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Identification of optimum seedbed preparation for establishment using soil structural visualisation

by

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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 were considered during this project. 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 and interactions with plant establishment were identified. Results showed significant reductions in plant populations were associated with increases in the soil porosity, with strong links to the pore size and roughness which influences 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 % soil porosity when measured by image analysis (i.e. mainly macropores). Recommendations for field cultivation for cereal crops are to perform minimal cultivation (discing) on light soils (sandy loam) as this produced the best structural requirements, with minimal to no reduction in establishment and yield. Heavier soils (clay loam) require greater soil loosening (disc & power harrow) to produce optimum structural conditions for seedbed drilling and crop establishment. Results show no advantage to rolling seedbeds, and in fact this resulted in poor seedbed soil structure in this study both as a result of compaction and of surface cracking, which are detrimental to the establishment and yield of the crop.

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1. 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 suggest the most suited conditions for crop growth. An important aspect of this is the physical characteristics of the seedbed such as soil strength, bulk density, moisture 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 (Guérif et al., 2001). 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 (Ball et al., 1994; Czyz, 2004; Servadio et al., 2005).

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 visualisation and analysis (Ringrose-Voase, 1987; Commins et al., 1991; Perret at al., 2002;). It is only now using tools such as X-ray Computed Tomography that this is possible. 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 Seedbed Dynamics

A seedbed is 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 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.

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 moisture, 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 et al., 2002; Blake et al., 2003, Lipiec and Hatano, 2003).

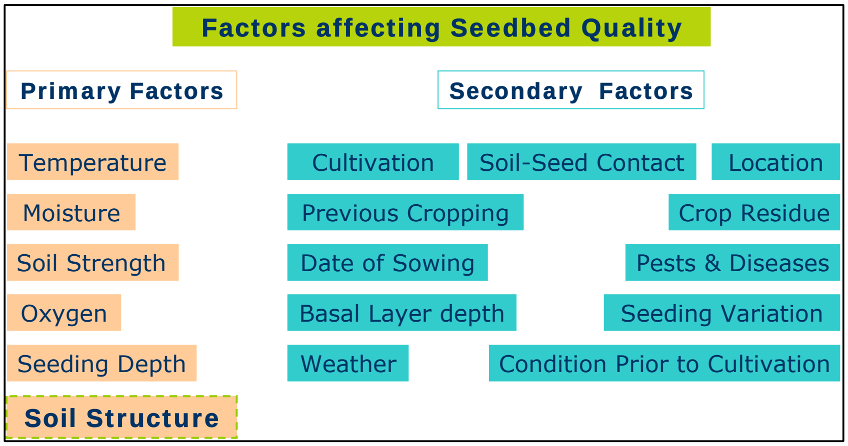

Figure 1.1: Key mechanisms associated with seedbed preparation and soil-plant interactions. We hypothesise soil structure should also be included as a primary influencing factor in plant establishment.

1.3 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.

1.4 Soil Structure

As a soil develops, mineral particles of sand, silt and clay mix together with organic matter creating stable aggregation and soil structure. Soil structure is defined as the spatial arrangement and heterogeneity to which soil particles, aggregates and pores have on the properties of a soil (Dexter, 1988). 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.

Soil structure can be characterised by the shape of aggregates; such as blocky, columnar, crumb, granular, massive etc. (Fitzpatrick, 1986) (Figure 1.2). 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, 2004; Degens, 1997). 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). 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 erodibility (Bronick & Lal, 2005).

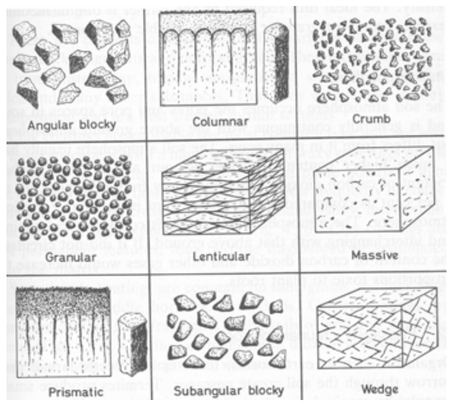

Figure 1.2: Representation of the main soil structure units / aggregates (Figure from Fitzpatrick, 1986).

1.4.1 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, 1996; Vogel, 1997; 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. Improved software and digital image processing procedures have also aided the enhancement in image analysis and the quantification of soil porosity (Moran et al., 1989; Ringrose-Voase & Bullock, 1984).

Image analysis of soils provides quantifiable data concerning the pore space (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., 2003); the movement or distribution of fluids and preferential flows within soil through pore space (Morris & Mooney, 2004); the assessment of pore connectivity (Vogel, 1997); determination of soil fractal parameters (Pachepsky et al., 1996); the effects of tillage applications on the soil environment and possible soil degradation such as compaction (Pagliai et al., 2004; Douglas & Koppi, 1997) and agricultural management such as organic farming (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). 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.

1.4.2 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 1.3). 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.

The use of X-ray CT within soil science 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 is also much faster and produced a greater quantity of images which can be analysed. 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.

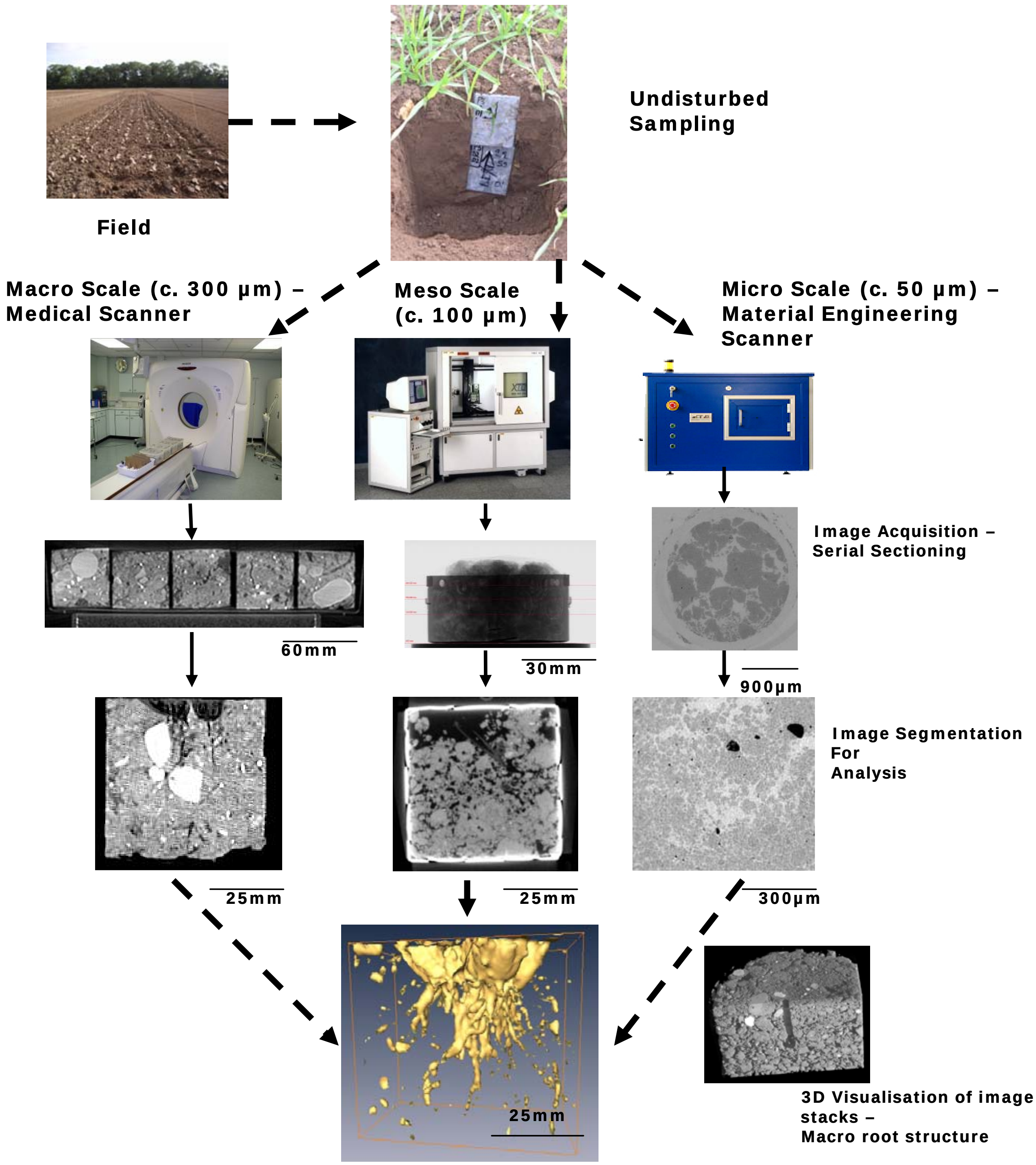

Figure 1.3: X-ray Computed Tomography scales of resolution and image acquisition through to analysis and 3D visualisation applications for quantifying soil structure.

1.5 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 hypothesis 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.

2. Materials & Methods

2.1 Field site and experimental design

2.1.1 Season 1 (2005/6)

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 2.1). 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. The soil structural experimental design was incorporated within the main trial with 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) or combined applications of both power harrowing and rolling (SR). 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.

2.1.2 Season 2 (2006/7)

A field experiment was established in 2006 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 2.1). 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 main 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.

Table 2.1: 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

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, in both seasons, 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.

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 Soil structure sampling

Soil samples were collected by sampling the top 70 mm of the soil profile in 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 at spring establishment (2005 only).

2.4 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 poured gently on to the samples and allowed to infiltrate into the pore space.

2.5 X-ray Computed Tomography

2.5.1 Macro Soil Structure

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.

2.5.2 Meso Soil Structure

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 2.1). Each sample was scanned at 20, 30 and 40 mm from the base of the sample tin.

2.6 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. The soil samples were then photographed under darkroom conditions. An Olympus Camedia C-4000 Z digital camera and an Ultra Violet light source was set at constant distance from the sample surface to maintain resolution. Images were acquired on digital media cards and transferred to a PC for digital processing (Figure 2.2).

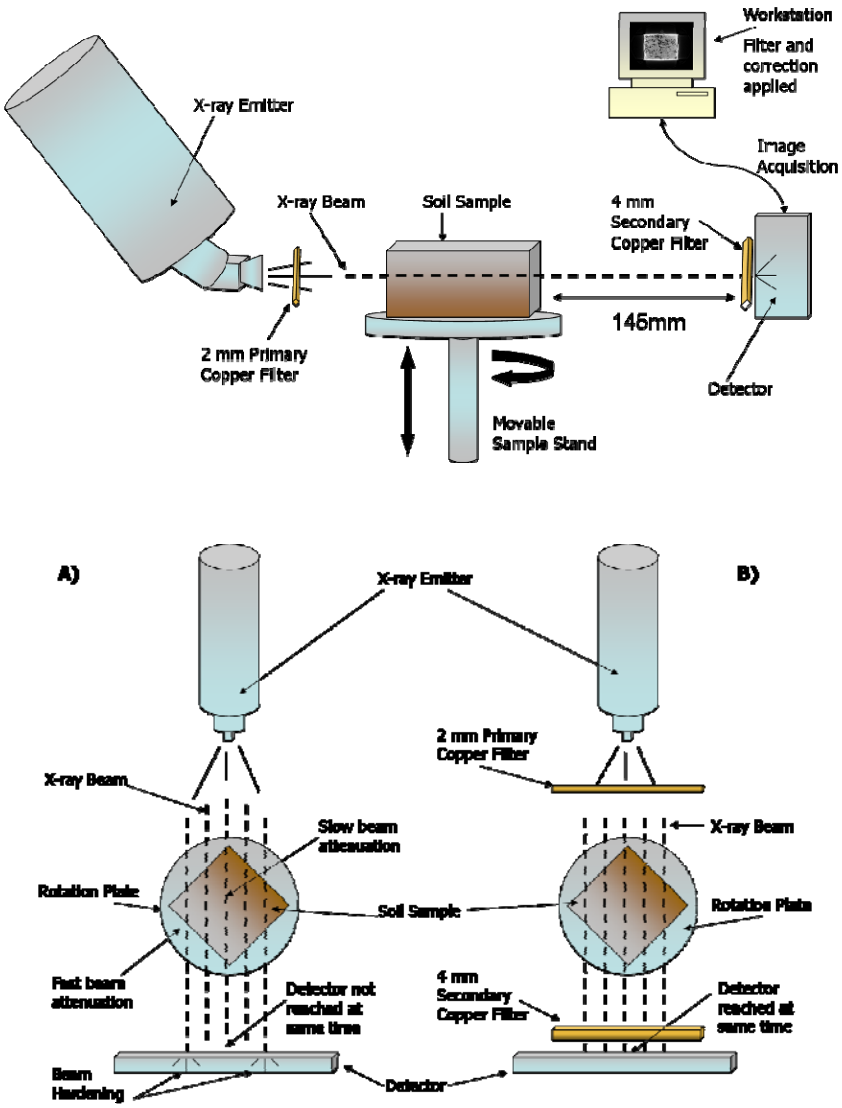

Figure 2.1: X-ray computed tomography diagram of set-up and the effect of beam hardening (a) due to faster x-ray and the correction applied using copper filters (b) in preventing beam hardening.

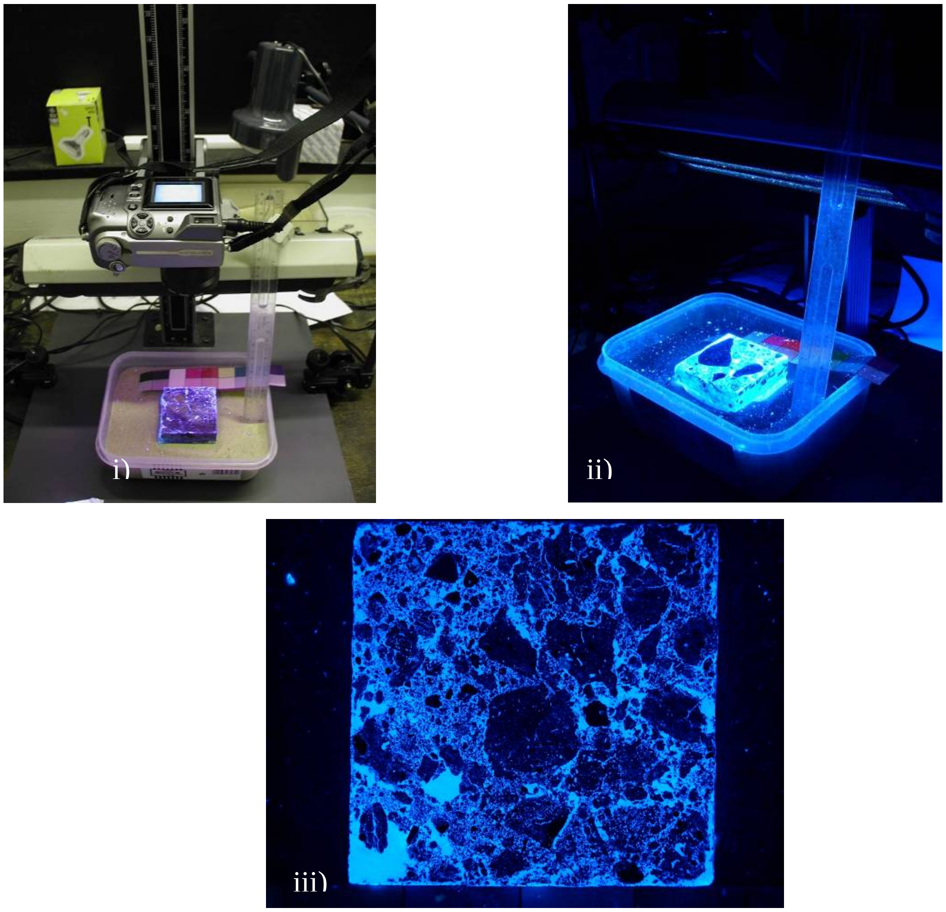

Figure 2.2: Images show Ultra Violet imaging of resin impregnated soil blocks. i) Copy stand, camera and UV light source set-up. ii) Florescent soil block surface. iii) Example of good impregnation and imaging of soil surface.

2.7 Image analysis of soil structure characteristics

2.7.1 Season 1 (2005) – Macro Scale Processing

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/). Thirty 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 used to clean image resolution. Images were then binarised by manual adjustments of a threshold (Hounsfield units – HU), this was performed individually for each sample (c. 1300-1600). Morphological analysis was performed on the binary images created 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.

2.7.2 Season 1 (2005) – Meso Scale Processing

Image manipulation was performed using AnalySIS® (Soft Imaging Systems (SIS), Münster, Germany) to isolate pore space. The image resolution was 62 µm pixel^{-1}. Images were initially cropped to a size of 43 x 43 mm, removing the majority of noise introduced by stones and edge effects. Colour filtering was performed to reduce noise effects within the samples. Plant material was included as pore space due to issues with density differentiation between air and root. Morphological analysis was performed on binary images 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; mean pore perimeter - defined as the sum of the pixel distances along the closed boundary of the pore analysed; and pore size distribution coefficient of uniformity (PSDcu) – ratio of pore size classes at 10% and 60% total porosity.

2.7.3 Season 2 (2006/7) – Meso Scale Processing

Image manipulation was performed using AnalySIS® (Soft Imaging Systems (SIS), Münster, Germany) to isolate pore space. 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 to reduce noise effects within the images (Figure 2.3). Images were then binarised using an auto threshold (removing operator bias) within AnalySIS®,. 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 2.4) were conducted as before (section 2.7.2).

2.8 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 between mean (S.E.D). 2006/7 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.

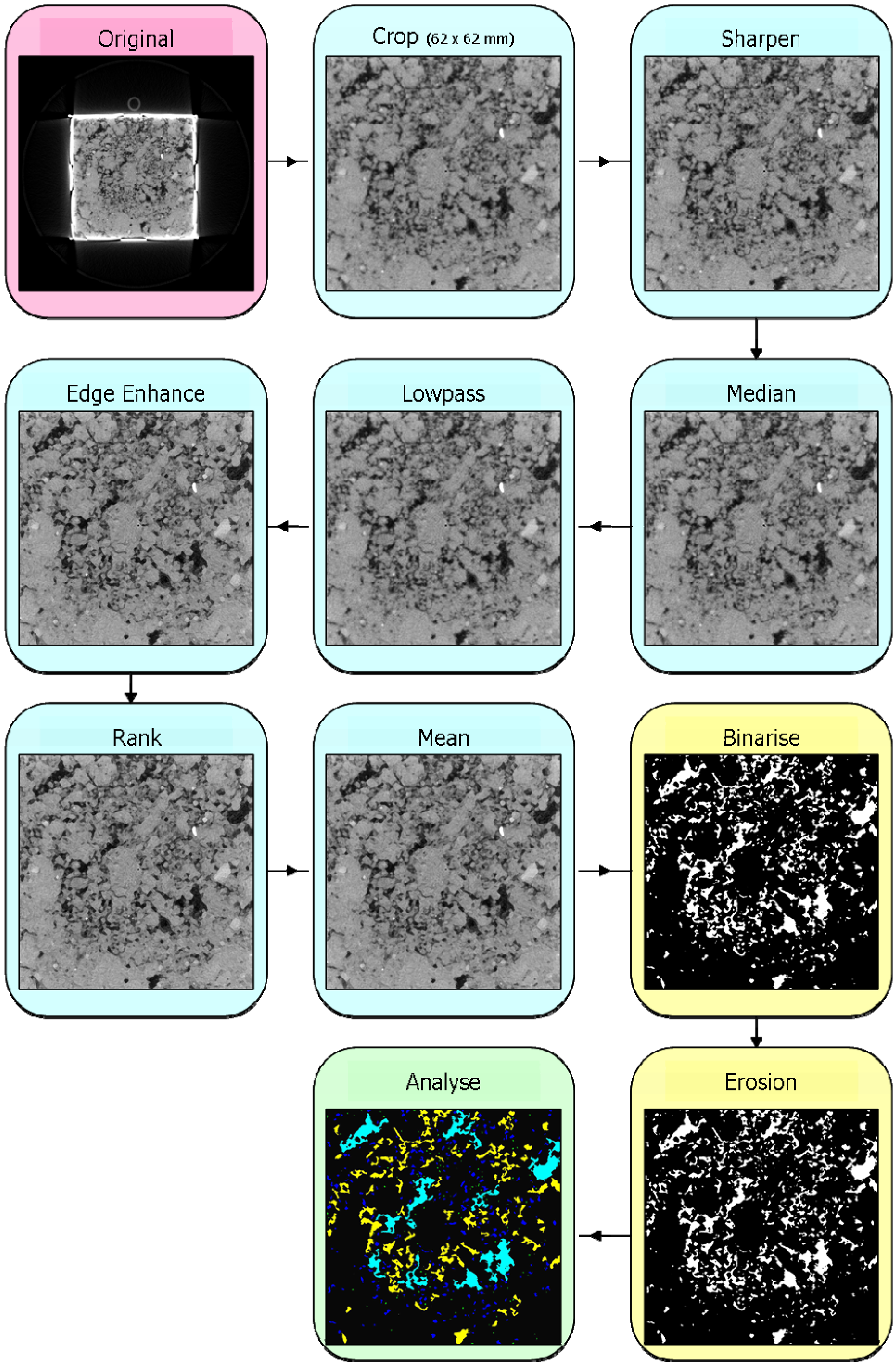

Figure 2.3: Image manipulation of X-ray CT soil block images.

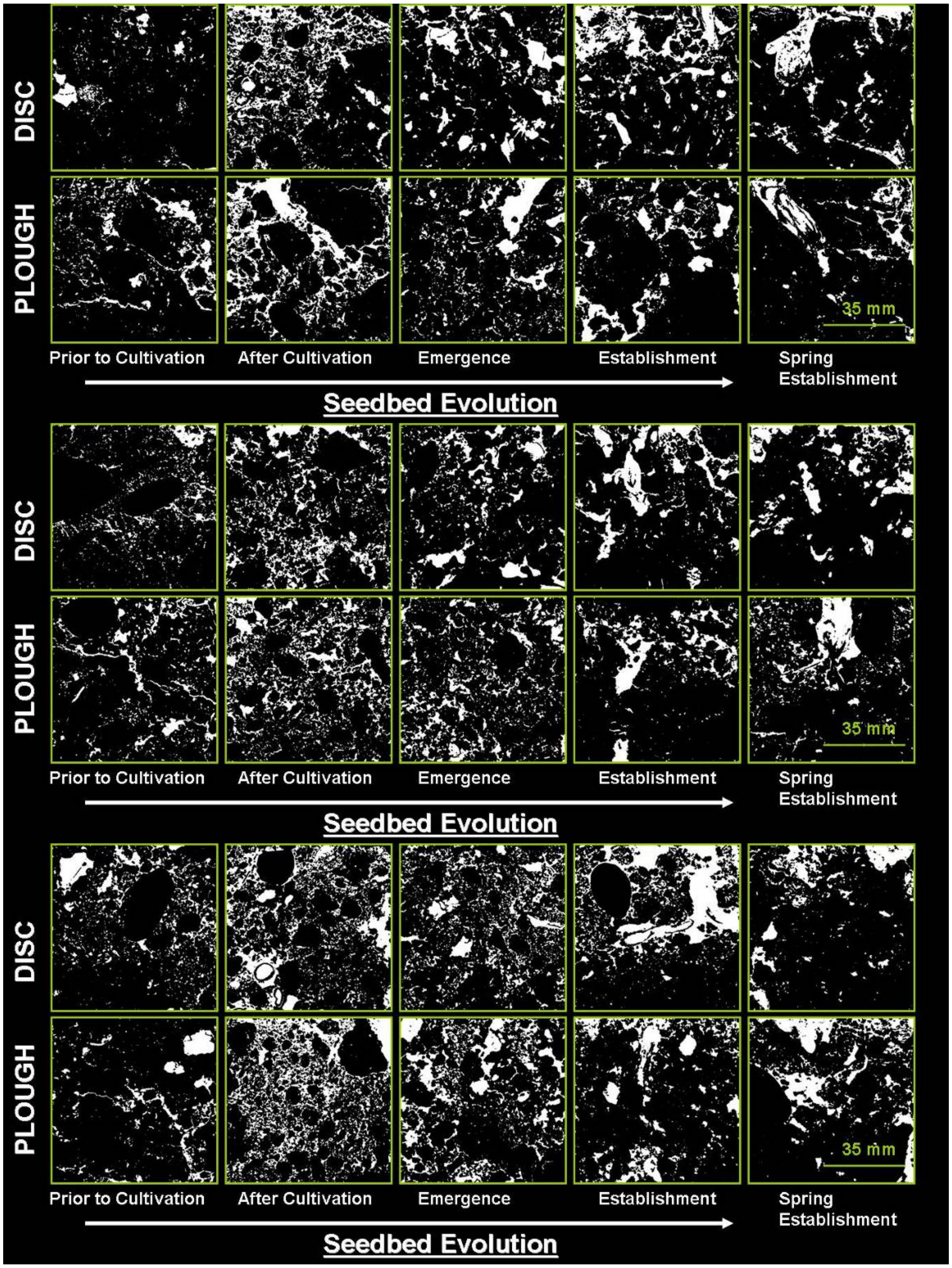

Figure 2.4: Example of seedbed evolutionary changes between primary treatments at the meso scale resolution. A) Primary and rolled. B) Primary and power harrowed. C) Primary, power harrowed and rolled. (white = pore space)

3. Summary of Results

- Reduced tillage strategies can produce unfavourable soil conditions (physical and structural) for winter wheat crop establishment, such as large porosity and pore size associated (Figure 3.1) with surface residue inclusion, but on a sandy loam soil this had minimal effect upon final establishment (due to 'catch up', Figure 3.2, 3.3) 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 (Figure 3.4), but the effect of structure upon yield is less clear.

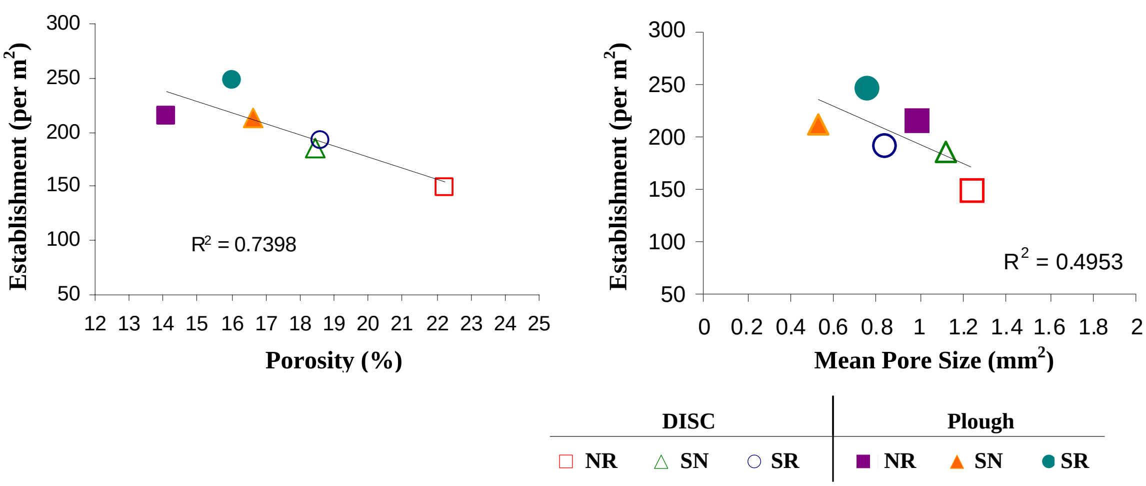

Figure 3.1: Selected relationships observed in season 1 (2005/6) between soil structure and crop establishment. These relationships continued across season and soil type. NR = Rolled, SN = Power harrowed, SR = Power Harrowed and Rolled.

- 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 (Figure 3.3).

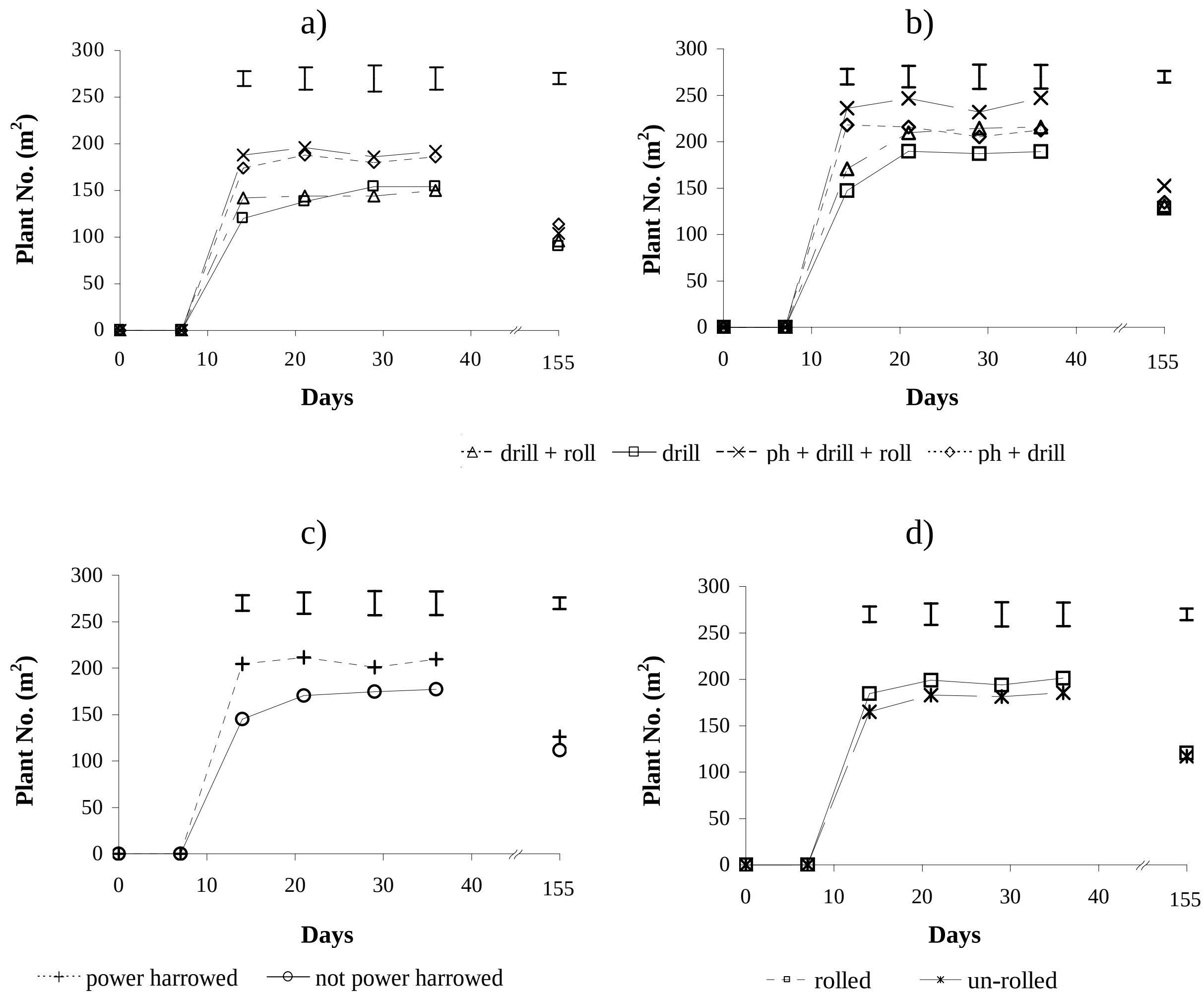

Figure 3.2: Season 1 (2005/6) establishment rates (per m^2) over time within a) Disc treatments. b) Plough treatments. c) Effect of power harrowing. d) Effect of rolling. Bars depict S.E.D., 23 d.f.

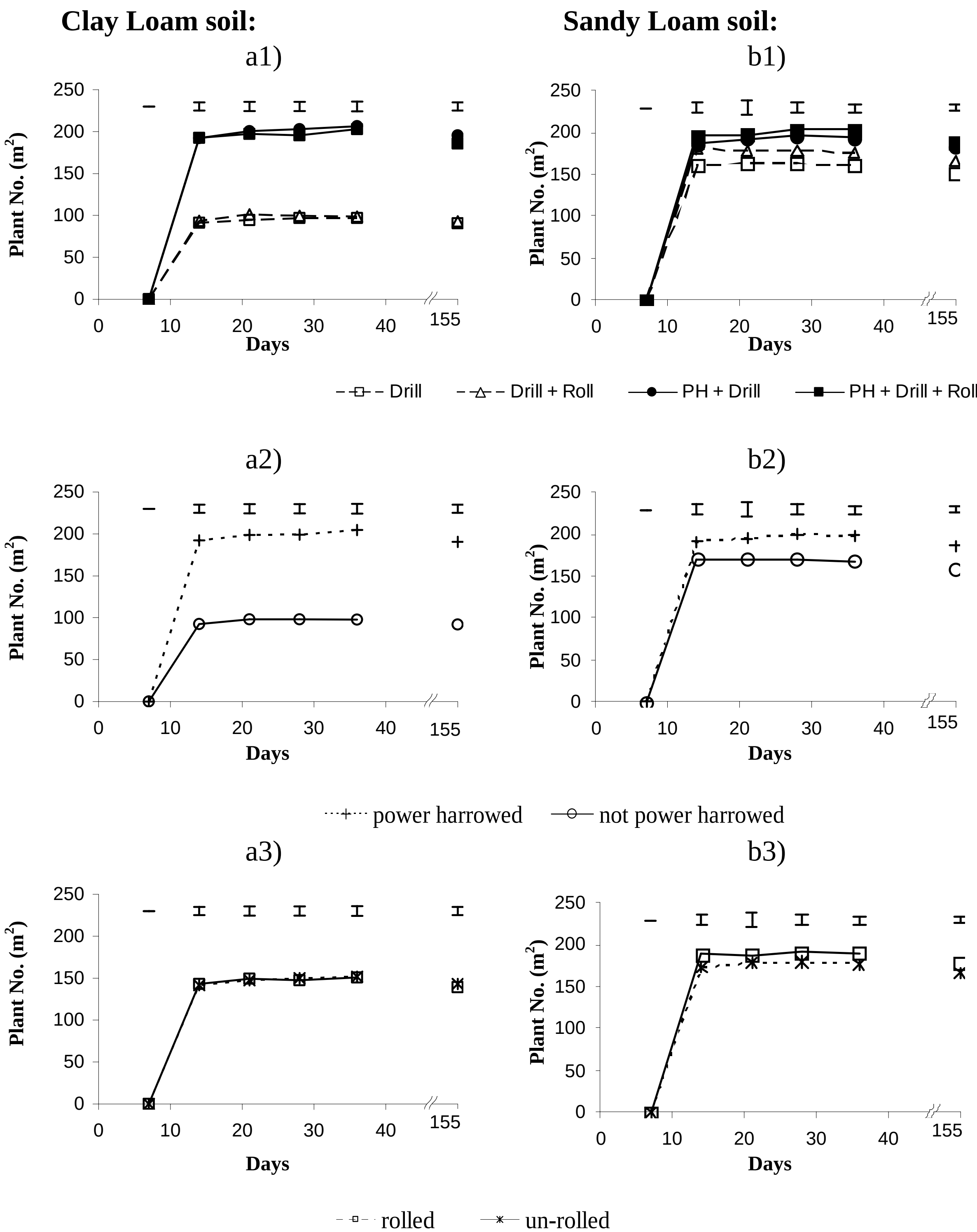

Figure 3.3: Season 2 (2006/7) establishment rates (per m^2) over time within a) Clay loam. b) Sandy Loam. 1) Effect of treatments. 2) Effect of power harrowing. 3) Effect of rolling. Error bars depict S.E.D., 11 d.f.

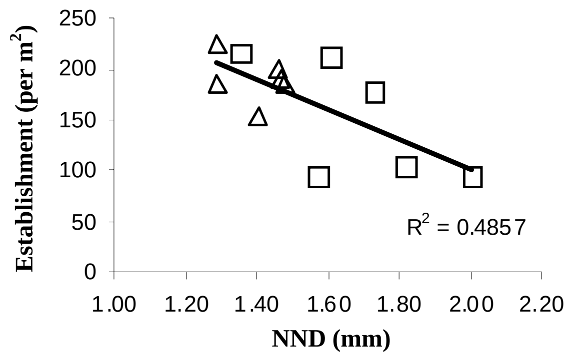

Figure 3.4: Season 2 (2006/7), observed structural relationship showing decreased plant populations with an increase in distance or interconnectivity between pores. Δ = sandy loam, □ = clay loam.

- Rolling causes excessive surface cracking and increases the soil porous architecture (Figure 3.5) resulting in reduced soil seed contact. Rolling increases crop emergence rates as a result of consolidation (Figure 3.2, 3.3); 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 (Table 3.1). Rolling has the same effect regardless of texture on both the physical and structural properties of the soil.

Table 3.1: Establishment and Yield return between rolled and un-rolled treatments during both seasons of experimentation and across soil texture. Error = s.e.

	2005/6		**2006/7**	
	Establishment (per m^2)	Yield (t/ha^{-1})	Establishment (per m^2)	Yield (t/ha^{-1})
Rolled	201 (± 12)	10.96 (± 0.19)	170 (± 14)	9.6 (± 0.27)
Un-Rolled	186 (± 11)	11.42 (± 0.15)	164 (± 13)	9.45 (± 0.20)

- Excessive soil loosening (i.e. too porous) is detrimental to crop establishment (Figure 3.1) within a sandy loam soil while excessive consolidation (increased soil strength and bulk density) is detrimental within a clay loam soil (initially) (Figure 3.6). Crop establishment is limited by the volumetric water content of the soil at low values (independent of texture), severely impeding germination, emergence and establishment (Figure 3.7).

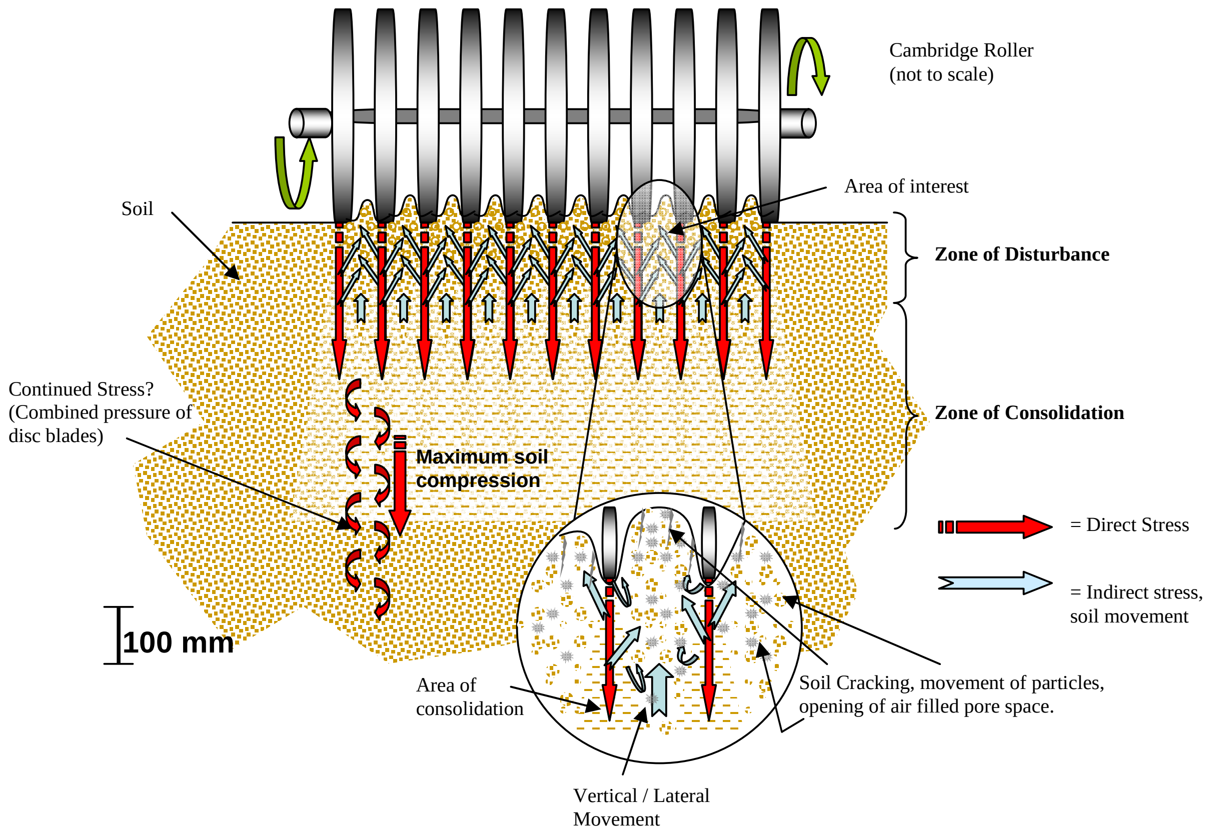

Figure 3.5: Compression stress regime which causes increased porous architecture under rolled cultivation applications.

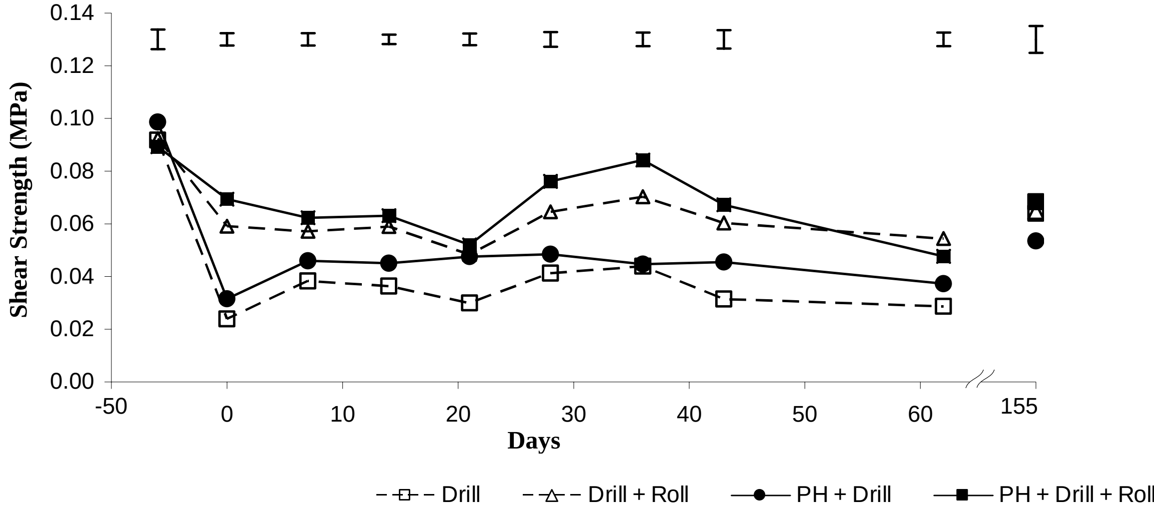

Figure 3.6: Soil compaction / consolidation within a clay loam soil caused by increased cultivation and rolling.

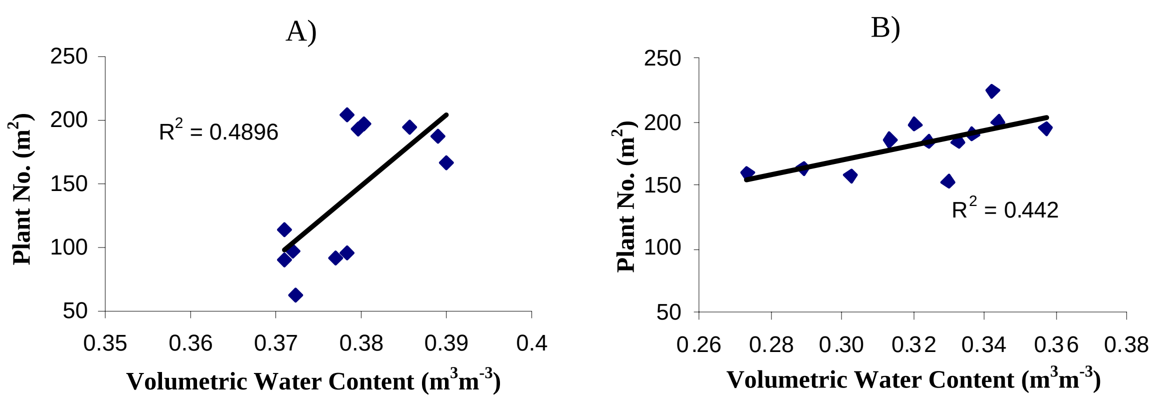

Figure 3.7: Establishment relationships with water content in a) Clay Loam. b) Sandy loam.

- Increased porosity characteristics e.g. porosity, pore area, ECD, NND etc. have significantly negative effects upon crop establishment, observed at all scales of resolution (Figure 3.1, 3.4). This may be associated with poor soil-seed contact, reduced nutrient and water availability. This is severely limiting within sandy loam soil. The only period where this is not the case is within a clay loam 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 (Figure 3.8).

Dynamic range optimum for
establishment and yield.

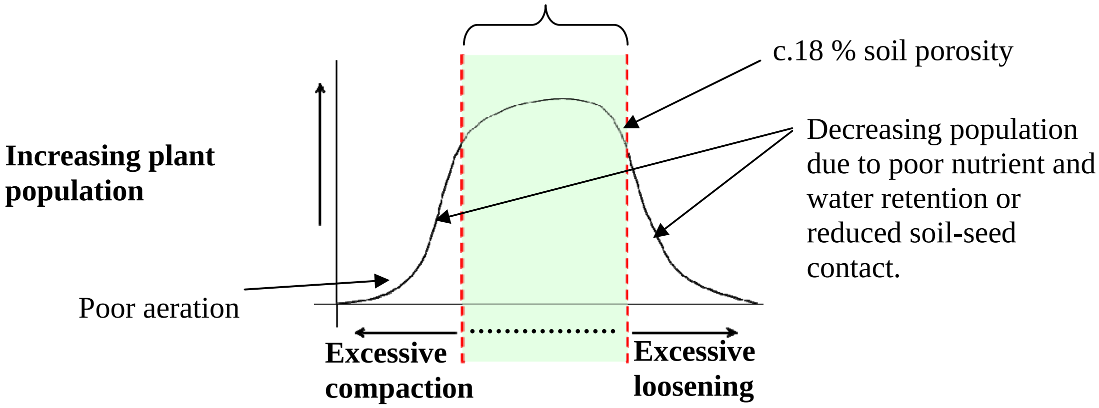

Figure 3.8: Dynamic range of soil conditions optimum for crop establishment with severe decreases in establishment and yield associated with excessive compaction and soil loosening.

- Preferred <u>macro</u> structural conditions of a seedbed for optimum crop establishment (Figure 3.9) are:
    - Porosity 15 – 20 % (image analysis)
        - equivalent to 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 effects upon crop establishment (shoot and root material) within the soil seedbed environment. Preferable conditions include (independent of texture) (Figure 3.4, 3.10):
    - Porosity 12 - 17 % (image analysis)
        - equivalent to c. 55 % total porosity
    - Pore area 0.4 – 1 mm^2
    - Pore perimeter 2 – 3 mm
    - NND < 1.4 mm
    - PSD_{cu} 80 – 110

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

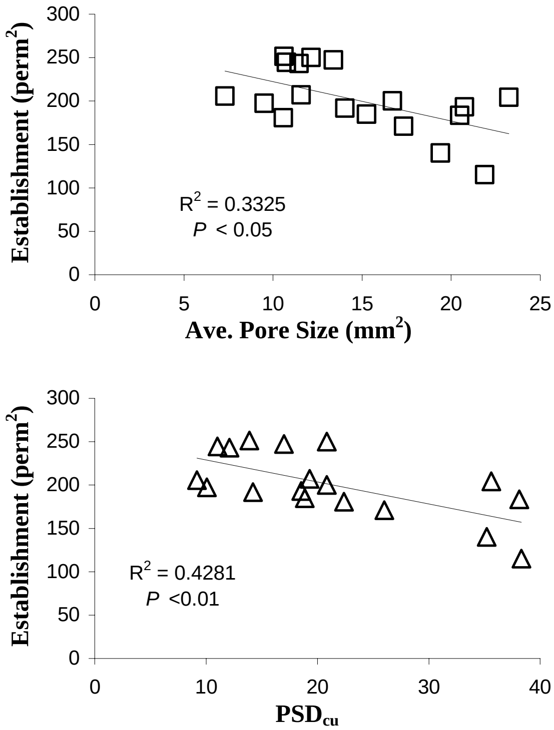

Figure 3.9: Correlations between establishment and increases in pore space of soil macro structure. Shows decreasing populations with increased porosity, and pore area, as well as an increase in larger pore ranges to small pores in overall pore size distribution.

❖ Meso structure significantly affects crop yield confirming the hypothesis. As with crop establishment higher structural conditions i.e. porosity result in reduced crop yield (Figure 3.11). 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.

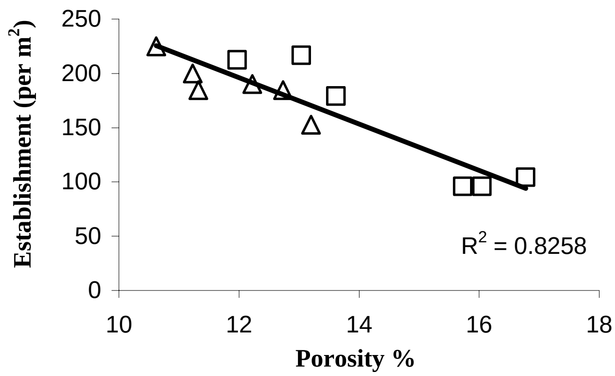

Figure 3.10: Significant relationships between seedbed structure and establishment at +36 day post cultivation across soil texture at meso scale resolution. Shows seedbed collapse post cultivation is beneficial to crop establishment after an initial porosity of between 12-17% for adequate seedbed drilling at cultivation. Δ = sandy loam, □ = clay loam.

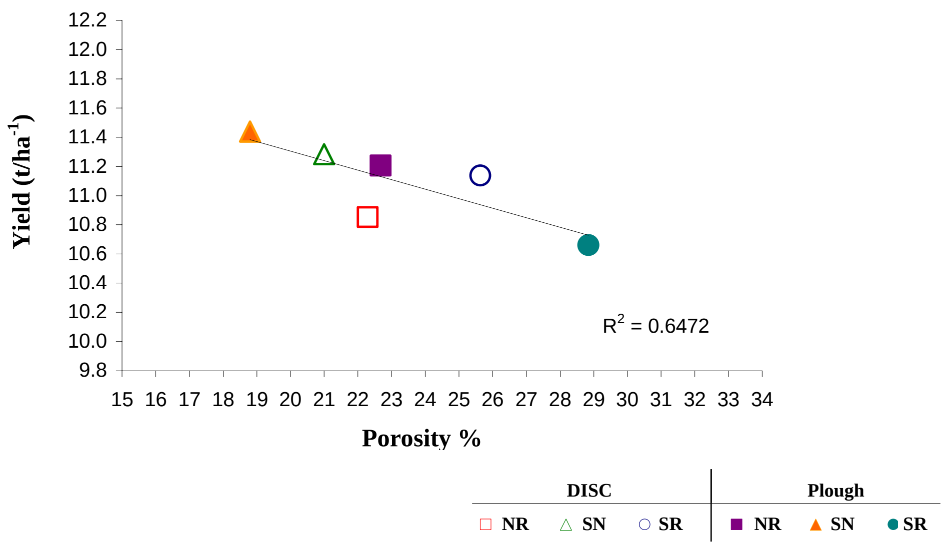

Figure 3.11: Relationship between yield and soil structure within season 1 (2005/6), this trend continued across season and soil type. NR = Rolled, SN = Power harrowed, SR = Power Harrowed and Rolled.

- 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 (Figure 3.12). 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).

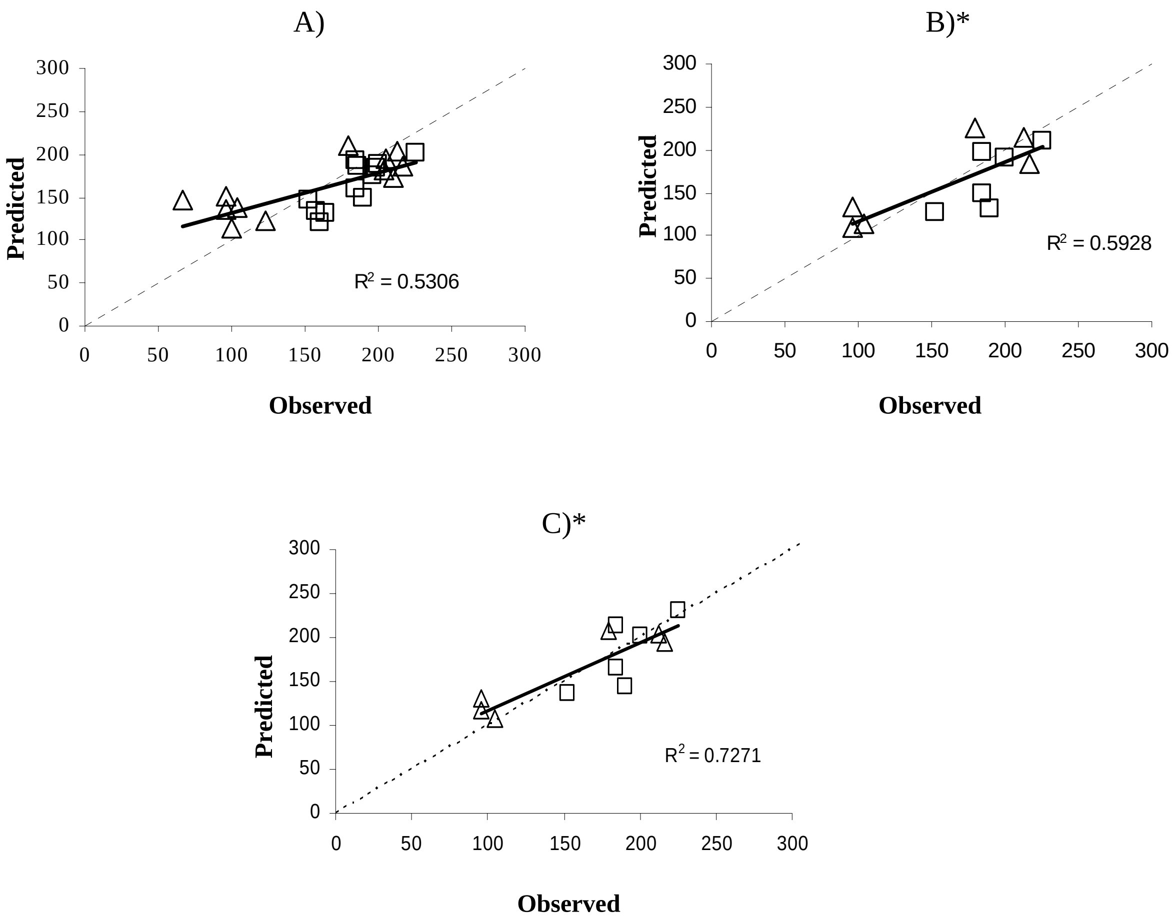

*Figure 3.12: Comparison of SQE model output for best fit models within the validation data, and the changes to model predictability from (a) physical input to (b) physical and macro porosity input (c) physical and meso structural attributes . Validation was conducted over two soil types, a clay loam (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.□ = sandy loam, Δ = clay loam.*

4. Conclusions

Cultivation techniques significantly condition the soil structural environment under which crop establishment occurs. Excessive loosening results in increased porous architecture which leads to poor soil seed contact and reduced water storage. Excessive cultivation leads to soil compaction and reduces crop establishment due to reduced porous architecture and reduces ease of movement for crop development as well as causing poor aeration.

A dynamic range optimum for establishment and yield occurs between these two extremes. The upper limits of this range in terms of structural condition occur at around 18 % soil porosity (measured by image analysis), however the lower limits were not observed estimated at around 10 % soil porosity. These limits are at the time of cultivation, and allow for adequate seedbed drilling (equivalent to a porosity c. 55 % in bulk density). Post drilling associated seedbed collapse or seedbed settling appears to be beneficial to crop establishment and indeed preferable to continued high porosity created at cultivation.

Recommendations based upon soil texture and the structural effects observed show that light soils (sandy loam) require minimal input to attain similar outputs observed within more intensive cultivation with little to no reduction in overall yield, therefore a single pass of disc application is required. Heavier soils (clay loam) require a slightly more intensive input of discing and power harrowing to achieve adequate soil structural conditions for seedbed drilling. Rolling can be detrimental both to the soil quality in terms of extra compaction effects, but also creates poor structural conditions near the soil surface which have negative effects upon cereal crop establishment and yield. It is therefore recommended rolling only be used if excessive loosening has been performed in light soils or if the crop requirements are such that a flat seedbed is require e.g. sugar beet.

4.1 Implications

- If agricultural policy suggests a move 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. On clay soils (accounting for ~ 60 % UK soils – Batey, 1988) establishment is likely to be compromised 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.

4.2 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 will 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 does the movement of these nutrients and their availability within different soil textures and structures influence crop establishment?

- 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 non-cereal crops (it must also be noted that other cereals might not necessarily respond in the same way as Wheat).

References

Anderson, S.H., Peyton, R.L., Wigger, J.W., Gantzer, C.J., 1992. Influence of aggregate size on solute transport as measured using computed tomography. Geoderma, **53**, 387-398.

Arvidsson, J., Rydberg, T., Feiza, V., 2000. Early sowing – a system for reduced seedbed preparation in Sweden. Soil and Tillage Research, **53**, 145-155.

Ball, B.C., Lang, R.W., Robertson, E.A.G., Franklin, M.F., 1994. Crop performance and soil conditions on imperfectly drained loams after 20-25 years of conventional tillage or direct drilling. Soil and Tillage Research, **31**, 97-118.

Blake, J.J., Spink, J.H., Dyer, C., 2003. Factors affecting cereal establishment and its prediction. HGCA Research Review 51, September.

Bronick C. J. and Lal R. 2005. Soil structure and management: a review. Geoderma **124**: 3-22.

Bui, E.N., 1991. Applications of image analysis to soil micromorphology. Agriculture, Ecosystems and Environment, **34**, 305-313.

Carter, M.R., 2004. Researching structural complexity in agricultural soils. Soil and Tillage Research, **79**, 1-6.

Commins, P.J., McBratney, A.B., Koppi, A.J., 1991. Development of a technique for the measurement of root geometry in the soil using resin-impregnated blocks and image analysis. Journal of Soil Science, **42**, 237-250.

Czyz, E.A., 2004. Effects of traffic on soil aeration, bulk density and growth of spring barley. Soil and Tillage Research, **79**, 153-166.

Degens, B., 1997. Macro-aggregation of soil by biological bonding and binding mechanisms and the factors affecting these: a review. Australian Journal of Soil Research, **35**, 431-459.

Dexter, A.R., 1988. Advances in characterization of soil structure. Soil and Tillage Research, **11**, 199-238.

Douglas, J.T., Koppi, A.J., 1997. Soil structural quality: a case study of soil macropore attributes after seedbed preparation with different wheel traffic systems. Soil and Tillage Research, **41**, 249-259.

Fitzpatrick, E.A., 1986. An introduction to soil science 2nd edition. Longman Scientific.

Gerhardt, R.A., 1997. A comparative analysis of the effects of organic and conventional farming systems on soil structure. Biological Agriculture and Horticulture, **14**, 139-157.

Håkansson, I., Myrbeck, Å., Etana, A., 2002. A review of research on seedbed preparation for small grains in Sweden. Soil and Tillage Research, **64**, 23-40.

Håkansson, I., von Polgár, J., 1984. Experiments on the effects of seedbed characteristics on seedling emergence in a dry weather situation. Soil and Tillage Research, **4**, 115-135.

Heijs, A.W.J., Ritsema, C.J., Dekker, L.W., 1996. Three-dimensional visualization of preferential flow patterns in two soils. Geoderma, **70**, 101-116.

Houndsfield, G.N., 1973. Computerized transverse axial scanning (tomography): Part I. Description of system. British Journal of Radiology, **46**, 1016-1022.

Lipiec, J., Hatano, R., 2003. Quantification of compaction effects on soil physical properties and crop growth. Geoderma, **116**, 107-136.

Lipiec, J., Kus, J., Slowinska-Jurkiewicz, A., Nosalewicz, A., 2006. Soil porosity and water infiltration as influenced by tillage methods. Soil and Tillage Research, **89**, 210-220.

Mooney, S.J., 2002. Three-dimensional visualization and quantification of soil macroporosity and water flow patterns using computed tomography. Soil Use and Management, **18**, 142-151.

Mooney, S.J., Morris, CA., Berry, P.M., 2006. Visualization and quantification of the effects of cereal root lodging on three-dimensional soil macrostructure using x-ray computed tomography. Soil Sci., **171**, 706-718.

Mooney, S.J., Morris, C., Craigon, J., Berry, P., 2007. Quantification of soil structural changes induced by cereal anchorage failure: Image analysis of thin sections. Journal of Plant Nutrition and Soil Science, **170 (3)**, 363-372.

Moran, C.J., McBratney, A.B., Koppi, A.J., 1989. A rapid method for analysis of soil macro-pore structure. I. Specimen preparation and digital binary image production. Soil Science Society of America Journal, 53, 921-928.

Morris, C., Mooney, S.J., 2004. A high-resolution system for the quantification of preferential flow in undisturbed soil using observations of tracers. Geoderma, **118**, 133-143.

Morris, C., 2004. Visualisation and quantification of soil wetting patterns in undisturbed soils using physical, chemical and morphological observations of tracers. PhD Thesis, University of Nottingham.

Nunan, N., Wu, K., Young, I.M., Crawford, J.W., Ritz, K., 2003. Spatial distribution of bacterial communities and their relationships with the micro-architecture of the soil. FEMS Microbiology Ecology, **44**, 203-215.

Pachepsky, Ya., Yakovchenko, V., Rabenhorst, M.C., Pooley, C., Sikora, L.J., 1996. Fractal parameters of pore surfaces as derived from micromorphological data: effect of long-term management practices. Geoderma, **74**, 305-319.

Pagliai, M., Vignozzi, N., Pellegrini, S., 2004. Soil structure and the effect of management practices. Soil and Tillage Research, **79**, 131-143.

Perret, A., Capowiez, Y., Belzunces, L., Moran, C.J., 2002. 3D reconstruction and quantification of macropores using X-ray computed tomography and image analysis. Geoderma, **106**, 247-271.

Perret, J., Prasher, S.O., Kantzas, A., Langford, C., 1999. Three-dimensional quantification of macropore networks in undisturbed soil cores. Soil Science Society of America Journal, **63**, 1530-1543.

Petrovic, A.M., Siebert, J.E., Rieke, P.E., 1982. Soil bulk density analysis in three dimensions by computer tomographic scanning. Soil Science Society of America, **46**, 445-450.

Protz, R., Sweeney, S.J., Fox, C.A., 1992. An application of spectral image analysis to soil micromorphology. I. Methods of analysis. Geoderma, **53**, 275-287.

Ringrose-Voase, A.J., 1996. Measurement of soil macropore geometry by image analysis of sections through impregnated soil. Plant and Soil, **184 (1)**, 27-47.

Ringrose-Voase, A.J., 1987. A scheme for the quantitative description of soil macrostructure by image analysis. Journal of Soil Science, **38**, 343-356.

Ringrose-Voase, A.J., Bullock, P., 1984. The automatic recognition and measurement of soil pore types by image analysis and computer programs. Journal of Soil Science, **35**, 673-684.

Rowell, D.L., 1994. Soil Science: Methods and Applications. Prentice Hall, pp. 29-32.

Servadio, P., Marsili, A., Vignozzi, N., Pellegrini, S., Pagliai, M., 2005. Effects on some soil qualities in central Italy following the passage of four wheel drive tractor fitted with single and duel tires. Soil and Tillage Research, **84**, 87-100.

Shepherd, M.A., Harrison, R., Webb, J., 2002. Managing soil organic matter – implications for soil structure on organic farms. Soil Use and Management, **18**, 284-292.

Soffe, R. J. (ed.) 2003. The agricultural notebook, 20th edition. Blackwell Science, Oxford.

Van Noordwijk, M., Schoonderbeek, D., Kooistra, M.J., 1993. Root-soil contact of field grown winter wheat. Geoderma, **56**, 277-286.

Vogel, H.J., 1997. Morphological determination of pore connectivity as a function of pore size using serial sections. European Journal of Soil Science, **48**, 365-377.