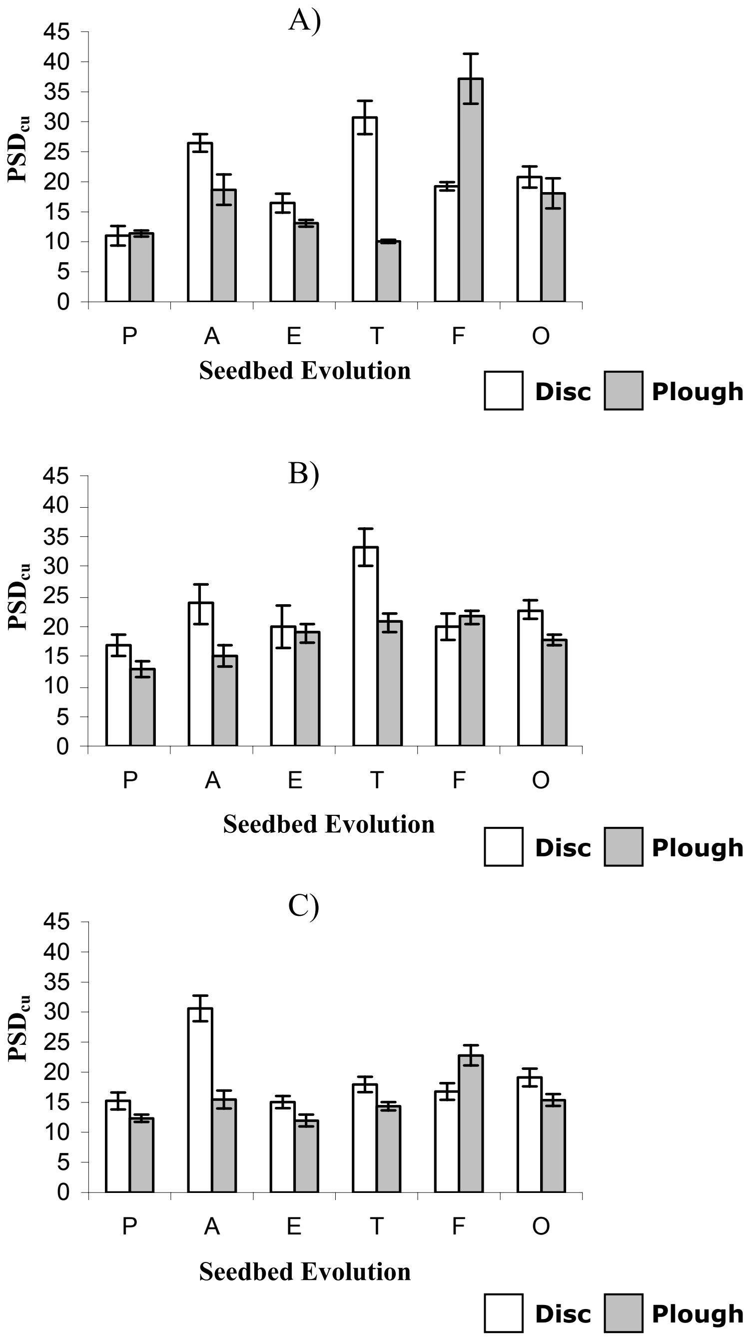


Figure 3.6: Mean variation in pore size distribution coefficient of uniformity. A) Mean variation of primary application and rolling. B) Mean variation of primary application and power harrowing. C) Mean variation of primary application, power harrowing and rolling. Figures show mean variation at each time series evolution of the seedbeds, P = prior to cultivation, A = after cultivation, E = Emergence, T = establishment, F = spring establishment, and O = mean variation across the time series. Error bars in s.e.d

cultivation and at establishment. These relationships showed increases within the structural components with an increase in strength or compaction, especially within the disc and rolled treatments.

Soil structural measurements were strongly correlated with crop establishment (per m^2). Establishment had a highly significant correlation with PSD_{cu}, with higher ratios associated with a reduction in crop establishment, showing that soil structures with larger pores are responsible for reducing establishment. This was also true with increasing porosity (%) and average pore size (mm^2), both of which resulted in reduced crop establishment with an increase in pore area (Figure 3.7).

3.4.5 Soil quality of establishment (SQE)

Previously, a model for predicting crop establishment (SQE) was developed based on the soil physical properties of a seedbed and the cultivation practices performed (Atkinson et al., 2007). The model accounted for 56 % of variation within the fitted data (collected in 2005) and 51 % of variation within a validation subset (collected in 2006). The model was successful in predicting crop establishment to within an error of 20 plants per m^2 at seven days post cultivation from soil physical measurements. Although the model worked, it was limited by the indirect and disturbed measurements which may not account for the actual field 2-D & 3-D soil porous architecture. It was therefore hypothesised that the model maybe further improved using soil structural measurements.

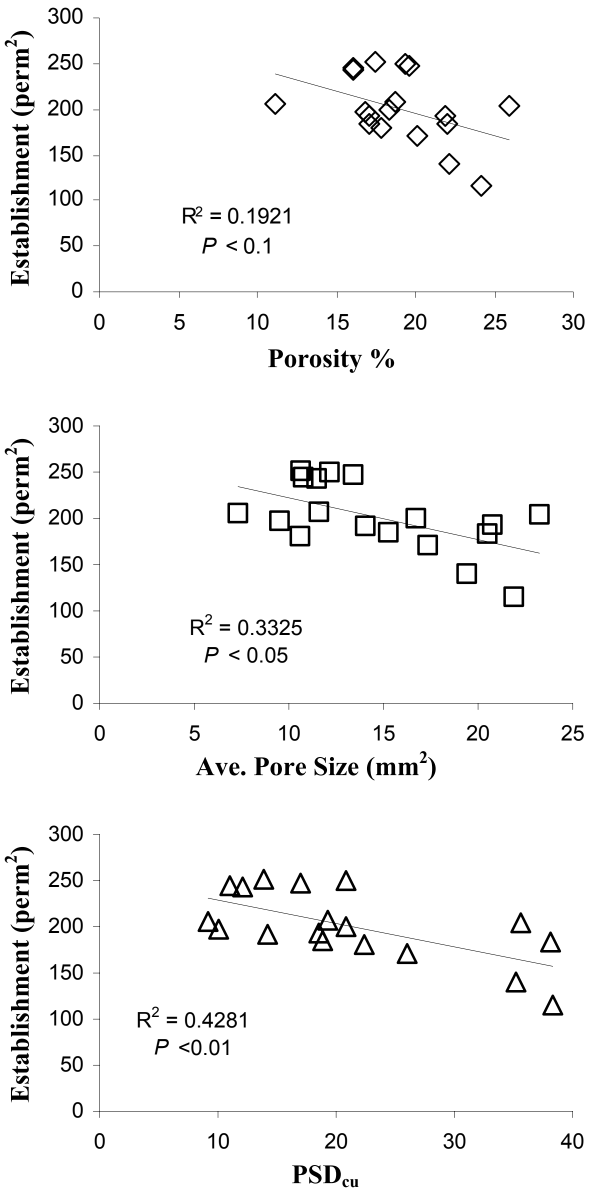


Figure 3.7: Correlations between establishment and increases in pore space of soil macro structure.

Multiple linear regression, using the macro structure data, was used to improve the model's predictive ability. Structural data was divided into time sequences; after cultivation, emergence and establishment. Each time period was then assessed against the original model, including porosity, average pore size and PSD_{cu}. As a model was created in each time period, its continued predictive ability was assessed against the subsequent time periods. Although perfect models, which included at least two of the structure factors, could be created especially after cultivation, the predictive power would not be the same with the subsequent time periods. This is most likely due to the large variations within the samples which occur at this period, as a result of soil natural heterogeneity over short distances and large disturbances in soil conditions. The issue with continued predictability at subsequent time periods created with data from after cultivation also applied to the emergence data, however this was not the case for the establishment data, models created at this time period were better at continued prediction at the different periods. Increasing the number of parameters within the model increased the error, and using the principle of parsimony it was found that models using single structural terms were more successful at continued prediction, especially porosity and average pore size. Both models including these factors were significant ($P < 0.01$) accounting for 66 % and 66.2 % with errors of 21.9 and 21.8 respectively. With the mean percentage difference across the time periods between predicted and observed establishment of 2 % within porosity and -4 % within average pore size, it was decided that total macro porosity provided the more consistent model.

The optimal model (Eq(2)) included the fitted terms of P = primary, S = secondary, R = rolled, BD = bulk density at 7 days and TP_m = total macro porosity (%). Regression analysis was significant as stated accounting for 74 % of variation, an increase of ca. 18 % from the original model, with an estimated error of ca. 17, a decrease of ca. 4, within the fitted data (Figure 3.8).

$$\mathrm{SQE} = 386 + 57.7 \times \mathrm{P} + 74 \times \mathrm{S} + 51.1 \times \mathrm{R} - 250.2 \times \mathrm{BD} - 0.18 \times \mathrm{TP_m} \tag{2}$$

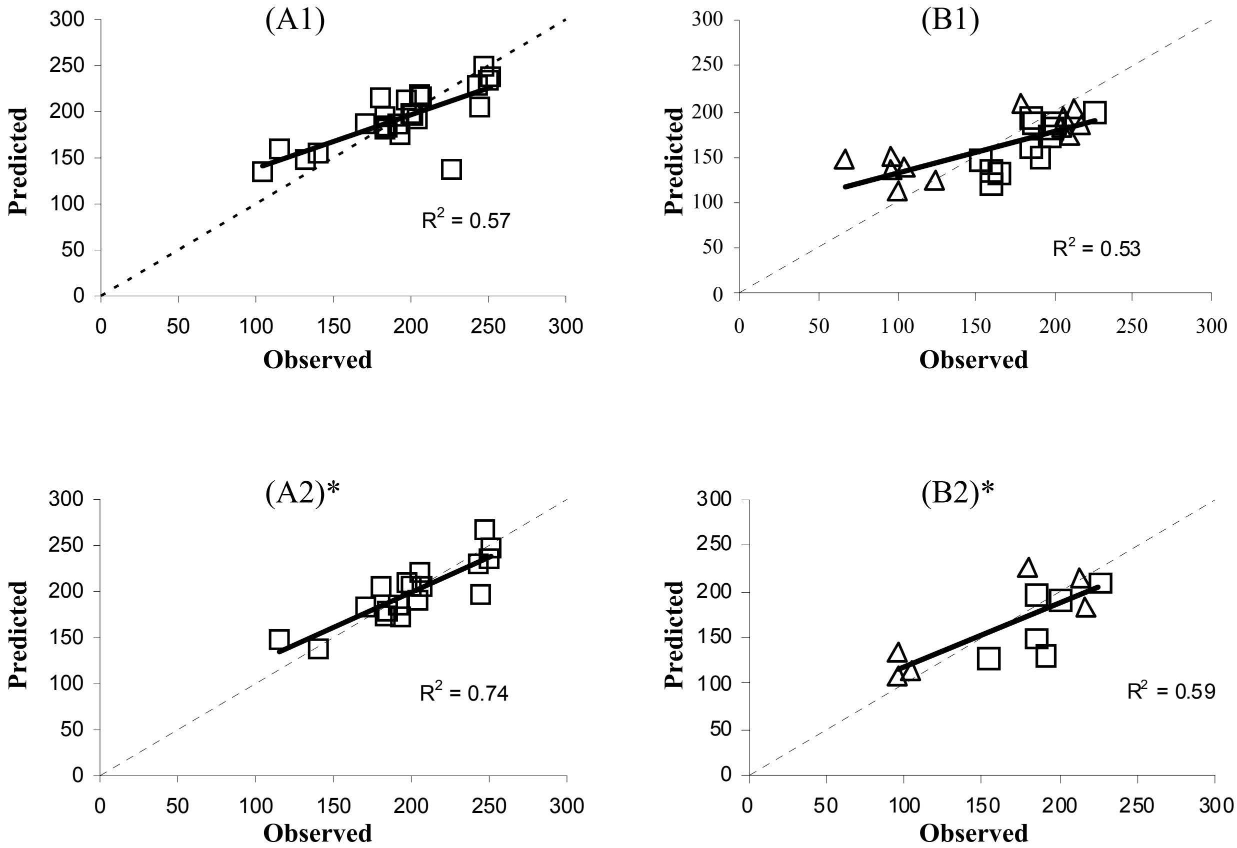


*Figure 3.8: Comparison of SQE model output for best fit models within (A) fitted data and (B) validation data, and the changes to model predictability from (1) physical input to (2) physical and macro porosity input. Validation was conducted over two soil types a clay loam (Δ) and sandy loam (□) as well as different environmental conditions to the data in which the model was created. Also note that structural additions in the validation are at difference scale of resolution to the fitted data. * Population change due to sample logistics.*

The improved SQE was validated against the 2006 / 7 season sub-set collected from experiments using disc treatments, ± power harrowing, with rolling post drilling and across two soil types (Dunnington Heath series – sandy loam and Worcester series – clay loam). Regression analysis performed on the validation sub-set gave a good fit which was significant ($P < 0.01$) accounting for 56 % of variation (Figure 3.8) and a standard error of 28. This was an improvement in the model with an increase in R^2 of 6, and an increased model fit to a 1:1 line of identity from 0.52 to 0.57 (Table 3.3). However, there was a slight increase in standard error by ca. 8.

*Table 3.3: Selected statistical variation between SQE model(s) previously developed and the addition of structural elements. ◊ Structural addition to the original models. * Observed population changes are a result of different seasons and changes in structural sampling regimes.*

	Original Fitted	**Original Validated**	**Fitted ◊**	**Validated ◊**
Significance (95% confidence limit)	<0.001	<0.001	<0.001	0.003
% Variation accounted	55.6	50.9	74	56
Estimated Standard Error	20.6	20.4	16.8	28.4
1:1 Line of Identity (R^2)	0.57	0.52	0.74	0.57
Slope	0.58 (SE 0.105)	0.46 (SE 0.093)	0.76 (SE 0.111)	0.69 (SE 0.181)
Intercept	80.79 (SE 20.94)	86.15 (SE 16.01)	46.73 (SE 22.71)	47.59 (SE 31.97)
Average Observed Population (per m^2)	193.34	167.24	200.54	170.14
Average Predicted Population (per m^2)	193	164.71	199.48	165.51
Mean % Deviation	-0.01	- 0.09	- 0.03	- 0.23

3.5 Discussion

The examined soil macro structure properties were significantly modified by cultivation techniques. Discing created seedbeds which had greater porous architecture compared to ploughed treatments. The porous architecture were likely a result of inversion and crop residue, which affects soil movement under passing cultivation equipment, with crop residue causing disturbance within the topsoil. This would lead to large scale movements of crop residue movement under the weight of the discs, resulting in increased porosity, whereas inversion allows for a more compact seedbed, due to a reduction in surface residue. Dao (1996) suggested large amounts of surface residue improves macroporosity near surface zones, which could also account for the higher porosity within disc treatments. However, a reversal occurred with seedbed age and crop establishment, this resulted in increased porosity of ploughed treatments, likely due to greater crop establishment.

Secondary cultivation was responsible for the greatest changes in soil structural conditions. Power harrowing resulted in consistent increases overall within pore area, this is possibly due to the fine seedbed development and the repetitive action power harrowing has upon the soil, which also allows for better soil-seed contact. Langmaack et al. (2002) found rotary harrowing resulted in a more stable bulk soil, which would account for reduced seedbed collapse which was also observed. Douglas & Koppi (1997) found the rotary harrow created a consistent seedbed regardless of the amount of previous or continued preparation, and attributed differences between macropore attributes as a consequence of rolling. Rolling had significant impact on the structural condition of the soil in particular, immediately after cultivation, resulting in very high porosity, pore size and PSD_{cu} which was unexpected as rolling is performed to consolidate the soil. The reason for this may be due to the way in which Cambridge rollers pass over the soil, creating compaction in some areas, but also pushing soil between the pressure points of the rollers, thus developing a higher percentage of larger pores (cracking) near the soil surface in a zone of disturbance, as illustrated conceptually in Figure 3.9. Over time however, seedbed collapse resulted in reduced porosity as an outcome of rolling, due to soft ridge collapse and infilling of pores.

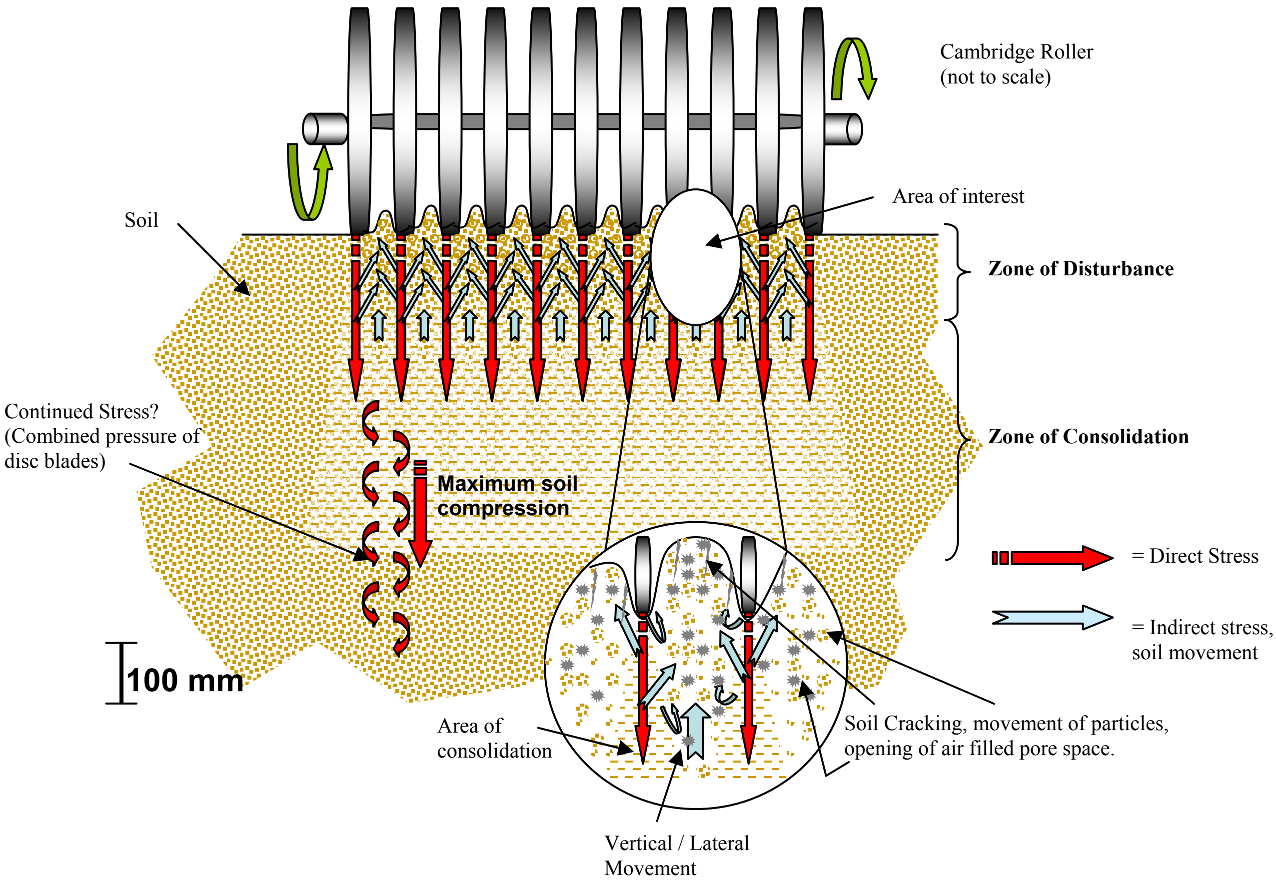


Figure 3.9: Compression stress regime which causes increased porous architecture under rolled cultivation applications.

Increases in pore space occurred around establishment and spring establishment, probably as a consequence of crop growth, due to the movement of the shoot through the soil and the opening of pore space around the plant shoot. This would explain why pore space increased more within ploughed treatments which had more established plants than disced plots. Seedbed evolution also resulted in increased soil strength, either resistance or shear, which led to a decrease in soil porosity, pore size and PSD_{cu} in most treatments with the exception of some disc treatments and rolled treatments, likely a result of shallow cultivation, crop residues, soil cracking and crop growth. These influences would result in higher overall strength of the soil, but at the same time increased larger pore space.

The SQE was statistically improved with the addition of macro porosity as an influencing factor upon establishment, accounting for ca. 60 % of the variation in establishment with relatively low standard errors in respect to natural variability. However, the addition of more than one element did result in larger errors through over prediction if assessed at both the different time periods and validation sub-set. This is because, although soil macro porosity, average pore size and PSD_{cu} are measures of the soil structural condition, they each account for size of pore space i.e. not shape or connectivity. The best model fitted was a combination of porosity and PSD_{cu}. However we suggest this was over-paramatised, and the parsimonious application of porosity worked well at each time period of soil structure sampling, giving accurate prediction. This addition of soil structure to the model and the improvements observed confirmed that soil structural properties are directly linked with crop establishment.

3.6 Conclusions

Quantified image analysis of seedbed soil structure revealed crop establishment was significantly reduced by increases in pore space, possibly a result of reduced soil seed contact and lack of nutrient capture from transmission pores. The greatest crop establishment occurred under consistent and finer seedbeds such as power harrowed, or the removal of surface residue (preventing soil disturbance) i.e. ploughing.

The effect of soil structural elements is therefore key to explaining establishment; this was further demonstrated with direct improvements to the soil quality of establishment (SQE) model with the addition of structural variables. Each structural variable on its own, and in combination, improved the original model developed using bulk density and cultivation techniques. The most parsimonious SQE model, which included the addition of macro porosity (%), produced the best fit model.

It is clear that the finer and more homogeneous seedbed structures produce the greatest establishment, mainly achieved through power harrowing and ploughing. The poorest soil structure and seedbed performance was produced by discing and rolling. Optimum structural conditions for establishment observed in this data (soils and resolution) occurred between ranges for porosity of 10-19 %, average pore size of 8-12 mm^2 and PSD_{cu} ratio of 8-17. These ranges are quite broad with a large amount of overlap between cultivation technique due to soil heterogeneity and it may therefore be further hypothesised that finer scale resolution may provide greater understanding of structural conditions and their effect on crop establishment.

3.7 Acknowledgments

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Chapter 4:

Effect of seedbed cultivation and soil meso structure on the establishment of winter wheat (*Triticum aestivum* cv. Robigus)

4.1 Introduction

Seedbed preparation has a significant influence on the physical properties of soil including soil structure as previously shown in chapter 3. The soil condition affects the ability of the crop to establish due to factors such as compaction, reduced soil seed contact, reduced nutrient uptake etc. The quantification of soil structure by image analysis has been performed by a number of researchers (Ringrose-Voase and Bullock, 1984; Ringrose-Voase, 1987; Ringrose-Voase, 1996; Vogel, 1997; Horgan, 1998; Lipiec et al., 2006). Advances in this technique have occurred relatively quickly due to technological improvements in digital imaging and computer processing e.g. Lipiec et al. (2006) allowing for high resolution imaging, large image storage, faster processing capability as well as developments in software. Images derived from resin impregnated soil blocks have been used in a variety of soil structural analyses ranging from the assessment of pore connectivity (Vogel, 1997) to the determination of soil fractal parameters (Pachepsky et al., 1996; Giménez et al., 1997).

Image analysis of soil structure is used regularly in agricultural experiments to study field management practices and their effect on the soil environment. The quantification of shape, size and continuity of pores helps the understanding of the effects of changes to soil induced by management practices (Pagliai et al., 2004). A number of studies have considered the effects of different tillage methods on soil porosity. Lipiec et al. (2006) observed the effect conventional, reduced and no till systems had on a silt loam and found marked differences in pore size and distribution which affected water infiltration, which was fastest under conventional tillage. Hubert et al. (2007) observed significant changes over the evolution of a seedbed in the pore morphology under conventional tillage, but little change in both total porosity and pore shape under reduced and no till systems. VandenBygaart et al. (1999) also observed morphological changes in the upper three cm of soil under no tillage systems, stating that increased time under no till management resulted in pore morphology changes of increased porosity, pore roundness and irregular pores. VandenBygaart et al. (1999) also found that under conventional tillage, pore morphology is maintained each year and that four years of no tillage is required to achieve the same levels of pore morphology observed under conventional tillage.

Poor management practices can also lead to soil degradation due to compaction or the formation of surface crusts. Pagliai et al. (2004) found ploughing in comparison to reduced tillage systems resulted in soil more susceptible to degradation. Douglas and Koppi (1997) found conventional tillage resulted in poorer structural conditions in terms of porosity and pore morphology at both the surface and at depth within a profile, whereas, reduced pressure systems result in degradation at shallower depth with zero traffic greatly improving structure conditions in comparison. Pagliai et al. (2003) also found significant decreases in porosity of the surface layer with single passes of tractors and further reductions with an increase in the number of passes. Soil degradation from poor management practices can also result in a surface crust which can be detrimental to crop growth and water infiltration (Fox et al., 2004). Usón and Poch (2000) found reduced tillage did not reduce surface crusting, and in fact, was more susceptible to slaking and deposition in a series of events, compared with crusting under conventional tillage which is discontinuous and results from a single event.

Examination of the macro structure of cultivated soil, using X-ray Computed Tomography, has shown a relationship between management type and soil structure with increased pore space resulting in reduced establishment for winter wheat (Atkinson et al., 2007). However, the relationship could not be explained beyond this and it was hypothesized that a further detailed assessment of the soil porous architecture at finer scales may provide a better understanding of the soil condition and its effect on crop establishment.

Previous studies of soil structure using image analysis have concentrated on the direct impact of management practices, mainly in terms of compaction. Very few have concentrated on the effects on crops and fewer still on the effect cultivation has upon soil structure and subsequently crop establishment. The objectives of this experiment were (i) to identify changes in soil meso structure in a range of evolving seedbeds created by different cultivation methods, (ii) to determine the effects of soil meso structure on crop establishment and (iii) to develop a model to predict crop establishment based on soil physical properties and the structure of the cultivated soils.

4.2 Materials and methods

4.2.1 Field site and experimental design

A field experiment was established at the University of Nottingham experimental farm, Sutton Bonington, Leicestershire, UK (52.5°N, 1.3°W). The soil was a sandy loam of the Dunnington Heath series (FAO class; Stagno-Gleyic Luvisol) (Chapter 3, Table 3.1).

The field was in a rotation of winter oats, winter wheat, sugar beet, winter wheat, with the current experiment in winter wheat following winter oats. The experimental design was a 2 x 2 x 2 factorial, arranged in a split plot with three replicate blocks. Primary cultivations (plough or disc) were arranged on the main plots, which were divided into four sub-plots on which the other treatments were factorally combined and allocated at random; secondary cultivation (+/- power harrow) and tertiary cultivation (+/- rolling) with Cambridge rollers post-drilling. Previous cultivations for two years had been performed by a single pass of a heavy disc cultivator incorporating a levelling board and roller (Vaderstad Carrier Super CR500). The experiment comprised of 24 plots that were 24 x 2.5 m wide, 8 plots per block in 3 blocks with 12 metre discards between the blocks. Plots were drilled using a Nordsten drill with winter wheat (*Triticum aestivum*) cv. Robigus at a rate of 250 seeds per m^2 on 27 September 2005. Cultivations were performed the day before drilling for primary cultivations and the day of drilling for secondary cultivations and rolling.

Sampling for model validation was conducted at the University of Nottingham, Sutton Bonington, Leicestershire, UK (52.5^{o}N, 1.3^{o}W), in an adjacent field to the previous year, and at Bunny, Nottinghamshire, UK (52.52^{o}N, 1.07^{o}W). The soils were a sandy loam from the Dunnington Heath series (FAO class; Stagno-Gleyic Luvisol) at Sutton Bonington and a clay loam from the Worcester series (FAO class; Argillic Pelosol) at Bunny (Chapter 3, Table 3.1). Both sites were drilled with winter wheat (*Triticum aestivum*) cv. Einstein at a rate of 300 seeds per m^2 in early October 2006.

4.2.2 Soil structure sampling

Soil samples were collected by removing undisturbed soil from the top 70 mm of the soil profile with Kubiena tins (70 x 70 x 50 mm) from a shallow pit within the centre 1 m of each plot leaving a 0.75 m distance from all wheel traffic in randomised locations and repeated twice per plot, totalling six replicates per treatment. The orientation was marked and samples carefully removed from the soil by excavating around the container. Samples were wrapped in cling film to prevent moisture loss and damage. Samples were taken at the key stages of seedbed evolution; prior to cultivation, after cultivation, emergence, establishment and spring establishment. Plots that only received primary cultivations were not considered here resulting in a 2 x 3 factorial design of primary (plough or disc) and secondary cultivation; rolled (NR), power harrowed (SN) and combined power harrow and rolled (SR).

4.2.3 Resin impregnation of undisturbed soil cores

This was conducted using the method included in chapter 3 section 3.3.3.

4.2.4 Image acquisition from resin impregnated soil blocks

A Logitech CS10 thin section diamond saw was used to cut the sample in the vertical plane, after which the sample face was dried and cleaned. Samples were smoothed by manual grinding using SiC Grinding paper (Buehler, UK) and lubricant, to remove surface irregularities caused by the diamond saw, different grades of grinding paper (240, 600, 1200) were used depending on the degree of roughness. The polished faces of the samples were protected in METCOAT specimen protective lacquer (Buehler, UK). The soil samples were then photographed under darkroom conditions.

The samples were levelled and orientated on sand (to ensure constant focal length) and placed on a copy stand. An Olympus Camedia C-4000 Z digital camera and an Ultra Violet light source (UVP – Model UVL-28 assembly, long wave, 230v, 50Hz, 0.32Amps) was set at constant distance from the sample surface to maintain the same resolution. The camera was set with the following image acquisition settings; macro lens; full zoom (3x optical); no flash; image size 1600 x 1200 pixel; and TIFF (tagged image format). A Raynox RT5241 F52-M41mm UV (o) filter was attached to the camera lens to prevent over exposure. Optimum image illumination was achieved through brightness settings. A Kodak colour chart for image calibration was placed in the field of view. Images were acquired on digital media cards and transferred to a PC for digital processing (Figure 4.1).

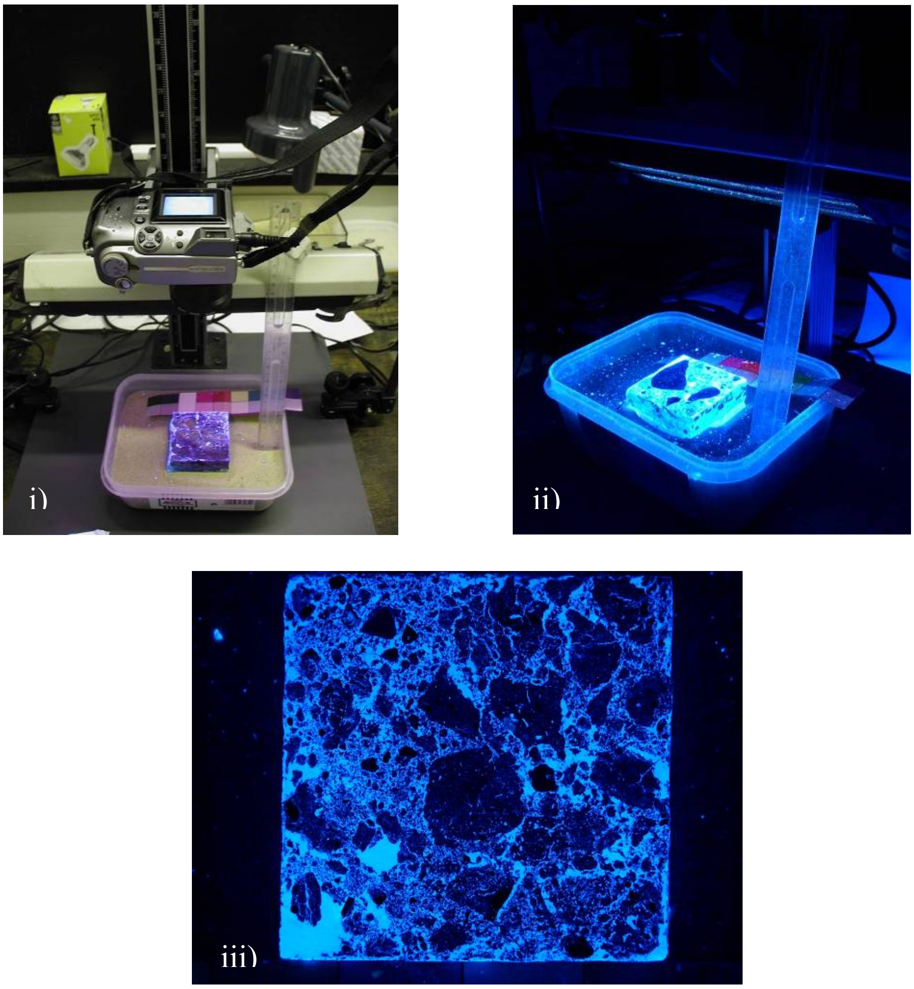


Figure 4.1: Images show Ultra Violet imaging of resin impregnated soil blocks. i) Copy stand, camera and UV light source set-up. ii) Florescent soil block surface. iii) Example of good impregnation and imaging of soil surface.

4.2.5 Image processing and analysis

Image manipulation was performed using AnalySIS® (Soft Imaging Systems (SIS), Münster, Germany) to isolate pore space (Figure 4.2). The image resolution was 62 µm pixel^{-1}. Images were initially cropped to a size of 65 x 65 mm, however at this resolution, large amounts of noise within some images was observed. Images were therefore re-cropped to a size of 43 x 43 mm, removing the majority of noise introduced by stones and edge effects.

Colour filtering was performed using the following steps: 1) Calibration and rotation. 2) Frame size set (43 x 43 mm); 3) Median filter, providing image smoothing; 4) Lowpass filter, as a noise filter and strong image contrast smoothed; 5) Rank filter, which removes spot noise from the original, adjusts pixel values in the centre to grey values in surrounding area; 6) Image converted to greyscale. Images were then binarised using an auto threshold (removing operator bias) within AnalySIS®, defined by the greyscale value of the pixel, allowing for identical threshold parameters. A single morphological filter was then applied to the binary image: 1) Erosion, reducing noise by replacing each pixel with the median neighbouring pixel value (Figure 4.2). Plant material was included as pore space due to issues with density differentiation between air and root.

Morphological analysis was performed on binary images (Figure 4.3) using AnalySIS®, this included the following pore measurements; porosity – total percentage pore area of the sample; mean pore area – average pore size of the sample; equivalent circle diameter (ECD) - the diameter of a circle that has an area equal to the area of the pore analysed; elongation - pore roundness as a result of sphericity, defined from 1 = spherical to 20 = elongate and flat; nearest neighbour distance - the average distance between pores from centre to centre; and mean pore perimeter - defined as the sum of the pixel distances along the closed boundary of the pore analysed.

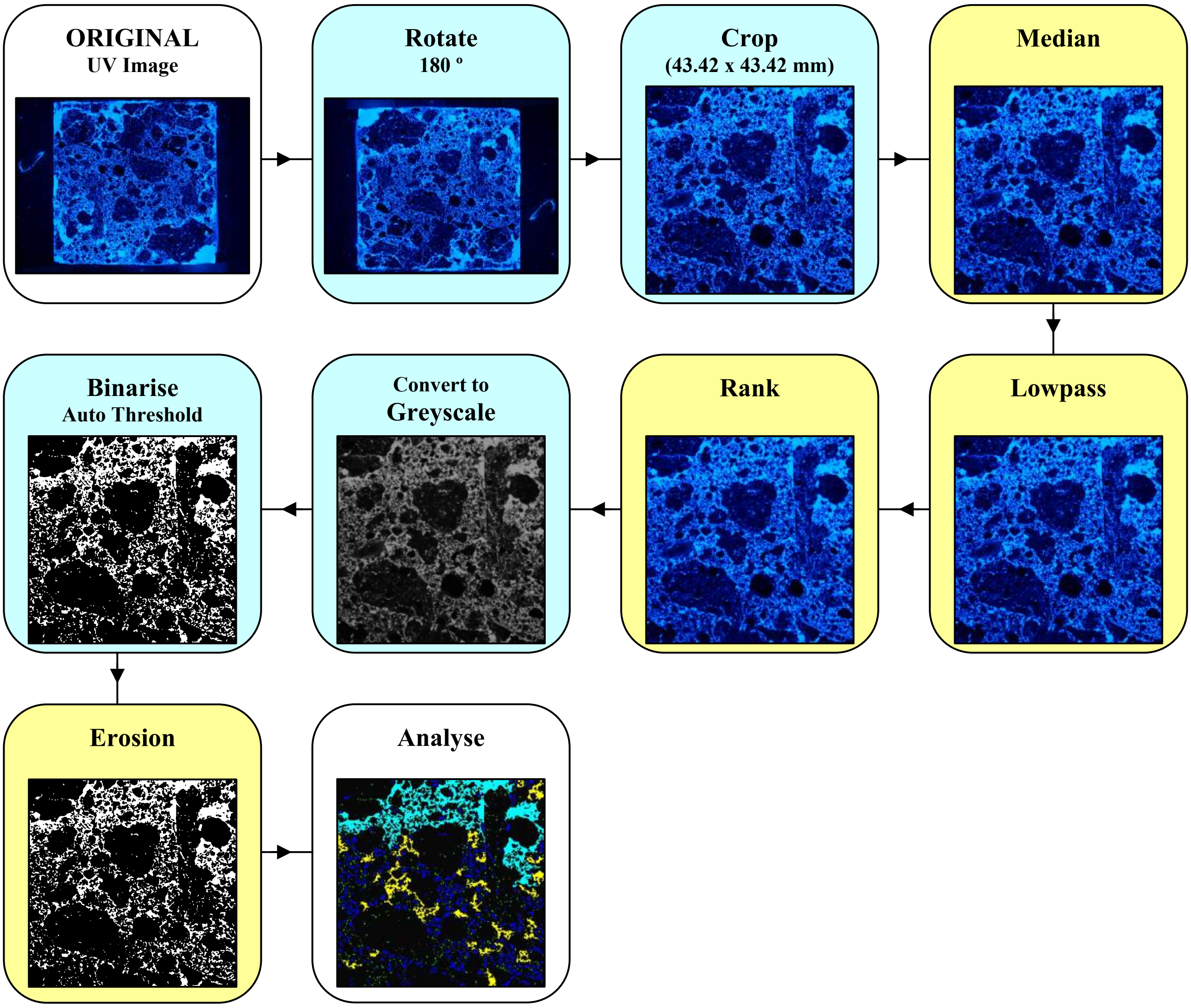


Figure 4.2: Image manipulation of resin impregnated soil block.

4.2.6. Statistical analysis

The statistical software package GenStat™ v.8.1 was used to analyse all data using an analysis of variance (ANOVA) to test for significant differences between treatments and to calculate standard errors of difference (S.E.D).

4.3 Results

4.3.1 Seedbed evolution

Seedbed evolution seen in *figure 4.3* clearly shows variation over time from prior to cultivation through to spring establishment. Pore space, displayed in white, increased significantly after cultivation with obvious variation between both primary (residue observable in disc treatments) and secondary cultivations. Increased root and shoot material was also evident as time passes. In the following sections these differences are described in detail from quantified image analysis.

4.3.2 Meso scale porosity

Soil porosity was not significantly different between plots prior to cultivation with the variability between 8-10 % (Table 4.1). Porosity was significantly increased with cultivation to between 19–29 %, although primary cultivation had no significant effect on soil porosity until establishment (P = 0.046), when increased porosity was observed within disc compared to ploughed treatments (c. 4.2 %). Over the evolution of the seedbed, secondary cultivation clearly increased soil porosity, particularly after cultivation with increased porosity under rolling (P < 0.001) compared with power harrowing (Figure 4.4). The greatest increase in porosity occurred in combined treatments. The increased porosity reduced over time but remained higher in treatments which were rolled until spring establishment (+155 days) (P = 0.023) (Figure 4.4). Significant interaction occurred over time between primary and secondary cultivations (P = 0.004) with increased porosity under rolling and reduced porosity under power harrowing within disc treatment and the reverse in ploughed treatments (Figure 4.4).

a)

b)

c)

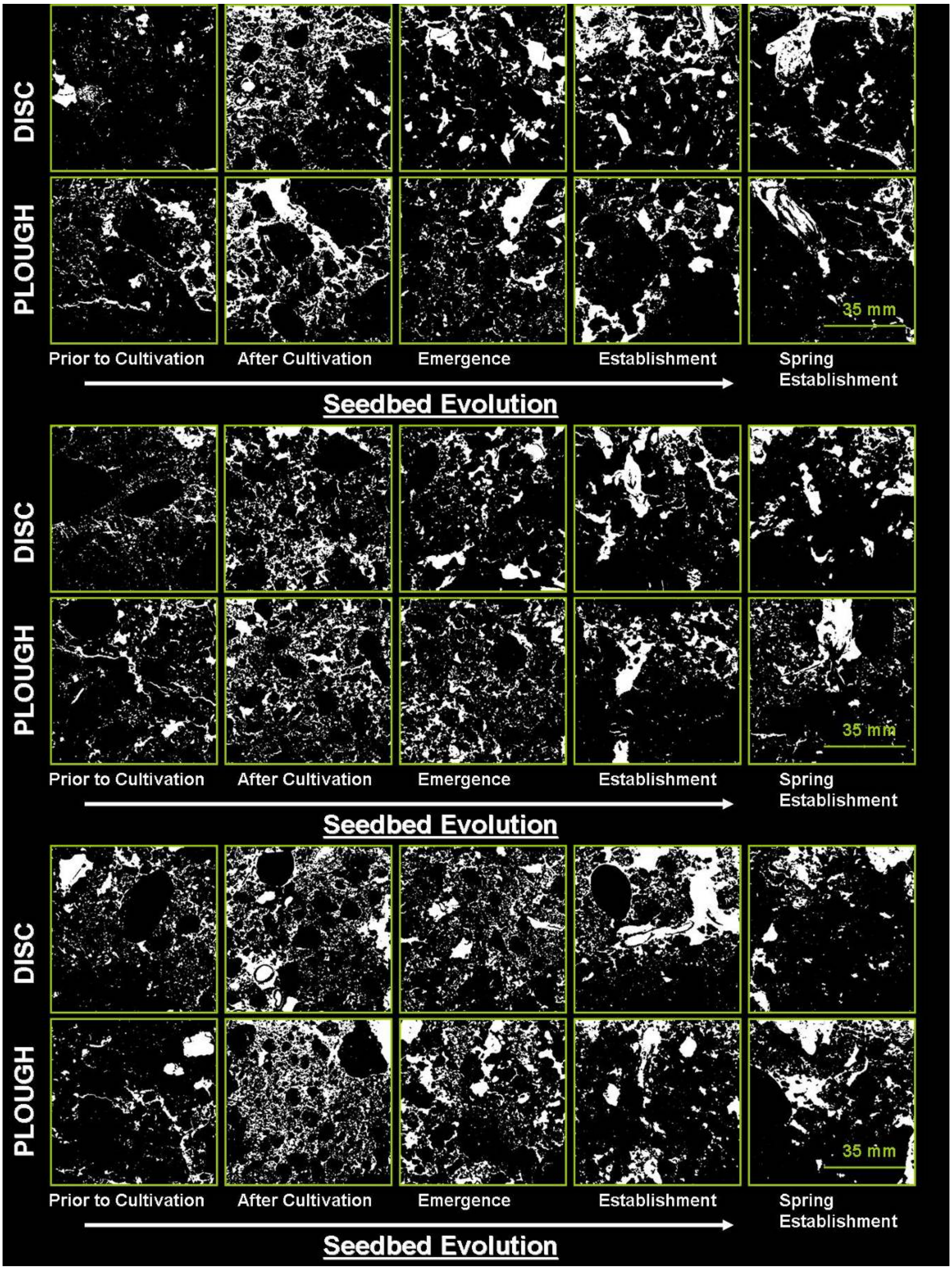


Figure 4.3: Seedbed evolutionary changes between primary treatments. A) Primary and rolled. B) Primary and power harrowed. C) Primary, power harrowed and rolled. (white = pore space) see section 4.3.1 for explination.

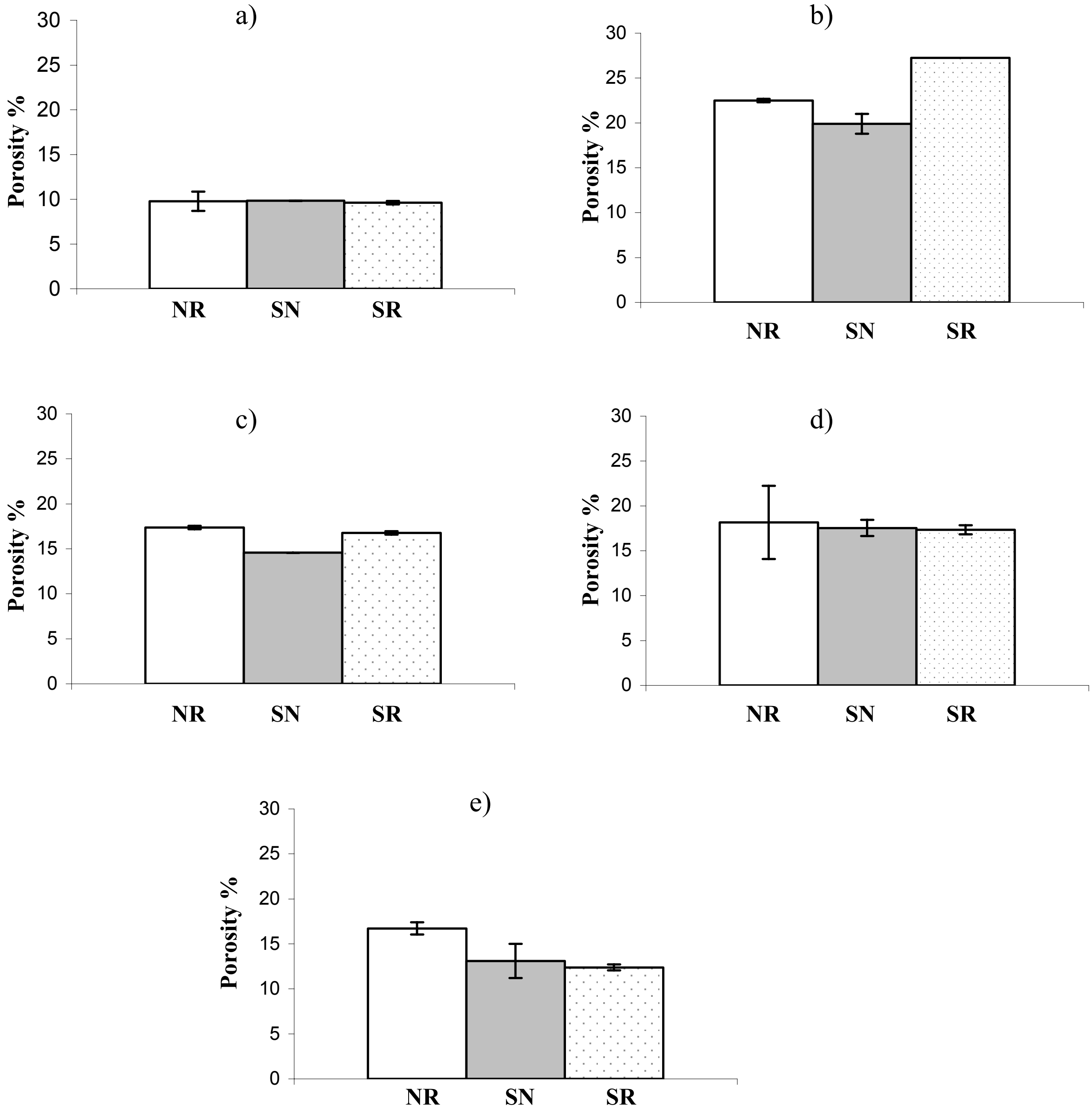
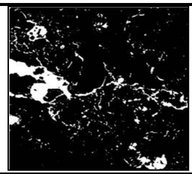


Figure 4.4: Mean porosity variation between secondary applications (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled) at each time period a) Prior to cultivation, b) After cultivation, c) Emergence, d) Establishment, e) Spring Establishment. Error bars represent s.e.d

Table 4.1: Mean soil porosity variation over the evolution of the seedbeds created by different cultivations. Images representative of PPD treatment, white represents porosity.

PRIOR to Cultivation

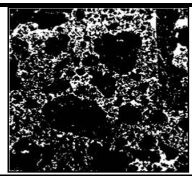
(- 6 Days)



Treatment	Primary	Secondary	Rolled	**Porosity %**	s.e.d	**PSD_{cu}**	s.e.d	**Area (mm^2)**	s.e.d
DDR	Disc	N	Y	8.70	1.465	45.58	12.666	0.30	0.062
DPD	Disc	Y	N	9.85	1.288	83.09	17.985	0.37	0.062
DPDR	Disc	Y	Y	9.94	1.181	66.12	12.656	0.36	0.055
PDR	Plough	N	Y	10.86	0.956	55.88	12.615	0.42	0.064
PPD	Plough	Y	N	9.82	1.666	101.43	24.303	0.38	0.089
PPDR	Plough	Y	Y	9.30	0.799	63.90	10.738	0.41	0.076

AFTER Cultivation

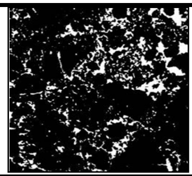
(+ 7 Days)



Treatment	Primary	Secondary	Rolled	**Porosity %**	s.e.d	**PSD_{cu}**	s.e.d	**Area (mm^2)**	s.e.d
DDR	Disc	N	Y	22.29	1.084	144.67	37.924	0.82	0.042
DPD	Disc	Y	N	21.00	1.045	45.50	5.759	0.58	0.032
DPDR	Disc	Y	Y	25.64	1.339	173.04	28.486	0.82	0.164
PDR	Plough	N	Y	22.68	0.999	105.11	23.260	0.97	0.084
PPD	Plough	Y	N	18.80	0.871	51.14	10.446	0.49	0.040
PPDR	Plough	Y	Y	28.84	1.359	140.52	28.590	0.91	0.155

EMERGENCE

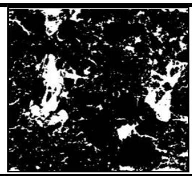
(+ 36 Days)



Treatment	Primary	Secondary	Rolled	**Porosity %**	s.e.d	**PSD_{cu}**	s.e.d	**Area (mm^2)**	s.e.d
DDR	Disc	N	Y	17.18	0.723	62.07	8.622	0.71	0.073
DPD	Disc	Y	N	14.61	1.285	57.03	23.129	0.66	0.142
DPDR	Disc	Y	Y	15.35	1.028	40.14	7.931	0.34	0.034
PDR	Plough	N	Y	17.57	1.021	65.00	15.431	0.60	0.068
PPD	Plough	Y	N	14.56	1.247	29.61	5.803	0.36	0.068
PPDR	Plough	Y	Y	18.19	1.389	69.94	19.907	0.49	0.058

ESTABLISHMENT

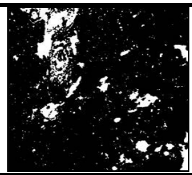
(+ 63 Days)



Treatment	Primary	Secondary	Rolled	**Porosity %**	s.e.d	**PSD_{cu}**	s.e.d	**Area (mm^2)**	s.e.d
DDR	Disc	N	Y	22.23	0.615	159.85	47.827	1.01	0.094
DPD	Disc	Y	N	18.43	0.659	199.09	60.898	0.96	0.110
DPDR	Disc	Y	Y	18.64	1.648	177.61	75.672	0.56	0.079
PDR	Plough	N	Y	14.10	1.048	50.30	9.390	0.50	0.077
PPD	Plough	Y	N	16.63	1.715	106.46	29.075	0.54	0.046
PPDR	Plough	Y	Y	16.03	0.624	104.46	22.079	0.58	0.033

SPRING Establishment

(+ 155 Days)



Treatment	Primary	Secondary	Rolled	**Porosity %**	s.e.d	**PSD_{cu}**	s.e.d	**Area (mm^2)**	s.e.d
DDR	Disc	N	Y	17.40	2.226	95.32	31.594	1.23	0.106
DPD	Disc	Y	N	14.99	1.811	29.81	5.619	1.12	0.159
DPDR	Disc	Y	Y	12.31	0.766	65.45	13.347	0.83	0.101
PDR	Plough	N	Y	16.04	1.325	97.29	42.219	0.98	0.099
PPD	Plough	Y	N	11.23	1.259	242.85	93.986	0.53	0.077
PPDR	Plough	Y	Y	12.46	1.430	79.32	11.144	0.75	0.141

4.3.3 Mean pore size (mm^2)

Average pore size (mm^2) was not significantly different prior to cultivation with mean values between 0.3-0.4 mm^2 (Table 4.1). Pore size significantly increased following cultivation to 0.5-1 mm^2. Primary application had no significant effect on pore size over the evolution of the seedbed. Secondary cultivation however, clearly increased pore size, particularly after cultivation with significantly (P = 0.045) increased pore sizes in treatments which were rolled (ca. 0.35 mm^2) (Figure 4.5) compared to unrolled. The increases in pore size reduced over time with a significant decrease in average pore size with increasing secondary cultivation intensity (P = 0.043) (Figure 4.5). By spring establishment average pore size was reduced by c. 0.3 mm^2 from the least to most intensive secondary cultivation (P = 0.05) (Figure 4.5). The interaction between primary and secondary cultivation significantly (P = 0.004) decreased average pore size with increasing secondary intensity under disc treatments. However, ploughing created relatively consistent pore sizes under treatments which were rolled or power harrowed and rolled, and reduced pore sizes under power harrowing.

4.3.4 Equivalent circle diameter (ECD)

No significant difference in ECD was observed prior to cultivation with a mean value c. 0.41 mm (Table 4.2). A significant interaction (P = 0.039) was observed after cultivation with disc treatments which received rolling having reduced ECD, with the most intensive cultivation having the smallest ECD. However, within ploughed treatments, the converse was true, rolled treatments had a higher mean ECD than unrolled (Figure 4.6).

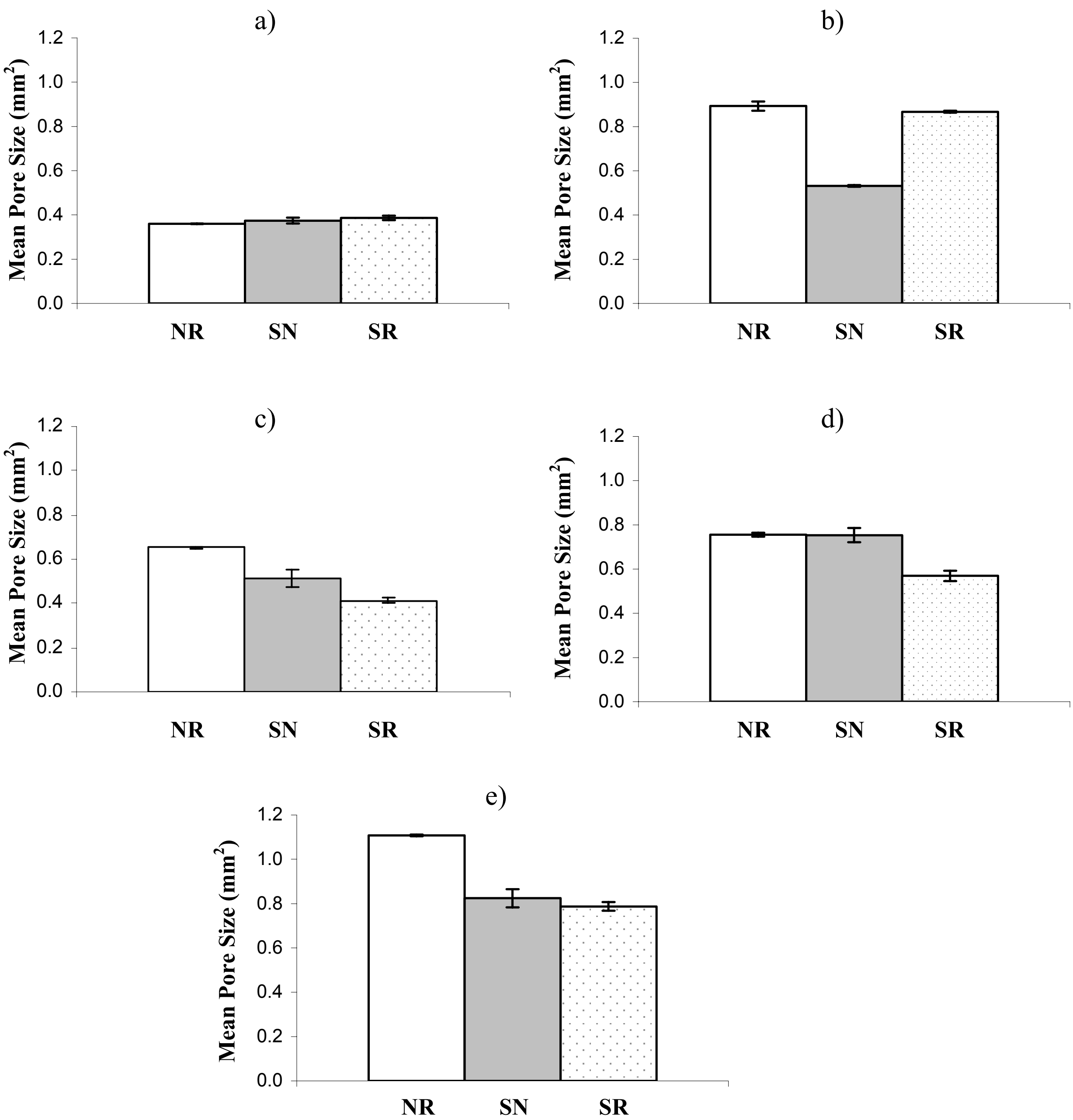


Figure 4.5: Mean pore size (mm^2) variation between secondary applications (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled) at each time period a) Prior to cultivation, b) After cultivation, c) Emergence, d) Establishment, e) Spring Establishment. Error bars represent s.e.d

No significant differences were observed at emergence or establishment. At spring establishment however, discing had much higher mean ECD than ploughed plots (P = 0.025). ECD also decreased with an increase in secondary cultivation intensity (P = 0.009). Consistent with measurements after cultivation, rolling reduced ECD in disced plots but increased ECD in ploughed plots (P = 0.011) (Figure 4.6).

4.3.5 Mean pore perimeter (mm)

No significant difference in pore perimeter was observed prior to cultivation or as a result of primary cultivation. However, rolled treatments had significantly (P = 0.012) larger pore perimeters than power harrowed treatments (Figure 4.7). Over the evolution of the seedbed, pore perimeter was significantly (P = 0.011) larger within the rolled treatment and decreased with an increase in cultivation intensity (Figure 4.7) (Table 4.2). Pore perimeter decreased with increasing cultivation intensity under disc treatments while under ploughed treatments both rolling and power harrowed and rolled treatments had greater pore perimeters than power harrow alone (P < 0.001) (Figure 4.8). The increases in mean pore perimeter are likely associated with increases in pore size as a result of cracking caused by rolling (Chapter 3, Figure 3.9).

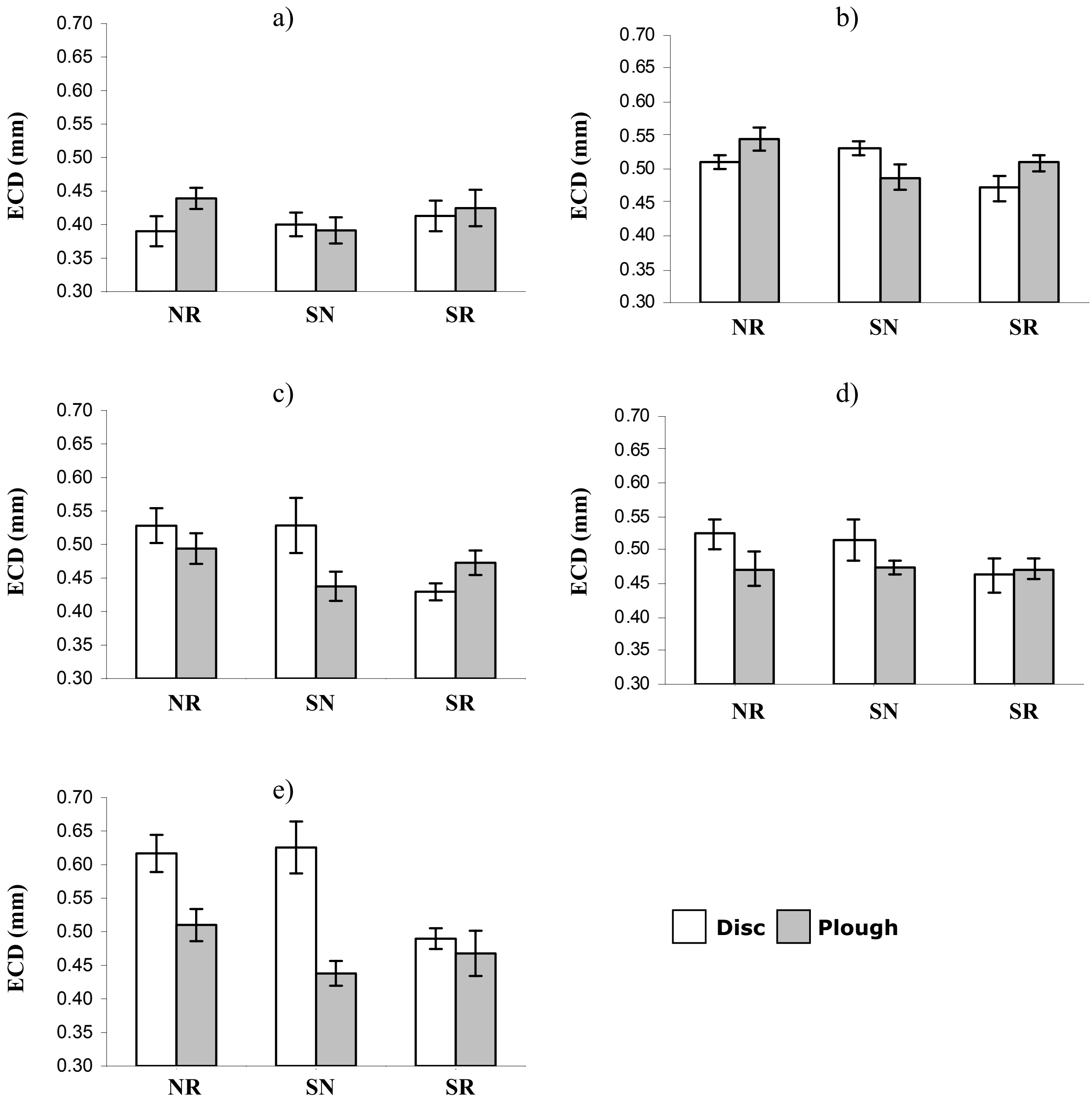
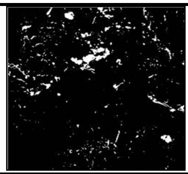


Figure 4.6: Mean ECD (mm) interaction between primary and secondary applications (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled) at each time period a) Prior to cultivation, b) After cultivation, c) Emergence, d) Establishment, e) Spring Establishment. Error bars represent s.e.d

Table 4.2: Mean meso structure variation over the evolution of the seedbeds created by different cultivations. Images representative of DDR treatment, white represents pore space.

PRIOR to Cultivation

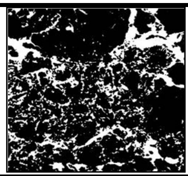
(- 6 Days)



Treatment	Primary	Secondary	Rolled	Perimeter (mm)	s.e.d	ECD (mm)	s.e.d	Elongation	s.e.d	Next Neighbor Distance (mm)	s.e.d
DDR	Disc	N	Y	1.95	0.211	0.99	0.060	83.91	1.047	0.99	0.060
DPD	Disc	Y	N	2.18	0.195	0.93	0.035	84.90	1.231	0.93	0.035
DPDR	Disc	Y	Y	2.15	0.161	0.95	0.050	85.29	0.590	0.95	0.050
PDR	Plough	N	Y	2.43	0.202	0.96	0.020	84.89	1.540	0.96	0.020
PPD	Plough	Y	N	2.18	0.327	0.96	0.036	84.49	0.928	0.96	0.036
PPDR	Plough	Y	Y	2.34	0.273	0.97	0.042	85.86	1.590	0.97	0.042

AFTER Cultivation

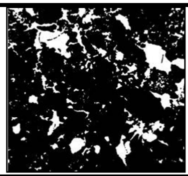
(+ 7 Days)



Treatment	Primary	Secondary	Rolled	Perimeter (mm)	s.e.d	ECD (mm)	s.e.d	Elongation	s.e.d	Next Neighbor Distance (mm)	s.e.d
DDR	Disc	N	Y	4.19	0.255	0.93	0.009	84.63	0.443	0.93	0.009
DPD	Disc	Y	N	3.47	0.119	0.93	0.013	86.23	0.501	0.93	0.013
DPDR	Disc	Y	Y	3.73	0.429	0.89	0.041	85.54	1.496	0.89	0.041
PDR	Plough	N	Y	4.83	0.271	0.99	0.032	85.53	1.200	0.99	0.032
PPD	Plough	Y	N	2.99	0.129	0.87	0.033	84.78	0.743	0.87	0.033
PPDR	Plough	Y	Y	4.71	0.436	0.85	0.034	87.38	0.656	0.85	0.034

EMERGENCE

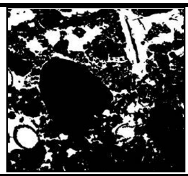
(+ 36 Days)



Treatment	Primary	Secondary	Rolled	Perimeter (mm)	s.e.d	ECD (mm)	s.e.d	Elongation	s.e.d	Next Neighbor Distance (mm)	s.e.d
DDR	Disc	N	Y	3.13	0.182	1.01	0.050	84.52	1.640	1.01	0.050
DPD	Disc	Y	N	2.80	0.244	1.06	0.089	85.56	0.739	1.06	0.089
DPDR	Disc	Y	Y	2.07	0.092	0.81	0.042	86.36	0.501	0.81	0.042
PDR	Plough	N	Y	2.98	0.264	0.93	0.032	86.81	1.702	0.93	0.032
PPD	Plough	Y	N	2.30	0.270	0.84	0.034	86.80	0.581	0.84	0.034
PPDR	Plough	Y	Y	2.67	0.231	0.88	0.031	85.75	0.377	0.88	0.031

ESTABLISHMENT

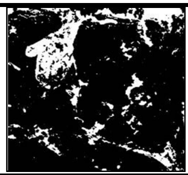
(+ 63 Days)



Treatment	Primary	Secondary	Rolled	Perimeter (mm)	s.e.d	ECD (mm)	s.e.d	Elongation	s.e.d	Next Neighbor Distance (mm)	s.e.d
DDR	Disc	N	Y	3.52	0.189	1.04	0.032	84.79	1.511	1.04	0.032
DPD	Disc	Y	N	3.52	0.289	1.07	0.053	87.48	2.143	1.07	0.053
DPDR	Disc	Y	Y	2.56	0.153	0.96	0.054	85.65	0.874	0.96	0.054
PDR	Plough	N	Y	2.58	0.226	0.98	0.056	86.87	1.386	0.98	0.056
PPD	Plough	Y	N	2.61	0.124	0.96	0.037	85.84	2.302	0.96	0.037
PPDR	Plough	Y	Y	2.61	0.141	0.98	0.032	83.84	1.260	0.98	0.032

SPRING Establishment

(+ 155 Days)



Treatment	Primary	Secondary	Rolled	Perimeter (mm)	s.e.d	ECD (mm)	s.e.d	Elongation	s.e.d	Next Neighbor Distance (mm)	s.e.d
DDR	Disc	N	Y	3.83	0.201	1.35	0.070	87.08	2.508	1.35	0.070
DPD	Disc	Y	N	3.62	0.271	1.39	0.105	85.47	1.272	1.39	0.105
DPDR	Disc	Y	Y	2.69	0.192	1.28	0.078	80.73	1.627	1.28	0.078
PDR	Plough	N	Y	3.36	0.162	1.18	0.056	83.93	1.464	1.18	0.056
PPD	Plough	Y	N	2.29	0.172	1.02	0.036	84.88	1.875	1.02	0.036
PPDR	Plough	Y	Y	2.67	0.284	1.17	0.079	83.72	0.660	1.17	0.079

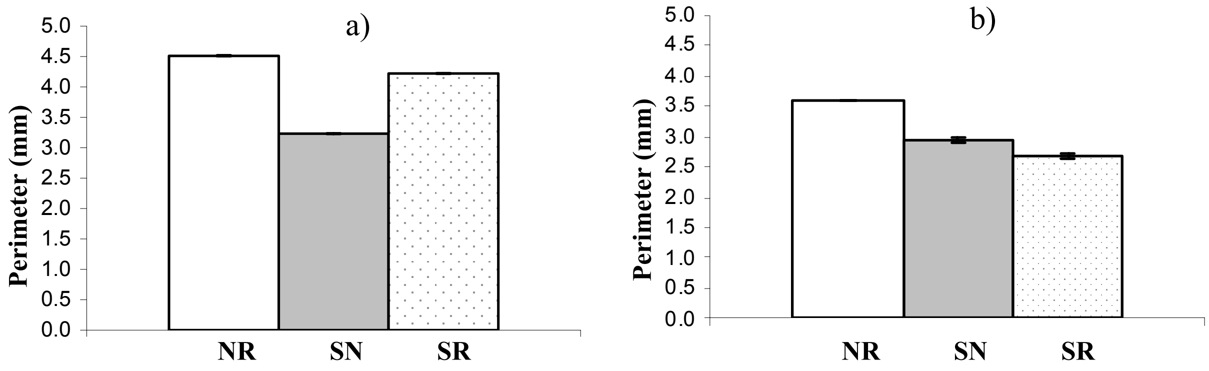


Figure 4.7: Mean pore perimeter (mm) variations effected by secondary cultivation at a) after cultivation (P = 0.012) b) spring establishment (P = 0.005). (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled). Error bars represent s.e.d

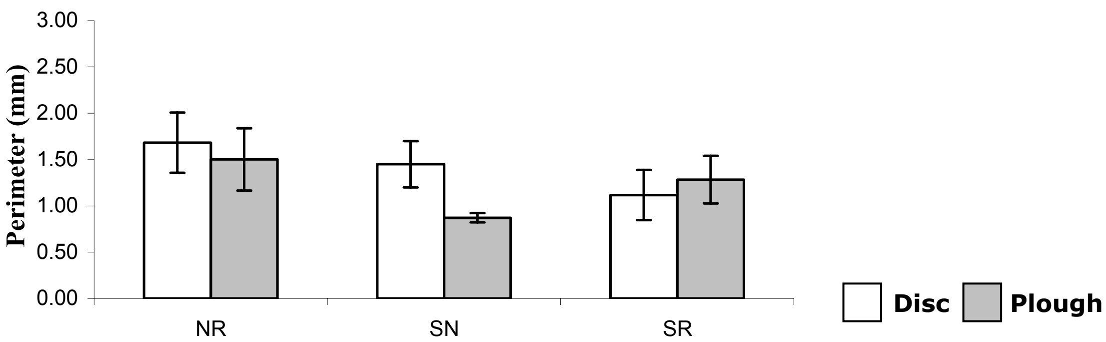


Figure 4.8: Mean interactions over time between primary and secondary cultivation on pore perimeter (mm). (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled). Error bars represent s.e.d

4.3.6 Pore size distributions (PSD)

Cultivation resulted in an overall increase in the total pore area (Figures 4.9 to 4.14). Primary cultivation had a minimal effect on the PSD but, secondary cultivation created large differences; rolled treatments increased the larger sized pores and power harrowing increased the mid range pore sizes creating a bimodal distribution after ploughing. Combined treatments typically resulted in a normal distribution with a small increase in pore size. Pore size distributions at emergence were similar to the previous stage but with a continued increase in larger pore sizes, notably within the ploughed and power harrowed treatment. At establishment, pore size distributions were similar between secondary treatments, with decreased smaller pore sizes and a slight increase in larger pore sizes. Rolled treatments had larger pore sizes at spring establishment than power harrowed and combined treatments which had bimodal distributions.

4.3.6.1 Pore size distribution - coefficient of uniformity (PSD_{cu})

No significant differences were observed in PSD_{cu} prior to cultivation with a mean ratio of c. 69.3 (Table 4.1). After cultivation, the PSD_{cu} had significant (P = 0.013) differences between secondary cultivations, with rolled treatments having much larger ratios than unrolled (Figure 4.15). No further significant differences were observed, although at emergence and establishment it was noted disc treatments had greater PSD_{cu} than ploughed, and is most likely a result of surface residue, this reduced with an increase in cultivation intensity (Figure 4.15). At Spring establishment, ploughed treatments had larger PSD_{cu} than disced (Figure 4.16), this could be associated with better crop growth in ploughed treatments. It should be noted due to heterogeneity within the data may have masked the significances.

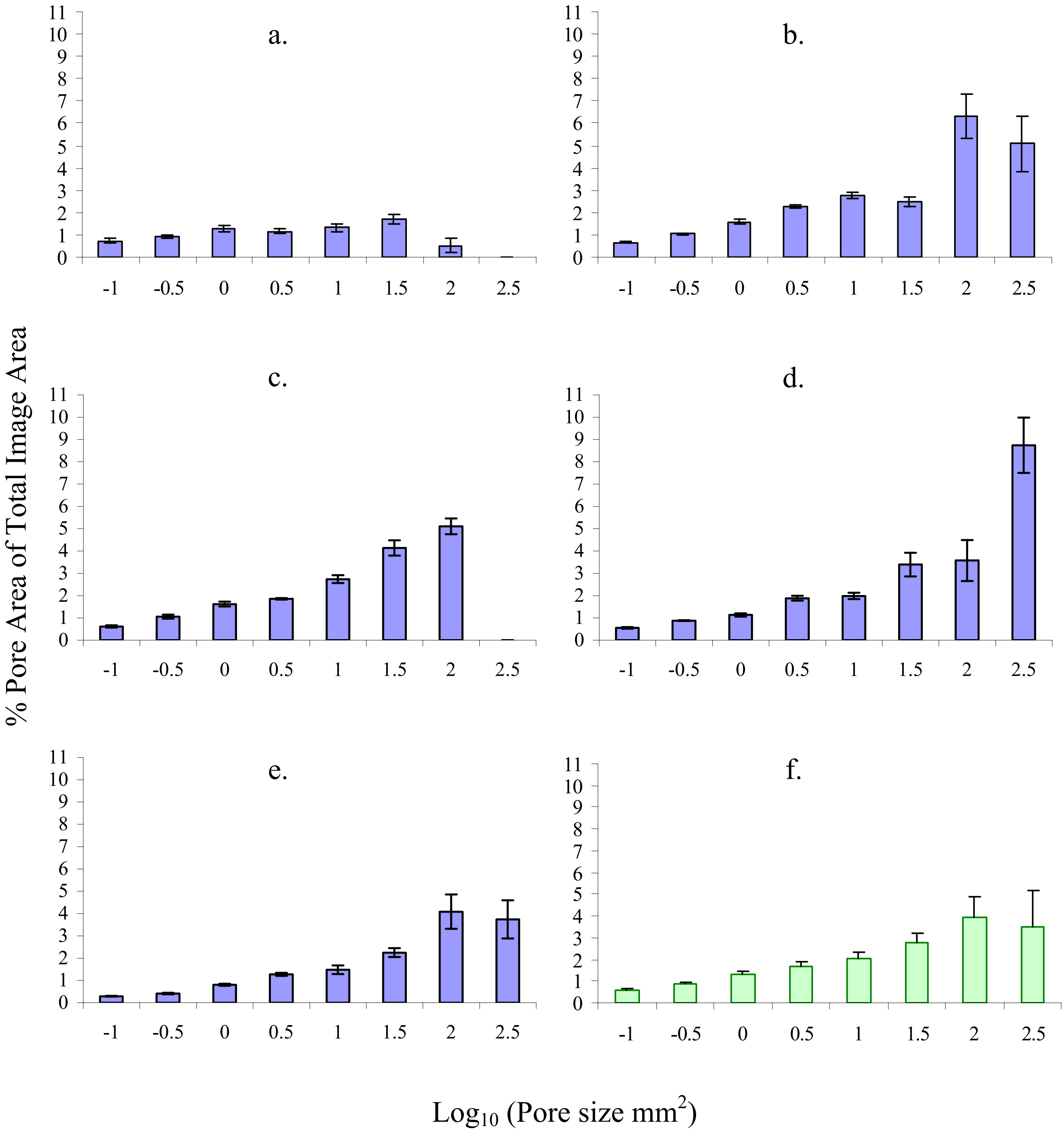


*Figure 4.9: Pore size distribution of **Disc + Drill + Roll** seedbed evolution at stages **a**. Prior to cultivation. **b**. After cultivation. **c**. Emergence. **d**. Establishment. **e**. Spring Establishment. **f**. mean values over time. Error bars represent s.e.d*

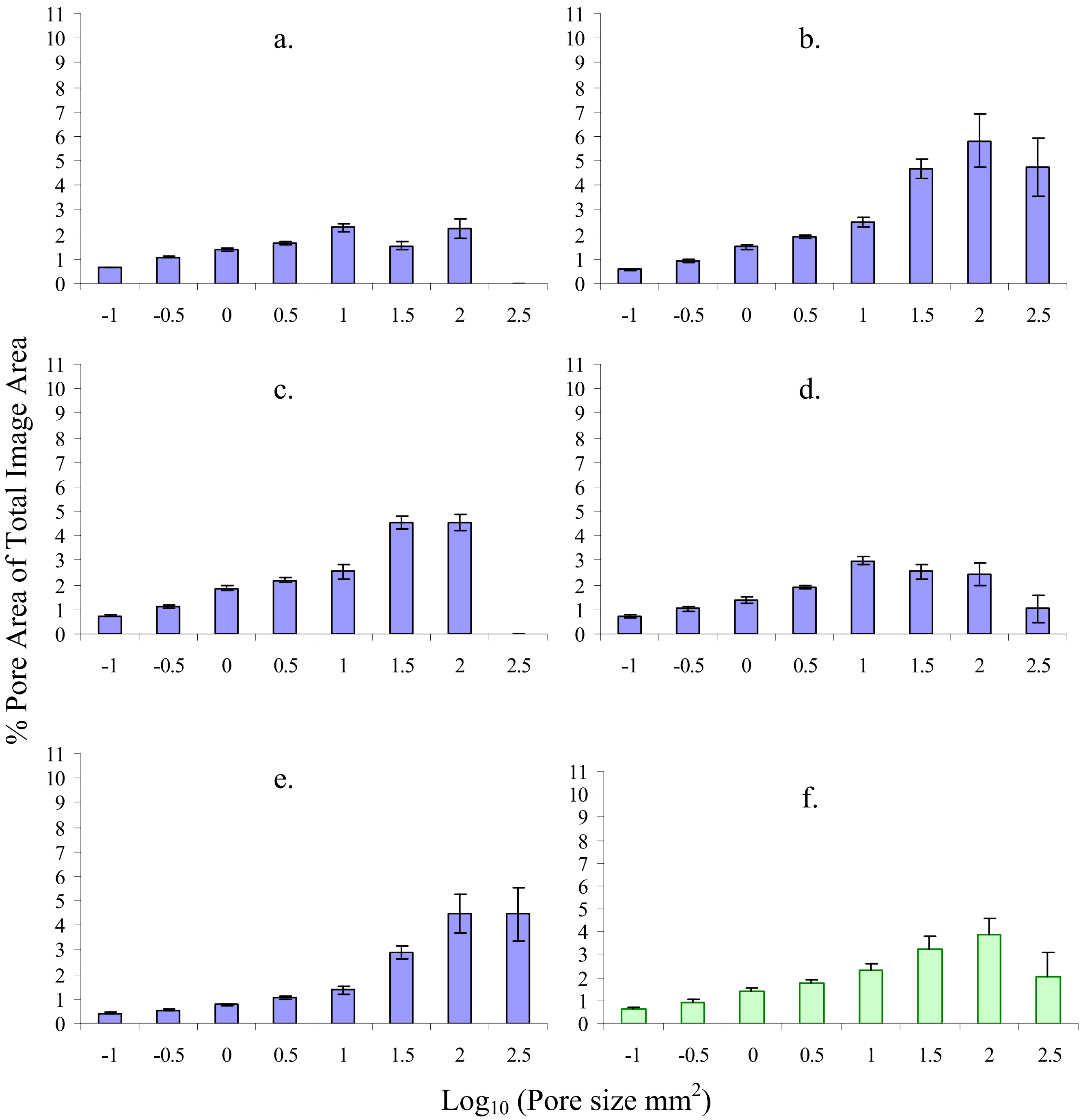


Figure 4.10: Pore size distribution of ***Plough + Drill + Roll*** *seedbed evolution at stages* ***a****. Prior to cultivation.* ***b****. After cultivation.* ***c****. Emergence.* ***d****. Establishment.* ***e****. Spring Establishment.* ***f****. mean values over time. Error bars represent s.e.d*

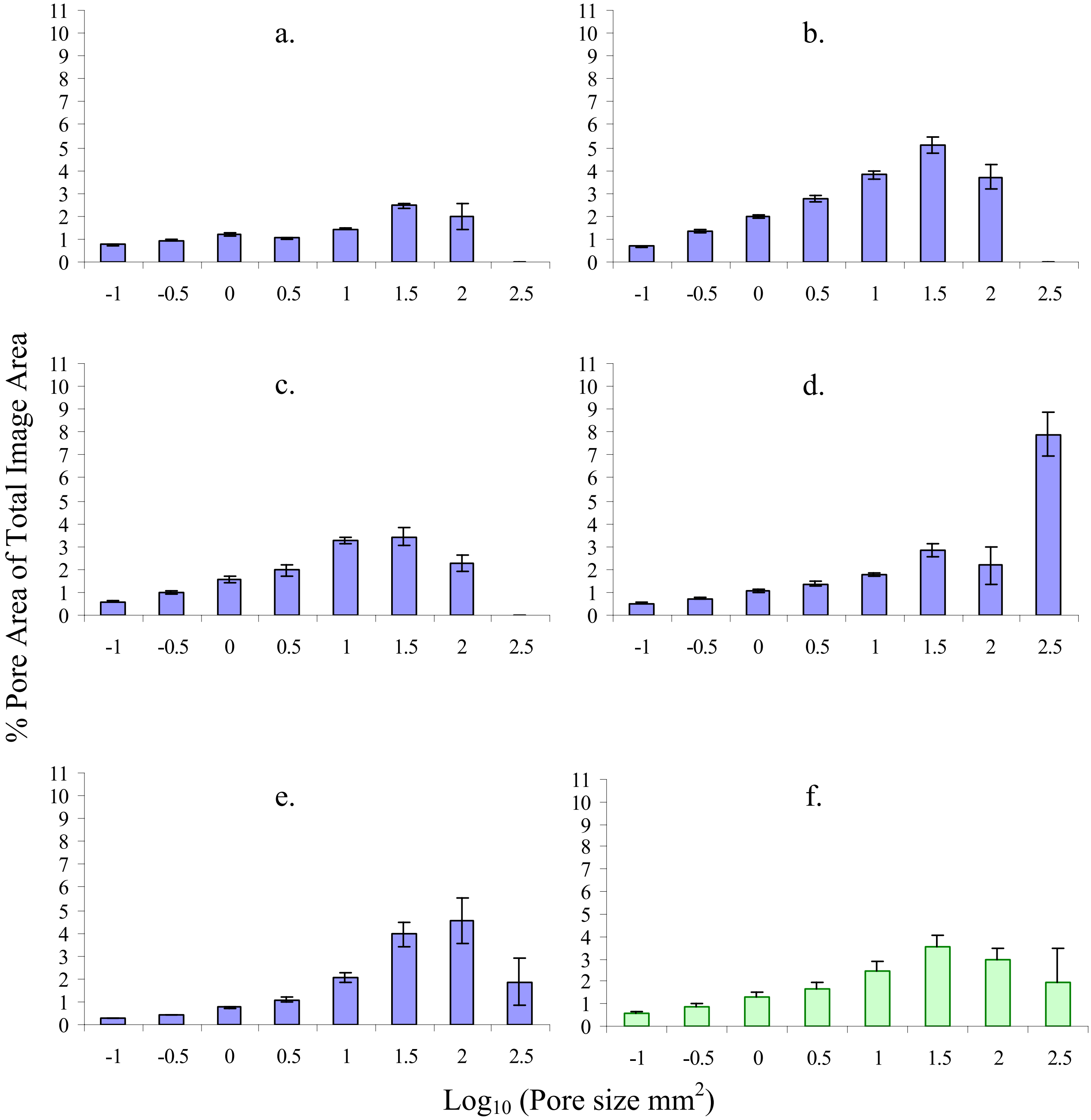


*Figure 4.11: Pore size distribution of **Disc + PH + Drill** seedbed evolution at stages **a**. Prior to cultivation. **b**. After cultivation. **c**. Emergence. **d**. Establishment. **e**. Spring Establishment. **f**. mean values over time.   Error bars represent s.e.d*

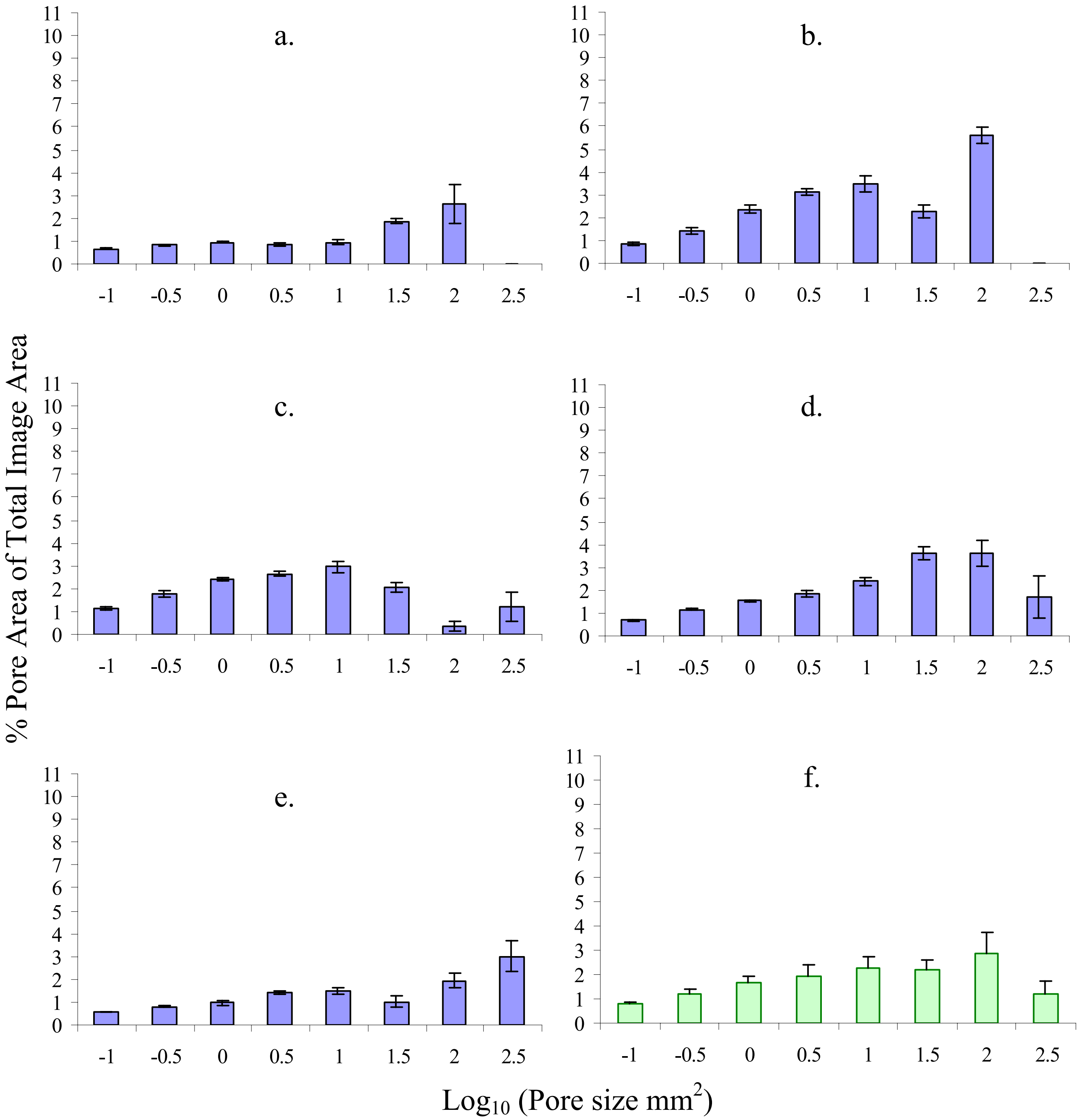


*Figure 4.12: Pore size distribution of **Plough + PH + Drill** seedbed evolution at stages **a**. Prior to cultivation. **b**. After cultivation. **c**. Emergence. **d**. Establishment. **e**. Spring Establishment. **f**. mean values over time. Error bars represent s.e.d*

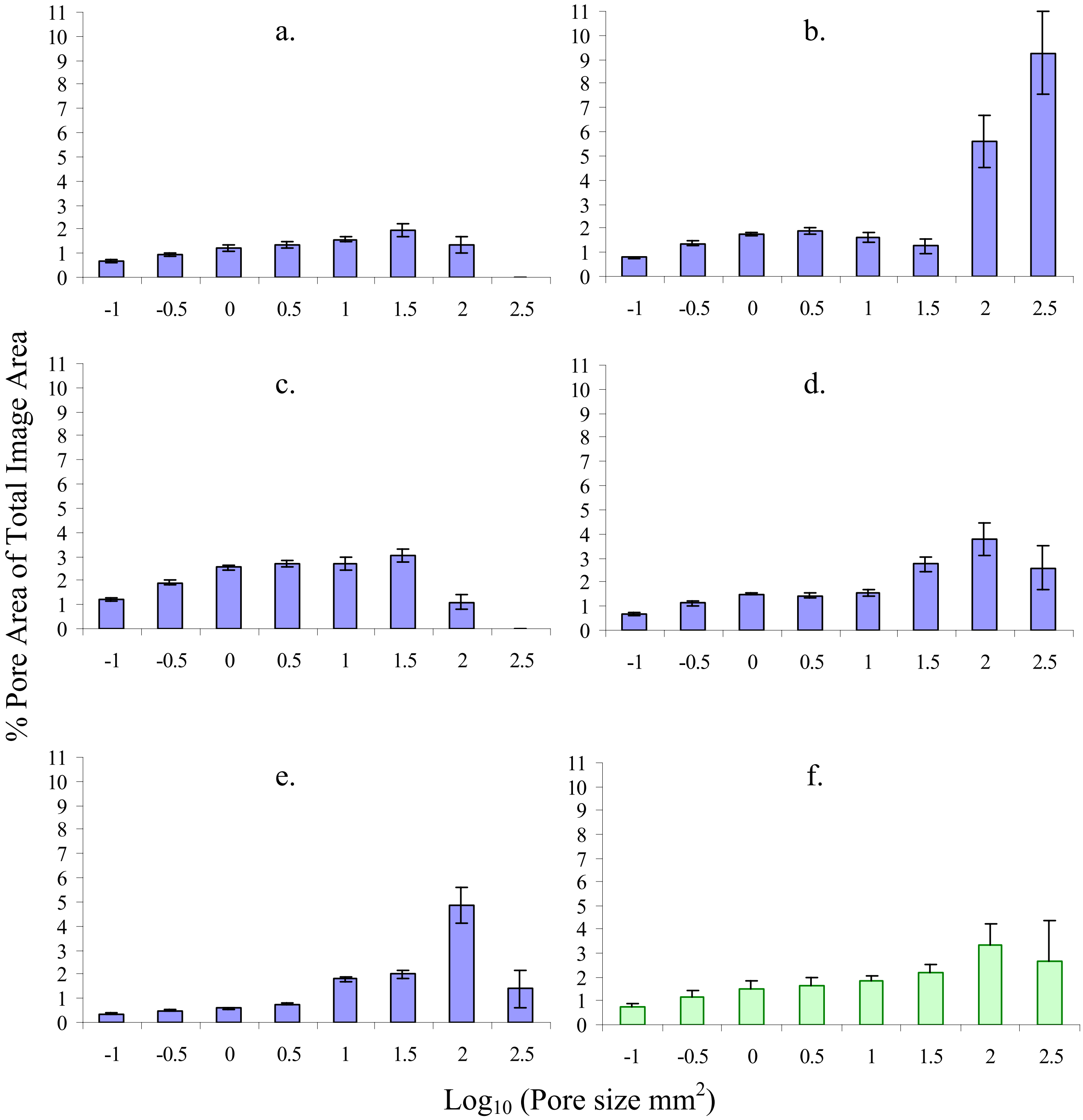


Figure 4.13: Pore size distribution of ***Disc + PH + Drill + Roll*** *seedbed evolution at stages* ***a****. Prior to cultivation.* ***b****. After cultivation.* ***c****. Emergence.* ***d****. Establishment.* ***e****. Spring Establishment.* ***f****. mean values over time. Error bars represent s.e.d*

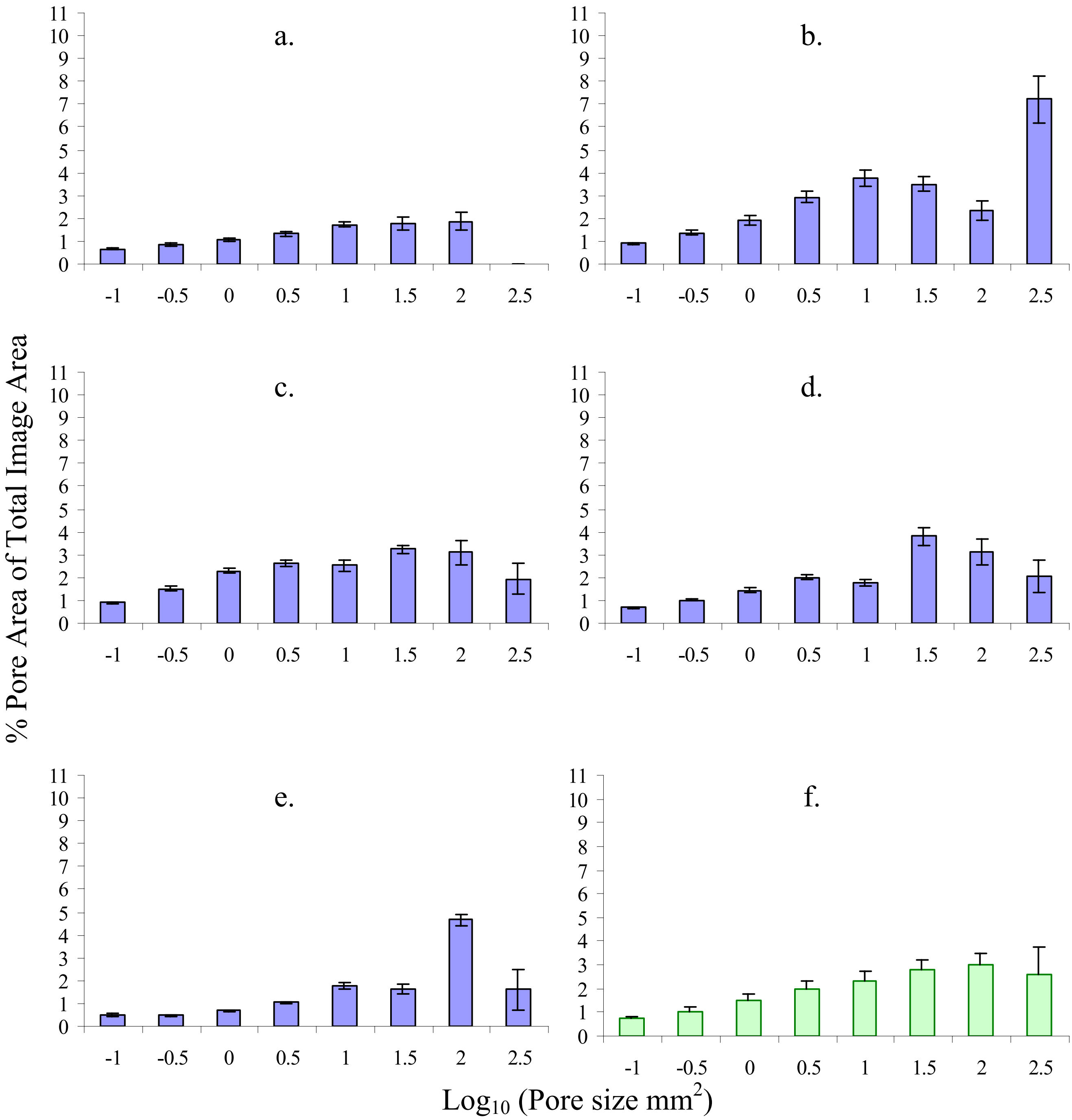


*Figure 4.14: Pore size distribution of **Plough + PH + Drill + Roll** seedbed evolution at stages **a**. Prior to cultivation. **b**. After cultivation. **c**. Emergence. **d**. Establishment. **e**. Spring Establishment. **f**. mean values over time.   Error bars represent s.e.d*

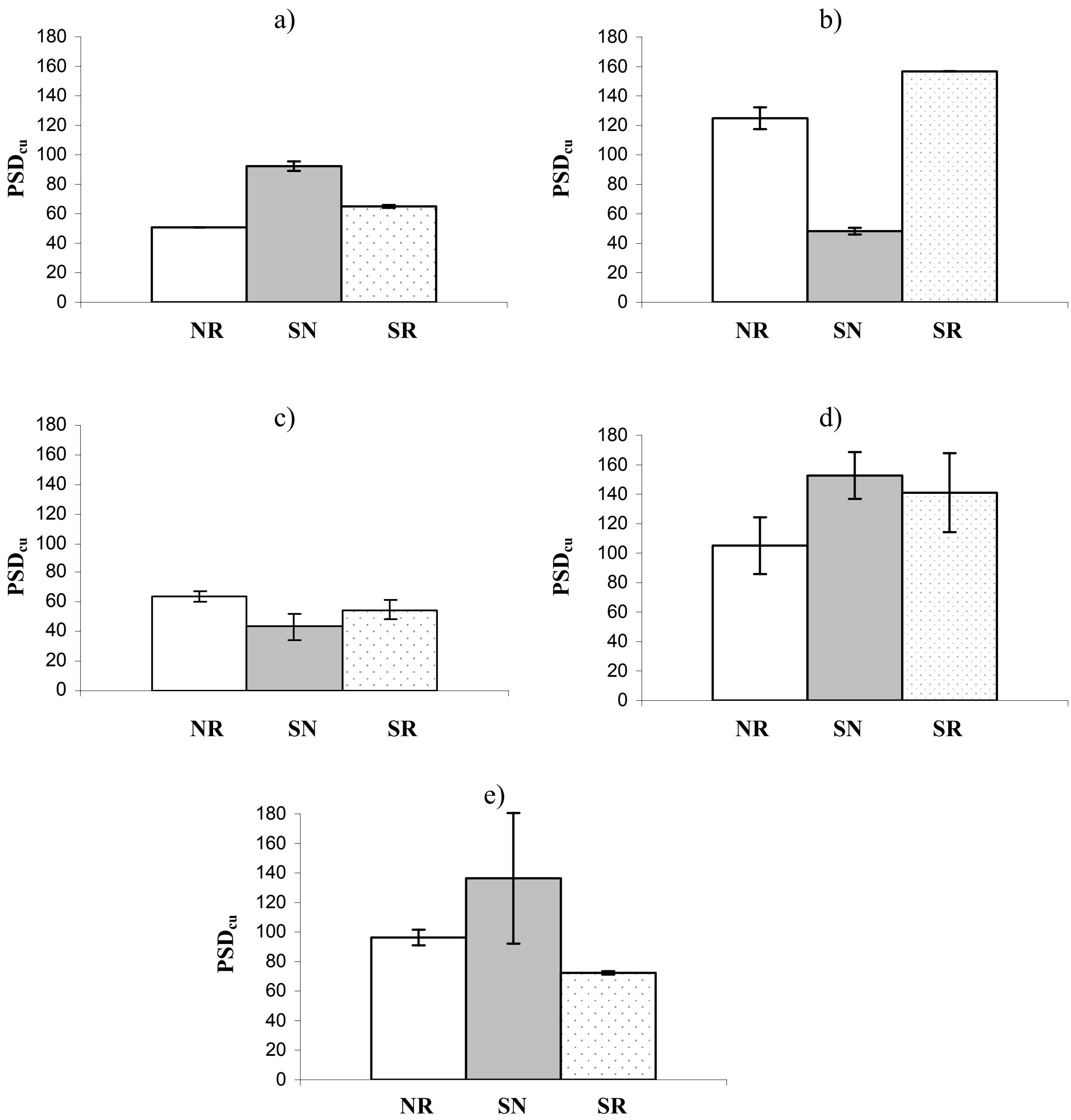


Figure 4.15: Mean PSD_{cu} variation between secondary applications (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled) at each time period a) Prior to cultivation, b) After cultivation, c) Emergence, d) Establishment, e) Spring Establishment. Error bars represent s.e.d

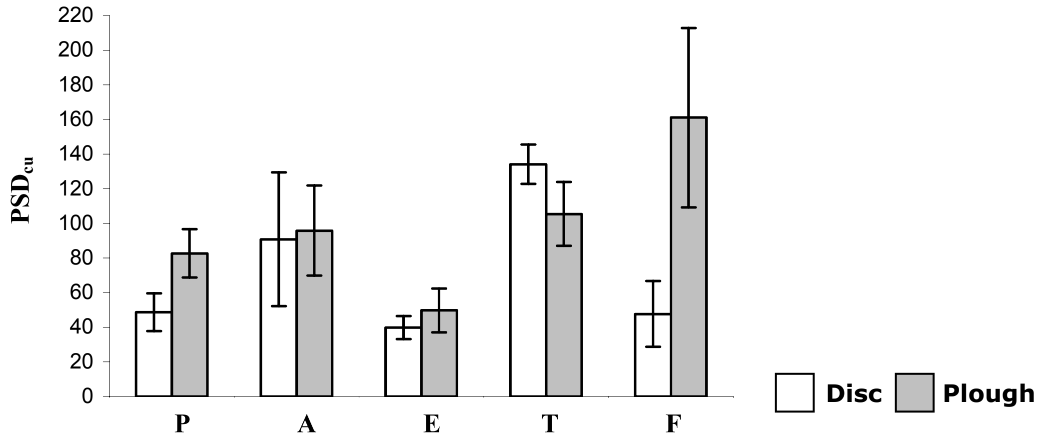


Figure 4.16: Changes in PSD_{cu} as a result of primary cultivation. Figures show mean variation at each time series evolution of the seedbeds, P = prior to cultivation, A = after cultivation, E = emergence, T = establishment and F = spring establishment. Error bars in s.e.d

4.3.7 Elongation

No significant difference in pore elongation was observed prior to cultivation or after cultivation. At emergence pore elongation decreased in the most intensive cultivations (P = 0.024) (Table 4.2). At establishment, no significant differences were observed, however, at spring establishment discing created more elongated pores than ploughing (P = 0.004), and increased intensity of secondary cultivations decreased pore elongation (P < 0.001).

4.3.8 Nearest neighbour distance (mm)

Nearest neighbour distance (NND) was not significantly different prior to cultivation with the mean values typically between 0.93-0.99 mm (Table 4.2). Primary cultivation had no significant effect on NND over the evolution of the seedbed except at spring establishment where ploughed treatments (1.12 mm) had reduced NND in comparison to disc treatments (1.34 mm) (P = 0.033). Secondary cultivation however, significantly effected NND, particularly after cultivation (P = 0.045) with decreased NND with increased secondary application from 0.96 mm in the least intensive to 0.87 mm in the most intensive (Table 4.2). Over time, similar trends continued with significant (P = 0.012) decreases in NND with increased cultivation intensity (Figure 4.17). Significant interactions occurred over time between primary and secondary cultivations (P = 0.003) with rolling decreasing NND within disc treatments but increasing NND in ploughed treatments.

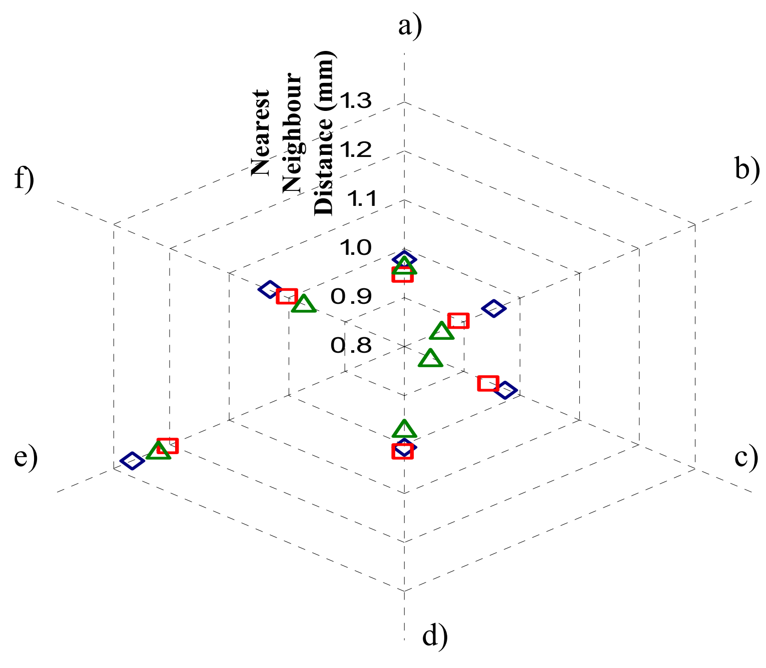


Figure 4.17: Mean variation in nearest neighbour distance (mm) secondary applications (◊= Rolled, □ = Power harrowed, Δ = Power harrowed and rolled) at each time period a) Prior to cultivation, b) After cultivation, c) Emergence, d) Establishment, e) Spring Establishment and f) mean variation over time.

4.3.9 Linking soil physical properties with establishment

4.3.9.1 Relationships between soil physical measurements and soil structure

The soil structural measurements correlated strongly with other soil physical properties over the evolution of the seedbeds. After cultivation, strong correlations between bulk density and soil structural measurements were recorded. For instance, as bulk density increased, porosity increased (P < 0.01, R^2 = 0.45) relating to rolling induced surface cracking (Figure 4.18a) but this relationship reversed by emergence. Shear strength at this period also had strong relationships with PSD_{cu} (P < 0.05) with observed increases in shear strength resulting in increased PSD_{cu} ratios and a R^2 of 0.44 (Figure 4.18b).

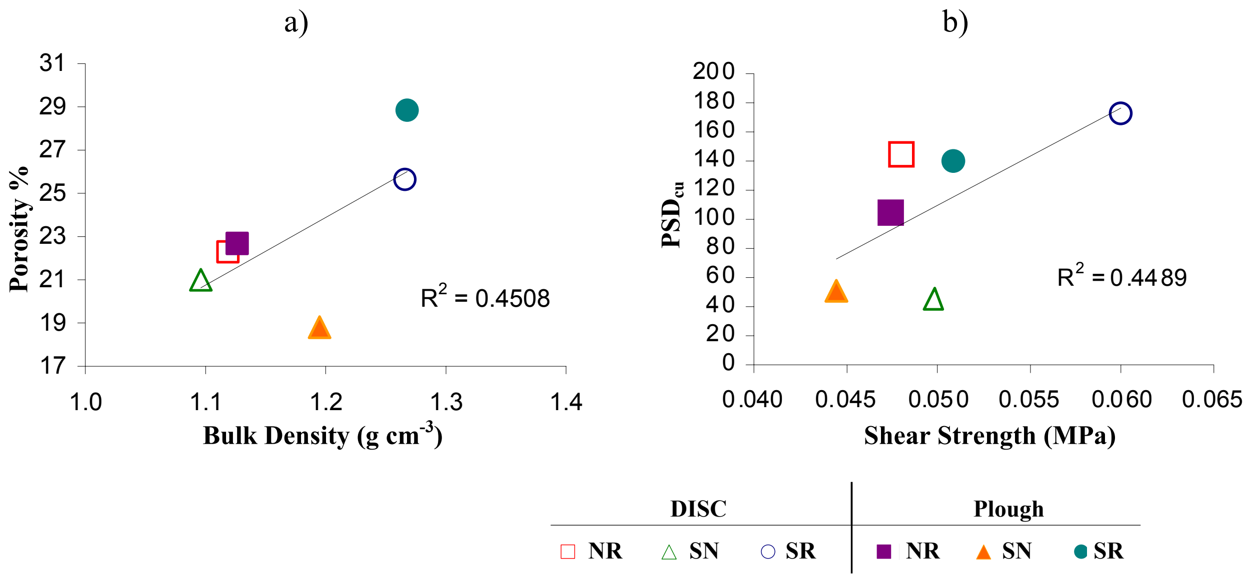


Figure 4.18: Mean treatment regressions after cultivation of treatment a) significant (P <0.01) correlation between bulk density and porosity, b) significant (P <0.05) correlation between shear strength and PSDcu. Both relationships were showing the opposite to expected relationship. (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled).

At emergence, pore perimeter increased with a decrease in bulk density ($P < 0.01$, R^2 0.60) (Figure 4.19a). Increased soil moisture content had a significant relationship with decreased elongation ($P < 0.05$, $R^2 = 0.41$) (Figure 4.19b). Decreased shear strength had strong relationships with increased pore size ($P < 0.01$, $R^2 = 0.61$) (Figure 4.19c), increased ECD ($P < 0.05$, $R^2 = 0.67$) (Figure 4.19d) and increased NND ($P < 0.05$, $R^2 = 0.83$) (Figure 4.19e). At establishment, strong positive relationships were observed with PSD_{cu} ($P < 0.01$) and moisture content. Penetration resistance was strongly related with porosity % ($P < 0.01$, $R^2 = 0.71$) and PSD_{cu} ($P < 0.01$, $R^2 = 0.95$) both of which showed increased resistance with increases in pore space, again associated with rolling induced surface cracking (Figure 4.20a, b). At spring establishment, there was a strong positive relationship between bulk density and ECD ($P < 0.05$, $R^2 = 0.41$) (Figure 4.20c).

4.3.9.2 Relationships between soil structure and crop establishment

Crop establishment (per m^2) was strongly related to soil structural measurements. Increased porosity had a significant negative relationship ($P < 0.01$) with crop establishment ($R^2 = 0.74$) (Figure 4.21). Other factors also had strong relationships ($P < 0.05$) with an increase in plant population as a result of decreasing in structure measurements such as pore size ($R^2 = 0.50$) (Figure 4.22a), PSD_{cu} ($R^2 = 0.37$) (Figure 4.22b), elongated pores ($R^2 = 0.83$) (Figure 4.22c) and ECD ($R^2 = 0.57$) (Figure 4.22d).

4.3.9.3 Relationships between soil structural properties and crop yield

Some soil structural properties had a strong relationship with crop yield (t ha^{-1}). Final crop yields were significantly affected by the structural condition of the soil after cultivation, most notably a significant negative relationship (P < 0.05, R^2 = 0.65) between yield and total porosity (Figure 4.23).

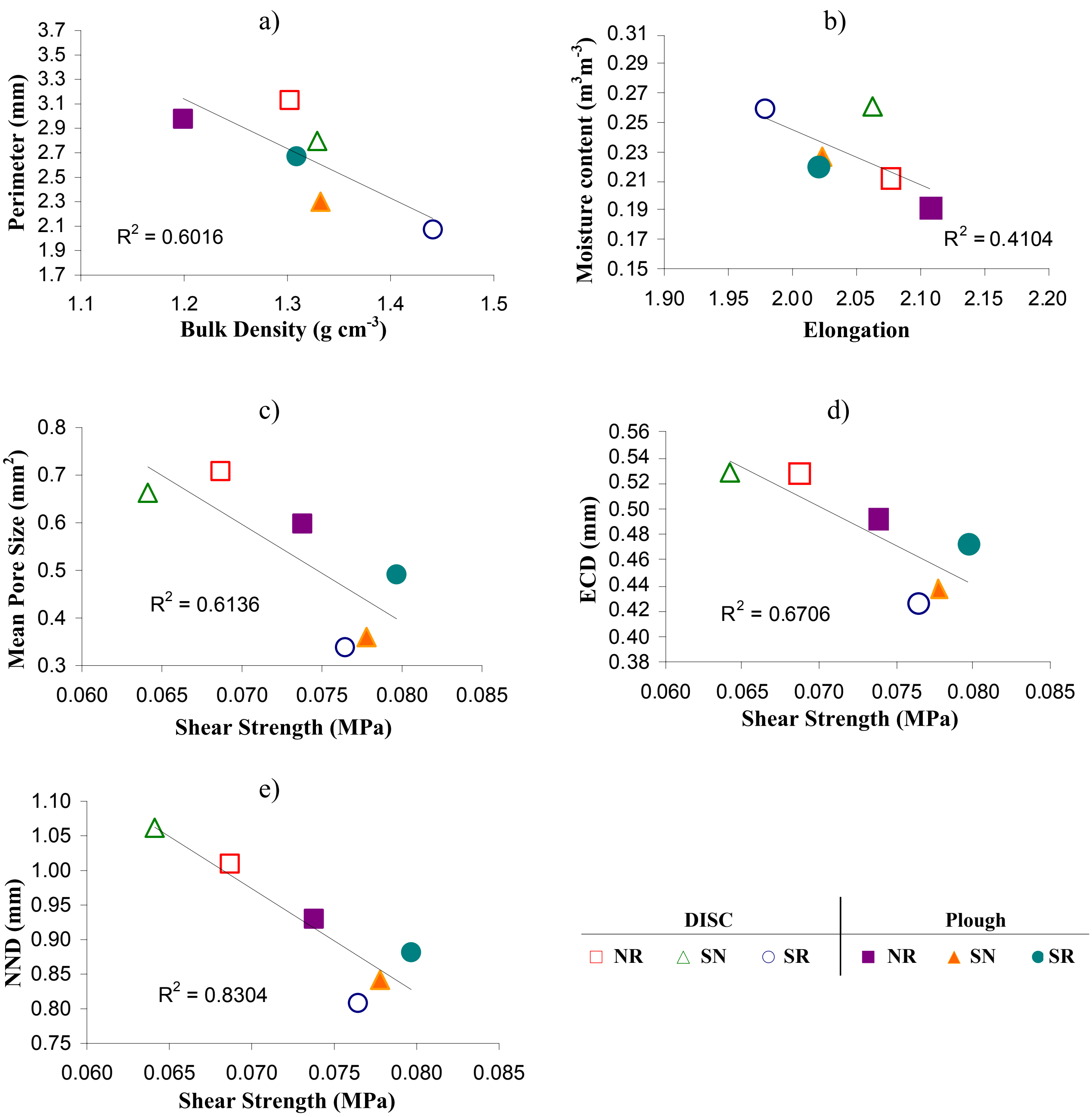


Figure 4.19: Relationships observed at emergence; a) significant (P <0.01) correlation and regression between bulk density and pore perimeter moisture content regressions; b) significant relationship (P <0.05) between moisture content and pore elongation. Shear strength relationships; c) significant correlation (P <0.01) and regression with pore area, d) significant correlation (P <0.05) and regression with ECD, e) significant correlation (P <0.01) and regression with nearest neighbour distance. (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled).

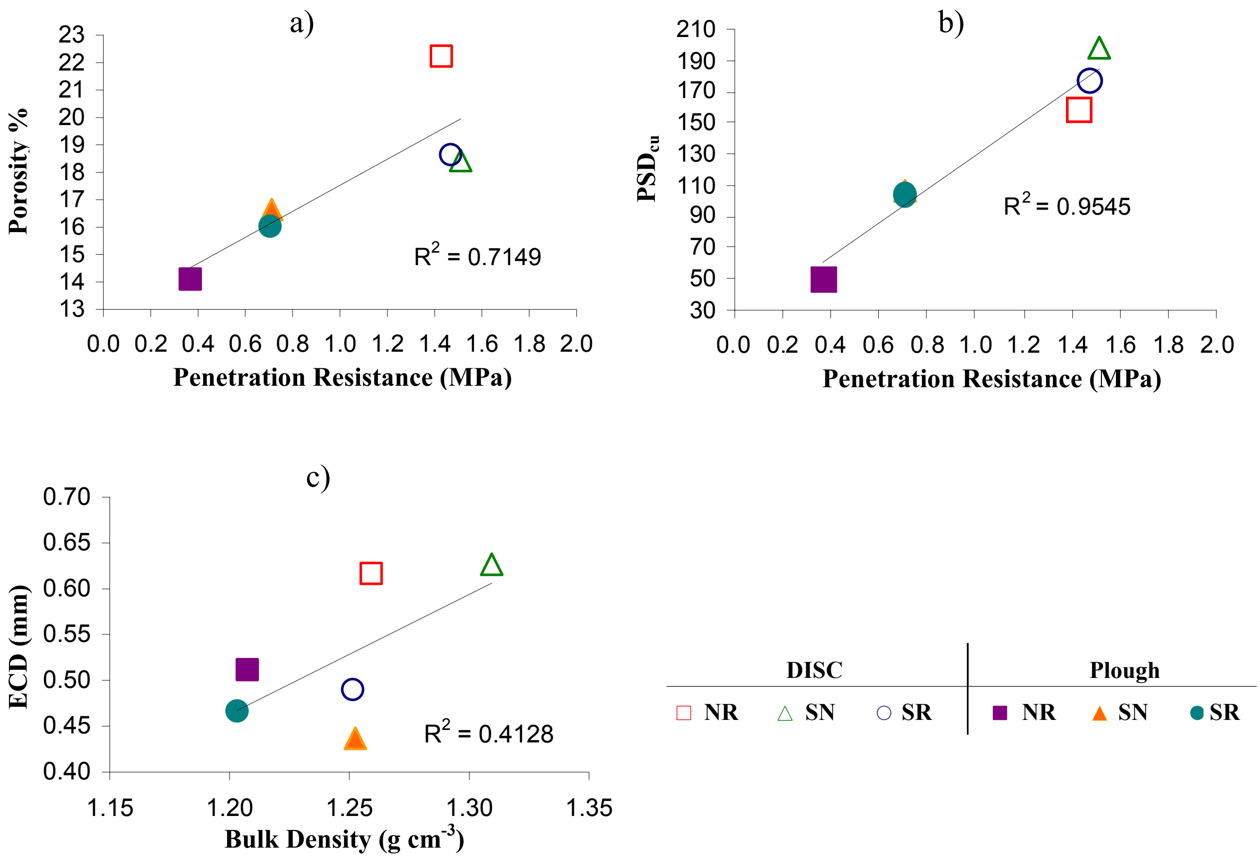


Figure 4.20: Mean treatment relationships at establishment a) significant (P <0.01) regression between penetration resistance and porosity, b) significant (P <0.01) regression between penetration resistance and PSDcu. Correlations at spring establishment c) significant (P <0.05) regression between bulk density and ECD. (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled).

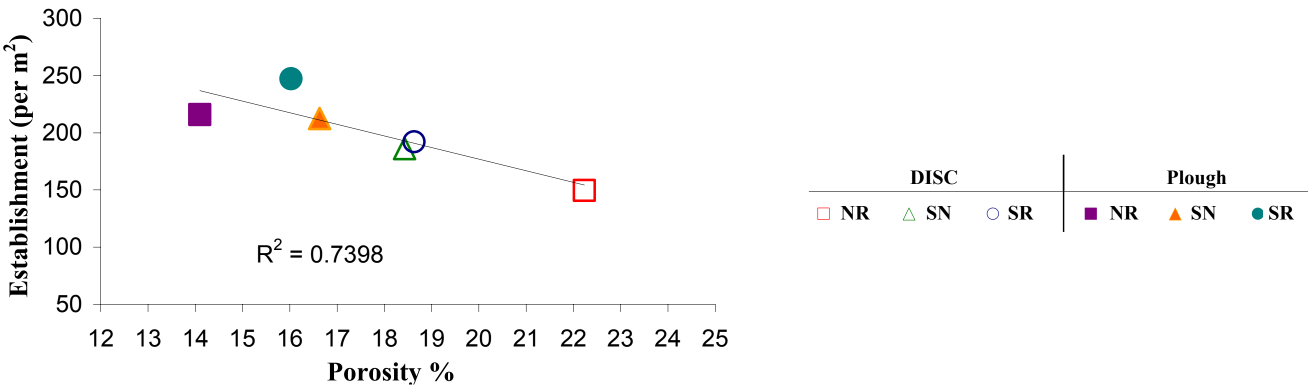


Figure 4.21: Significant (P <0.01) regression between crop establishment (numbers per m^2) and soil porosity (%), showing a significant decrease with a 10% increase in porosity %. (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled).

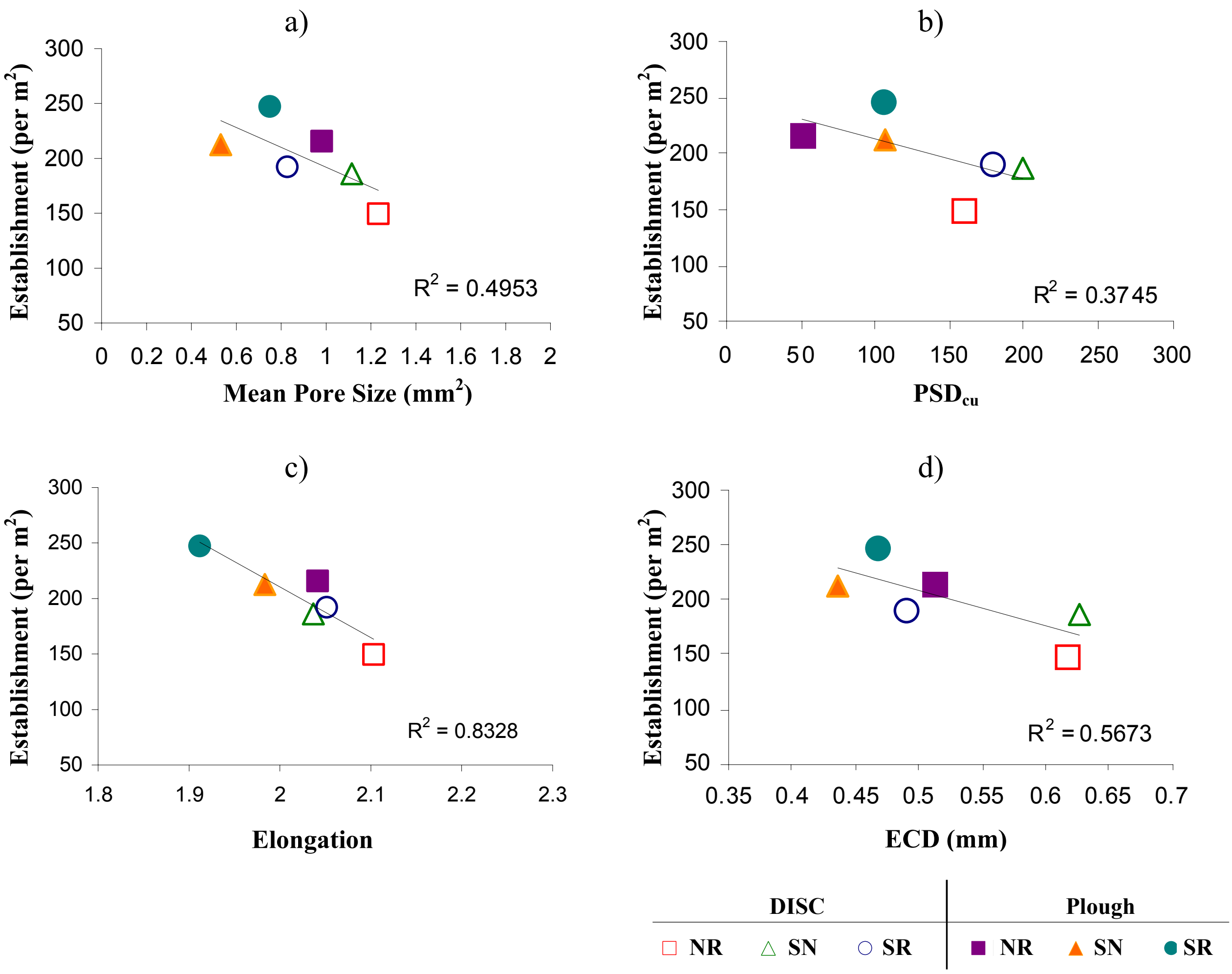


Figure 4.22: Significant (P <0.05) regressions between crop establishment (numbers per m²) and soil structural properties a) average pore size, b) PSDcu, c) elongation and d) ECD. (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled).

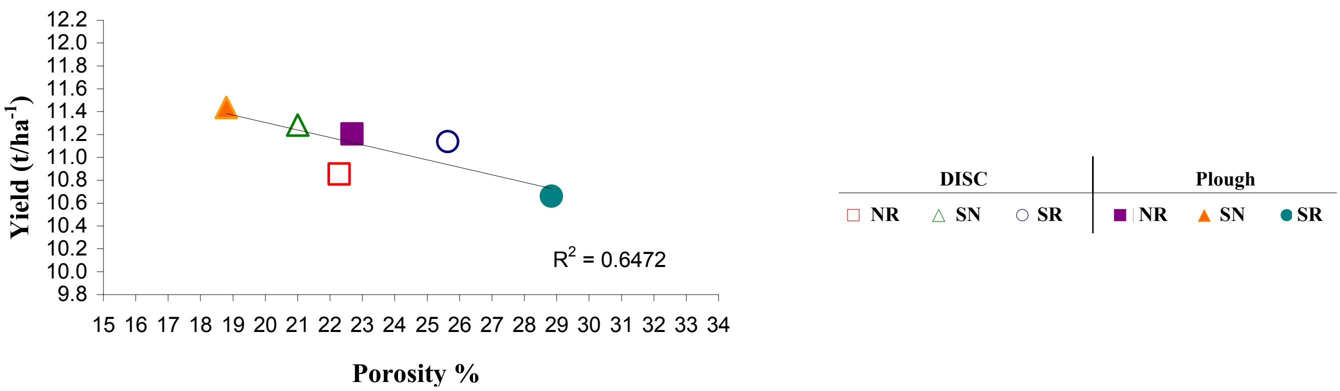


Figure 4.23: Significant (P <0.05) regression between porosity and crop yield, showing a significant drop in crop yield with an 11 % increase in soil porosity. (NR = Rolled, SN = Power harrowed, SR = Power harrowed and rolled).

4.3.10 Soil quality of establishment (SQE) and soil meso structure

In the previous Chapters (2 & 3), a model for predicting crop establishment was developed based on soil physical properties and the cultivation practices performed, which was then refined through the addition of soil macro structure properties. The model based upon bulk density measurements, was successful in predicting crop establishment, initially accounting for 56 % variation in the fitted data and 51 % variation in validation data set. This model was improved with the addition of macro porosity, increasing the total accounted variance to 74 % within the fitted data and 56 % within the validation data set. It was hypothesised that the addition of finer scaled soil structural data would improve the model's predictive ability.

Multiple linear regression, using the meso structure data, was used to improve the model's predictive ability. Structural data was divided into the plant development sequences; after cultivation, emergence, and establishment. Based upon the findings of the previous chapters and for consistency, the models were developed from establishment data (although attempts were still made using the other time periods to observe if differences could be found), and were assessed using the structural data acquired at the same resolution; porosity, average pore size, equivalent circle diameter (ECD), elongation, nearest neighbour distance, pore perimeter and sphericity. As the model was created with data from one sampling period, it was assessed for its continued predictive ability within the subsequent two time periods (similar issues were observed to those in Chapter 3 with models created within after cultivation and emergence time periods). During the model creation it was again apparent that the addition of cultivation type was needed for adequate prediction. This is most likely due to the heterogeneity of the soil over short distances and the large errors within the data which is not sensitive enough to predict accurately without the large area covered by cultivation and the small error provided by this. Meso structure data on its own was insufficient in improving the previous model and the addition of soil physical properties, notably bulk density (at 7 days post cultivation) was required. This is most likely due to the soil physical properties relating to bulk density such as soil strength and moisture content which cannot be solely explained by the meso soil structure data used in the model. Due to the number of parameters to be fitted to the model, over prediction occurred as a result of repeated measures. This was due to either strong correlations with the factors which fitted best within the model (Eq. 1), or because the measurements exhibited some similarity such as ECD and pore area.

The optimal model (Equation 1) included the fitted terms of P = primary, S = secondary, R = rolled, BD = bulk density at 7 days, MA_p = mean pore area (mm^2) MP_p = mean pore perimeter (mm), NND = nearest neighbour distance (mm). Regression analysis was significant ($P < 0.001$), however, the model accounted for a minor decrease in variance c. 3 % from the improved original model, with an estimated error of c. 17.29, an increase of c. 0.5, within the fitted data (Figure 4.24).

$$\mathrm{SQE} = 344 + 53.6 \times \mathrm{P} + 74.2 \times \mathrm{S} + 52.1 \times \mathrm{R} - 258 \times \mathrm{BD} - 62 \times MA_p + 19.5 \times \mathrm{MP_p} + 35 \times NND \tag{1}$$

The improved SQE was validated against the 2006 / 7 season sub-set collected from experiments using disc treatments, ± power harrowing, with rolling post drilling and across two soil types (Dunnington Heath series – sandy loam and Worcester series –

clay loam). Regression analysis on the validation sub-set gave a good fit which was highly significant (P < 0.001) accounting for 70 % of variation (Figure 4.25) and a standard error of c. 26.1. This was a significant improvement on the previous model (Chapter 3) as the validation sub-set had an increased percentage variance accounted for of 14 % and a decrease in estimated standard error of c. 2.3. This was an improvement in the model with an increase in R^2 of c. 0.12. The model output was also significantly improved within the validation subset with an increase in fit to a 1:1 line of identity from 0.52 (original), 0.57 (macro porosity) to 0.66 (Table 4.3) as well as decreased intercept and increased slope. The overall additions did improve the predictability of crop establishment within the validation data; however the additions did not greatly increase the predictability within the fitted data, and thus may be a source of over parameterisation in some datasets. However, this is the more consistent model with both fitted and validation data sets accounting for > 70 % of the variation within the data opposed to > 70 % in the fitted and < 60 % within the validation within the other models.

Attempts were made to further improve the model by the addition of soil macro structural data as well as the physical and meso morphology data (Eq. 2) using fitted terms of P = primary, S = secondary, R = rolled, BD = bulk density at 7 days, TP_m = Total Macro Porosity (%), MP_p = mean pore perimeter (mm), NND = nearest neighbour distance (mm).

$$\mathrm{SQE} = 390 + 57.9 \times \mathrm{P} + 74.3 \times \mathrm{S} + 51.3 \times \mathrm{R} - 251 \times \mathrm{BD} - 0.24 \times \mathrm{TP_m} + 1.3 \times \mathrm{MP_p} - 6 \times \mathrm{NND} \tag{2}$$

However, this results in over parameterisation, with the optimal model accounting for 74 % and 56 % of the variation within the fitted and validated respectively (Table 4.3). The standard error, line of identity, slope, intercept etc. were also significantly worse than those predicted within the model (Eq. 1).

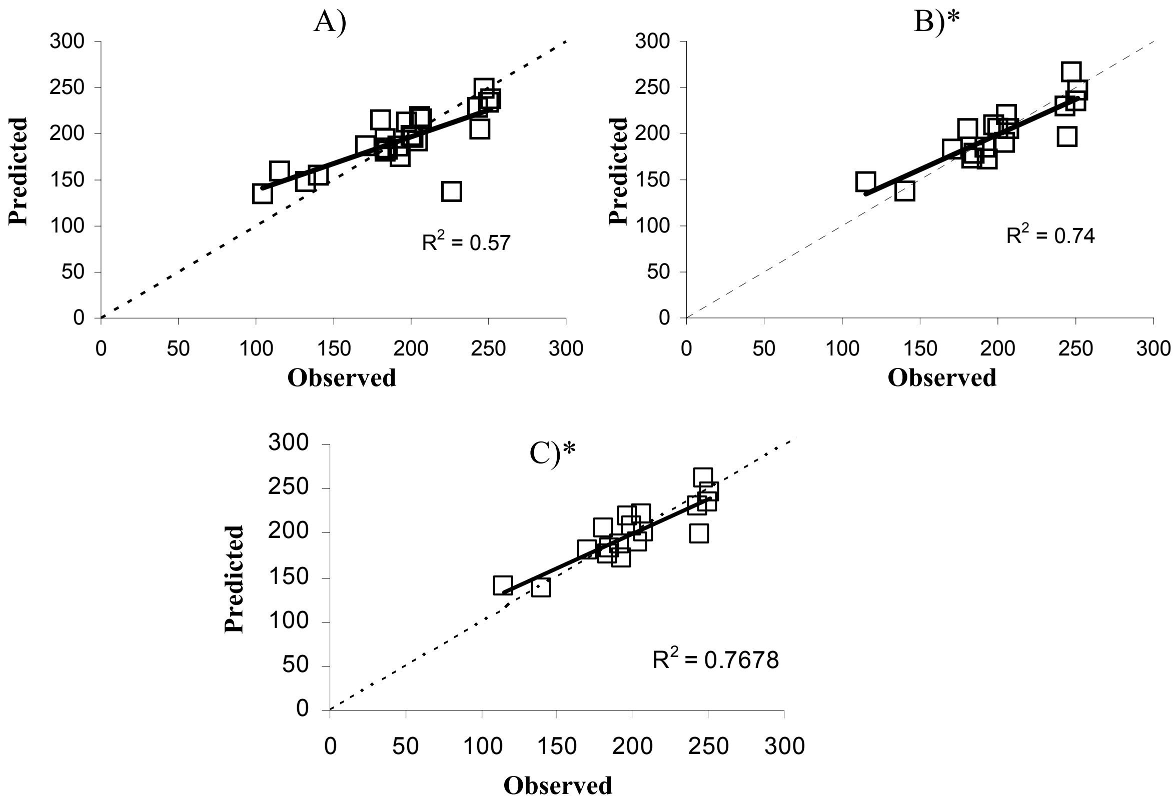


*Figure 4.24: Comparison of, fitted data, previous best fit model (A) with model including macro soil structure (B) and the new improved model containing meso scale structural elements (c). * Population (6) change due to sample logistics.*

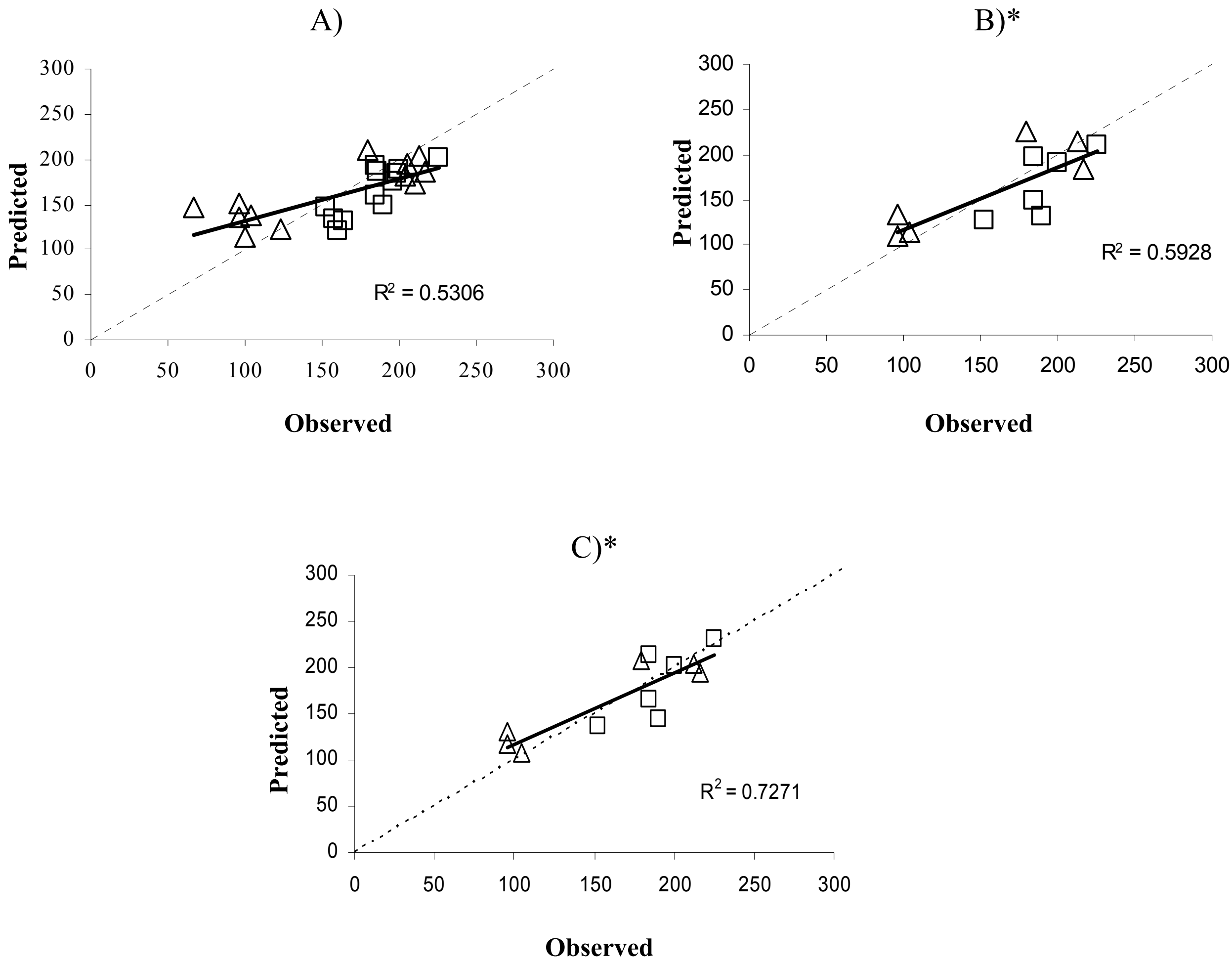


*Figure 4.25: Comparison of SQE model output for best fit models within the validation data, and the changes to model predictability from (a) physical input to (b) physical and macro porosity input (c) physical and meso structural attributes . Validation was conducted over two soil types, a clay loam (Δ) and sandy loam (□) as well as different environmental conditions to the data in which the model was created. Also note that structural additions in the validation are at difference scale of resolution to the fitted data. * Population (12) change due to sample logistics.*

*Table 4.3: Selected statistical variation between SQE model(s) previously developed and the addition of new structural elements. Optimum model includes additional parameters (from the original) of mean pore area, pore perimeter and nearest neighbour distance. * Observed population changes are a result of different seasons and changes in structural sampling regimes.*

	Significance (95% confidence limit)	% Variation accounted	Estimated Standard Error	1:1 Line of Identity (R^2)	Slope	Intercept	Average Observed Population * (per m^2)	Average Predicted Population (per m^2)	Mean % Deviation
Original Fitted	<0.001	56	20.6	0.57	0.58 (SE 0.106)	80.79 (SE 20.94)	193.34	193	-0.01
Original Validated	<0.001	51	20.4	0.52	0.46 (SE 0.093)	86.15 (SE 16.01)	167.24	163.71	- 0.09
ADDITION: - Macro Soil Structure data									
Fitted	<0.001	74	16.8	0.74	0.76 (SE 0.109)	46.73 (SE 22.15)	200.54	199.48	-0.03
Validated	0.003	56	28.4	0.57	0.69 (SE 0.182)	47.59 (SE 32.03)	170.14	165.51	- 0.15
ADDITION: - Macro / Meso Soil Structure data									
Fitted	<0.001	74	17.03	0.75	0.77 (SE 0..110)	46.66 (SE 22.45)	200.54	200.65	0.00
Validated	0.003	56	28.22	0.57	0.70 (SE 0.180)	44.98 (SE 31.76)	170.14	164.22	- 0.19
OPTIMUM MODEL: – Physical & Meso Soil Structure data									
Fitted	<0.001	71	17.29	0.69	0.74 (SE 0..112)	57.52 (SE 22.79)	200.54	205.1	0.13
Validated	<0.001	70	26.1	0.66	0.87 (SE 0.167)	25.76 (SE 29.37)	170.14	173.31	0.10

4.4 Discussion

Soil meso structure properties were significantly modified by cultivation technique. Primary cultivation had minimal effect on the soil structure at this scale of resolution until later in seedbed evolution. In general, the soil porosity properties significantly increased within disc compared to ploughed treatments, due to crop residue inclusion and reduced seedbed collapse over time. An increase in NND between pores within disc treatments suggests reduced pore connectivity. The increased pore area within disc treatments also explains some of the relationships observed (Figure 4.20a). For example, the increase in penetration resistance occurring at the same time as an increase in porosity; this relationship shows the combined effect of shallow cultivation and increased pore space as a result of crop residue inclusion and rolling as previously described in chapter 3. The breakdown of crop residue within the disc treatments may also have led to the continued increase in pore space at surface depths as the seedbed evolved (De Gryze et al., 2006).

Secondary cultivation was responsible for the greatest changes in soil meso structural conditions. Increased pore size initially occurred as a result of both rolled and combined applications. However, seedbed ageing resulted in decreased porosity measurements with increasing cultivation intensity, with the exception of PSD_{cu} ratios which increased in both power harrowed and combined applications after emergence, most likely related to better crop establishment in these treatments. This would result in increased pore space around the plant shoot and root. The addition of surface residue significantly increases porosity negating the development of micro pores. Dao (1996) found that large amounts of surface residue increased macroporosity near the surface. Pore elongation decreased with increased cultivation intensity showing that power harrowing, regardless of continued cultivation, had the greatest effect on pore shape. Although surface residue initially resulted in irregular pores associated with collapsed structure within disced, power harrowed and rolled treatments, the opposite occurred for ECD and NND measurements with a decrease in disc and rolled treatments and an increase under ploughed and rolled treatments. This was a result of increased pore roughness and development under ploughed and rolled treatments (although lower overall than disc treatments – due to surface residue).

Power harrow and roll as well as rolling had the greatest porosity and largest bulk density as a result of compaction. Rolling creates surface cracking and shallow depth increases in porosity, however bulk density remained the same or increased at depths just below the surface. Moisture content was significantly correlated with pore shape as increased moisture was related to increased pore roughness, whilst pore elongation resulted in decreased moisture content. These factors affect the surface tension of water in pores and the ability for water storage and transmission. Pagliai et al. (2004) found that more elongated transmission pores were created under minimal rather than conventional tillage. Increased penetration resistance was related with increased porosity and PSD_{cu}, this relationship is the result of cultivation depth. However, within ploughed treatments significant differences between power harrowed and non-power harrowed treatments (Figure 4.20_{a+b}) showed significant loosening of the soil occurs as a result of ploughing which is then consolidated by power harrowing.

The SQE was statistically improved by the addition of soil structural measurements from the meso scale as an influencing factor on establishment accounting for ca. 70 %

of the variation in establishment with relatively low standard error. The measures included within the model were average pore size; pore perimeter; and nearest neighbour distance; accounting for the size and roughness of pores on establishment and the ease of root development over short distances between pores. The improvements observed confirm the hypothesis that soil structure significantly affects crop establishment. The improvements in the model with the addition of soil structure measurements is most likely related to the fact that this scale of resolution i.e. the meso scale is dynamically altered by plant root and shoot development. Therefore the soil structure at this scale in particular has a direct influence on crop growth and establishment, whereas the soil structure at the macro scale does not affect plant / root growth and nutrient capture to the same extent.

4.5 Conclusions

Discing was responsible for the greatest increase in porosity attributed to the inclusion of crop residue. This large increase in pore space is a direct cause of poorer crop establishment likely due to reduced soil seed contact. Power harrowing created similar porous architecture regardless of continued applications or previous soil condition. Rolling increased pore size as a result of surface induced cracking (see chapter 3 Figure 3.9). Meso scale image analysis (in comparison with macro scale) provided an improved understanding of the soil porosity response induced by cultivation and the effect on crop establishment with increases in porosity (%); average pore size (mm^2); PSD_{cu}; elongation; ECD (mm); and nearest neighbour distance (mm) resulting in a decreased plant population. These results indicate establishment is significantly hampered by reduced seed-soil contact and nutrient capture. Final yield also decreases with increased porosity, determined at seven days post drilling.

The influence of soil structure on crop establishment was again clearly illustrated with a large improvement to the soil quality of establishment (SQE) model with the addition of meso structural measurements. The optimal model was fitted with cultivation, bulk density and meso morphology measurements of mean pore area, perimeter, and nearest neighbour distance. Establishment is therefore linked with the size and roughness of the pores and the connectivity of the pore network, which has significant influence over the movement of solutes and nutrients as well as the movement of biological activity within the soil. Bulk density is a major influence within the models and obviously accounts for factors which are not measurable using image analysis such as strength and moisture content.

Finer seedbeds created by power harrowing produce the most suitable condition for crop establishment and yield. The poorest soil structures and seedbed performances were created under rolling, in particular disced and rolled plots. The preferable structural conditions for establishment at this scale of resolution occurred between ranges of; porosity 12-17 %, average pore size 0.4 - 1 mm^2, PSD_{cu} 80-110, elongation < 2, average pore perimeter 2 - 3 mm and ECD 0.42 - 0.54 mm. Optimum ranges for crop yield immediately after cultivation; porosity 18 - 20 % and PSD_{cu} 25 - 35. These ranges show the values where establishment is maximised, above these ranges significant reductions in establishment and yield occurred. However, below these ranges, significant reductions in crop establishment and yield might be expected, but this was not observed because soil properties below these ranges did not occur.

As macro and meso structural elements significantly help to understand the relationship with soil structure and crop establishment, it may be hypothesised that micro scale soil structure measurements may also provide further refinement, but this may lead to further over parameterisation. However, it may also be stated that any further investigation may not improve the SQE and that in fact the development may have reached a plateau beyond which the relationships examined here may be being controlled by other factors such as weather and disease or soil biological and chemical properties.

Chapter 5:

A comparison of soil physical properties in reduced cultivation systems and the effect on winter wheat (*Triticum aestivum* cv. Einstein) establishment across two soil types.

5.1 Introduction

In recent years there has been a drive toward the use of reduced or minimal tillage, as opposed to conventional tillage, with the aim to reduce soil degradation, CO_2 and nutrient losses (Addiscott & Thomas, 2000). Reduced cultivation can be defined as a system which is less expensive, less energy demanding, quicker and has lower labour demands than traditional cultivation systems (Davies & Finney, 2002). Reduced tillage usually results in leaving crop residues on the soil surface as a result of non-inversion techniques such as disc harrowing. A number of considerations are needed when applying reduced cultivation such as the soil type and prevalent weather conditions, more so than when using conventional ploughing techniques. It is generally considered that stable structured soils are most suited for reduced tillage strategies such as heavy soil (clay), due to aggregate stability, but these have a small window of opportunity for cultivation due to the narrow friable range within which a clay soil can be cultivated (Jordan & Leake, 2004).

In Europe the proposed Common Agriculture Policy (CAP) reform is a major driver towards reduced and in particular zero tillage application in an attempt to prevent soil degradation, CO_2 losses and as a source for carbon sequestration. Research into tillage operations has been driven by the changes in cultivation practice (and high costs of ploughing) with observations in soil and crop responses to different tillage systems, concentrating on the comparisons between conventional and reduced cultivation. Comia et al. (1994) found no significant difference in crop emergence between conventional (ploughed) and reduced tillage methods (both with secondary applications of harrowing) on heavy clay soils. Comia et al. (1994) further stated yield (in barley, wheat, oats and rape) were significantly greater in reduced tillage systems than conventional throughout seven years of experimentation. Filipovic et al. (2006) found on a silty loam that reduced tillage lowered bulk density and soil resistance while increasing wheat and maize yield (after the first year in a five year trial) in comparison to conventional tillage. Arvidsson (1998) however, found reduced cultivation (discing at 10 cm) decreased barley yield compared with conventional tillage. Reduced cultivation also affects the stability of soil structure. Stenberg et al. (2000) observed improved aggregate stability in shallow tillage depths due to increased soil organic matter and biomass activity. Increased bulk density and strength within untilled soil creates crop development issues such as restricted root movement under reduced tillage (Arvidsson, 1998; Rasmussen, 1999).

Whilst previous studies have sought to differentiate the effects of conventional and minimal cultivation on soil quality and degradation, very few have concentrated on the effect on crop establishment and fewer still on the effects of degrees of minimal cultivation or the need for secondary application in pursuit of preferable soil conditions for crop growth. Many studies have concentrated on only one soil type to exclude the effects across soil type and the variations between these. The objectives of this experiment were; (i) to identify changes in soil physical properties as a result of different minimal cultivation practices on heavy and light soil textures; (ii) observe the evolution of seedbeds of differing soil texture; (iii) to determine the effects of the soil physical properties of each texture on crop establishment, yield and the specific effects of secondary and tertiary cultivation; and (iv) determine the most suitable cultivation strategy for each soil texture based on establishment rates, yield and cost to output ratio.

5.2 Materials and methods

5.2.1 Field site and experimental design

A field experiment was established in 2006 at the University of Nottingham experimental farm, Sutton Bonington, Leicestershire, UK (52.5^{o}N, 1.3^{o}W)(in an adjacent field to the previous year's trial, Chapters 2-4), and Bunny, Nottinghamshire, UK (52.52^{o}N, 1.07^{o}W). The soils were a sandy loam from the Dunnington Heath series (FAO class; Stagno-Gleyic Luvisol) at Sutton Bonington and a clay loam of the Worcester series (FAO class; Argillic Pelosol) at Bunny (Chapter 3, Table 3.1). The soil at Sutton Bonington was in a rotation of winter oats, winter wheat, sugar beet, winter wheat, with the current experiment in winter wheat following winter oats. The soil at Bunny was in a rotation of two years winter wheat with a break crop of oilseed rape, with the current experiment in the second year of winter wheat.

The experimental design was a 2 x 2 factorial, arranged in three replicate blocks. Primary cultivation was performed by disc cultivar across the whole experimental area at each site. The treatments, secondary cultivation (+/- power harrow) and tertiary cultivation (+/- rolling) with Cambridge rollers post-drilling, were factorally combined and allocated at random. Previous cultivations for two years had been performed by a single pass heavy disc cultivator incorporating a levelling board and roller (Vaderstad Carrier Super CR500). The experiment comprised of 12 plots that were 24 x 2.5 m wide, in sets of 4 plots in 3 blocks with 12 metre discards between blocks at each site. Both sites were drilled using a Nordsten drill with winter wheat (*Triticum aestivum*) cv. Einstein at a rate of 300 seeds per m^2 on 4 October 2006. Cultivations were performed on the same day.

5.2.2 Measurements of soil physical characteristics

Soil physical measurements were taken prior to cultivation and at weekly intervals until early November where the crop had exceeded a 'well emerged' stage, noted by successive plant counts recording the same or approximate value. Further measurements were taken at the end of November (pre-winter establishment) and at spring establishment in early March (2007) to account for any over winter plant losses. The soil physical properties of the seedbed were quantified by measurements of soil shear strength, penetration resistance, water content and bulk density, as well as crop establishment. Bulk density measurements were recorded at five key stages; prior to cultivation, after cultivation, emergence, pre-winter establishment and spring establishment. All measurements were conducted within the centre 1 m of each plot, leaving a 0.75 m distance from the passage of any wheeled traffic.

Physical properties were collected using the same methodology approach included in Chapter 2 section 2.2.

5.2.3 Statistical analysis

The statistical software package GenStat^{TM} v.8.1 was used to analyse all data using an analysis of variance (ANOVA) to test for significant differences between treatments and to calculate standard errors of difference (S.E.D). Data was analysed as a split plot between sites to attain interactions between site (soil type) and cultivation applications. Due to un-replicated sites it must be noted that soil type effects can only be inferred and indeed may also be related to site specific variations in other factors such as weather, slope angle, pests, disease etc.

5.3 Results

5.3.1 Prior to cultivation

Soil physical data was collected one month prior to cultivation to provide a base-line measurement. No significant variation was observed within each soil texture for volumetric water content, shear strength and bulk density. However, differences were found in penetration resistance of the soil at Bunny ($P < 0.001$), with plots designated to be unrolled having higher resistance (by 0.46 MPa) than those to be rolled. This may have been due to tracks from harvest equipment, which crossed the field in these locations. However, these differences did not persist after cultivation at the depths measured.

5.3.2 Penetration resistance

Penetration resistance was affected more significantly within the sandy loam soil compared with clay loam soil after cultivation. After cultivation, penetration resistance was greater within the non-power harrowed (1.74 MPa) plots of the clay loam soil than the power harrowed (1.57 MPa), but within the sandy loam soil, the power harrowed plots (1.90 MPa) had much greater penetration resistance than non-power harrowed (1.59 MPa) plots ($P < 0.001$; Figure 5.1). This significant interaction continued throughout the experiment ($P = 0.033$), although the magnitude of differences decreased as the seedbed aged and the soil resistance became more uniform between plots. On the sandy loam trial, penetration resistance increased in response to rolling by 0.24 MPa, whereas on the clay loam, the increase was only by 0.10 MPa ($P = 0.001$; Figure 5.1). Power harrowing resulted in similar increases in penetration resistance regardless of further rolling, whereas penetration resistance in non-power harrowed plots which were rolled was significantly higher than unrolled plots ($P < 0.001$; Figure 5.1). Penetration resistance within the clay loam significantly ($P < 0.001$) increased at a greater rate than within the sandy loam soil by 0.1-0.4 MPa per 35mm increases in depth (Figure 5.1).

5.3.3 Shear strength

Shear strength in both soils was significantly affected by secondary and tertiary cultivation, with the exception of measurements at spring establishment. A soil type (site) interaction over time with power harrowing resulted in a significant decrease in soil shear strength within the clay loam but an increase within the sandy loam soil ($P < 0.001$; Figure 5.2). Rolling was also significantly different ($P < 0.001$) across sites with an overall increased soil shear strength within both soil types throughout the experiment, but slightly larger effects within the sandy loam (0.02 MPa opposed to 0.01 MPa, per sampling period) (Figure 5.2). A significant interaction over time (P = 0.023) between site, power harrowing and rolling showed minimal variation between power harrowing within the sandy loam with only rolling affecting shear strength, while within the clay loam non-power harrowed plots had greater soil shear strength than power harrowed plots, but with an overall increased shear strength as a result of rolling (Figure 5.2).

5.3.4 Volumetric water content

Power harrowing and rolling resulted in soils with significantly (P < 0.001) increased water content (ca. 2 %) within the upper layer of the seedbed compared to either non-power harrowed or un-rolled plots. This trend continued, with gradual increases in water content due to increased seasonal rainfall, however, a difference of between c. 2 – 5 % remained (Figure 5.3). At cultivation soil water content increased in response to rolling within the sandy loam and decreased within the clay loam (P < 0.001). This interaction continued through to + 36 days when no significant difference was observed within the clay loam but water content was greater under rolled treatments within the sandy loam (P = 0.049).

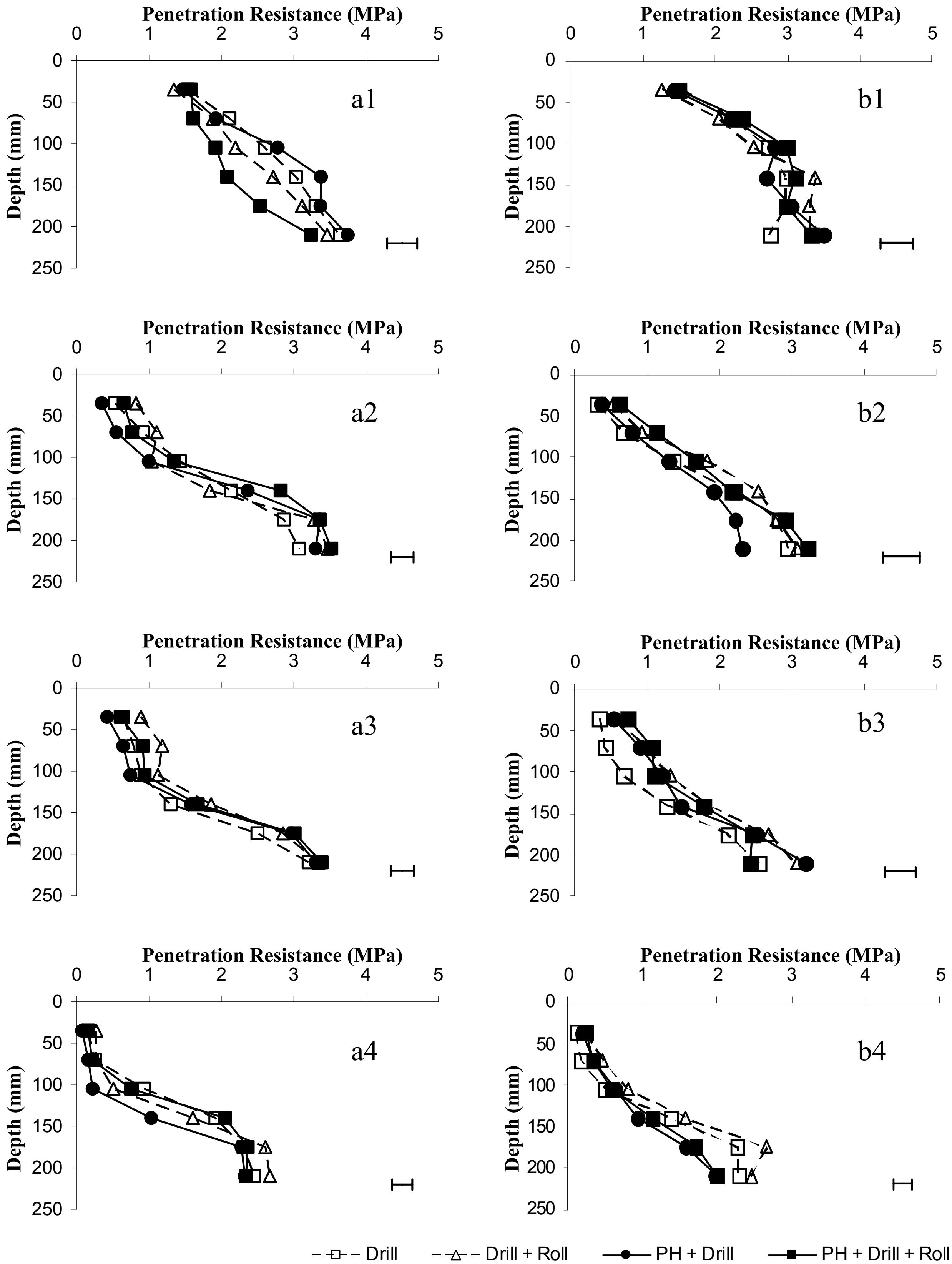


Figure 5.1: Penetration resistance (MPa) with depth, showing the differences in soil penetration resistance between (a) clay loam and (b) sandy loam, (1) Prior to cultivation, (2) After cultivation, (3) Emergence and (4) Pre-winter establishment. Error bars depict S.E.D., 71d.f

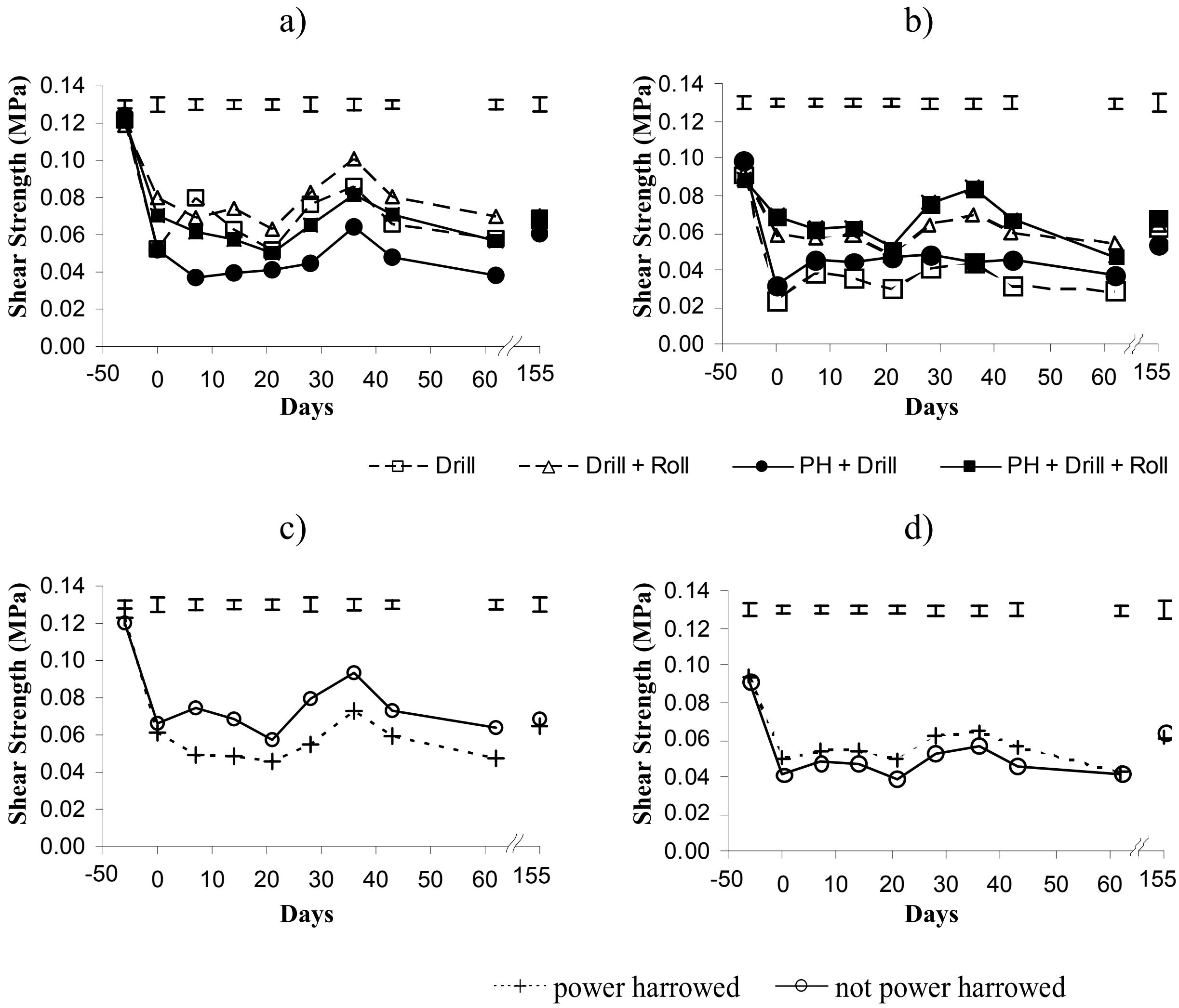


Figure 5.2: Variation in soil shear strength over time. a) Effect of cultivation on a clay loam. b) Effect of cultivation on a sandy loam. c) Effect of power harrowed cultivation on clay loam. d) Effect of power harrowed cultivation on sandy loam. Date of cultivation taken as 0 days. Error bars depict S.E.D., 11 d.f.

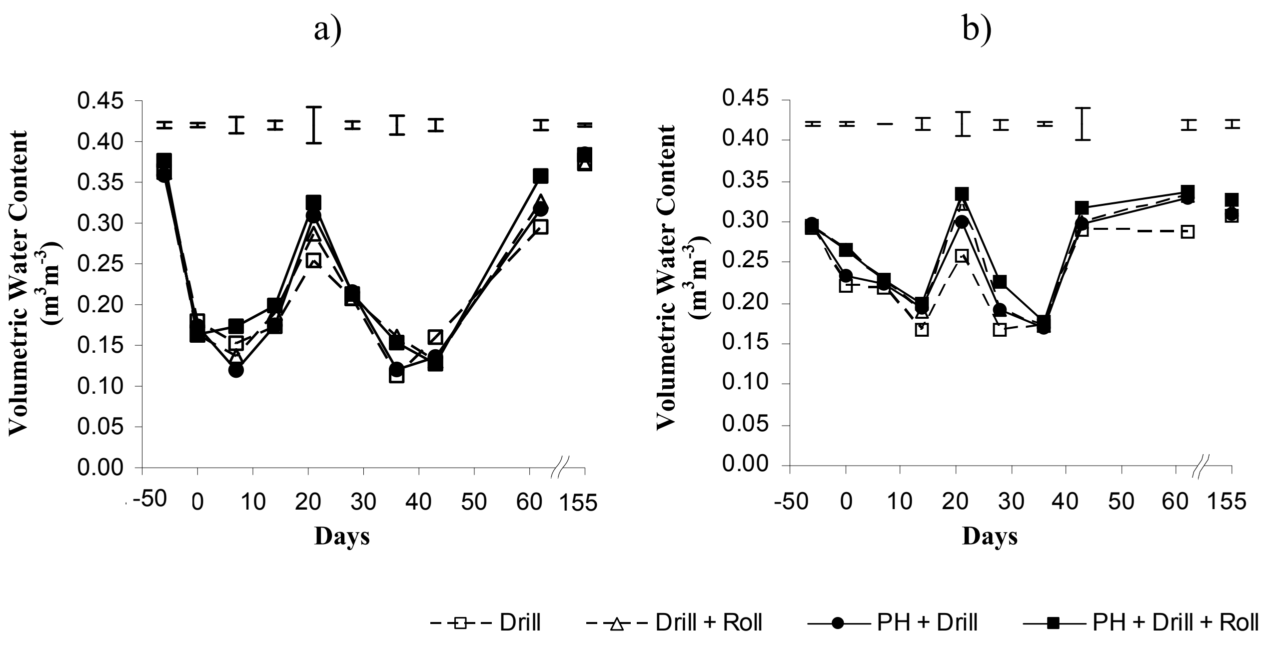


Figure 5.3: Variation in soil water content over time. a) Clay loam. b) Sandy loam. Date of cultivation taken as 0 days. Error bars depict S.E.D., 11 d.f.

5.3.5 Bulk density

Bulk density was less variable in the sandy loam than clay loam (Figure 5.4). Rolling (1.25g cm^{-3}) at both sites significantly (P = 0.006) increased bulk density compared to unrolled (1.23 g cm^{-3}) treatments throughout the experiment (Figure 5.4). Bulk density increased in response to rolling on the sandy loam, but not on the clay loam at establishment (P < 0.001). An interaction over time between soil type (site) and power harrowing occurred (P = 0.017) with reduced soil bulk density in non-power harrowed plots (1.25 g cm^{-3}) compared with power harrowed (1.28 g cm^{-3}) within the clay loam and the opposite effect in the sandy loam (1.21 and 1.23 g cm^{-3} respectively) (Figure 5.4). When averaged over time sandy loam had lower bulk density than the clay loam, with the highest recorded in the most intensive application on the sandy loam c. 1.25 g cm^{-3} (power harrowed and rolled), while the highest in the clay loam was recorded in the least intensive applications 1.26 g cm^{-3} (non-power harrowed and unrolled) and 1.30 g cm^{-3} (non-power harrowed and rolled) (Figure 4). These are typical values for bulk density within these soil types i.e. not considered compacted.

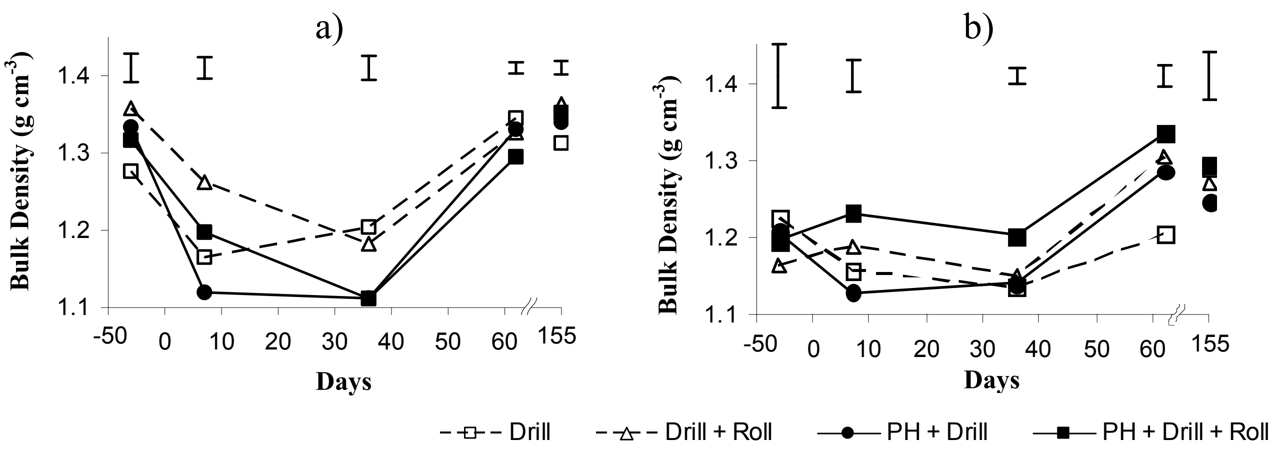


Figure 5.4: Variation in soil bulk density over time. a) Clay loam. b) Sandy loam. Date of cultivation taken as 0 days. Error bars depict S.E.D., 11 d.f.

5.3.6 Crop establishment

Initial emergence occurred between 7 and 14 days at both sites, with the first recorded measurements taken 14 days after drilling. At this point power harrowing resulted in c. 20 plants per m^{-2} more on the sandy loam soil than non-power harrowed plots, while on the clay loam the difference was c. 100 plants per m^{-2} ($P < 0.001$; Figure 5.5). These trends ($P < 0.001$) continued throughout the experiment with differences between power harrowed and non-power harrowed plots of c. 99 plants per m^{-2} in the clay loam and c. 28 plants per m^{-2} in the sandy loam at spring establishment.

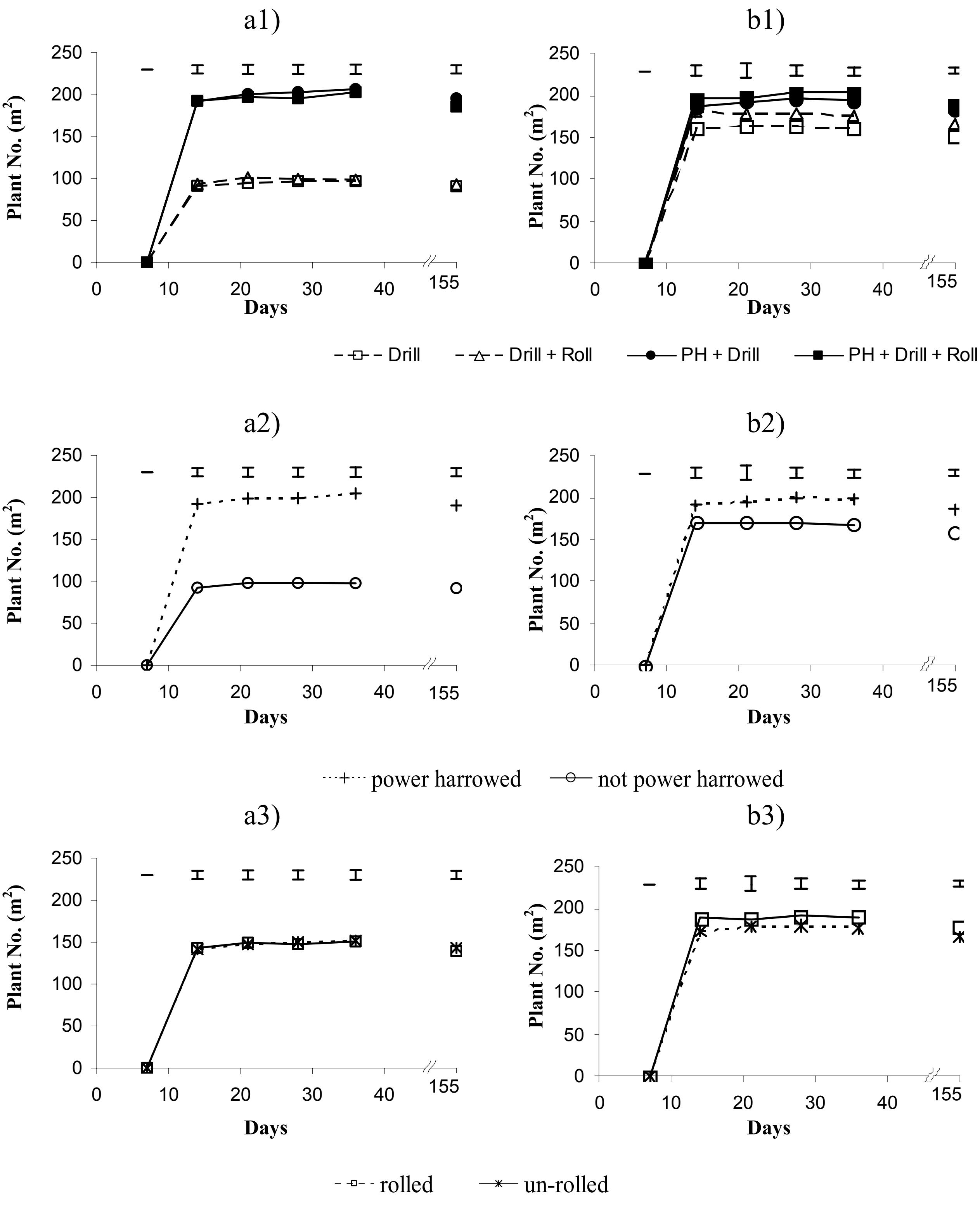


Figure 5.5: Plant number per m^2 over time within a) Clay loam. b) Sandy Loam. 1) Effect of treatments. 2) Effect of power harrowing. 3) Effect of rolling. Error bars depict S.E.D., 11 d.f.

A significant interaction between site and rolling (*P* = 0.007) also occurred over time with increased establishment under rolled treatments (187 plants per m^{-2}) compared to un-rolled (175 plants per m^{-2}) within the sandy loam, but the opposite within the clay loam (Figure 5.5).

5.3.7 Soil physical properties and establishment

Increases in soil penetration resistance, shear strength (Figure 5.6) and bulk density were all negatively correlated ($P < 0.05$) with crop establishment in the clay loam, while increased soil water content resulted in a positive relationship with crop establishment ($P < 0.05$, $R^2 = 0.49$) in the clay loam (Figure 5.6). The reverse was true for the sandy loam soil with increased soil shear strength ($R^2 = 0.38$), bulk density and water content ($R^2 = 0.44$) resulting in increased crop establishment ($P < 0.05$) (Figure 5.6). No significant relationships were observed between soil penetration resistance and establishment in the sandy loam, except at emergence where increased soil penetration resistance was correlated with an increased establishment.

Strong positive relationships ($P < 0.05$) occurred between each of the selected soil physical properties, in particular shear strength, bulk density and water content variations in both soil types. On the clay loam soil, water content decreased as bulk density increased ($R^2 = 0.22$) while on the sandy loam ($R^2 = 0.72$), the reverses was true (Figure 5.7). Soil penetration resistance only had a strong relationship with bulk density after cultivation; with increased bulk density leading to increased soil resistance in both soil textures.

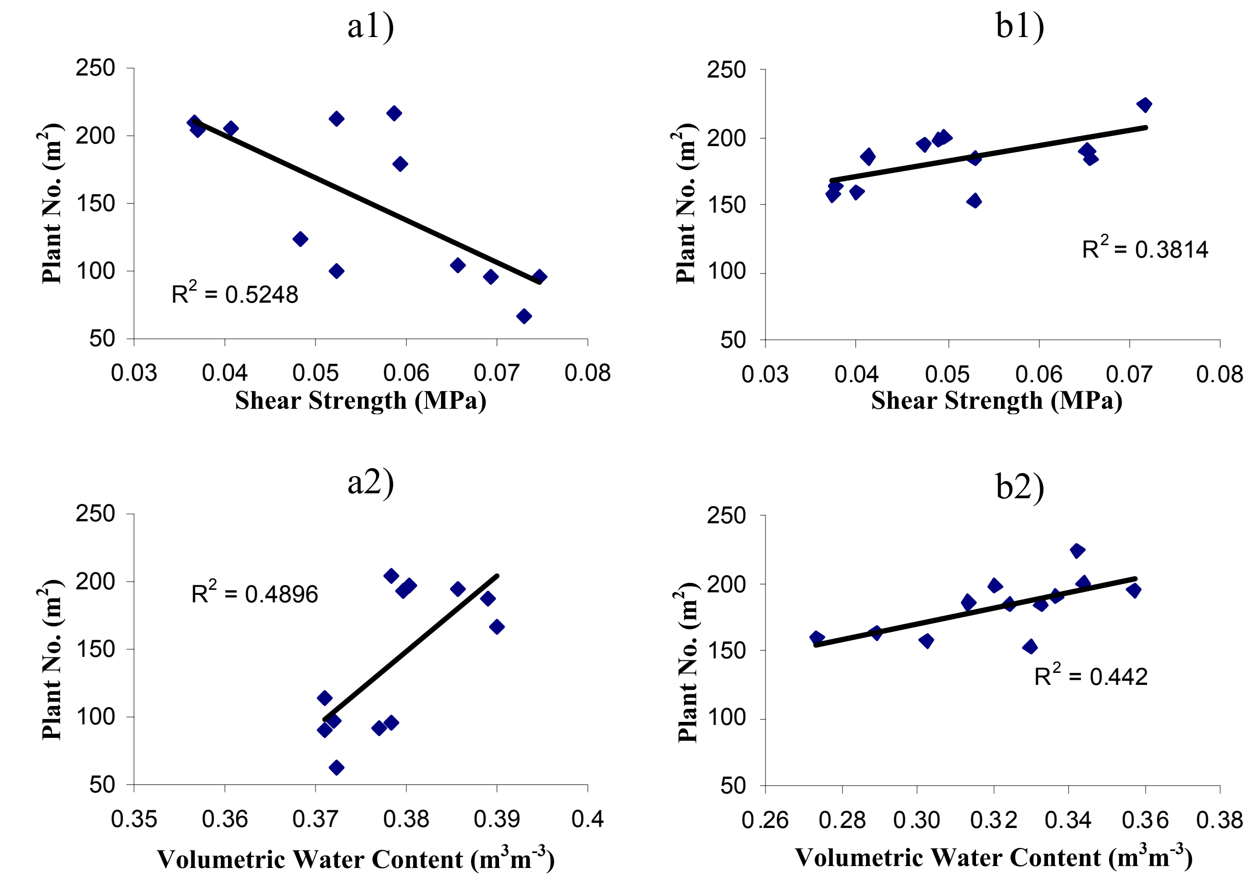


Figure 5.6: Establishment relationships with a) Clay Loam. b) Sandy loam. 1) Shear strength. 2) Water content.

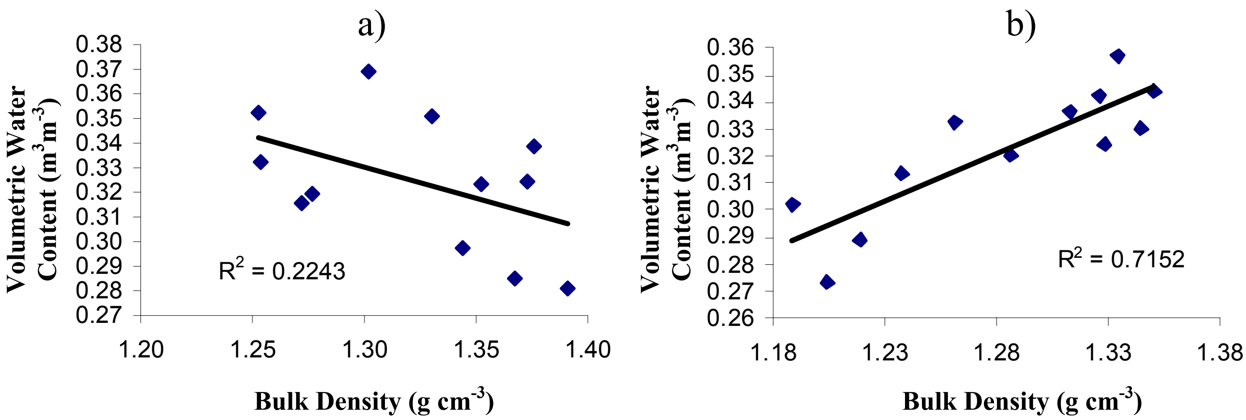


Figure 5.7: Relationship between soil water and bulk density in both; a) Clay Loam. b) Sandy loam.

5.3.8 Yield

Crop yield was not significantly affected by cultivation technique on either soil texture (Figure 5.8). However, mean yield was greater on the sandy loam at 10.17 t ha^{-1} compared with 8.88 t ha^{-1} within the clay loam (Figure 5.8). Significant relationships (P < 0.05) between yield and soil physical properties were observed, particularly after cultivation at seven days post drilling. In the clay loam, increased soil bulk density resulted in a decrease in crop yield (R^2 = 0.38) (Figure 5.9). Whilst in the sandy loam similar observations between increased penetration resistance and reduced yield occurred (R^2 = 0.26) (Figure 5.9).

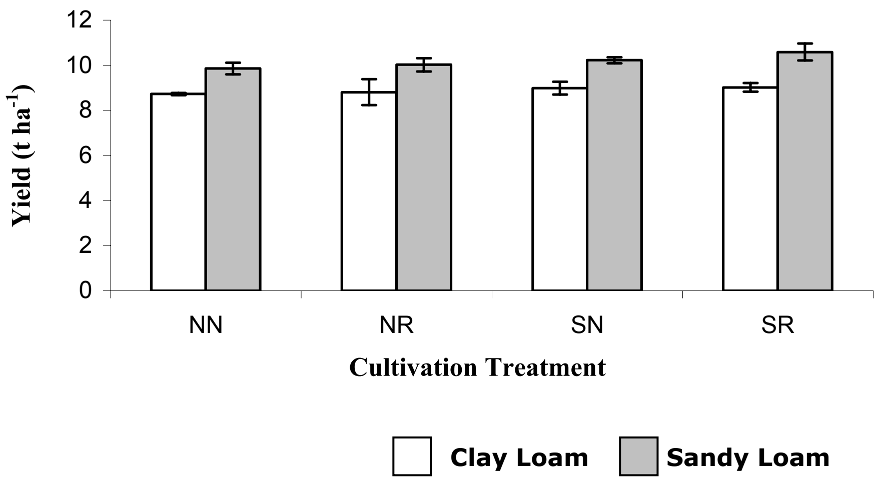


Figure 5.8: Yield variation between treatment applications of; NN = no secondary or rolling; NR = no secondary but rolled; SN = secondary but not rolling; SR = secondary and rolled. Error bars depict S.E.D., 11 d.f.

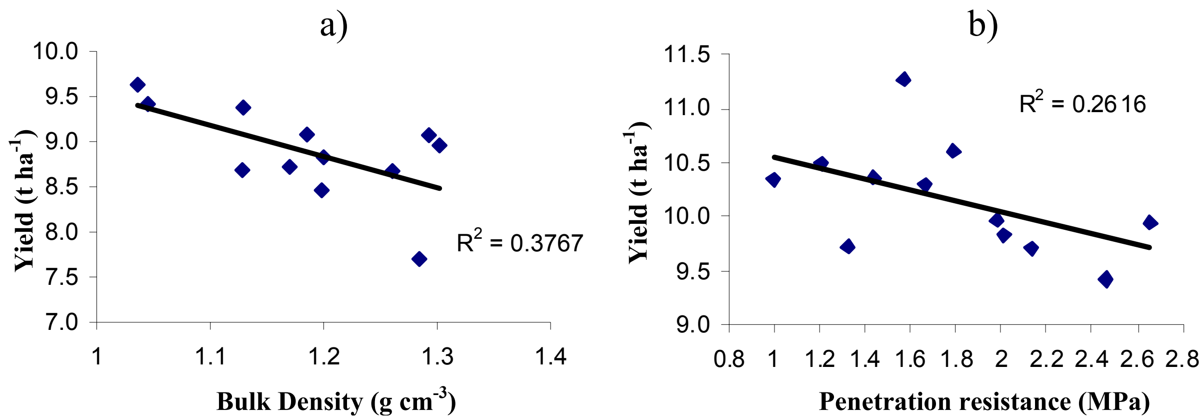


Figure 5.9: a) Relationship between bulk density and crop yield in Clay Loam. b) Relationship between yield and penetration resistance within the Sandy loam. At +7 days post drilling.

5.4 Discussion

Soil texture plays a vital role in determining the effect of cultivation on soil physical properties with significantly different responses in crop establishment. Secondary cultivation (power harrowing) showed the most marked differences in altering the two soil textures. Increased soil penetration resistance, shear strength, and bulk density, due to surface compaction, occurred within the sandy loam soil, supporting observations from previous experiments made on the same soil texture in Chapter 2. However, secondary cultivation on the clay loam was responsible for reducing soil penetration resistance, shear strength and bulk density, which supports findings by Comia et al. (1994). This is likely due to the hard, cloddy and massive structure of clay soils, with the passing of the power harrow breaking down this massive structure into a loose fine tilth. The reason for the opposite to occur in the sandy loam soil is because it is not as strongly cohesive as the clay and thus the extra tillage weight causes compaction. It is also most likely the result of water content conditions within the soils at the time of cultivation and therefore the friability ranges of the two soil textures. Similarities between the textures were observed as a result of secondary cultivation with increased soil water content, due to fine aggregates and increased water storage, and establishment (although only c. 25 plants per m^2 on the sandy loam), due to increased soil-seed contact.

Rolling, unlike secondary cultivation, produced similar responses in both soil textures with increases in penetration resistance, shear strength, bulk density and water content. This is the result of consolidation and compaction of the surface which also led to surface hardening in both textures as the seedbed matured. This again supported observations made in Chapter 2. Crop establishment as a result of rolling however was different between soil textures, under the sandy loam this led to a slight increase in plant numbers (similarly observed in Chapter 2), while on the clay loam, which had been power harrowed, plant numbers were reduced, but increased numbers if power harrowing had not been performed. This is likely due to the fine aggregated tilth prepared in the clay loam which when compacted decreased the pore space and the nutrient capture ability for the seed due to over compression of soil-seed contact area. The reason for the increase within the sandy loam soil is due to the larger pore sizes and the improved soil-seed contact that consolidation provides. The response of water content to bulk density also shows this relationship, with a decrease in water content following an increased bulk density in the clay loam as a result of reduced pore space and an increase in the sandy loam with a reduction in pore size.

Establishment was significantly affected by cultivation technique, particularly within the clay loam soil as a result of secondary cultivation. However, the significant differences in establishment did not translate into yield differences as a result of treatment effects, but there was a difference between soil textures with consistently reduced yield in the clay loam soil compared to the sandy loam. Both the lack of result in treatment variation (not consistent with previous observations in yield decrease on a sandy loam due to rolling) and the difference between textures may have been caused by adverse weather conditions. In 2007 there were unusual rainfall patterns throughout the year with an 85 % decreased rainfall in April followed by 100-140 % increase in average rainfall through May to July (Figure 5.10). This may have resulted in crop damage through lack of water initially and then through water logging causing a reduction in growth and development and in some cases death at a later date. This also meant that there was plenty of water available within the sandy loam soil (which in most summers is lacking), accounting for increased yield within the sandy loam soil which under normal circumstances would under perform against a clay soil.

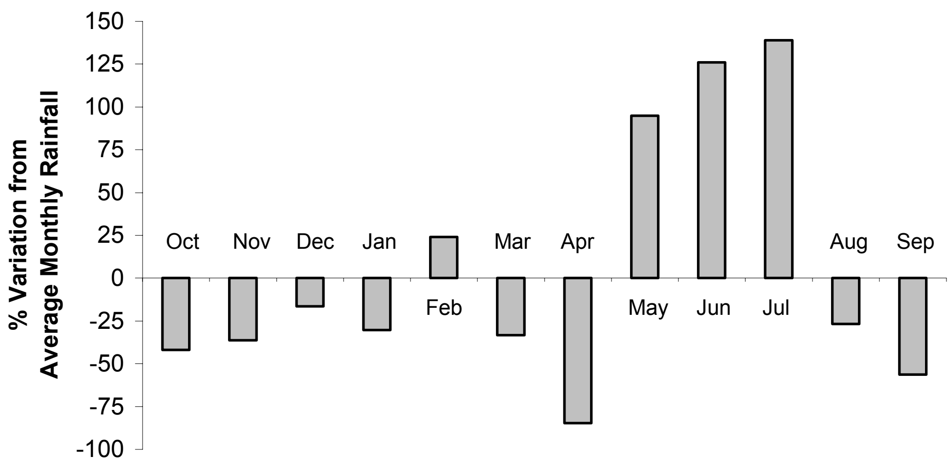


Figure 5.10: Percentage variation from average monthly rainfall as a result of adverse weather conditions between October 2006 and September 2007 (Figure courtesy of Tim Payne).

However, yield was strongly related to bulk density initially after cultivation within the clay loam and with penetration resistance in the sandy loam, with decreases in both resulting in observed increases in yield. The cause of this for the clay loam may be the result of poor drilling due to hard under-prepared surfaces in the non-power harrowed plots. Penetration resistance decreases within the sandy loam appear to negate the previous observations of increased establishment with consolidation, and may be the result of increased soil loosening at depth being preferential to yield while surface consolidation improves establishment.

5.5 Conclusions

Seedbed preparation on a clay loam requires added cultivation input from power harrowing to loosen the soil structure (i.e. increase porosity) adequately for improved drilling, nutrient availability and crop growth. Minimal cultivation (discing) alone does not provide optimal soil physical conditions for crop establishment, with c. 100 plants per m^{-2} more recorded following power harrowing. This increased establishment did not translate to yield, due to adverse weather or optimum plant populations within the non-power harrowed plots, but perhaps may have in different conditions. There was no advantage to rolling the clay loam which produced poor seedbed conditions with seedbed age.

The sandy loam did not however require further cultivation from minimal cultivation (discing) for adequate seedbed preparation with only slight increases in crop establishment and yield as a result of consolidation and increased soil-seed contact under power harrowed and rolled treatments. The advantages gained by secondary and tertiary cultivation of the soil do not appear to out-weigh the cost of the time and effort for the cultivation additions. Observations in the sandy loam soil support findings previously shown in chapter 2 with increased establishment due to consolidation, but no overall advantage in yield under minimal cultivation.

It is therefore prudent to suggest that the European Union CAP reform on the use of zero or minimal tillage application across the whole of the UK, especially as UK soils are around 60 % clay rich (Batey, 1988), or indeed Europe is perhaps not viable in clay soils due to the poor establishment achieved under these applications. Therefore further study is needed to assess viable options for soil degradation, nutrient loss, CO_2 loss or sequestration need to be addressed for clay rich soils.

Chapter 6:
A comparison of soil meso structure in reduced cultivation systems and the effect on winter wheat (*Triticum aestivum* cv. Einstein) establishment across two soil types.

6.1 Introduction

Minimal or reduced tillage can reduce soil degradation, CO_2 and nutrient loss, as well as benefit management costs compared with traditional cultivation systems. The European Union, through common agricultural policy reform (CAP), is also pushing farm management practice towards zero or reduced tillage for environmental / soil protection. The comparison between conventional and reduced (or even zero traffic) cultivation systems has been widely documented in terms of soil properties such as strength, bulk density etc. (Comia et al., 1994; Arvidsson, 1998; Rasmussen, 1999; Jordan & Leake, 2004; Filipovic et al., 2006). Previous studies have also compared the impact of reduced cultivation strategies on soil structure taking into account reduced cultivation applications, disturbance, residue management and reduced ground pressures (Douglas & Koppi, 1997; Moran et al., 1988; De Gryze et al., 2006; Servadio et al., 2005; Gantzer & Anderson, 2002; Pagliai et al., 2004).

Douglas & Koppi (1997) using image analysis to study soil macropore attributes of a clay loam under three management practices, zero, conventional and reduced ground pressure, found that average pore size was greater under zero cultivation (0.83 mm) and similar under conventional and reduced cultivation (0.59 mm). Similar results were observed by Wairiu & Lal (2006) on a silt loam soil, with higher average pore radii under continuous long term zero tillage compared with conventional and reduced systems. However, observations have shown that soil under conventional and minimum tillage has a much higher total macroporosity than zero tillage systems (Hubert et al., 2007). These observations are in direct conflict with each other. Servadio et al. (2005) observed reduced soil degradation with the use of reduced pressure equipment with increased macro porosity in dual tyre compared with single tyre systems. Pagliai et al. (2004) found macroporosity was generally higher and more homogenously distributed in alternative tillage systems such as ripper and disc harrowing compared to conventional tillage. This allowed for better water movement through the soil as well as creating more stable aggregates, reducing crust susceptibility in minimal techniques compared to conventional tillage. Pagliai et al. (1983) previously showed soils were more susceptible to surface crusting under traditional cultivation systems than under direct drill techniques, with horizontal layering occurring on, or just below, the surface of the soil in conventional tillage. Pagliai et al. (1995), in a study of long-term conventional and minimal tillage, found conventional tillage damaged soil physical properties and structure with observed decreased transmission and elongated pores under conventional tillage compared with minimal tillage as a result of compaction. Douglas & Koppi (1997) observed differences in pore nearest neighbour distances, with zero tillage (16 mm) having closer pore networks than either conventional (33 mm) or reduced (25 mm), but that soil degradation was moderated when conventional practices used reduced pressure equipment.

In recent years, X-ray Computed Tomography (CT) has been applied to the assessment of reduced tillage strategies as a quick and relatively non-destructive method for the study of the effects of minimal cultivation on soil structure. Olsen & Børresen (1997) were able to differentiate cultivated soils using X-ray CT, observing conventional tillage led to a loose structure within the ploughed layer but significantly reduced macroporosity at depth due to compaction. Reduced tillage resulted in uniform bulk density throughout the profile but overall increased macroporosity compared with conventional tillage. Recent improvements in the resolution of X-ray CT have since allowed for more detailed analyses for example; Gantzer & Anderson (2002) utilised high resolution X-ray CT in the assessment of conventional versus zero tillage. They found conventional tillage resulted in generally higher structural attributes such as pore area; macropore number; perimeter and fractal dimension. Other studies using X-ray CT have shown the effects of surface residue (reduced tillage) decomposition upon soil structure with increased porosity in the 27-67 µm range in association with decomposing residue and microbial activity (De Gryze et al., 2006).

Whilst previous studies using X-ray CT sought to differentiate the effects of conventional and minimal cultivation (or zero tillage) on soil properties (Gantzer & Anderson, 2002), none have concentrated on the effect on crop establishment. Optimum soil conditions for crop growth have similarly been omitted in previous studies. The objectives of this experiment were; (i) to identify changes in soil structural properties as a result of degrees of minimal cultivation on a heavy and light soil texture; (ii) to determine the effects of the soil structure on crop establishment and yield and the specific effects of secondary cultivation application; and (iii) determine the most suitable cultivation strategy of minimum cultivation for each soil texture.

6.2 Materials and methods

6.2.1 Field site and experimental design

A field experiment was established in 2006 at the University of Nottingham experimental farm, Sutton Bonington, Leicestershire, UK (52.5^{o}N, 1.3^{o}W), in an adjacent field to the previous year (Chapters 2 - 4), and Bunny, Nottinghamshire, UK (52.52^{o}N, 1.07^{o}W). The soils were a sandy loam of the Dunnington Heath series (FAO class; Stagno-Gleyic Luvisol) at Sutton Bonington and a clay loam of the Worcester series (FAO class; Argillic Pelosol) at Bunny (Chapter 3, Table 3.1). The soil at Sutton Bonington was in a rotation of winter oats, winter wheat, sugar beet, winter wheat, with the current experiment in winter wheat following winter oats. The soil at Bunny was in a rotation of two years winter wheat with a break crop of oilseed rape, with the current experiment in the second year of winter wheat.

At each site, the experiment was organized as a randomly distributed block design with two treatments (+/- power harrow), arranged in three replicate blocks. Primary cultivation, with a disc cultivar, and tertiary cultivation, with Cambridge rollers post-drilling, were performed across all plots at both locations as part of the experimental set-up opposed to treatments. Previous cultivations for two years had been performed by a single pass heavy disc cultivator incorporating a levelling board and roller (Vaderstad Carrier Super CR500). The experiment comprised of 6 plots that were 24 x 2.5 m wide, in sets of 2 plots in 3 blocks with 12 metre discards between blocks at each site. Both sites were drilled using a Nordsten drill with winter wheat (*Triticum* *aestivum*) cv. Einstein at a rate of 300 seeds per m^2 on 4 October 2006. Cultivations were performed on the same day.

6.2.2 Soil structure sampling

Soil samples were collected using the same method as in Chapter 3 section 3.3.2. However, samples were only taken at four key stages of seedbed evolution; prior to cultivation, after cultivation, emergence and establishment. Samples were also stored at 4 ºC prior to X-ray CT scanning.

6.2.3 X-ray Computed Tomography

Soil samples were scanned using an X-TEK Venlo high resolution X-ray CT scanner set at exposure limits of 175 Kv, 90 ms and 3 mÅs. Samples were set 145 mm from the detector with a 2 mm primary (at the source) and 4 mm secondary (at the detector – to prevent beam hardening / saturation) copper filters to eliminate low kV scatter and raise mean detection (Figure 6.1). The detector consisted of 3710 diodes set 83µm apart. A correction filter was applied to the diodes using a white and black image to adjust for exposure variations within the diodes of the detector. Each sample was scanned at 20, 30 and 40 mm from the base of the Kübiena tin (Figure 6.2).

6.2.4 Image analysis of soil structure characteristics

Image manipulation was performed using AnalySIS® (Soft Imaging Systems (SIS), Münster, Germany) to isolate pore space (Figure 6.2). The image spatial resolution was 66 µm pixel^{-1}. Images were cropped to a size of 62 x 62 mm (940 x 940 pixels) for processing. Greyscale filtering was performed using the following steps (Figure 6.3): 1) Calibration and rotation. 2) Frame size set (62 x 62 mm); 3) Sharpen, image contrast enhancement; 4) Median filter, providing image smoothing; 5) Lowpass filter, as a noise filter and strong image contrast smoothed; 6) Edge enhance, enhances contrast of image edges; 7) Rank filter, which removes spot noise from the original, adjusts pixel values in the centre to grey values in surrounding area; 8) Mean filter, for image smoothing. Images were then binarised using an auto threshold (removing operator bias) within AnalySIS®, defined by the greyscale value of the pixel, allowing for identical threshold parameters (exceptions were made on occasions of poor image quality, which needed manual manipulation, caused by small amounts of beam hardening, radial scatter and in some cases damaged diodes). A single morphological filter was then applied to the binary image: 9) Erosion, reducing noise by replacing each pixel with the median neighbouring pixel value (Figure 6.3). Plant material was included as pore space due to issues with density differentiation between air and root. Morphological analysis and measured parameters on binary images (Figure 6.4) were conducted as before (Chapter 4 section 4.2.5).

6.2.5 Statistical analysis

The statistical software package GenStat™ v.8.1 was used to analyse all data using an analysis of variance (ANOVA) to test for significant differences between treatments and to calculate standard errors of difference (S.E.D). Data was analysed as a split plot between sites to attain interactions between site (soil type) and cultivation applications. Due to un-replicated sites it must be noted that differences between soil textures can only be inferred and indeed may also be related to site specific variations in other factors such as weather, slope, soil degradation etc.

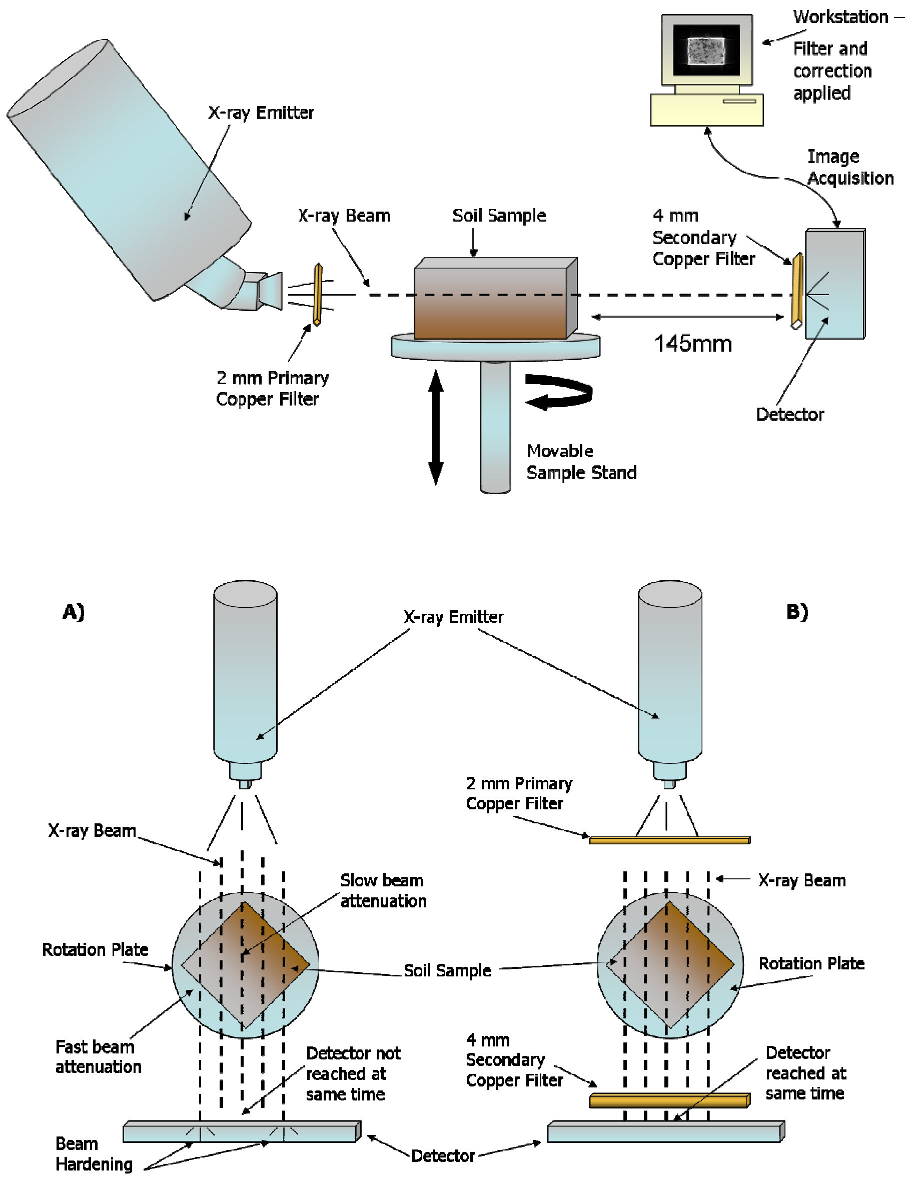


Figure 6.1: X-ray computed tomography diagram of set-up and the effect of beam hardening (a) due to faster x-ray and the correction applied using copper filters (b) in preventing beam hardening.

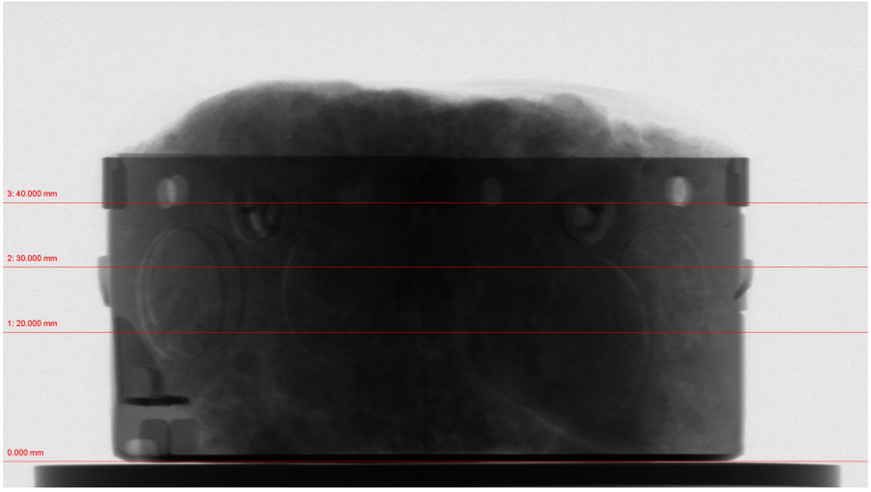


Figure 6.2: Cross section of soil sample showing X-ray beam locations at 20, 30 and 40 mm from base of sample.

6.3 Results

6.3.1 Seedbed evolution

Seedbed evolution (Figure 6.4) shows variation over time from prior to cultivation through to establishment. Pore space, displayed in white, is increased significantly after cultivation. Secondary cultivation (power harrowing) increased pore space at the finer scale compared to non-power harrowed treatments. Visible differences between soil textures are also evident in the images as well as increased root and shoot material (classified as porosity due to un-definable density with air) as time passes. In the following sections these differences are described in detail from quantified image analysis.

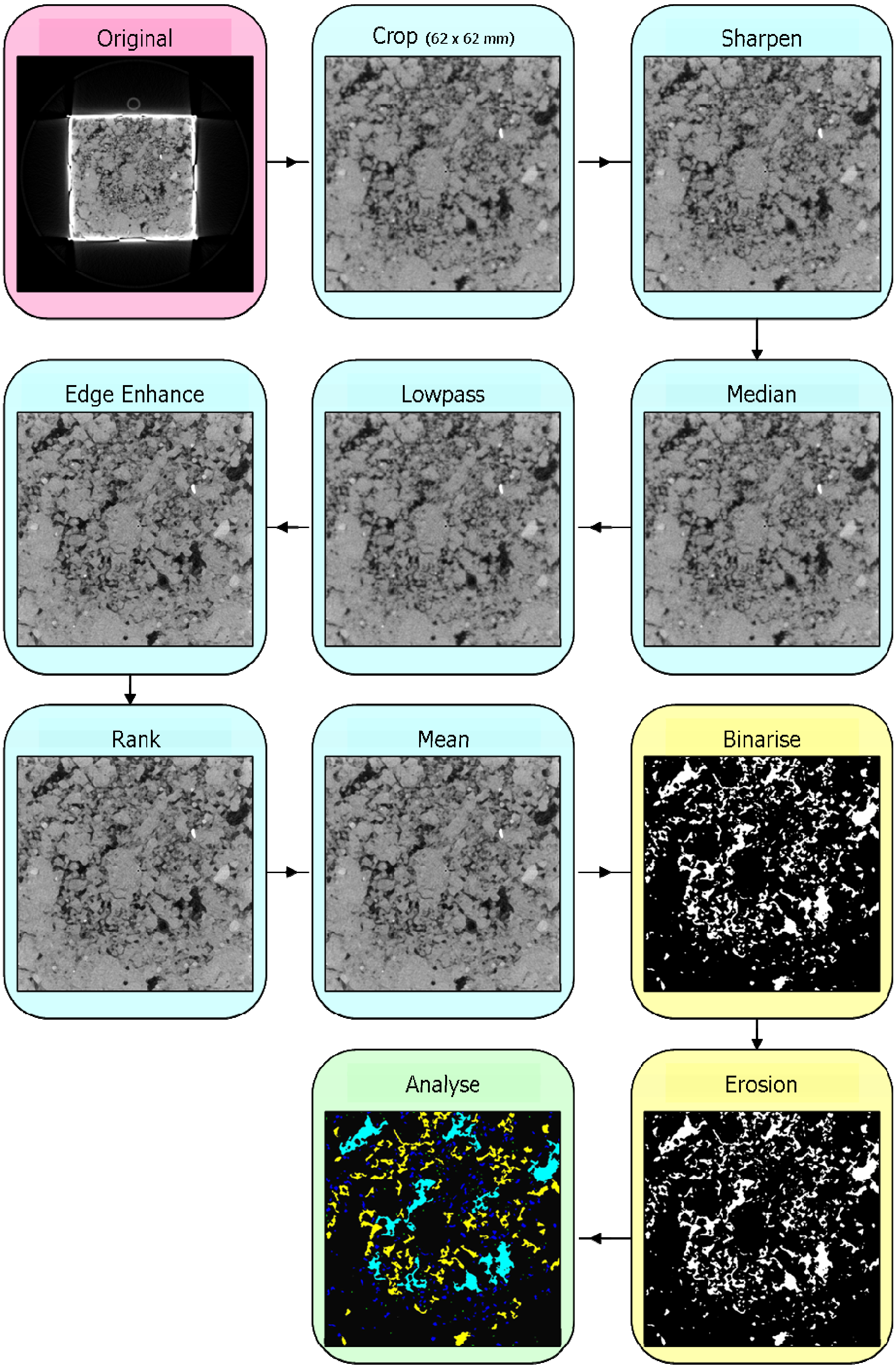
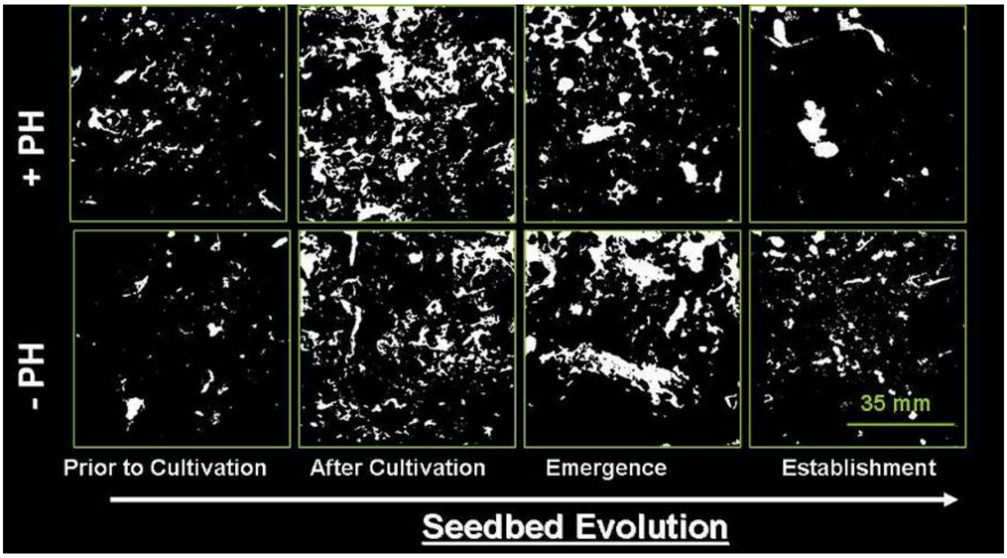


Figure 6.3: Image manipulation of X-ray CT soil block images.

(A)



(B)

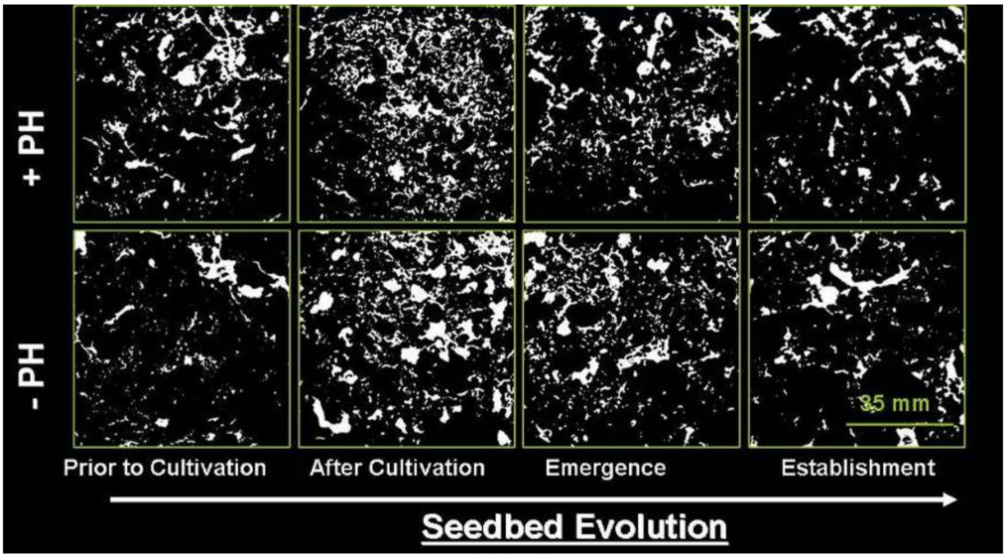


Figure 6.4: Seedbed evolutionary changes between secondary cultivation (power harrowing, PH) and soil texture (A) Clay loam; (B) Sandy loam. (White = pore space) See section 6.3.1 for detailed description.

6.3.2 Meso Scale Porosity

Soil porosity was not significantly different between plots or sites prior to cultivation with the variability between c. 11-12 % and c. 6 % within the sandy loam and clay loam respectively (Table 6.1). After cultivation, porosity was significantly increased with both sites having c. 18 % porosity (Figure 6.5). Plots which received power harrowing generally had greater porosity by c. 2 %. The two soils responded differently to power harrowing with a 4 % increase in porosity in the clay loam and 1 % decrease in the sandy loam in response to power harrowing (P = 0.031) (Figure 6.5). At emergence, plots which had received power harrowing (c. 12 %) had significantly lower porosity (P = 0.003) than non-power harrowed plots (c. 14 %) (Figure 6.5). The interaction between soil type (site) and power harrowing also changed, with both clay loam and sandy loam soils having reduced porosity under power harrowed plots, with clay loam having the greater difference between treatments. Both trends continued through to establishment. Over time, soil porosity significantly (P < 0.001) decreased, resulting in a much reduced porosity within the soil at establishment compared with prior to cultivation, particularly within the sandy loam soil (Figure 6.5).

6.3.3 Mean Pore Size (mm^2)

Average pore size was not significantly different prior to cultivation with a mean value of c. 1.1 and c. 1.3 mm^2 within the sandy loam and clay loam respectively (Table 6.1). Mean pore size was increased at both locations after cultivation to c. 1.3 and c. 2.0 mm^2 within the sandy loam and clay loam respectively, with the largest pore sizes observed under non-power harrowed plots (particularly within the sandy loam) compared with power harrowed plots (Figure 6.6). This trend continued until establishment where a slight increase in average pore size under power harrowed plots, perhaps relating to crop development, was observed at both sites, with the greatest increase occurring in the sandy loam (Figure 6.6). However the above trends were not significant, perhaps due to large errors within the data.

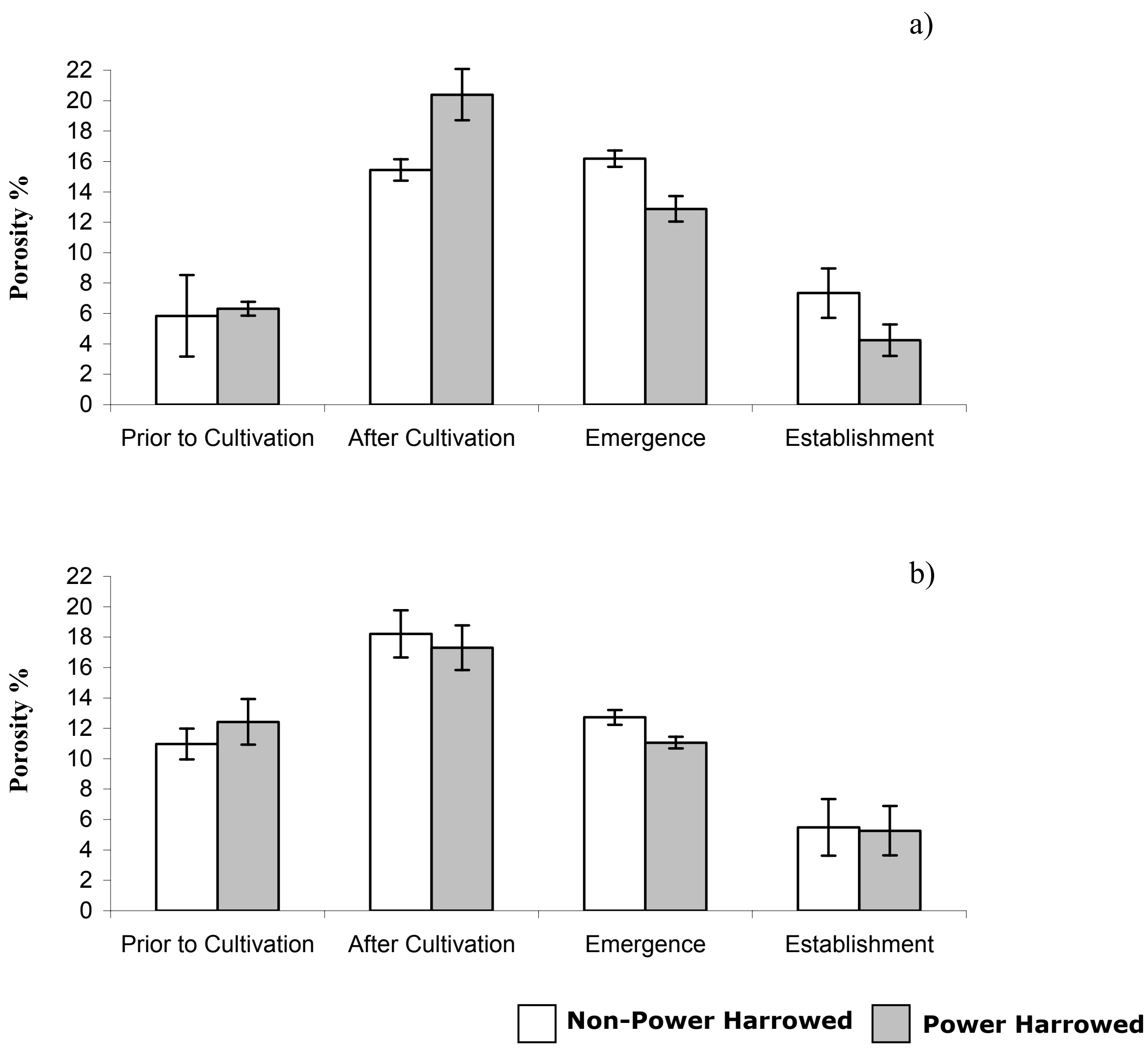
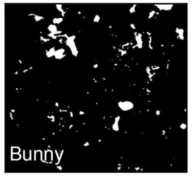


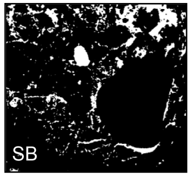
Figure 6.5: Mean porosity variation between secondary cultivation and site at each time period a) Clay Loam, b) Sandy Loam. Error bars represent s.e.d.

Table 6.1: Mean soil structure variation over the evolution of the seedbeds in both soil type (sites) and in response to power harrowing. Images representative of DDR treatment at both locations, white represents pore space.

PRIOR to Cultivation

(- 44 Days)

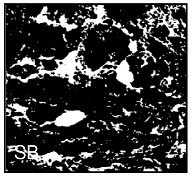




Treatment	Site	Soil Type	Secondary	Porosity %	s.e.d	Area (mm^2)	s.e.d	ECD (mm)	s.e.d	Perimeter (mm)	s.e.d
DDR	Bunny	Clay Loam	- PH	5.84	2.68	1.44	0.55	0.82	0.17	4.02	1.10
DDR	SB	Sandy Loam	- PH	10.96	1.01	1.09	0.20	0.67	0.03	3.79	0.29
DPDR	Bunny	Clay Loam	+ PH	6.31	0.45	1.14	0.23	0.75	0.08	3.55	0.40
DPDR	SB	Sandy Loam	+ PH	12.42	1.50	1.05	0.17	0.71	0.07	3.95	0.58

After Cultivation

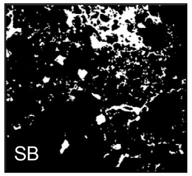
(7 Days)



Treatment	Site	Soil Type	Secondary	Porosity %	s.e.d	Area (mm^2)	s.e.d	ECD (mm)	s.e.d	Perimeter (mm)	s.e.d
DDR	Bunny	Clay Loam	- PH	15.44	0.71	1.94	0.63	0.91	0.17	5.41	1.31
DDR	SB	Sandy Loam	- PH	18.21	1.55	1.39	0.18	0.80	0.03	4.87	0.58
DPDR	Bunny	Clay Loam	+ PH	20.39	1.69	2.02	0.68	0.84	0.09	5.65	1.06
DPDR	SB	Sandy Loam	+ PH	17.30	1.47	1.14	0.32	0.76	0.07	4.44	0.66

Emergence

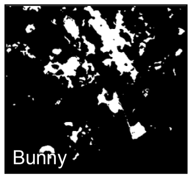
(43 Days)

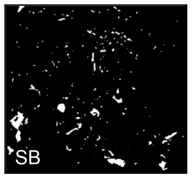


Treatment	Site	Soil Type	Secondary	Porosity %	s.e.d	Area (mm^2)	s.e.d	ECD (mm)	s.e.d	Perimeter (mm)	s.e.d
DDR	Bunny	Clay Loam	- PH	16.18	0.54	2.29	0.73	0.94	0.14	5.67	1.22
DDR	SB	Sandy Loam	- PH	12.72	0.49	1.15	0.27	0.72	0.01	3.99	0.18
DPDR	Bunny	Clay Loam	+ PH	12.88	0.84	2.02	0.77	0.90	0.10	4.98	0.82
DPDR	SB	Sandy Loam	+ PH	11.06	0.38	1.07	0.06	0.70	0.04	3.74	0.25

Establishment

(63 Days)





Treatment	Site	Soil Type	Secondary	Porosity %	s.e.d	Area (mm^2)	s.e.d	ECD (mm)	s.e.d	Perimeter (mm)	s.e.d
DDR	Bunny	Clay Loam	- PH	7.34	1.62	2.00	0.52	0.94	0.11	4.55	0.63
DDR	SB	Sandy Loam	- PH	5.49	1.86	0.80	0.12	0.66	0.06	3.04	0.33
DPDR	Bunny	Clay Loam	+ PH	4.25	1.03	1.92	0.32	0.98	0.06	4.67	0.37
DPDR	SB	Sandy Loam	+ PH	5.26	1.63	0.95	0.27	0.70	0.08	3.32	0.61

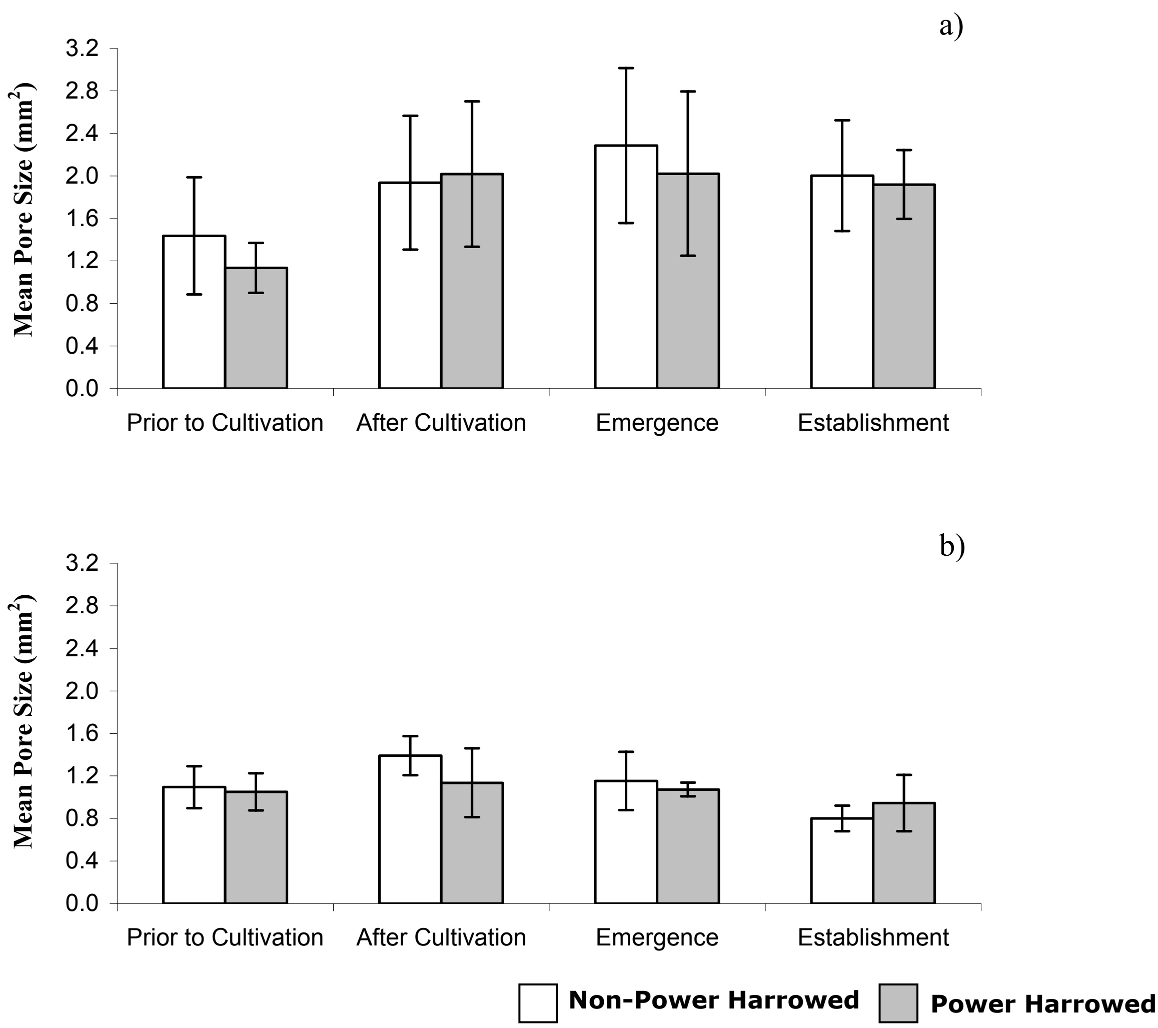


Figure 6.6: Mean pore size (mm^2) variation between secondary cultivation and site at each time period a) Clay Loam, b) Sandy Loam. Error bars represent s.e.d.

6.3.4 Equivalent Circle Diameter (ECD)

No significant difference in ECD was observed prior to cultivation with a mean value of c.0.79 and c. 0.69 mm within the clay loam and sandy loam respectively (Table 6.1). No significant differences were observed as a result of secondary cultivation, although trends follow similar patterns as observed within average pore area, with increased ECD after cultivation within non-power harrowed plots compared to power harrowed and the reverse by establishment. A highly significant interaction (P <

0.001) between soil type (site) occurred over time with significant increases occurring in both soil types after cultivation (c. 0.1 mm) (Figure 6.7). However, as the seedbed aged, the ECD within the clay loam increased by 0.8 mm while a decrease was observed within the sandy loam (c. 0.12 mm) (Figure 6.7).

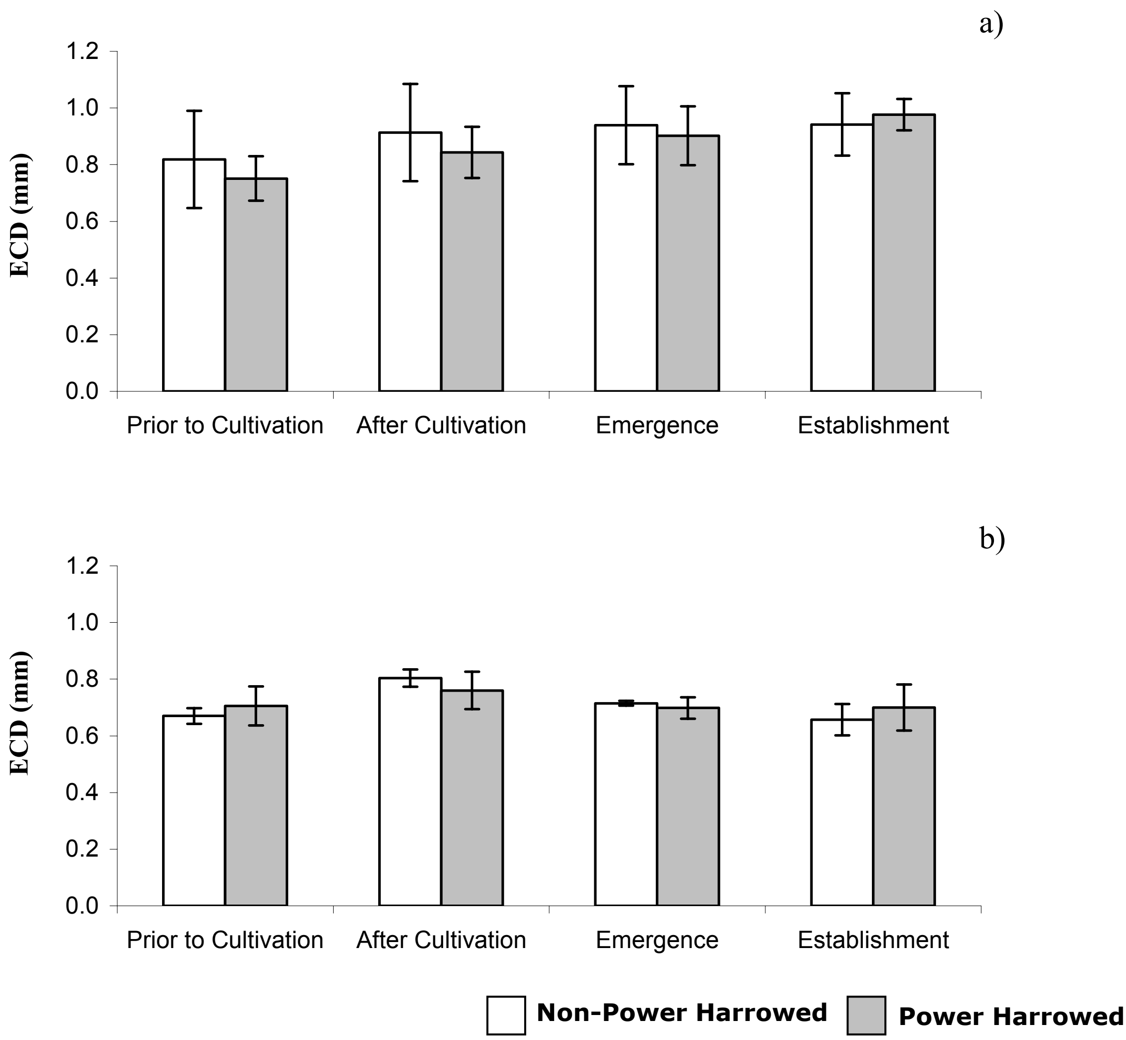


Figure 6.7: Mean ECD (mm) variation between secondary cultivation and site at each time period a) Clay Loam, b) Sandy Loam. Error bars represent s.e.d.

6.3.5 Mean Pore Perimeter (mm)

No significant differences were observed prior to cultivation with mean pore perimeter at both sites c. 3.83 mm (Table 6.1). After cultivation, pore perimeter increased in all treatments, with the greatest increase observed in non-power harrowed compared to power harrowed plots within the sandy loam, but the reverse within the clay loam (Figure 6.8). At emergence, trends in pore perimeter decreased slightly across treatments but remained highest within non-power harrowed plots (c. 5 mm) at both sites compared to power harrowed (c. 4 mm) (Figure 6.8). At establishment this trend reversed with higher pore perimeter recorded within the power harrowed opposed to the non-power harrowed plots at both sites. Averaged over time pore perimeter was between 1 – 1.5 mm greater within the clay loam than the sandy loam soil ($P = 0.036$) (Figure 6.8).

6.3.6 Pore Size Distribution (PSD)

The difference in PSD (Figures 6.9 and 6.10) prior to cultivation at both sites, although roughly similar in distribution order, showed a greater proportion of pores within each size class of the sandy loam soil compared with the clay loam i.e. higher porosity. Cultivation resulted in the distributions of the non-power harrowed treatments were roughly similar between soil types with increasing larger pore sizes in a normal distribution. However, the difference between power harrowed treatments and soil types (site) was significantly different; the sandy loam non-power harrowed had a reduced overall pore area, but the clay loam had an increase in larger pore sizes. PSD at emergence was roughly similar in response to treatments at both sites, and by establishment the PSD were very similar regardless of soil type, but with overall variations in total area between treatments and soils.

6.3.6.1 Pore Size Distribution - Coefficient of Uniformity (PSD_{cu})

No significant differences were observed in PSD_{cu} prior to cultivation with a mean ratio of c. 30 and c. 51 within the clay loam and sandy loam respectively (Table 6.2). No significant differences were observed as a result of power harrowing throughout the experiment, which is probably due to large standard errors within the data e.g. average > 20 s.e.d.. A significant ($P = 0.013$) difference in PSD_{cu} over time between the soil types (site) was observed, with cultivation significantly reducing PSD_{cu} within the sandy loam (c. 33) and increasing PSD_{cu} within the clay loam (c. 67) (Figure 6.11). This again was reversed by emergence (c. 39 and c. 72 within the clay and sandy loams respectively) and remained through the experiment (Figure 6.11).

6.3.7 Pore Shape - Elongation and Sphericity

No significant difference in pore shape was observed prior to cultivation or after cultivation. At emergence, pore elongation decreased within power harrowed compared to non-power harrowed plots ($P = 0.04$) (Table 6.2). However, a reverse in this trend was observed at establishment with greater elongation occurring within power harrowed plots compared with non-power harrowed. Pore sphericity was greatest after cultivation within power harrowed plots but over time this reversed ($P = 0.033$) (Table 6.2). Pore sphericity was greatest over time within the clay loam compared with the sandy loam soil ($P = 0.019$) (Table 6.2).

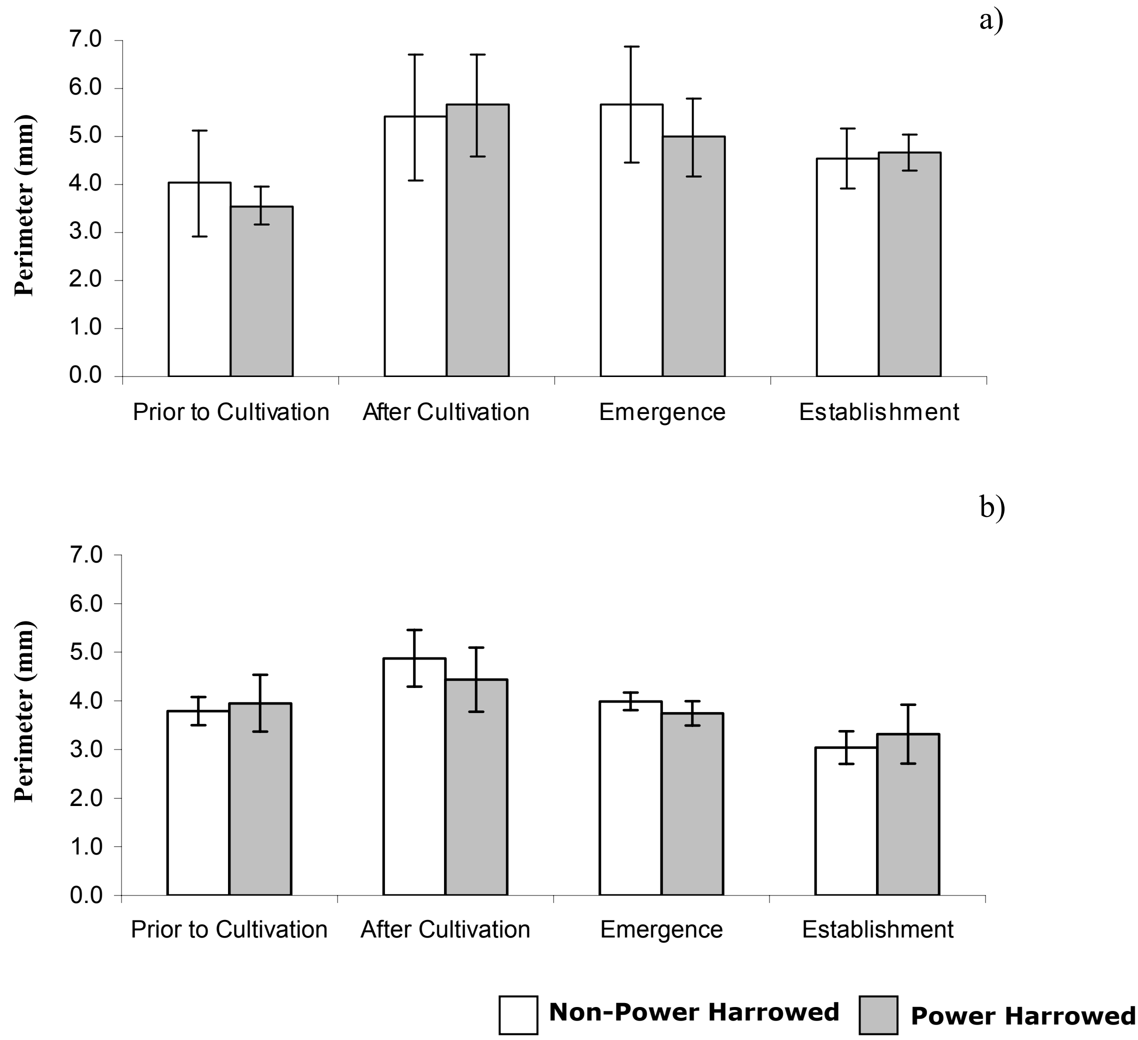
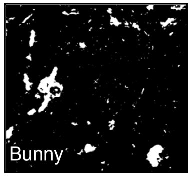


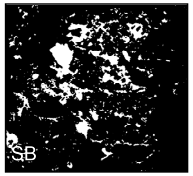
Figure 6.8: Mean pore perimeter (mm) variation between secondary cultivation and site at each time period a) Clay Loam, b) Sandy Loam. Error bars represent s.e.d.

Table 6.2: Mean soil structure variation over the evolution of the seedbeds in both soil type (sites) and in response to power harrowing. Images representative of DPDR treatment at both locations, white represents pore space.

PRIOR to Cultivation

(- 44 Days)

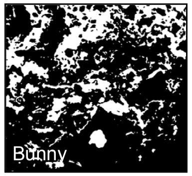


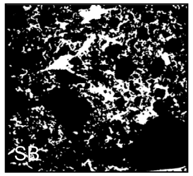


Treatment	Site	Soil Type	Secondary	PSD_{cu}	s.e.d	Elongation	s.e.d	Next Neighbour Distance (mm)	s.e.d	Sphericity	s.e.d
DDR	Bunny	Clay Loam	- PH	31.79	14.41	2.01	0.05	2.30	0.08	0.36	0.01
DDR	SB	Sandy Loam	- PH	60.15	35.81	2.06	0.04	1.51	0.07	0.34	0.01
DPDR	Bunny	Clay Loam	+ PH	25.57	8.49	1.97	0.04	2.08	0.41	0.37	0.01
DPDR	SB	Sandy Loam	+ PH	41.93	18.14	2.03	0.02	1.46	0.06	0.35	0.00

After Cultivation

(7 Days)

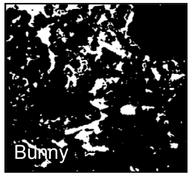


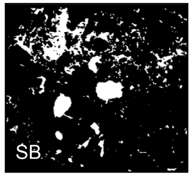


Treatment	Site	Soil Type	Secondary	PSD_{cu}	s.e.d	Elongation	s.e.d	Next Neighbour Distance (mm)	s.e.d	Sphericity	s.e.d
DDR	Bunny	Clay Loam	- PH	45.87	20.12	2.02	0.02	1.80	0.22	0.35	0.01
DDR	SB	Sandy Loam	- PH	37.19	7.37	2.00	0.04	1.45	0.04	0.35	0.01
DPDR	Bunny	Clay Loam	+ PH	88.30	58.53	1.99	0.01	1.56	0.19	0.35	0.01
DPDR	SB	Sandy Loam	+ PH	29.69	1.64	2.00	0.04	1.35	0.10	0.35	0.01

Emergence

(43 Days)

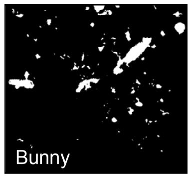


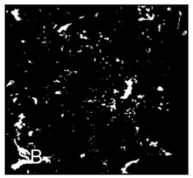


Treatment	Site	Soil Type	Secondary	PSD_{cu}	s.e.d	Elongation	s.e.d	Next Neighbour Distance (mm)	s.e.d	Sphericity	s.e.d
DDR	Bunny	Clay Loam	- PH	41.91	10.20	1.98	0.02	1.82	0.28	0.36	0.00
DDR	SB	Sandy Loam	- PH	60.89	18.34	2.02	0.00	1.46	0.08	0.35	0.00
DPDR	Bunny	Clay Loam	+ PH	35.91	19.60	1.94	0.01	1.89	0.27	0.37	0.00
DPDR	SB	Sandy Loam	+ PH	83.88	41.85	1.98	0.04	1.54	0.06	0.36	0.01

Establishment

(63 Days)





Treatment	Site	Soil Type	Secondary	PSD_{cu}	s.e.d	Elongation	s.e.d	Next Neighbour Distance (mm)	s.e.d	Sphericity	s.e.d
DDR	Bunny	Clay Loam	- PH	23.04	6.76	1.96	0.04	2.25	0.16	0.37	0.01
DDR	SB	Sandy Loam	- PH	37.00	14.39	1.95	0.03	1.77	0.20	0.37	0.01
DPDR	Bunny	Clay Loam	+ PH	14.93	6.87	1.99	0.06	2.81	0.13	0.36	0.01
DPDR	SB	Sandy Loam	+ PH	34.28	7.33	1.97	0.03	1.95	0.05	0.36	0.01

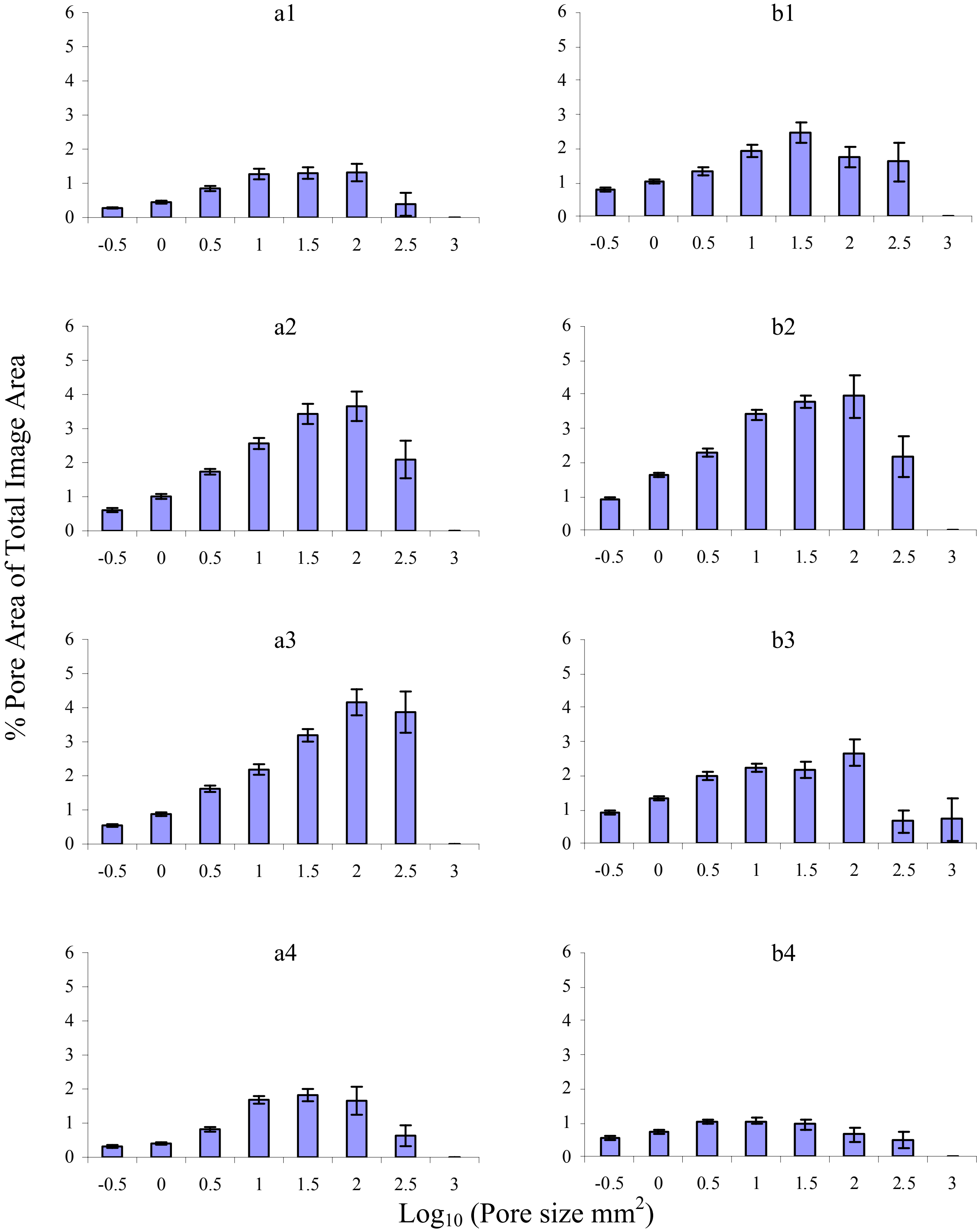


Figure 6.9: Pore size distribution of non-power harrowed plots of a) Clay loam and b) Sandy loam at key seedbed evolution stages of 1) prior to cultivation; 2) after cultivation; 3) emergence; 4) establishment. Error bars represent s.e.d.

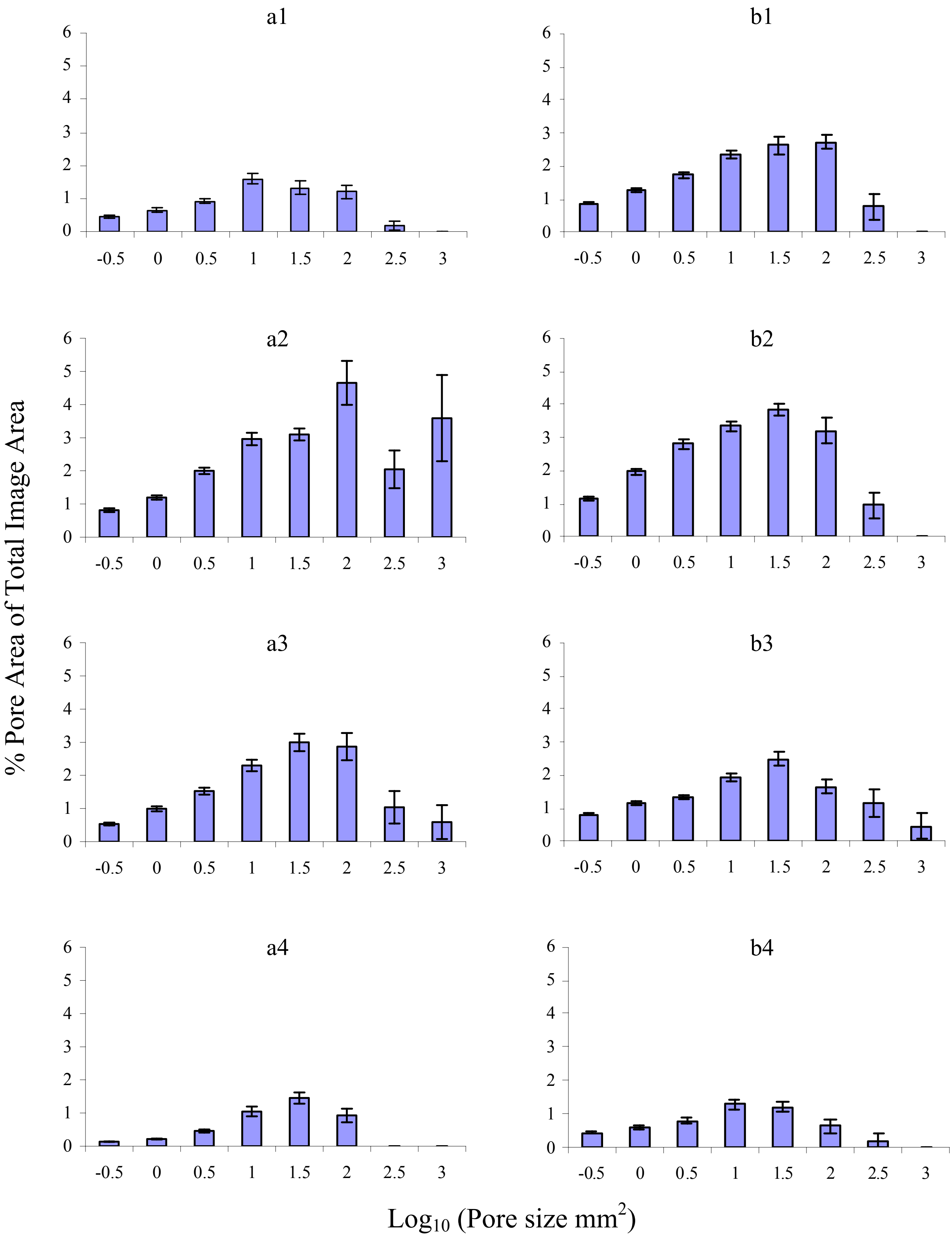


Figure 6.10: Pore size distribution of power harrowed plots of a) Clay loam and b) Sandy loam at key seedbed evolution stages of 1) prior to cultivation; 2) after cultivation; 3) emergence; 4) establishment. Error bars represent s.e.d.

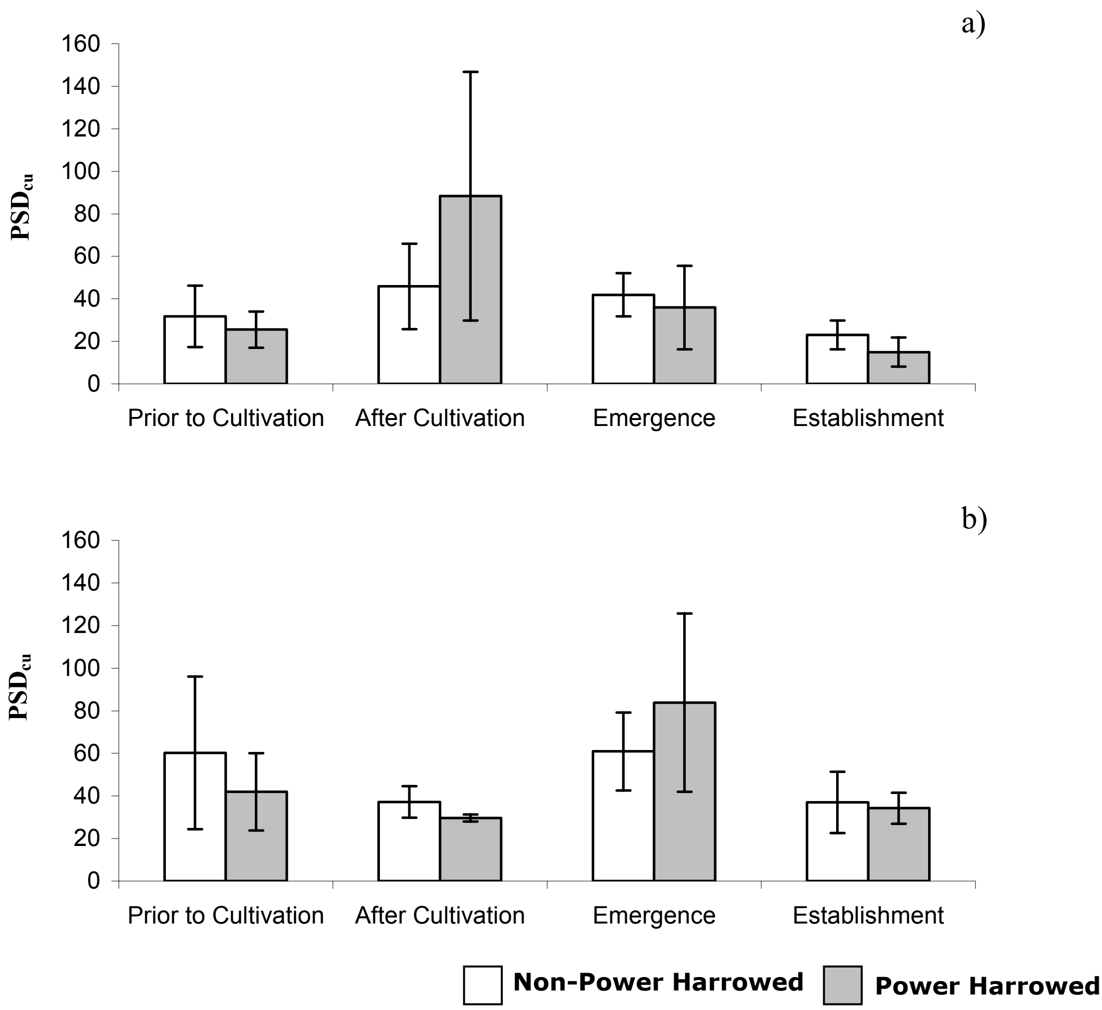


Figure 6.11: Mean PSD_{cu} variation between secondary cultivation and site at each time period a) Clay Loam, b) Sandy Loam. Error bars represent s.e.d.

6.3.8 Nearest Neighbour Distance (mm)

Nearest neighbour distance (NND) was not significantly different prior to cultivation with the mean value between 1.5 – 2.3 mm, with generally higher mean distances between pores occurring within the clay loam compared with the sandy loam (Table 6.2). A reduction in NND was observed at both sites after cultivation, with a significant difference between power harrowed (1.45 mm) and non-power harrowed (1.62 mm) plots (P = 0.003). This was particularly true within the clay loam with a difference of 0.24 mm between power harrowed and non-power harrowed plots and only a difference of 0.1 mm within the sandy loam (Figure 6.12). By emergence NND between treatments was roughly equal although generally lower NND was observed in the sandy loam compared with clay loam. At establishment NND had increased in all treatments with a reverse in the trend observed after cultivation with power harrowed (2.4 mm) plots having higher NND than non-power harrowed (2.0 mm) plots (P = 0.015) (Figure 6.12). This reversal was uniform across sites but the clay loam (0.56 mm), as before, had a higher NND between treatments than the sandy loam (0.17 mm). Over time the clay loam had significantly (P = 0.003) higher NND than the sandy loam soil (Figure 6.12).

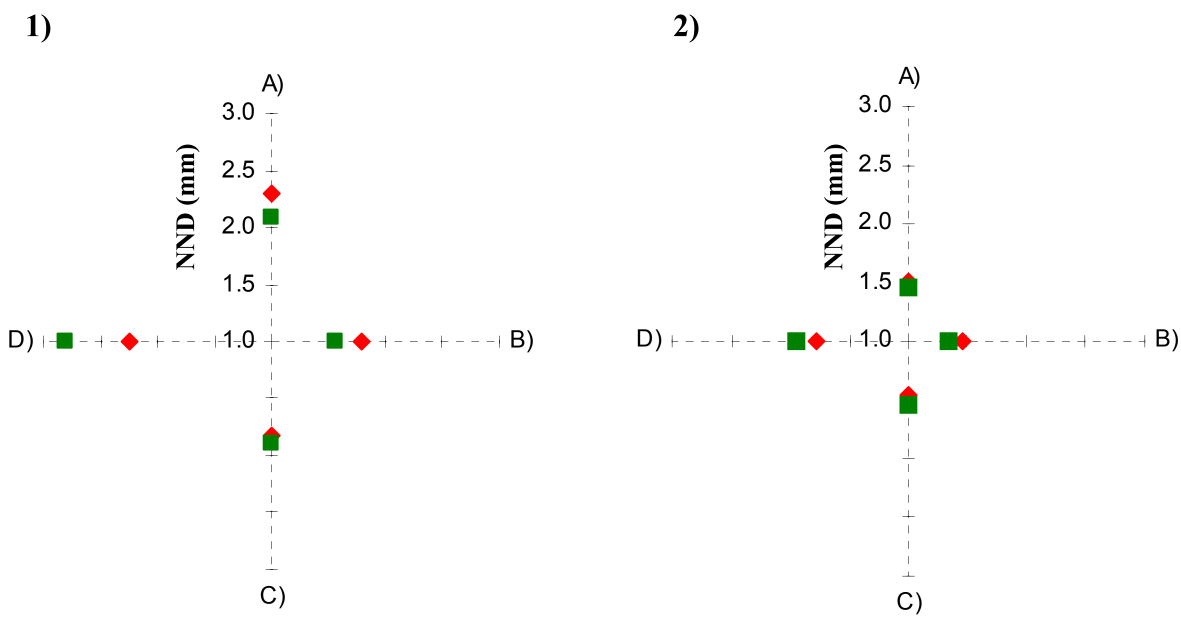


Figure 6.12: Mean variation in nearest neighbour distance (mm) between secondary cultivation (◊ = non-power harrowed, □ = Power harrowed) and site 1) Clay Loam and 2) Sandy Loam at each time period a) Prior to cultivation, b) After cultivation, c) Emergence and d) Establishment.

6.3.9 Linking soil physical properties with establishment

6.3.9.1 Relationships between soil physical measurements and soil structure

The soil structural measurements correlated strongly with a number of soil physical properties over the evolution of the seedbeds at both sites. After cultivation, strong correlations with water content and measurements of pore area and NND occurred (*P* < 0.05, R^2 = 0.4 and 0.58 respectively) showing an increase in water content with both a decrease in the distance between pores and pore size (increased number of finer pores) (Figure 6.13). Increased soil penetration resistance was also strongly linked with increased pore elongation (*P* < 0.05, R^2 = 0.4) (Figure 6.13).

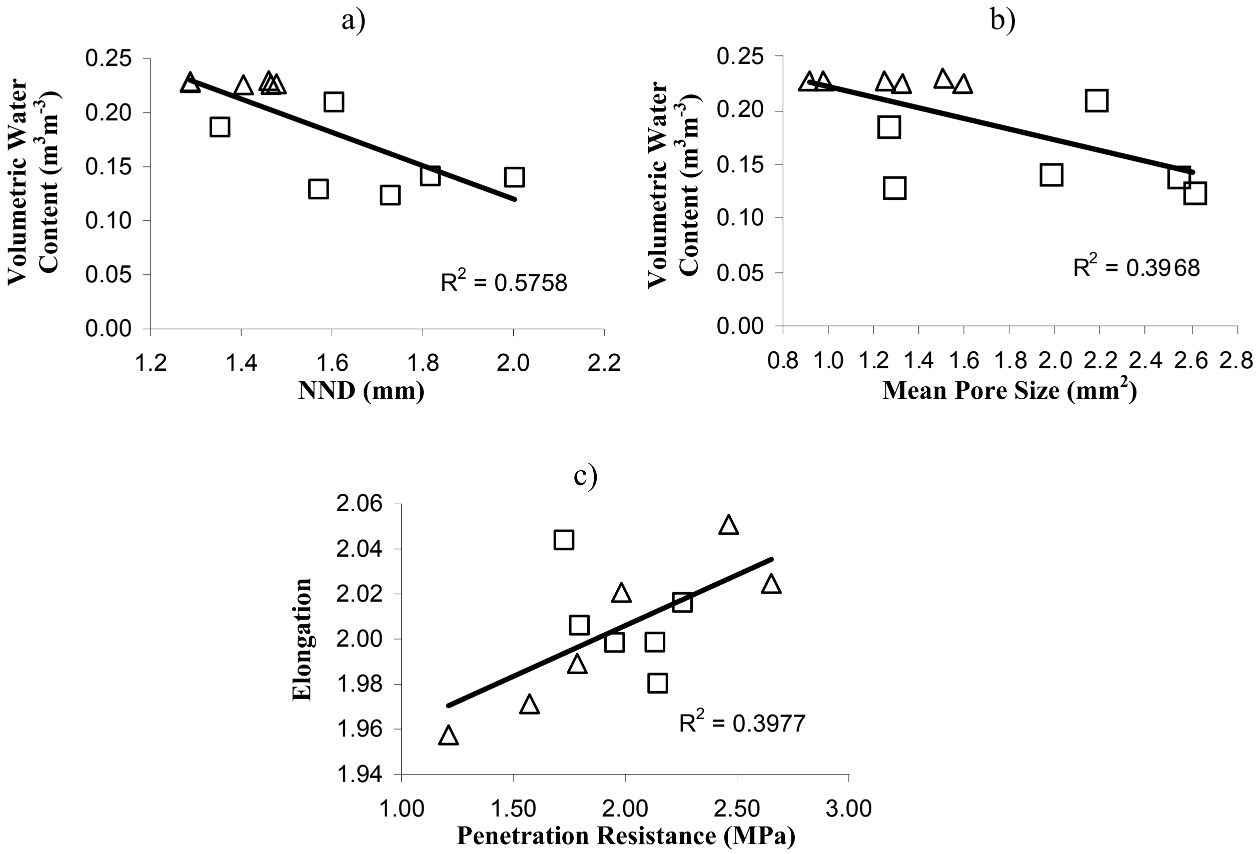


Figure 6.13: Mean regressions after cultivation (□ = clay loam, Δ =sandy loam). a) Significant (P < 0.05) correlation between water content and nearest neighbour distance; b) Significant (P < 0.05) correlation between water content and pore size; c) Significant (P < 0.05) correlation between soil resistance and pore elongation.

At emergence, the relationship between VWC and NND remained the same ($P < 0.05$, $R^2 = 0.44$) (Figure 6.14). Increased water content at this period was also significantly correlated with decreased ECD ($P < 0.05$, $R^2 = 0.41$) and increased penetration resistance was significantly correlated with an increase in pore perimeter ($P < 0.05$, $R^2 = 0.37$) (Figure 6.14). At establishment, the observed relationship between NND and water content reversed with an increased water content related to an increase in NND ($P < 0.05$, $R^2 = 0.5$) (Figure 6.14).

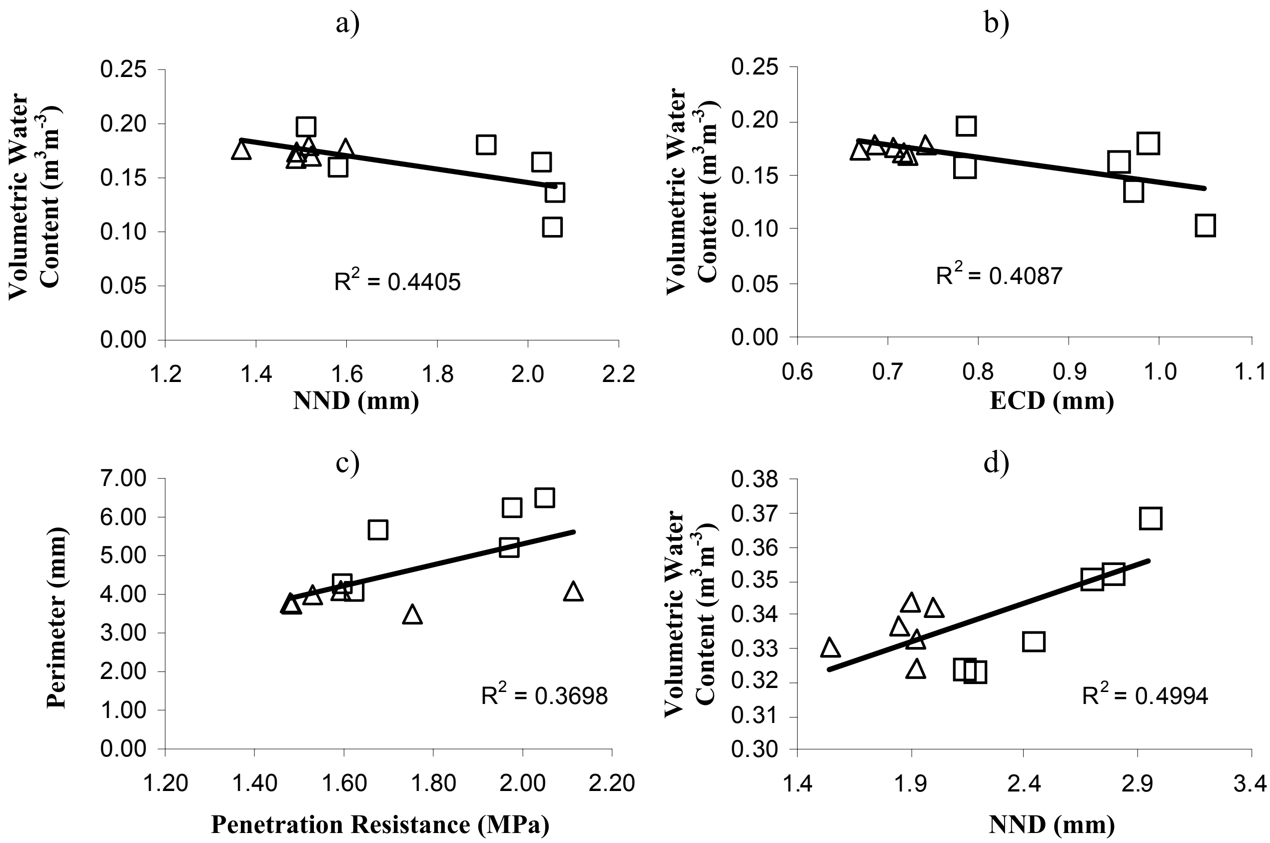


Figure 6.14: Mean site regressions at emergence (□ = clay loam, Δ =sandy loam). a) Significant (P < 0.05) correlation between water content and nearest neighbour distance; b) Significant (P < 0.05) correlation between water content and ECD; c) Significant (P < 0.05) correlation between soil resistance and pore perimeter; and at establishment d) significant (P < 0.05) correlation between water content and nearest neighbour distance the reversal of previous periods.

6.3.9.2 Relationships between soil structure and crop establishment

Crop establishment (per m^2) was strongly correlated with soil porosity throughout the experiment and across both sites. Initially, increased porosity after cultivation resulted in a positive relationship with crop establishment ($P < 0.05$, $R^2 = 0.38$), although this appears to be driven mostly by the physical conditions of the clay loam soil allowing for improved drilling (Figure 6.15). After this initial unexpected result, a reversal was observed with increased soil porosity resulting in a decrease in crop establishment at emergence ($P < 0.01$, $R^2 = 0.83$) and establishment ($P < 0.01$, R^2= 0.51) (Figure 6.15). A significant correlation between crop establishment and the distance between pores was also observed, with a decreased plant population occurring with increased distances ($P < 0.05$, $R^2 = 0.49$) (Figure 6.15).

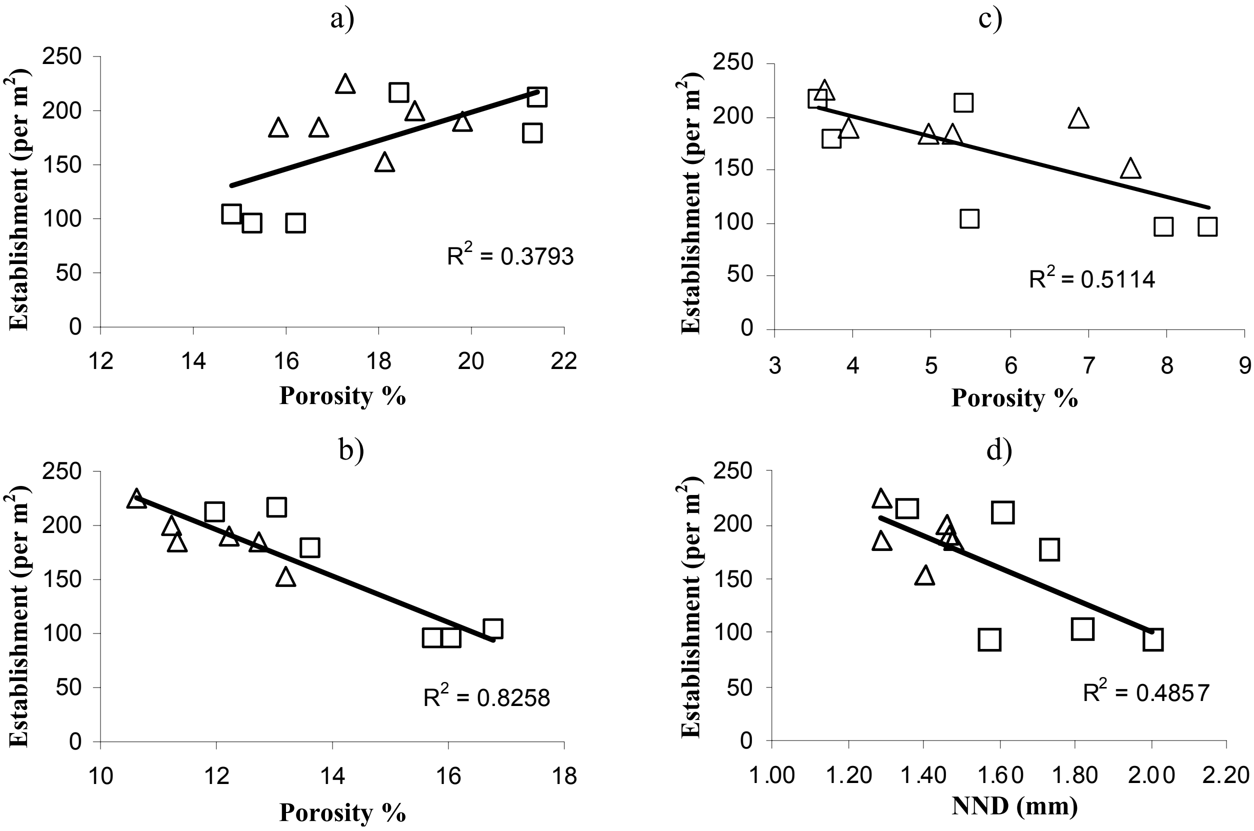


Figure 6.15: Significant regression between crop establishment (per m2) with structural properties; porosity over time a) after cultivation ($P < 0.05$); b) emergence ($P < 0.01$) and c) establishment ($P < 0.05$); and d) NND ($P < 0.05$) (□ = clay loam, Δ =sandy loam).

6.3.9.3 Relationships between soil structure and crop yield

Soil structural properties had strong relationships with crop yield (t ha^{-1}). Final crop yields were significantly affected by the structural condition of the soil at emergence, most notably significant negative relationships between yield and increases in total porosity (P < 0.05, R^2 = 0.39), ECD (P < 0.05, R^2 = 0.38) and pore perimeter (P < 0.05, R^2 = 0.41) (Figure 6.16).

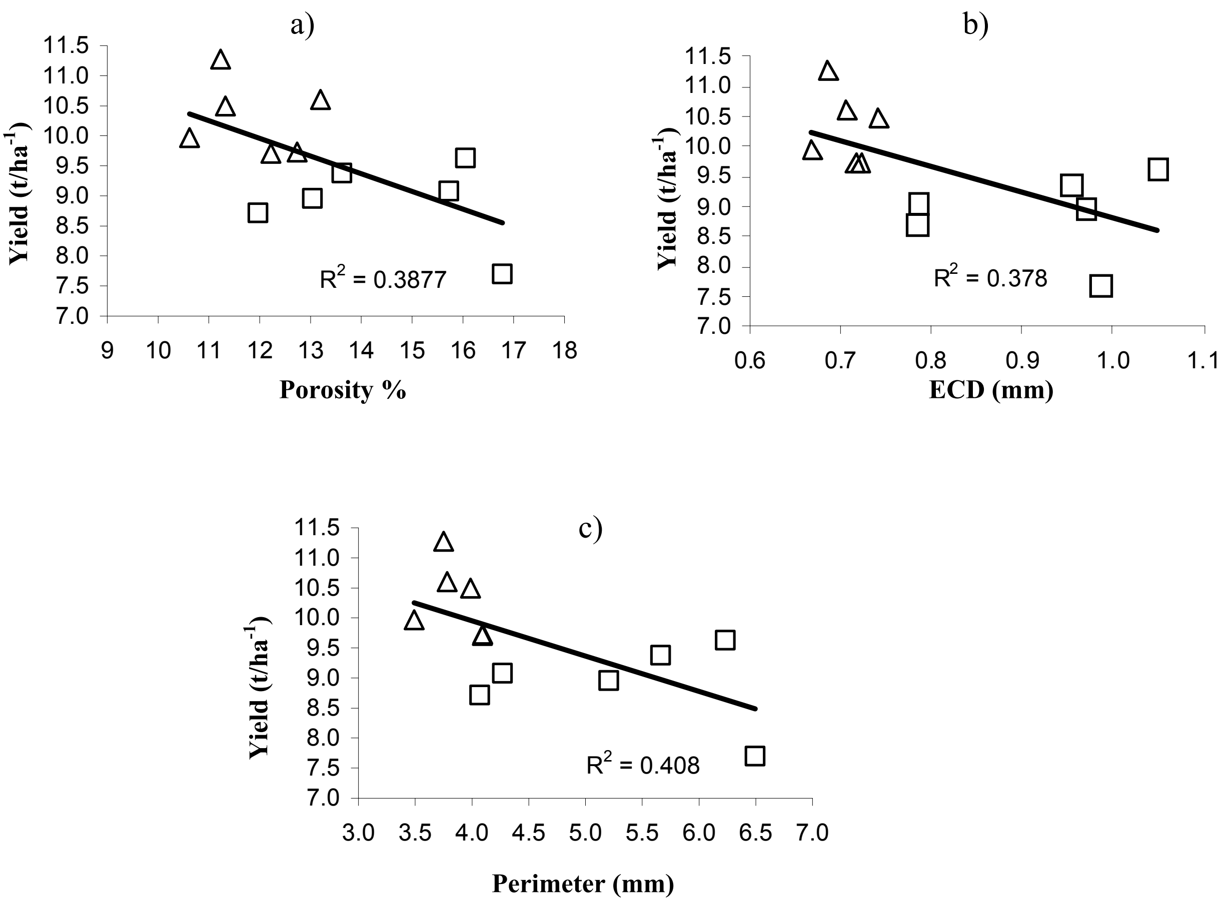


Figure 6.16: Significant (P < 0.05) regressions between crop yield (t ha^{-1}) and structural properties; a) porosity; b) ECD and c) pore perimeter (□ = clay loam, Δ =sandy loam).

6.4 Discussion

Soil structural properties between the soil types were modified by cultivation technique, although high levels of heterogeneity within the data as a result of rolled applications (see chapter 3), which would be expected to perform the opposite, have masked some of the treatments effects. Soil texture plays a vital role in determining the effects of cultivation on structure with initially different responses to cultivation between soil types, but over time (seedbed evolution) similarity between the sites occurred. The structural condition initially after cultivation is highly determinate of both final plant numbers and yield. Cultivation generally increased soil pore size properties (e.g. porosity, pore area / perimeter etc.) at both sites after cultivation (compared with prior to cultivation data).

Initially after cultivation, power harrowing within the clay loam resulted in increased porosity, reduced pore area, increased pore perimeter and decreased NND. However, with the exception of pore area and NND, the converse was true within the sandy loam soil. The decrease in pore area and NND is likely the result of the cultivation equipment, which is designed to break up clods etc, and thus creating smaller pores. The reverse differences in porosity and pore perimeter between soil types is linked with the textural properties of the soils at each site. The clay loam is much more cohesive and therefore cloddier if not broken by power harrowing. However, the sandy loam is less cohesive and therefore the extra weight causes compaction and reduction in porosity and with this an overall reduced pore perimeter. This was also observed with greater ECD and pore sphericity associated within the clay loam than sandy loam soil throughout the experiment, as well as lower NND within the sandy loam compared to clay loam soil over time, indicating less soil cohesion.

As the seedbeds evolved, the differences observed at cultivation were reversed with structural measurements the same under the different cultivation treatments regardless of soil texture. Porosity decreased within power harrowed compared with non-power harrowed treatments, whilst pore area, perimeter and NND all increased under power harrowed treatments. The reason for the reduction in porosity is the result of seedbed collapse of the fine aggregated structure created at cultivation due to heavy rainfall and seedbed settling, this also accounts for the increase in NND as infilling of pores occurs. Bresson & Moran (2003) similarly observed decreased porosity associated with seedbed slumping resulting in clogging of the interaggregate packing pore and a coalescence of aggregates as a result of rainfall kinetic energy. The increase in pore area and perimeter however, are not easily explained as an increase in either would increase porosity. The increase in both therefore must be associated with a number of factors such as aggregation of the soil during seedbed collapse resulting in larger pore spaces (at the loss of finer pore spaces) but overall reduced porosity, and the movement of soil associated with the development of root and shoot material through the soil which was significantly greater within the clay loam than sandy loam under power harrowed compared with non-power harrowed treatments. Observations by Moret and Arrúe (2007) have previously shown a relationship with macropores changes induced by rainfall events in conventional and reduced tilled seedbeds. It may be hypothesised the increased pore area and perimeter may be associated with preferential flow development through the soil during heavy rainfall and seedbed collapse.

Across both sites strong relationships between NND, pore area, and ECD with the soil water content were observed. Increased pore size and ECD resulted in a decrease in soil water content, and is likely due to the ability to store water at increasing pore size ranges, especially at this scale of resolution (66 µm pixel^{-1}). The same was true of NND initially after cultivation showing increased distance between pores and therefore a presumed reduction in smaller storage pores which resulted in decreased soil water content. However, by establishment this reversed showing increased water content within the soil with an increase in NND; the explanation for this is less clear and may in fact be related to textural differences in the soils as the sandy loam soil has little variation in NND compared to the high amount of heterogeneity within the clay loam. Increased soil strength at both sites was strongly related to increased pore elongation and perimeter, and is likely the result of compaction and the collapse of pores increasing surface roughness.

Crop establishment, as previously observed in chapter 3 and 4, was strongly related to soil porosity, showing in general decreased crop establishment with an increase in soil porosity. The exception to this, not previously observed, was an initial response after cultivation which showed an increase in crop establishment numbers with an increase in soil porosity. This may be caused by the textural differences between sites, where increased loosening of the soil within the clay loam was preferable to crop establishment, but on the sandy loam too much loosening was detrimental (see chapter 5). Interestingly, crop establishment was strongly related to NND across the two sites, showing that increased distance between pores resulted in reduced crop establishment, and is likely related to the ability of the root and shoot material to move through a path of least resistance. In a study of compaction effects on crop development in soils, it was assumed macro-pores provided a way for easier root penetration (Whalley et al., 2008). Whalley et al. (2008) similarly stated a strong correlation exists between the yield of winter wheat and the strength of the surface layers of a seedbed but observed no difference between soil textural response (sand and loam). Final crop yields were significantly reduced with increased soil porosity, pore perimeter and ECD across both sites, showing increased pore space is less conducive for final crop yield. This is related to reduced water storage; lack of nutrient capture; possible reduced soil temperature as well as increased susceptibility to severe changes in climate; and perhaps reduced anchorage stability due to reduced soil contact. Optimum structural elements of the two soil textures are achieve under different conditions, on the clay loam this was best achieve through the use of a power harrow creating porosity ranges initially at c. 20 % and dropping to between 12 – 14 % once settled. The opposite was true within the sandy loam with optimum conditions created under minimal input creating porosity ranges initially between 16-17 % and dropping to between 11 – 13 % once settled. This increased optimum within the clay loam is needed for adequate drilling of the seeds, while the sandy loam requires less loosening and in fact deteriorates with excessive loosening.

6.5 Conclusions

The structural condition of the soil has a clear influence on winter wheat establishment and yield at this scale of resolution (66 μm pixel^{-1}) showing the interaction between the meso and macro scale soil dynamics and soil to crop input / output. Increased pore space significantly hampers establishment and yield through reduced seed-soil contact and nutrient capture with the exception observed at cultivation, with a reversal of the above statement more beneficial within the clay loam soil at this period with a limit of around c. 18 % porosity beyond which a decreasing trend appears to occur. Reduced NND (< 1.4 mm) is favourable for crop establishment and is independent of soil texture. The advantages or disadvantages of the use of a power harrow were not clear with large amounts of heterogeneity within the data, which most likely relate to the use of a Cambridge roller, which induces cracking and compaction of the soil (see chapter 3). The most preferable structural conditions are; total porosity 12-17 %; average pore size 0.4 – 1 mm^2; PSD_{cu} 80-110; elongation < 2, average pore perimeter 2 – 3 mm; NND < 1.4 mm and ECD 0.42 – 0.54 mm, but due to the high level of structural heterogeneity, this could not be refined or distinguished between treatments. It may be stated however from visual observation and physical data (chapter 5) that the benefit of power harrowing within clay loam remains and the need for rolling is not required, while in the sandy loam soil, little observable changes in structure between treatments and establishment and yield show minimal input is needed to achieve the similar output.

Preferable soil structure conditions within the clay loam require greater input from agricultural machinery whereas preferable conditions in the sandy loam can be created by minimum input. This shows that the European Union CAP reform on the use of zero or minimal tillage application across the whole of the UK is not viable in clay soils due to the poor structural conditions and establishment achieved under these applications. Therefore further study is needed to assess viable options for preferable soil structural creation which is both viable for crop establishment but also reduces soil degradation, nutrient loss, CO_2 loss and increases soil carbon sequestration need in clay rich soils.

Chapter 7: General Discussion

7.1 Introduction

The main objective of this work was to investigate and quantify the effects of selected tillage applications on the soil physical environment, with emphasis on the structural condition of the soil (as this had not been previously considered), and the effect on cereal crop establishment (*Triticum aestivum*) and yield. This was working towards the hypothesis that soil structure significantly affects crop establishment, growth and ultimately yield. This was primarily performed through field experiments, on a sandy loam (Dunnington Heath series, FAO class; Stagno-Gleyic Luvisol) and a clay loam (Worcester series; FAO class; Argillic Pelosol) soil, using intensive to reduced tillage treatment combinations (plough, disc, power harrow, Cambridge roller). Data sets were collected across two seasons for both the physical condition of the soil (e.g. volumetric water content; bulk density) and the structural condition of the soil using X-ray CT and image analysis techniques (e.g. porosity; pore area).

7.2 Seedbed physical properties and establishment

The physical conditions of a seedbed were strongly affected by the various cultivation techniques and this, in turn, had an effect on crop establishment. The most intensive applications (using two or more pieces of equipment) produced the most compaction resulting in an increase soil strength and bulk density. This was similarly observed in previous research with heavy cultivation equipment and multiple pass management strategies resulting in severe mechanical resistance within soils (Whalley et al., 2008; Soane et al., 1982; Wu et al., 1997). Primary cultivation (disc or plough) had no initial effect upon shear strength or bulk density, but over time bulk density was greater with discing. Discing resulted in higher penetration resistance overall, due to the shallower depth of cultivation, and increased the surface volumetric water content of the seedbed, likely a result of more compacted soil (higher resistance) at depth, restricting drainage. Coquet et al. (2005) similarly observed reduced vadose zone flow and transport processes in large compacted soil zone particularly under wheel tracks. Similar observations were made of the hydraulic conductivity of soil in seedbeds with reduced conductivity in ploughed and wheel trafficked areas compared with untilled soils (Coutadeur et al., 2002), while preferential flow within soils can also be created under compacted conditions (Kulli et al., 2003; Petersen et al., 2001). Reduced tillage (discing) compared with conventional (ploughing) reduced crop emergence after cultivation (+ 14 days) despite the increased water content and assumed higher soil-seed contact (higher strength), which is likely the result of incorporated crop residues reducing contact (Bordovsky et al., 1998; Kushwaha et al., 1994). Establishment rates were roughly equal by establishment (+ 63 days), however, discing suffered the greater winter kill (measured at + 155 days). Overall, yield was not affected by the different primary treatments.

Power harrowing was responsible for the largest changes in the soil physical properties of the seedbeds and was consistent across two seasons of experimentation within the sandy loam soil, resulting in increased penetration resistance, shear strength, bulk density and volumetric water content. The increased strength and density of the soil was caused by the extra tillage weight and compaction of the soil.

The reason for the higher volumetric water contents within the soil was the finer tilth created under power harrowing (and associated finer pore space, see section 7.3). However, unlike the sandy loam, the clay loam soil responded differently to power harrowing with a reduction in soil penetration resistance and shear strength, as well as initially a reduced bulk density at cultivation (although this increased over time as a result of seedbed collapse under power harrowed treatments). The difference in the soil strength response to the application of power harrowing is therefore related to the textural differences of the two soils, with the sandy loam being less cohesive (plastic deformation) and therefore less resilient to soil stresses than the clay loam (Horn et al., 1995; Tobias et al., 2001). However, power harrowing caused increased volumetric water content in both soils, as a result of finer tilth creation and pore size (section 7.3). Power harrowing increased the establishment rates and final plant population independent of soil texture, although the difference in response between power harrowed and non-power harrowed within the sandy loam is much reduced compared with the clay loam. Overall yield was not affected by power harrowing on either soil texture or the different seasons, however, this may have been masked within the second year experiment due to adverse weather conditions.

Rolling produced the most consistent response from both soil textures and was responsible for increasing soil strength (penetration and shear) and soil bulk density as a result of surface compaction / consolidation effects. Similarly, this surface compaction resulted in increased surface water contents. Crop emergence rates increased under rolled seedbeds in both textures. However, un-rolled seedbeds 'caught up' over time negating this advantage. Rolled seedbeds in combination with power harrowing produced severe compaction, and in the clay loam soil this hindered crop establishment numbers compared with power harrowed seedbeds. Overall, yield was affected by rolling in the first season (sandy loam soil) of experimentation with a 0.5 tonne reduction in yield in treatments which were rolled, however this was not observed in the second season or across soil texture. Again this may have been masked by adverse weather conditions in the second season, or it may be that the reduced yield under rolling was more severe under ploughed (not used in the second season) compared to disced treatments.

7.2.1 Limiting physical properties on establishment

- Compaction of the soil through excessive cultivation affected both soil textures equally.
- Excessive loosening of sandy loam soil resulted in a reduced soil-seed contact. This resulted in a negative response in crop establishment to decreased soil penetration resistance, shear strength and bulk density.
- Compaction of clay loam soil was detrimental to crop establishment. There was a positive response in crop establishment to increased soil loosening, i.e. decreased soil penetration resistance, shear strength and bulk density, in contrast to the sandy loam.
- Volumetric water content was a limiting factor for establishment in both soil textures and across seasons. Crop establishment was severely limited by reduced water content in the soil (especially at cultivation).

7.3 Seedbed structural properties and establishment

The cultivation techniques strongly affected the structural conditions of the seedbed and their response to crop establishment at both scales of resolution used in this research (Macro structure c. 824 µm $pixel^{-1}$ and Meso structure c. 66 µm $pixel^{-1}$). Primary cultivation (disc or plough) in general had more of an effect on the macro structure of the soil, increasing the soil porosity, although this was much greater under discing (creating larger macropores compared to ploughing) due to the incorporation of crop residue at surface level. Dao (1996) also found high amounts of surface residue resulted in increased macroporosity in the near surface horizons. Observations at the meso scale showed little difference between the two primary tillage treatments with the exception of higher PSD_{cu} ratios within disc compared to ploughed application until spring establishment when ploughing was greater. This is a result of surface residue inclusion within the disc treatment creating a bimodal pore size distribution. The reason for the reversal at spring establishment is the result of improved crop development under ploughed treatments causing cracking within the soil as the plant develops (plant matter was also measured as pore space due to difficulties in isolating variations between air and water). Previous studies have also observed these changes associated with root and shoot development resulting in the modification of soil properties / structure and the detachment / disturbance of the soil both in the development of soil aggregation, pore space and the expansion of existing pore networks (Pierret et al., 2007, 1999; Moran et al., 2000; Stewart et al., 1999; Gregory, 2006). Modification by roots of the soil structure can have a knock on effect to other soil properties such as the water retention and water flow regimes within the soil. Whalley et al. (2005) observed an increase in the number of larger pores within the rhizosphere soil which lead to enhanced drainage at large matric potentials as well as possible changes to the wetting angle and surface tension of pores. Macro porosity and pore area increased as a result of power harrowing and was roughly consistent regardless of primary application except in combination with rolling, as rolling resulted in increased porosity and pore area due to surface cracking and soil stress in a zone of disturbance (chapter 3; figure 3.9). Over time, rolling resulted in seedbed collapse and a reduction in soil macro porosity and pore area due to the infilling of inter-aggregate pore space from soft ridge collapse during heavy rainfall events (Figure 7.1). Similarly Bresson and Moran (2004) found a decrease in soil macroporosity was associated with physical dispersion and aggregate breakdown in simulated heavy rainfall events. Pore size ratios as a result of secondary application were affected differently by the primary applications, with an increase in ratio associated with more intensive cultivation (compaction / loading) within the ploughed treatment and the reverse within disc. This is due to residue removal within the ploughed treatments and less heterogeneity as a result of power harrowing whilst compaction and rolling severely cracks and disturbs the loose soil. Within the disc treatments, residue causes wide disturbance of the soil and the consolidation effect of rolling reduces this disturbance by compressing the soil close to the residue surfaces.

Power harrowing similarly showed reduced porosity and pore area at the mesoscale and was consistent across season on the sandy loam soil. However in the clay loam an initial increase in porosity was observed, and is likely related to the textural cohesiveness of clay. Pore size ratios at the meso scale showed a dissimilar pattern to that observed at the macroscale with a consistent response from secondary cultivation, regardless of the primary application to increased ratios (higher proportion of larger pores) with an increase in cultivation intensity and rolling. This is most likely related to the zone of disturbance at the surface caused by rolling.

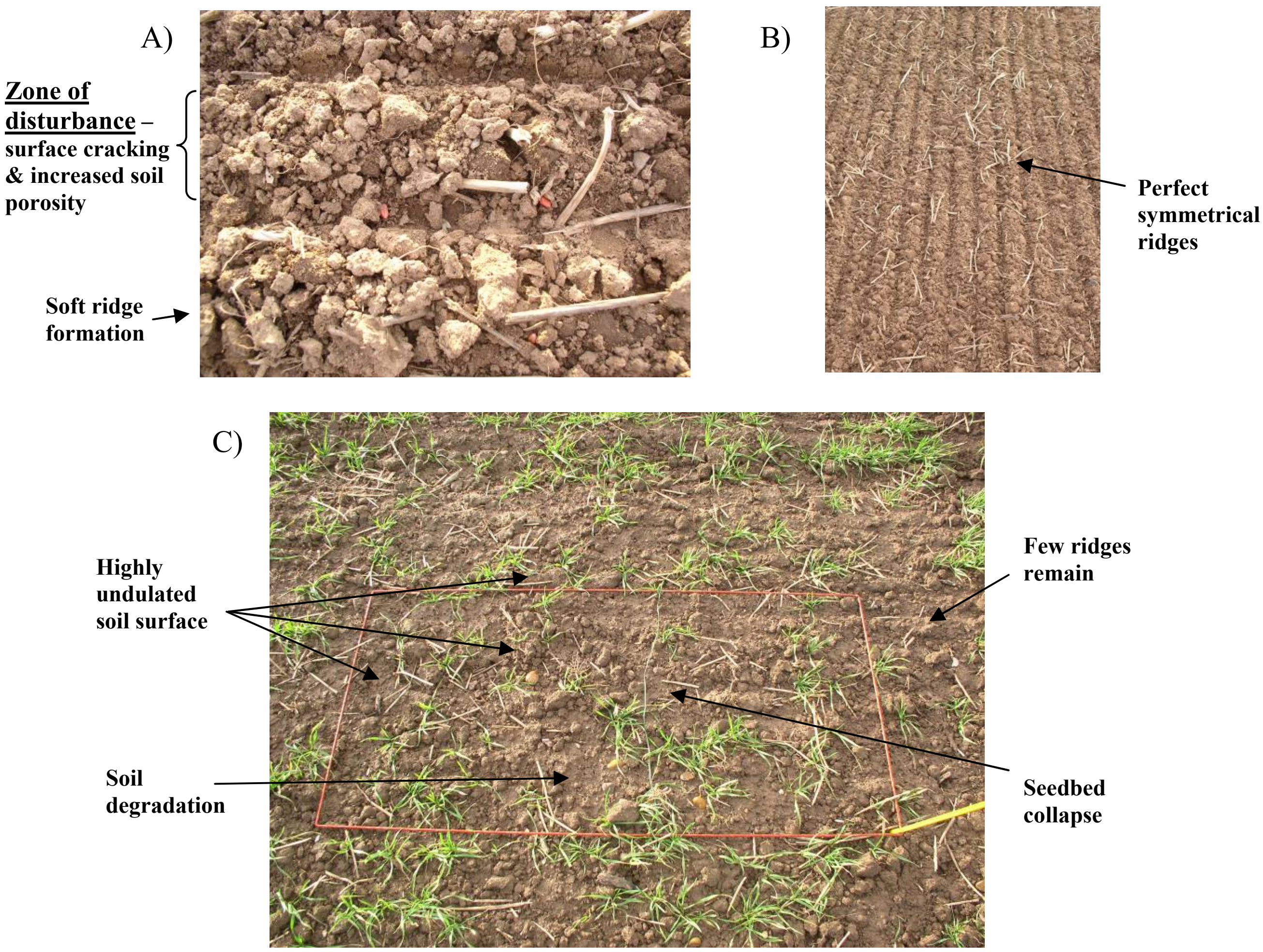


Figure 7.1: Seedbed collapse associated with soft ridge degradation in heavy rainfall events resulting in the infilling of inter-aggregate pore space and a reduction in soil macro porosity and pore area over time. A) Close up of soil disturbance associated with rolling resulting in surface cracking and soft ridge formation at cultivation. B) Wide view of rolled effect at cultivation with perfect ridges. C) Image shows the same seedbed post a heavy rainfall event, resulting in soft ridge collapse and infilling of pores.

Differences between soil texture and pore size ratios as a result of cultivation showed reduced pore size ratios within the clay loam until establishment and the reverse in the sandy loam. This is due to the textural cohesiveness of the soils and the collapse of the seedbed over time as well as the development and movement of the soils in relation to plant material (root and shoot).

At the mesoscale there were consistent responses to secondary cultivation across season on the sandy loam soil, with increased ECD and pore perimeter under power harrowed and unrolled treatments following discing but the reverse under ploughing. This shows the strong relationship between surface residue inclusion resulting in the increased pore space within disc treatments as a result of residue disturbance within the soil under passing cultivation equipment. A decreased pore space within plough plots was due to the removal of residue and thus reduced disturbance associated with this. On the clay loam (discing only) the reverse of the sandy loam was observed showing increased ECD and pore perimeter under power harrowing, with an increase in pore roughness and overall size as a result of power harrowing. This was due to the soil textural differences and the cohesive nature of the clay. The response to increasing cultivation intensity was consistent across seasons and soil textures and resulted in increased pore elongation and a zone of disturbance associated with rolling. This consistency was also shown at establishment with an increase in pore elongation associated with crop development.

A decrease in soil macro structural properties (porosity, pore area and PSD_{cu}) occurred with an increase in soil strength, with the exception of disced and rolled treatments (due to surface residue disturbance) caused by the compaction of the soil associated with increased surface traffic. Meso structure was similarly affected by soil strength with increases in pore area, pore perimeter, ECD and NND at the same time as decreases in soil shear strength and bulk density, showing reduced compaction (increased soil strength) allowed for a more porous structure. Increased penetration resistance of the seedbed results in increased pore elongation and pore perimeter. This shows seedbed compaction results in lateral and vertical (rolling) pore creation associated with soil cracking, which in turn is associated with an overall increase in pore roughness and surface area (Figure 7.2). Previously it had been stated that volumetric water content was a limiting factor for crop establishment (Passioura, 2002; DaSilva et al., 1994; Leão et al., 2006). Observations at this scale showed strong links with reduced soil water content (independent of texture) and increases in pore elongation, pore area, ECD and NND. These measurements all relate to the size and number of pores which are able to store water or facilitate flow, therefore it is reasonable to hypothesise that with an increase in pore area and ECD, fewer water storing pores exist, increased elongation may increase preferential flow patterns assuming vertical opposed to lateral movement, while increased NND is most likely related to overall reduced pore numbers and thus ability to store water.

At both scales of resolution and across season and soil texture (with the exception of initially at cultivation within the clay loam) a consistent response is seen showing that with an increase in the soil structural architecture (porosity, pore area, pore perimeter, PSD_{cu}, elongation, ECD and NND), a decrease in crop establishment is observed. Therefore an increase in pore space (porosity, area, perimeter, PSD_{cu}, elongation and ECD) has detrimental effects on establishment due to a hypothesised reduced soil seed contact and the availability of nutrients and water necessary both for germination and plant stability.

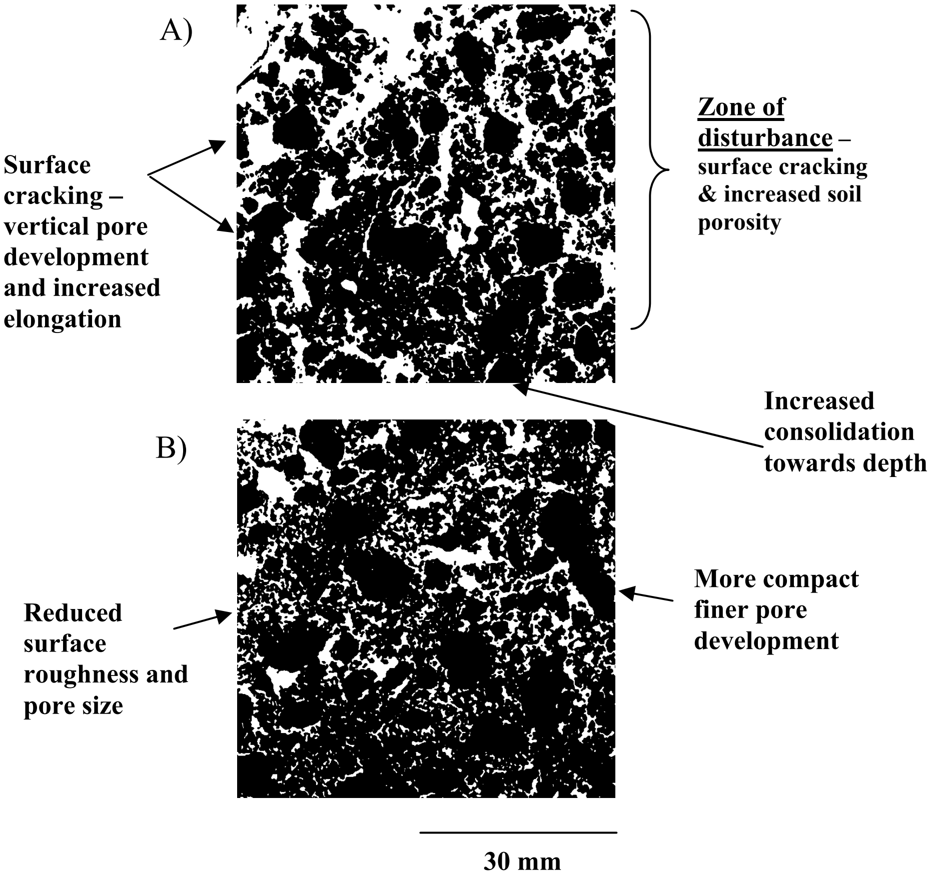


Figure 7.2: Meso scale binary images showing the effect of compaction (in particular rolling) effects in the creation of surface cracking and the development of vertical pores in a zone of disturbance. Treatments shown: A) Plough + Power Harrow + Rolled; B) Plough + Power harrow. White = pore space.

It may be expected that a decrease in pore space representing compaction may also reduce establishment, but this was not observed (Figure 7.3). The only exception to the rule is that an increase in porosity within the clay loam (as a result of power harrowing - increased soil loosening) at cultivation to allow for improved seed drilling and better soil nutrient / water movement (assumed avoidance of preferential flow) improves crop establishment. This maybe contrary to thoughts that increased porosity i.e. more aeration is equal to better soil structure and soil quality.

Yield, as with establishment, was similarly linked with increases in soil structural architecture, with decreased yield occurring as a result of increases in soil porosity, pore perimeter and ECD. This was not observed in the macro structure, which shows that establishment and therefore yield was affected more by influences or changes to soil at the meso scale. The reduction in yield due to these factors is most likely the result of early effects on emergence and establishment rate, as well as a reduction in nutrient availability (Addiscott and Thomas, 2000; Malo et al. 2005) and soil anchorage stability (Mooney et al., 2007). For both establishment and yield, the most influential factor is excessive soil loosening, it is also hypothesised that excessive compaction of the soil structure would also have detrimental effects upon establishment and yield; however this was not observed in either season (Figure 7.3). This could mean either of two factors; a) as stated this was simply not observed but that it may still occur, and b) structural compaction (within reason) is not an overriding limitation to crop establishment and yield but instead limitation is related to other factors such as water availability and nutrient capture.

A dynamic range of structural and physical conditions must exist, whereby a seedbed which is excessively loose or compacted is detrimental to crop establishment, therefore between these extreme conditions there must be an optimum range for crop establishment and yield (Figure 7.3). Although only the upper limits associated with excessive loosening were observed within these experiments, previous work has observed severe reductions in crop numbers as a result of excessive compaction

(Jakobsen and Dexter, 1987; Pardo et al., 2000; Atwell, 1993; Kirby and Bengough, 2002).

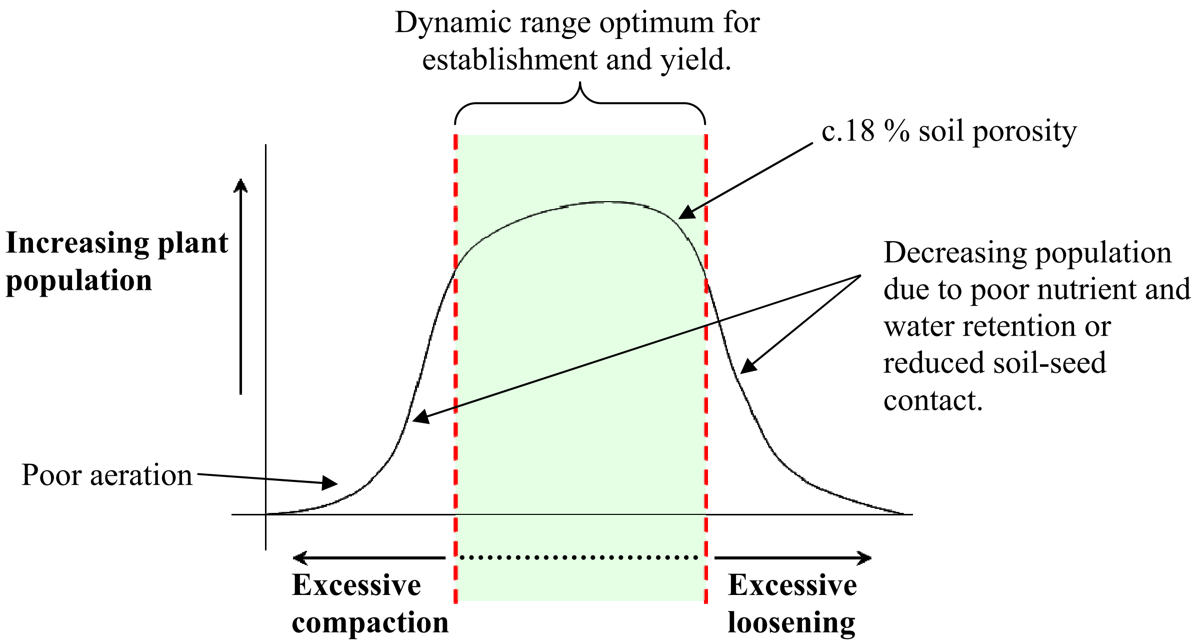


Figure 7.3: Dynamic range of soil conditions optimum for crop establishment with severe decreases in establishment and yield associated with excessive compaction and soil loosening.

7.3.1 Limiting structural properties on establishment

- Increased porosity lead to reduced soil seed contact, nutrient availability and water storage resulting in reduced establishment and yield. This was particularly true within sandy loam soils although the effect was independent of texture.
- Increased pore spatial distribution, i.e. greater distance between pores, reduces the ease of movement for plant shoot and root material. This

results in reduced emergence, establishment and perhaps yield due to the stresses associated with passing through soil as opposed to pore space.

- A soil porosity of 12 -18 % within a clay loam is preferable for adequate crop establishment at a very early stage to allow for adequate drilling, followed by seedbed settling, beyond which a high porosity (>20 %) will be detrimental to crop establishment due to reduced soil-seed contact.

- Crop residue incorporation results in increased soil porosity in pore space as a result of disturbance / movement under passing cultivation equipment. This can cause reduced soil-seed contact and decreased crop establishment.

- Rolling causes surface cracking (Figure 7.1; 7.2; Chapter 3 Figure 3.9) resulting in an increase in soil porosity, pore size and pore elongation in a zone of disturbance. This can create limited soil-seed contact and nutrient availability resulting in reduced crop establishment.

- Increased pore structural properties and pore elongation (associated with rolling) reduce soil water content, perhaps due to water flow and / or reduction in water storage pores. Volumetric water content is a limiting factor for crop establishment, therefore increased pore area limit crop establishment due to the association with reduction in soil water content.

7.4 Modelling seedbed properties and establishment

This research brings together observations from a variety of different scales of resolution from field measured physical conditions and soil structure, as well as a variety of cultivation techniques from intensive to reduced cultivation strategies across seasons and soil textures. The interaction between these scales of resolution and their effect on crop establishment has been shown, but which factors are the most influential for crop establishment? This was determined by modelling the effects of physical and structural data on the sandy loam (season one) in the prediction of crop establishment, which could then be used in the assessment of other soil textures (clay loam) and in other cultivations. A model was developed which could predict crop establishment numbers as early as seven days after cultivation (seven days prior to initial emergence numbers) based on the soil bulk density at this period in time. The Soil Quality of Establishment (SQE) model was validated against the data taken in season two to determine the effectiveness of the model at continued prediction. The model could therefore be used either prior to cultivation to determine the need for cultivation (based on bulk density measurements) or after reduced cultivation to determine the need for further cultivation.

Interestingly, the model required the addition of cultivation intensity within the data (because of improved model output associated with a smoothing of heterogeneity within the field as cultivation accounted for a large area), which was applied in 0 = reduced or absent, 1 = intensive or used for the cultivation practices within the experiments. Cultivation strategy alone accounted for c. 50 % of the variation within the establishment data. The model was then adjusted with the addition of soil physical data, which produced a model based on cultivation and soil bulk density. This addition improved model predictability accounting for 51 - 56 % of the variation within establishment. At this point the model provides the farming community with a quick assessment (which can be performed by themselves) of the soil quality for establishment without the need for structural assessment, through soil bulk density measurements. However, this does not answer our hypothesis that soil structure significantly affects crop establishment, growth and ultimately yield which is shown when a macro porosity addition improved the model further accounting for 56 – 74 % of the variation in establishment. However, when the model with macro structure additions was assessed with meso structure additions, further improvement with 'meso structure' properties did not occur whilst macro structure properties remained, and is related to the repetition of data, namely macro porosity and meso pore area / perimeter which are essentially the measurements of the same factor at both scales thus over prediction occurs due to counting the same factor twice. However, using cultivation strategy, bulk density and meso structure (pore area, pore perimeter and NND) at the exclusion of macro structure this resulted in a vastly improved model which was able to account for 70 - 71 % of the variation in establishment across season and soil texture.

Cultivation strategy accounts for the bulk of variation within establishment with a further c. 20 % of variation accounted for by bulk density and the meso structure (pore area, pore perimeter and NND) of the soil. This could mean either: a) cultivation strategy and not soil condition affects establishment, accounting for all described variables as well as the chemical and biological impacts upon crop establishment. This would mean that only zero tillage would be affected by soil condition as cultivation is not present. Or b) the numerical assignment, i.e. 0 = reduced, 1 = intensive, to cultivation strategy allows for the high levels of heterogeneity within the data, in effect creating a smoothing of the data which allows for greater prediction over a large area. This would mean that the addition of cultivation strategy therefore accounts for the strength, water content, porosity, ECD, elongation, PSD_{cu} etc. of the soil as a result of the application applied i.e. rolling increases all above properties and reduces overall establishment and yield in some cases but also acts as a consolidator and increases emergence rate. The improvement observed through the addition of bulk density to the model therefore brings something which is not explained by cultivation, this may be related to the relationship of bulk density to both soil water content and an indicator of the structural condition of the soil. Tapela and Colvin (2002) similarly found bulk density as an adequate indicator of soil quality, soil condition index (SCI), observing that a decrease in soil moisture was related to increased soil bulk density and resulted in a reduction in plant growth.

The improvement observed with the addition of macroporosity (confirming the hypothesis that soil structure does significantly affects establishment) is unsurprising with the strong negative correlation between soil porosity and crop establishment seen throughout the experiment and scales of resolution. The best scale of resolution for observing variation in establishment was the meso structure scale. This was because of the larger percentage variation accounted for at this scale most likely relating to the direct influence between plant material, i.e. root and shoot, and the soil environment at this resolution. The meso structure additions account for the size and roughness of the pores and therefore the ability for greater soil-seed contact, nutrient availability and water storage. NND accounts for the ease of movement through the soil of plant shoot and root material, which is not easily explained through the other factors, it may also be inferred that this links with pore connectivity and flow regimes within the soil, although this is only conjectural.

7.4.1 Modelling limitations on establishment

- Cultivation accounts for c. 50 % variation in establishment through smoothing of heterogeneous variation in observed measurements. Cultivation type therefore accounts for the wider scope of influencing factors such as water content, bulk density and structural condition of the soil and the adequacy of those conditions for crop establishment.
- Establishment is significantly influenced by soil bulk density. An SQE using cultivation intensity and soil bulk density provides an assessment of the soil environment for crop establishment which can be easily replicated by farms in the development of soil management strategies and the need for cultivation either reduced or intensive.
- Soil meso structure (c.66 µm pixel^{-1}) provides a more realistic environment for model prediction than macro structure due to the direct influence between plant material, i.e. root, and the soil environment at this resolution. Macro structure is therefore more related to the movement of air and water into this environment.
- Establishment is most accurately predicted from meso scale pore size, roughness and pore density (NND), relating to the contact of seed and soil,

the availability of nutrients and water and the ease of root and shoot movement through a path of least resistance.

- The model accurately predicts across season and soil texture showing tillage degree and type, soil bulk density and meso structural elements are accurate predictors of crop establishment. The fact that soil texture is independent (i.e. not an influencing factor) within the model shows that crop establishment is dependent upon the terms included within the model.
- The model is limited by being unable to account for unforeseen circumstances such as disease, weather conditions (such as extreme heat or excessive rainfall) and pest damage. These factors may cause severe reductions in crop establishment and yield at any point in the development of the plant.
- A further 30 % of variation in crop establishment was not explained by the model and may be related to the above statement. Equally the variation in establishment not explained by the model may also be related to the genetics of the crop (i.e. incorrect choice for seasonal conditions or time of year etc.), soil chemical status (i.e. nutrient deficient soils) or the biological activities within the soil (i.e. microbial community symbiosis with the plant).

Chapter 8: Conclusions

8.1 Seedbed establishment conditions

- Reduced tillage strategies can produce unfavourable soil conditions (physical and structural) for winter wheat crop establishment, such as large porosity and pore size associated with surface residue inclusion, but on a sandy loam soil this had minimal effect upon final establishment (due to 'catch up') and yield. No observed advantage, other than initially more favourable conditions for crop establishment, was provided under ploughing and power harrowing as the cost of input to output was much greater than discing alone. This confirms the hypothesis that soil structure significantly affects crop establishment, but the affect of structure upon yield is less clear.

- Reduced tillage (discing) on a clay loam soil is restrictive to crop establishment preventing adequate drilling of the seedbed due to the hard cloddy nature of the soil (1.25 g cm^{-3}) and reduced porosity (15 %). An application of power harrowing was required to produce favourable soil conditions for drilling and establishment through structural change of the soil and subsequent seedbed collapse post drilling.

- Rolling causes excessive surface cracking and increases to the soil porous architecture resulting in reduced soil seed contact. Rolling increases crop emergence rates as a result of consolidation; however, this compaction also results in lower overall establishment (due to poor soil seed contact and poor root and shoot mobility) and yield. Rolling should only be used in cases where level seedbed surfaces are required as the cost to benefit of rolling is not sufficient in establishment and yield returns. Rolling has the same effect regardless of texture on both the physical and structural properties of the soil.

- ❖ Excessive soil loosening (i.e. too porous) is detrimental to crop establishment within a sandy loam soil while excessive consolidation (increased soil strength and bulk density) is detrimental within a clay loam soil (initially). Crop establishment is limited by the volumetric water content of the soil at low values (independent of texture), severely impeding germination, emergence and establishment.

- ❖ Increased porosity characteristics e.g. porosity, pore area, ECD, NND etc. have significantly negative effects upon crop establishment, observed at all scales of resolution. This may be associated with poor soil-seed contact, reduced nutrient and water availability. This is severely limiting within <u>sandy loam</u> soil. The only period where this is not the case is within a <u>clay loam</u> soil at cultivation i.e. where increased porosity etc. is beneficial to drilling but this can reach a limit within a dynamic range beyond which would be detrimental to establishment due to excessive loosening.

- ❖ Preferred <u>macro</u> structural conditions of a seedbed for optimum crop establishment are:
    - o Porosity 15 – 20 % (image analysis) c. 55 % total porosity

- Pore area 5 – 15 mm^2
- PSD_{cu} 10 – 20

❖ <u>Meso</u> structure (c. 66 µm $pixel^{-1}$) is more comparable to the conditions relating to direct affects upon crop establishment (shoot and root material) within the soil seedbed environment. Preferable conditions include (independent of texture):

- Porosity 12 - 17 % (image analysis) c. 55 % total porosity
- Pore area 0.4 – 1 mm^2
- Pore perimeter 2 – 3 mm
- Elongation < 2
- ECD 0.42 – 0.54 mm
- NND < 1.4 mm
- PSD_{cu} 80 – 110

NB: PSD_{cu} range higher than previous (Macro structure) due to greater pore size range at this scale.

❖ Meso structure significantly affects crop yield confirming the hypothesis. As with crop establishment higher structural conditions i.e. porosity result in reduced crop yield. This can be observed at both seven and thirty six days after cultivation, with both conditions at this stage of seedbed evolution having significant beneficial or detrimental effect upon crop yield. Preferred conditions occur with a porosity range between 18 -20 % at cultivation.

❖ Seedbed preparation, physical condition and structural properties were successfully modelled across soil texture and season to create the soil quality of establishment (SQE), to predict the combined effects upon crop establishment numbers. Cultivation accounts for c. 50 % of the variation in crop establishment, and is a smoothing of the underlying heterogeneity within the soil. A further c. 20 % of variation in crop establishment was explained directly by bulk density (presumably accounting for porosity and water content variation in the soil), meso pore size, roughness and spatial distribution (accounting for soil-seed contact, water storage and ease of movement within the soil).

8.2 Implications

- The European Union Common Agricultural Policy reform (CAP) stipulates a move in all agricultural practices towards reduced or zero tillage systems. These findings show this may be possible for wheat grown on sandy loam soils with minimal loss in establishment and little to no loss from yield under discing alone. However in clay rich soils (accounting for ~ 60 % UK soils – Batey, 1988) will fail to meet with the CAP reform due to the inadequate structural environment created with single pass discing. A further application of power harrow will be required to provide adequate seedbed conditions in these circumstances resulting in increased cost, possible soil degradation and an increased CO_2 output.

- Quick and accurate prediction of soil quality for establishment can be used to provide a relatively easy assessment of the soil condition for informed decision making by farmers to prevent excessive and unnecessary soil movement and degradation. This can be achieved with the simplified model which incorporates cultivation intensity and soil bulk density both of which can be easily obtained. Field assessments may also be carried out using the full model should access to equipment be unhindered. The benefit of visualising structure and pore space of the soil is that it provides a greater understanding of the physical environment under which crops grow and also allows for a greater model prediction of the establishment.

8.3 Further work

- Perhaps the most influential factor on crop establishment within the soil was the assumed reduction in soil-seed contact associated with increased soil pore conditions. It is recommended that further study of both the appropriate contact degree and the angle within the soil would be beneficial in the understanding of crop establishment as well as the spatial distribution of the interconnecting pores and flow paths through a seedbed environment. This may be best achieved through Micro Computed Tomography (µCT) and fine resolution imaging.

- The impact of soil crop residue plays a vital role in crop establishment under reduced cultivation strategies affecting both the soil porosity and porous architecture of the soil and the physical properties of the soil i.e. strength. Further study of how specific the effects of residue inclusion within the soil is recommended in the assessment of soil-seed contact, residue breakdown etc and how this affects root growth and anchorage, increases disease risk and changes the soil architecture.

- Unaccounted variability in establishment (30 %) is perhaps driven by factors not considered within the scope of this research such as the chemical and biological influences upon crop establishment. Further study of the biological communities and the relationships with soil pore development and association with rhizosphere development in cultivated soil is therefore needed. This could determine how much of an effect these communities have in the interlink between the soil and rhizosphere and, how much they aid in the development of pore networks within the soil seedbed environment. Nutrient availability was mentioned throughout the thesis as a key factor in limiting crop establishment, therefore how much of an influence does the movement of these nutrients and their availability within different soil textures and structures influence crop establishment also needs to be considered.

- This study has successfully determined the structural conditions of the soil conducive to winter wheat establishment and has successfully predicted c. 70 % of the variability within this establishment across two soil textures and two seasons. Further study should now be used to assess if the terms and model output can be used successfully to predict crop establishment both on a number of different soil textures and cereal crops such as oil seed rape.

- A study of further cultivation equipment and their interaction with the seedbed structure and crop establishment would provide greater understanding of the seedbed environment and perhaps help to explain the c. 50 % variability within crop establishment. This would also lend to producing a grading system to cultivation equipment based upon the response of the soil. The grading system could then be used within the SQE as a more developed cultivation intensity parameter.

- During this study it was not possible to differentiate the soil porosity from the plant material (i.e. root and shoot) due to the close density values of air and plant material, in effect accounting for more pore space than was effectively there. A further study designed specifically to observe this porosity differentiation and how much of the porosity which is plant material affects the soil hydrology would be beneficial, as well as studying potential effects upon SQE output.

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