The effect of tillage depth and traffic management on soil properties and root development during two growth stages of winter wheat (*Triticum aestivum L.*)

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~~4.1~~ Abstract

The management of agricultural soils during crop establishment can affect root development by changes to soil structure. This paper assesses the influence of tillage depth (250 mm, 100 mm & zero) and traffic management (conventional tyre pressure, low tyre pressure & no traffic) on wheat root system architecture during winter wheat (*Triticum aestivum L.*) tillering and flowering growth stages (GS) on a long-term tillage trial site. The study revealed that zero-tillage systems increased crop yield through significantly greater root biomass ($P < 0.001$), root length density and deeper seminal rooting analysed using X-ray Computed Tomography (CT) ($P < 0.001$) compared to trafficked treatments. In general, conventional pressure trafficking had a significant negative influence on crop yield ($P < 0.01$), root development (0.001), bulk density ($P < 0.05$) and total soil porosity ($P< 0.05$) of deep and shallow tillage conventional pressure systems compared no traffic zero and deep tillage systems. Visual improvements in soil structure under zero tillage may have improved crop rooting in zero tillage treatments through vertical pore fissures (biopores), enhancing water uptake during the crop flowering period. This study highlights the increasing implications of soil structural damage on root system architecture created by ~~compaction~~ machinery trafficking in crop production. Although tillage method was less important, the~~The~~ constricted root systems ~~found in~~were more pronounced in conventional pressure shallow tillage and ~~, zero and~~ deep tillage systems, ~~trafficked regimes~~ emphasiz~~es~~inges the importance of using controlled traffic farming methods~~technology~~ to improve soil management and reduce the trafficked areas of agricultural fields.

1.~~4.2~~ Introduction

Soil resources are under significant pressure from anthropogenic activities especially conventional tillage. The resulting soil degradation has significant implications for food security globally (Lal, 2010). Changing weather patterns from prolonged rain to drought periods are being experienced on a global scale, substantiating the challenges faced by food producers. In 2018, worldwide wheat production fell by 34.5 million ton due to prolonged droughts across Europe, Australia, and Canada. Soil compaction from field traffic is a well-recognized problem in many parts of the world (Chan et al., 2006; Arvidsson and Keller, 2007; Naderi-Boldaji et al., 2018 (Chan *et al.*, 2006; Arvidsson and Keller, 2007; Naderi-Boldaji *et al.*, 2018) affecting 33 million hectares in Europe alone (Akker and Canarache, 2001). Soil compaction is a form of physical degradation caused by short crop rotations and heavy farm machinery working on low organic matter soils in wet conditions resulting in the loss of pore space due to an externally applied load, forcing soil aggregates together (Defossez and Richard, 2002).

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The resulting anaerobic high density soils have significantly reduced capacity to store water and nutrients required by growing crops (Hamza and Anderson, 2005) and severely compacted soils prevent soil exploration from root growth (Tracy et al., 2012a).

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Soil compaction is due in part to the pressure to complete field operations such as harvesting or drilling often in short windows of good weather, which is exacerbated by the increasing use of larger machinery with increasing axle loads designed to improve operational efficiencies. Common agricultural operations are conducted using wheeled farm machinery which has tripled in weight and power since 1966 with wheel loads rising by a factor of six (Chamen, 2006). When soils are cultivated in moist or wet conditions, soils can not withstand the compressive forces applied post cultivation by heavy farm machinery traffic during operations such as seeding (Raper, 2005), resulting in soil degradation (Batey, 2009). When soil is wet, tyre stress can propagate a greater distance down through the soil profile. The depth and severity of soil stress is related to soil moisture, traction device applied (track or tyre), track size, tyre inflation pressure and wheel load (Naderi-Boldaji et al., 2018).

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Reforming the approach to soil management to mitigate challenges such as soil compaction and soil erosion offer significant financial and environmental benefits compared to conventional agriculture. Cultivation practice using minimal, or zero tillage techniques are widespread across many climatic conditions from semi-arid Canadian plains to the temperate climates of Western Europe. In conventional tillage, the soil is either inverted >200 mm using a mouldboard plough or deeply ripped using tines. The soil is then cultivated again to break down soil aggregates to a crumb structure or fine tilth that is suitable to plant seeds (Morris et al., 2010). Conservation tillage, also known as non-inversion tillage or reduced tillage, has been used for decades to improve soil structure and health (Skaalsveen, Ingram and Clarke, 2019). Under conservation tillage, soil is disturbed to a lesser extent (<100 mm using tines or discs) or not disturbed at all such as under zero tillage which involves the direct placement of seed into undisturbed crop residues (Soane et al., 2012).

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The successful adaption of reduced tillage systems is not universally guaranteed with factors such as soil texture and drainage, crop type and weather influencing successful implementation (Soane et al., 2012). In northern Europe, crop yields under reduced cultivation systems rarely exceed those achieved by ploughing (Arvidsson, 2010). The exception under drier arid climates such as Spain, no tillage improved crop yields by moisture retention in below average rainfall years (Muñoz-Romero *et al.*, 2010). Higher bulk density and penetration resistance are typically found throughout the formerly tilled or “plough pan” layer in no tillage soils within the first two years of adoption, resulting in root mechanical impedance (V. Boguzas et al., 2006). Yet, over time, long term zero tillage has shown to attribute improvements in soil pore architecture and continuity throughout the soil profile by bioturbation, suggesting roots could penetrate to lower soil horizons (Cooper et al., 2021).

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To date, studies have focused on how tillage influences physical soil properties (bulk density, cone penetrometer, soil aeration) with root and crop yield responses (Whalley et al., 2008; Pires et al., 2017; Czyż, 2004). Soil types and tillage systems have a considerable influence on the structural integrity of soil which controls rooting potential (Morris *et al.*, 2017a). Studies have shown that low pressure tyres can reduce surface compaction compared to high tyre pressure (Soane et al., 1980; Boguzas and Hakansson, 2001). As trafficking increases soil strength and reduces a plant root’s ability to penetrate soil layers, it is important to understand the relationship

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between tillage depth and root system architecture during the growing season in response to trafficking. A dearth of information exists on how tillage depth and tyre pressure affect rooting properties and crop yield on longer term field sites. Yield reduction by soil surface compaction can increase abiotic stress in plants in three ways. It reduces soil aeration, increases mechanical impedance of roots which in turn reduces root exploration of soil thus, mitigating the extraction of water and nutrients from the soil resource (Chamen, 2011).

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Quantitative measurement of root system architecture in three dimensions (3D) has become tractable using X-ray CT in pot experiments (Mairhofer et al., 2017). Few examples of root studies using high resolution X-ray computed tomography have been successfully conducted in field trials using undisturbed soil cores. Many studies have focused on measuring soil structural properties such as porosity, soil pore size and distribution and the influence of tillage method and trafficking (Millington et al., 2017; Rab et al., 2014). However, studying root development and architecture in three-dimensional field structured soils remains challenging with X-ray CT due to a bottleneck of rapid and standardized root extraction methods available, insufficient resolution and inability to segment similarities in grey scale values between root and organic materials (Zhou et al., 2021; Mooney et al., 2012; Pfeifer *et al.*, 2015).

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The purpose of this paper was to identify ~~the in-situ relationships~~the effect and interaction of machinery traffic and~~between~~ tillage depth ~~and ~~using commercial crop establishment methods.~~ on~~ R~~r~~oot architecture, soil physical structure and crop yield ~~under different traffic methods~~were studied during two key growth stages of winter wheat. X-ray CT was deployed to show if root architecture behaviors could be captured in-situ to the soil structural environment created by the tillage method. Three cultivation practices and traffic management systems were studied: Deep tillage (250 mm), shallow tillage (100 mm) and zero tillage, under no traffic, low tyre pressure and conventional tyre pressure. The objectives of this study were to (i) assess the relationship between of traffic management and three tillage depths and its effects on root system architecture and soil physical properties (ii) Utilise 3D image analysis along with 2D destructive methods to verify rooting properties responsible for crop yield.

2.~~4.3~~ Materials and Methods

2.1~~4.3.1~~ *Site and soils*

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The study took place during the 2018/19 growing season. The experimental site is 3.12 ha, located at Harper Adams University (HAU), Edgmond, Newport, England (52.779738 N, -2.426886 W). The HAU site is a loamy sand soil consisting of the Olerton and Salwick series soils (Eutric Endogleyic Arenosol and Chromic Endostagnic Luvisol respectively) (Millington et al., 2017). Further details of the soil properties are described in Table 1. To highlight if any site variability existed across the site, soil properties were examined for fertility (pH and nutrient levels), bulk density, soil strength and soil moisture. Particle size analysis (Gee and Or, 2002) was conducted to determine soil texture classifications. The trial site was established in 2011 for previous studies with plots and treatments carried out in the same location.

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The experimental site was established in 2011 with each plot receiving the same tillage and traffic treatment as this study. ~~In the year prior to this study, it was necessary to plant a break crop (2017/18) as part of a standard crop rotation to improve soil conditions and reduce diseases such as take all *(Gaeumannomyces*~~

~~*graminis var.* tritici). A field bean (*Vicia Fabia*) break crop was planted, and yields were assessed to ensure the trial site was uniform with no underlying issues.~~ During the trial period, the site was treated with a standard ~~Since the trial site began, the~~ crop rotation ~~has been first~~with winter wheat (*Triticum aestivum L.*) harvested in 2012 followed winter wheat in 2013, winter barley (*Hordeum vulgare L.*) 2014, winter barley 2015, followed by a cover crop "TerraLife-N-Fixx" (DSV United Kingdom Ltd, 2015); Spring oats 2016, spring wheat 2017 and winter beans 2018. In the year prior to this study, it was necessary to plant a break crop (2017/18) as part of a standard crop rotation to improve soil conditions and reduce diseases such as take all *(Gaeumannomyces graminis var.* tritici). A field bean (*Vicia Fabia*) break crop was planted, and yields were assessed to ensure the trial site was uniform with no underlying issues. For this trial, winter wheat (*Triticum. aestivum L. cv.* Graham*)* followed the bean crop and was drilled early October 2018 when the soil was dry, friable and soil temperatures >6 °C. The seeding rate was 250 seeds per m^2 and drilling took place on the 5th of October. This is in line with local normal farming practice.

Table ~~4.~~1: Description of the topsoil (0-300 mm) properties for Harper Adams University trial site, Shropshire, UK.

Property	**Units**	
Location	Latitude	52.779738 N
	Longitude	-2.426886 W
Soil type	Landis group*	Argillic brown earths, brown sands
	Landis series*	Salwick, Ollerton
	FAO	Luvisol & Arenosol
Sand (2000-65µm)	g g^{-1} dry soil	0.743
Silt (63-2µm)	g g^{-1} dry soil	0.115
Clay (<2µm)	g g^{-1} dry soil	0.143
Texture	SSEW class	Loamy sand
Organic matter (LOI)	g g^{-1} dry soil	0.044

*Landis Soil guide (University, 2021).

LOI, Loss of Ignition.

2.~~4.3.~~2 Experiment design

The experiment was a randomised 3 x 3 factorial arrangement of 9 treatments in four complete replicate blocks. Each plot was 4 m wide x 84 m long with exception of block 4. Block 4 is 78.2 m long for operational reasons. Tramlines were at a 90° angle to plots with 24 m spacing for fertilising and spraying operations throughout the growing season. A split-plot design was used, half the plot (30 m) designated for sampling and the other half was undisturbed for yield data collection. The half plot for sampling was sub-divided for the two sampling stages, ensuring sampling did not occur near the same location as the previous sample. Cultivation for spring beans in 2017 was performed at three depths, 250 mm for deep tillage, 100 mm for shallow tillage and direct into stubble

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for zero tillage. In the winter wheat trial, soil cores were collected at tillering (Growth stage (GS) 25) and the flowering stage (GS 61-69) (Zadoks et al., 1974) in July 2019.

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Three commercial crop establishment systems were used consisting of three different tillage depths. The following tillage treatments are denoted as: Treatment 1 = Deep tine cultivator at 250 mm (DT) for deep tillage similar to (Ren *et al.*, 2019), treatment 2 = shallow disc cultivation at 100 mm (ST) and treatment 3 = zero tillage using a direct seed drill (ZT). In combination with the different tillage depths, three traffic regimes were used in this study no traffic (NT), conventional tyre pressure (CP) and low tyre pressure (LP). Tillage depths were combined with traffic management practices for the 9 treatments (DTNT, DTCP, DTLP, STNT, STCP, STLP, ZTNT, ZTCP & ZTLP). Using GPS guidance and markers, trafficked areas of each plot were marked out to ensure samples were taken from the correct location. A GPS (Trimble FMX display unit) was used to apply all tillage and drilling applications. All wheelings from cultivation and drilling occurred in the same traffic lanes for the duration of the trial. During drilling, the drill coulters directly behind the tractor wheeling were marked to aid identification of trafficked crop rows. During harvest, it was necessary to avoid driving on non-trafficked areas with the plot combine restricted the wheelway zones. This ensured a CTF system was replicated.

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2.~~4.3.~~2.2~~3~~ Tillage equipment and tyres

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Primary cultivations in HAU involved a rigid tine and conical disc cultivator (Vaderstad Topdown) at 250 mm depth to cut surface residues, loosen, mix, and consolidate the seedbed. The same implement was used for shallow tillage treatments with tines adjusted upwards to reduce tillage depth (100 mm). A 290 hp Massey Fergusson 8480 with a track width of 2.1 m was used. Increased flexion AxioBib tyres were fitted IF 650/85 R38 179D TL on the rear axle and (IF 600/70 R30 159D TL) at the front. A pneumatic disc seed drill (Vaderstad Spirit) was used to sow the crop with 167 mm row spacing. The same drill was used to sow the zero tillage plots with the tines and discs lifted to minimise disturbance (Kaczorowska-Dolowy *et al.*, 2019a).

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For the tyre pressure treatment, the conventional tyre treatments were inflated to 1 bar for front and rear tyres during cultivations. Low tyre pressure treatments and controlled traffic farming (CTF) plots operated on 0.7 bar front and 0.8 bar on the rear axle. A front weight block of 540 kg was applied to the tractor for tillage primary cultivation. All operations were performed under the same wheel-ways to keep traffic free zones for CTF plots. During harvest, a Claas Dominator combine operated on a 4-m header, matching plot sizes (Smith, 2016). Crop husbandry was carried out in accordance to the AHDB guidelines and soil fertility test analysis (AHDB, 2018).

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2~~4.3~~.3.14 Soil physical properties

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Soil bulk density samples were also collected within the trafficked and non-trafficked area of the plot, to represent the bulk density of the tillage treatments. Samples were replicated three times. Each core sample was 50 mm in

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width and 300mm in length. An Eijkelkamp® soil corer was used to take bulk densities samples. Each bulk density sample was taken within 0.5 m of the location of the soil cores taken for X-ray CT. The objective was to represent the physical constraints (or lack of) for root growth in each plot examined. The method used in this study involved splitting the bulk density sample into three 100 mm sections (0-100 mm, 100-200 mm and 200 – 300 mm) similar to (Smith, 2016). The corer was opened in the field and split using a knife and ruler.

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The core sections were stored in resealable bags and labelled before transporting to the laboratory for analysis. Intact fresh soil cores were weighed prior to drying to record sample fresh weights. Samples were placed into an oven at 105ºC for 24 h and reweighed to determine moisture % as per equation 1 and dry bulk density as per equation 2 (Campbell and Henshall, 2000).

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Moisture % = fresh weight(g) – dry weight (g) / dry weight(g) *100 Equation 1

Dry bulk density (Mg m^{-3}) = dry soil weight (Mg)/ soil volume (m^{-3}) Equation 2.

2~~4.3~~.3.2~~5~~ Penetration resistance (PR)

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Soil penetration resistance data were collected on each plot (in the wheel-ways and in the centre of the plot) down to 450 mm with a depth increment of 25 mm between each recorded penetrometer reading. A cone penetrometer (Data Field, Ukraine) was used, recording soil strength in kPa, the location and depth via built-in GPS device. Only the PR samples were recorded at 450 mm to complete a reading on the data logger. It is also widely known that roots penetrate past "tillage pans" (Bengough et al., 2011) Bengough et al., 2011) . Five penetrations were made both under and between the wheel ways on each plot at GS 25 sampling to represent each treatment. PR was measured when soil conditions were at field capacity to ensure accuracy of each reading.

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2~~4.3~~.3.3 ~~6 ~~Soil porosity analysis

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Before soil porosity analysis on ImageJ software (version 1.52) (Schneider et al., 2012) could commence, an image stack was created in VG Studio Max® for each scan. The contrast was adjusted to improve the uniformity and visibility of the soil pores. The register object tool corrected scan discrepancies for soil core angle. Straightening the scan allowed a cylindrical shape to be cropped and the tube edges and air space outside of the soil core removed. This enabled soil data to be captured throughout the soil core. A new volume was selected and extracted from the original. This created a separate cropped image volume to work from. The surface determination tool in VG Studio Max® was used to threshold pore spaces within the solid matrix. The tool defines the contour of objects, separating 3D data into regions, providing meaningful soil data (Borges de Oliveira et al., 2016). The image was then inverted to remove the extracted variables from the image and highlighting the pore spaces in the soil core. The processed image was exported as an *.TIFF image stack for further analysis using ImageJ software.

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Soil pore characteristics were measured using X-ray CT to establish information about the 3D soil environment for root growth without disrupting the structural integrity of the soil core. The original grey-scale X-ray CT images were analysed using ImageJ software. The scale was set for each dataset to define to spatial scale of the active image. The unit of length was set in millimeters and the known distance was 0.045mm (45µm). Each scanned core was cropped to remove the area outside of the soil column. The action of soil coring during sampling had the effect of loosening the bottom 20 mm of the core, therefore 415 slices at the bottom of each scan were discarded to remove the loosening effect due to the sampling process. The downward movement of the PVC pipe also caused a smearing effect on the soil at the outside edge of the core and this area was also removed by cropping.

The processed image was 1220 x 1220 pixels in size. Applying the contrast enhancement filter helped normalize all slices. The filter reduces the differences in pixel grey-level between slices known as beam hardening (Wildenschild et al., 2002). The ImageJ Huang automatic threshold algorithms were used for each scan to create binarized images and separate the air-filled pores from the background region. The binarized scans were de-speckled twice to remove unwanted noise within each scanned image, improving analysis and accuracy of the investigated pores. The Look Up Table (LUT) was inverted to change the white pores to black, ensuring analysis calculated the air-filled pores and not the soil matrix. The resulting binary images were analysed using the Analyze Particles tool which provided information for average pore size, total area and percentage porosity for each individual image.

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2.4.1~~4.3.6~~ Soil core sampling

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Field soil core size was chosen to capture as much root material growing in the field as possible while minimizing the trade-off that exists with the X-ray CT technology between image resolution and core size (Mooney et al., 2012; Zhou et al., 2021). The core dimensions were consistently 70 x 300 mm (diameter x depth) for each sample. Soil cores were extracted from the field sites at GS 25 in February and again at GS 61 in June. Sampling was carried out at GS 61 during wheat anthesis, when root growth is at its peak (Gregory et al., 1978). Due to high moisture deficits in HAU (43 mm) during sampling at GS 61 in early July, the soil sample area was wetted with 2.5 L of water and allowed to infiltrate. This lubricated the soil, reduced soil fracturing, and allowed tube insertion and soil core extraction to take place as smoothly as possible. Polyvinyl chloride (PVC) drainage pipes were cut to size (70 x 300 mm) and these tubes were used to collect soil cores (as per Millington et al, 2017).

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A single wheat plant sample was located at random in each plot. The selected plant was cut at the base of the stem with a scissors and the above ground biomass discarded The PVC tube was placed (plant centred) directly over the remaining plant stubble to maximise root system capture. Tubes were inserted into the soil using a mallet in the crop rows in the centre of the plots between the wheel tracks (not trafficked by wheel) for untrafficked samples for no traffic samples. A second core was taken in the wheel way for the tyre pressure treatments. A small block of timber was used when hammering in the tube to protect tubes and soil cores from damage. A total of 72 samples were extracted on each sampling occasion and examined in this study. The PVC tubes were inserted into the soil to a depth of 300 mm. The soil core was extracted carefully using a spade and the sample locations were backfilled with soil. Following sampling, cores were sealed (top and bottom) using tape, labelled, and carefully placed into boxes protected with bubble wrap. Cores were tightly packed and insulated to minimise movement and drying of samples during transit to the laboratory for analysis. Samples were transferred to refrigerated storage (<4°C) to prevent and reduce compositional changes to the soil through biological degradation.

2.5.1~~4.3.7~~ X-ray computed tomography (CT) – Root analysis

Soil cores were transferred to the University College Dublin (UCD) X-ray CT facility at the Rosemount Experimental Research Station at Belfield Campus, UCD, Ireland. The soil cores were scanned using a Phoenix® v|tome|x M 240 kV scanner (GE Measurement and Control solution, Wunstorf, Germany). The v|tome|x M was set at a voltage of 90 kV and current of 400 µA to optimize contrast between background soil and root material. A voxel resolution of 45 µm was achieved by using the 'Multi Scan option' to scan in 4 segments. A total of 1800 projection images per section were taken at 200 m/s per image using the 'Fast Scan option', which has the default values of an image averaging of 1 and 0 skip. No filters were used during scanning. The total scan time per core was 24 minutes or 6 minutes per section. Once scanning was complete, the images were reconstructed using Phoenix datos|x2 rec reconstruction software, the four scans were assembled into one 3D volume for the whole core. Core samples were scanned within a week of the sampling date, the scanned core was 300 mm in length and 70 mm diameter. The software corrected movements during the scanning process and removed noise from scanned images.

~~*4.3.8*~~ 2.5.2 X-ray CT root segmentation

Image analysis for X-ray CT images was performed using the software VGStudioMax®, version 3.2 (Volume Graphics GmbH, Heidelberg, Germany) to segment roots and soil porosity. Roots were segmented by setting seed points and using selected threshold values in the "*Region grower*" that enabled fast and accurate selection of grey-scale voxels (3D pixels) pertaining to root materials. The root system was extracted from the greyscale CT image of soil using the VGStudioMax® semi-automated local adaptive thresholding "*Region Growing*" selection tool, similar to (Tracy et al., 2013). Root volumes were calculated by segmenting the root region of interest (ROI). Once the roots were segmented from the image, erosion and dilation tool was selected at 1 pixel using the *Region Growing* tool. Root system architecture parameters such as root vertical depth, root volume and root surface area were measured from the segmented root systems. Root vertical depth was calculated on the Z axis in VGStudioMax® from the length of a complete root from the base seed point.

2.5.3~~4.3.9~~ Destructive 2D root analysis

After the soil cores were scanned, the soil and root material were separated by root washing gently with a water jet hose. Two sets of sieves with a mesh size of 2 mm and 1 mm collected root material. Roots were washed and soil material removed before the roots were placed into a sealed and labelled bag filled with water. The washed root samples were placed into a freezer until scanning and analysis with WinRHIZO™ scanning and software (version 2016a Regent Instruments, Canada) commenced. The root samples were thawed before scanning with the WinRHIZO™ software. Large root stumps were removed from the sample prior to placing it inside the tray to reduce root misrepresentation (Wang and Zhang, 2009). Roots were placed onto a clear transparent tray (30 cm x 20 cm) with water. A pair of plastic forceps were used to spread out root seminal and lateral roots. Images were scanned at a resolution of 600 dpi (42 µm pixel size) with an Epson Perfection V800 scanning system. Root images were measured for root length, root surface area, average root diameter and root volume for the total soil core. This output was used to verify the 3D root outputs from VGStudioMax® (Flavel et al., 2017; Tracy et al.,

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2012a). The WinRHIZO™ software enabled rapid assessment of root parameters. It calculated the root volume by determining the average root diameter and root length by pixel counting the 2D root image and then assuming the root shape was cylindrical. The WinRHIZO™ used a skeletonization method for characterizing root systems (Himmelbauer, Loiskandl and Kastanek, 2004). The software uses greyscale values in *.TIFF file format. The output of the images was distinguished by global thresholding analyses for root diameter while root length was validated by skeleton images. After WinRHIZO™ scanning, the roots were removed from the scanning tray using forceps. The root samples were dried at 70°C for 24 hours and the root biomass samples were weighed.

2.6~~4.3.10~~ Soil Moisture Deficit Model

Soil Moisture Deficit (SMD) was calculated based on the SMD hybrid model for Irish grassland (Schulte et al., 2005). The model is based on weather parameters and soil drainage classes. The inputs of the model include data on maximum and minimum temperatures, r~~R~~ainfall (mm), wind speed (m/s), sunshine hours~~, maximum and minimum temperature~~ which~~data~~ were taken from the nearest weather station located in Newport, Shropshire 6km from the site (Met office, 2019).

~~4.3.11~~2.7 Statistics

Data from the scanned (destructive and non-destructive) images and root biomass were not normally distributed. Non-normal data do not meet the assumptions underpinning ANOVA (Analysis of Variance); therefore, all data underwent log transformation (in Microsoft Excel) before being exported to Minitab 18® where analysis of variance (ANOVA) was performed to homogenize the variances of the compared means (Poorter and Garnier, 1996). A two-way ANOVA was performed using the general linear model using the minitab software package. All means were analysed for normality before the test was run. When significant effects of rooting were detected, regression analysis was utilised to observe the relationship between the variables. For linear regression analysis, residuals of data were made to ensure that the assumptions of the analysis were met (normal distribution, constant variance, etc). Normality was tested using the Anderson-Darling test in Minitab 18®.

3.~~4.~~4 Results

~~4.4.1~~3.1 Growing conditions during crop season

In 2018, crops were established at low soil moisture levels, which may have reduced soil compaction caused by tillage operations across all site locations. From January to August (2019), 418.6 mm of rainfall was recorded at HAU, 68 mm in total for January and February. Soil moisture deficits reached 66.2 mm in HAU (Supplementary Figure 4.10) by early June 2019. High soil moisture deficits were recorded from early April to June, causing drought stress during rapid growth periods (Met office, 2019).

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~~4.4.~~3.2.1~~2~~ Soil properties – Bulk density & Penetrometer resistance

The calculated probability (*P*-value) ~~and standard error of the mean (SEM) from one-way ANOVA analysis is given in Figure 4.1, while~~using two way linear model analysis (ANOVA) results are shown in Table 2~~4.~~4. ~~in the supplementary section of this paper. Bulk density presented for 0-100 mm, 100-200 mm, and 200-300 mm measurements in Figure 4.1.~~ In the top 0-100 mm, bulk density was significantly higher in DTCP (1.66 Mg m^{-3}) and STCP (1.44 Mg m^{-3}) treatments compared to ZTNT (0.994 Mg m^{-3}) and DTNT (0.97 Mg m^{-3}) (P<0.01). STNT (1.09 Mg m^{-3}) was significantly higher than ZTNT and DTNT and only significantly lower than DTCP. In the middle horizon (100-200 mm), a significant interaction between trafficking treatment was found. Bulk density was significantly lower in DTNT (1.07 Mg m^{-3}) compared to DTCP (1.63 Mg m^{-3}) and ZTCP (1.58 Mg m^{-3}) treatments (P<0.05). In the bottom 200-300 mm layer measured, no significant tillage x traffic interaction was found (P>0.05). Table 2~~4.~~4 shows a significant traffic effect on soil bulk density in the 0-100mm layer and 100-200mm layer (P < 0.01). No traffic in both layers revealed a lower bulk density compared to trafficked treatments.

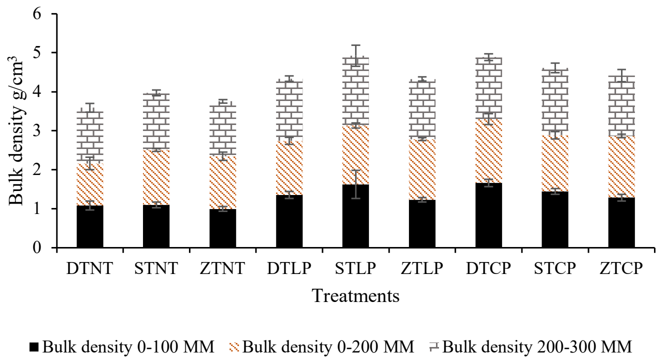

Table 2~~4.~~4: Variance of analysis for bulk density x traffic, tillage and tillage x traffic.

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HAU	Deep	Shallow	Zero	Mean
Traffic/ Tillage 0 – 100 mm				
No traffic	0.971	1.099	0.994	1.058_{b}
LP	1.351	1.625	1.230	1.401_{a}
CP	1.661	1.444	1.282	1.462_{a}
P < 0.01				
Traffic/Tillage 100 – 200 mm				
No traffic	1.079	1.406	1.353	1.279_{b}
LP	1.389	1.509	1.552	1.483_{a}
CP	1.637	1.437	1.583	1.553_{a}
P < 0.01				
Traffic/Tillage 200 – 300 mm				
No traffic	1.429	1.466	1.404	1.433
LP	1.593	1.787	1.619	1.666
CP	1.537	1.548	1.548	1.544

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Penetration resistance (PR) was recorded in February 2019 when the soil was at field capacity. Measurements were grouped into three groups, 0-150 mm, 150-300 mm, and 300-450 mm depth layers and a linear variance of analysis between tillage, traffic and tillage x traffic interaction conducted and shown in Table 3. Figure ~~4.~~2 depicts the combined three layers grouped into one 0-450 mm graph. The one~~-~~-way ANOVA analysis revealed highly significant differences for each layer. In the 0-150 mm layer, DTNT recorded the lowest kPa (kilopascals) readings and was significantly lower than ZTCP, STCP, STLP, ZTLP and ZTNT (P< 0.000). DTCP and DTLP were significantly lower kPa than ZTLP, STLP, STCP and ZTCP. ZTCP recorded the highest kPa reading and was significantly higher than ZTLP, ZTNT, STNT, DTLP, DTCP and DTNT. In the second layer (150-300 mm), similar trends were found and highly significant (P<0.000). STCP showed the highest kPa (3193.5 kPa) and was significantly higher than STNT, ZTNT, DTNT, DTLP and DTCP. In contrast, DTNT recorded the lowest reading (1268.4 kPa) and was significantly lower than ZTNT, STNT, ZTLP, ZTCP, STCP and STLP. STNT revealed significantly lower kPa than STLP, ZTCP and STCP. ZTNT penetrometer readings were significantly lower than all trafficked ZT and ST treatments. In the lower depth (300-450 mm), DTNT was significantly lower than STLP, STCP, ZTCP, ZTLP and STNT (P<0.000). ~~An analysis of variance table is presented in **section 4.7** of this thesis for penetrometer resistance (Table 4.5).~~ The results revealed a significant traffic interaction for 0 – 150mm (P < 0.001), 150 – 300mm (P < 0.000) and 300 – 450 mm (P < 0.000). Again, no traffic PR was significantly lower than trafficked treatments. When tillage was measured, a significant effect was observed for each layer studied (0 – 150mm = P < 0.000, 150 – 300mm = P < 0.000, 300 – 450mm = P < 0.000). In the top layer, deep tillage was significantly lower than shallow and zero. Further, shallow tillage was significantly lower than zero tillage PR. In the second and third layer, deep tillage was lower than shallow and zero. A tillage v traffic interaction was observed in the first layer (0 – 150mm) (P < 0.001) but the second and third layer were not significant (P < 0.067, P < 0.313 respectively).

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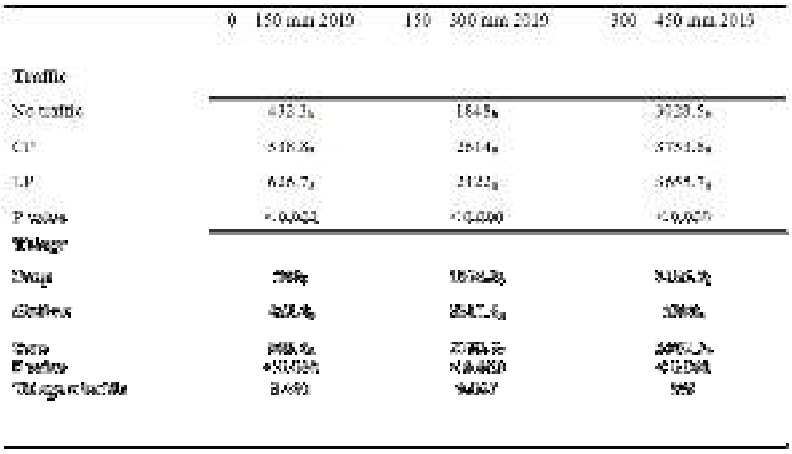
Table 3: Analysis of variance table for penetration resistance x tillage, traffic and tillage x traffic interactions between 0 – 150 mm, 150 – 300 mm and 300 – 450 mm



	0 – 150 mm 2019	150 – 300 mm 2019	300 – 450 mm 2019
Traffic			
No traffic	432.3_b	1845_b	3928.5_b
CT	548.8_a	2614_a	3754.8_a
LP	626.7_a	2122_a	3655.7_a
P value	<0.002	<0.000	<0.007
Tillage			
Deep	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
Zero	[illegible]	[illegible]	[illegible]
P value	[illegible]	[illegible]	[illegible]
Tillage x traffic	[illegible]	[illegible]	[illegible]

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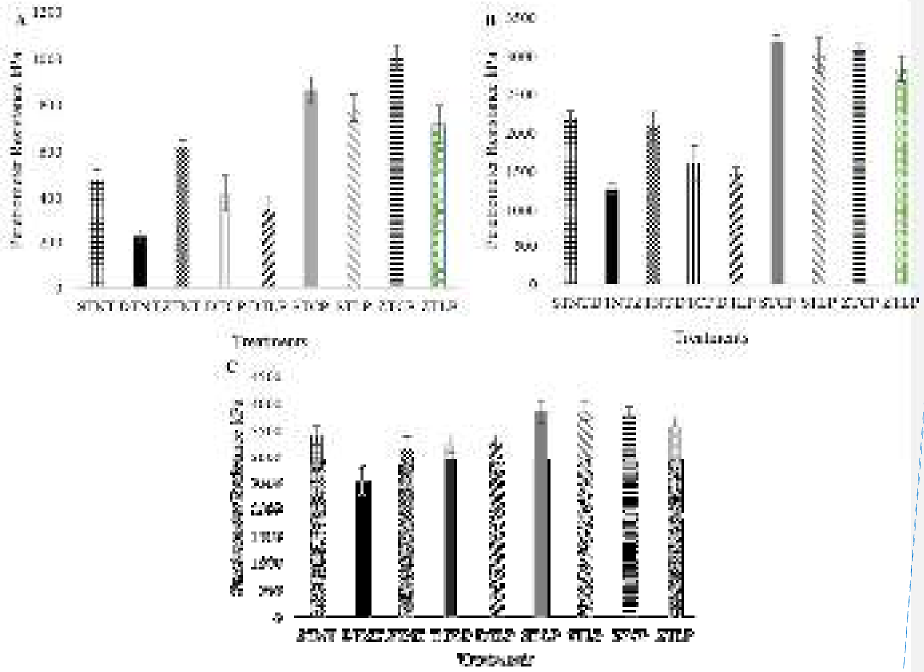

Figure 4.1~~2~~: Penetration resistance for three layers (a) 0-150 mm (P<0.000), (b)150-300 mm (P<0.000) and (c) 300-450 mm (P<0.000) during wheat tillering (GS25). Soil moisture conditions were at field capacity during sampling. Bars represent the standard error of the mean.

3.2.2~~4.4.3~~ Soil porosity

The results of the ANOVA analysis of the CT-measured porosity (0-220 mm) are presented in Table 4~~2~~. Soil porosity results were split into two soil layers of 0-100 mm and 100-200 mm respectively. In the top 0-100 mm layer, DTNT showed significantly higher total pore space (P<0.01) compared to all other treatments except ZTNT. Tillage had a significant effect on soil porosity in the no traffic samples in the 0-100 mm layer (P< 0.05). Deep tillage with no traffic had higher soil porosity (22.72%) than in shallow tillage (no traffic) (10.58%). There was no significant difference between soil porosity under zero tillage and shallow tillage in the no traffic samples. Trafficking had a significant effect on overall porosity. In deep tillage treatments, overall porosity 22.72% (no traffic) was reduced to 8.08% (under low tyre pressure) and 6.50% under conventional tyre pressure. Traffic had little effect on shallow and zero tillage porosity in the top 0-100 mm when compared to the no traffic samples with small reductions in porosity. In the second examined layer, 100-200 mm zone, tillage and traffic were not significantly different (P< 0.487). The percentage porosity shown in Table 4~~2~~, indicate a sharp decline in the lower depth with only 9.02% in DTNT. DTCP treatments recorded the lowest porosity (3.96%).

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Table 4~~.2~~: Soil porosity for tillage x traffic for two soil layers.

ImageJ soil porosity % 0-100mm	***n***	No traffic	low tyre pressure	Conventional tyre pressure
Deep	4	22.72 **a**	8.08 **b**	6.50 **b**
Shallow	4	10.58 **b**	8.64 **b**	7.23 **b**
Zero	4	10.77 **ab**	8.41 **b**	8.49 **b**
P<0.01				
ImageJ Soil porosity % 100-200mm	***n***			
Deep	4	9.02	6.16	3.96
Shallow	4	4.06	6.44	5.32
Zero	4	2.895	6.44	5.32
P<0.487				

*Significant differences between means are represented by different letters.

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3.3.1~~4.4.4~~ Destructive 2D root analysis

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The interaction between tillage system and trafficking protocols using destructive root measuring methods (WinRHIZO™) are shown in Figure S2~~4.3~~ for GS 25 and Figure S3~~4.4~~ for GS 61 in the supplementary section. The variance of analysis results ~~are~~ for WinRHIZO™ are presented~~shown~~ in Table ~~4.6~~ 5~~of the supplementary section~~. At GS25, no significant differences were found between tillage, ~~traffic~~traffic, and traffic x tillage interactions. However, the WinRHIZO™ analysis revealed a tendency towards increased root growth in no traffic treatments. At the later growth stage (GS61), ~~Figure 4.4~~Table 5 depicts the results showing highly significant interactions between trafficking and tillage systems on root length density (RLD) (P<0.001) and root length (P< 0.001), root surface area (P<0.002) and a traffic effect on root volume (P< 0.05). Variance of analysis results showed a significant effect of tillage system (P < 0.01) for deep tillage compared to shallow and zero tillage. When trafficking was considered, an even greater significance under was recorded (P < 0.000) for root length with no traffic significantly greater than conventional (CP) and low pressure (LP) treatments. For root surface area (mm^2), a significant tillage (P < 0.05) and traffic (P < 0.000) was found. Deep tillage showed significance over shallow tillage but not zero. Root surface area was significantly lower in CP than no traffic but not LP. Root volume (mm^3) showed a significant traffic ~~effect~~effect, but tillage was not significant. Indeed, no traffic was significantly greater than CP but not LP. For RLD mm^3, a significant tillage (P < 0.01) and trafficking effect (P < 0.000) was found. Deep tillage established greater RLD compared to zero and shallow tillage while no traffic was significantly greater than CP and LP.

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When traffic x tillage interactions were compared, no significant difference was found (Table 5~~4.6~~). However, individually, treatments were significantly greater than others. For example, DTNT showed significantly higher RLD, root surface area and root length compared to ZTCP, STCP and STLP. Root volume was significantly higher in DTNT over ZTCP and STCP. DTNT produced nearly double the root length compared to ZRCP. In contrast to DTCP, root surface area reduced by 36% compared to untrafficked areas (no traffic samples). In shallow and zero tillage, root surface area was reduced by 32% and 63.6% respectively in conventional pressure samples compared to untrafficked samples. There was no significant difference for root diameter and between all tillage and trafficking regimes. The results demonstrate that there was no significant difference in RLD at the tillering stage, nor could trends be found as roots were undeveloped. However, at anthesis, the RLD was significantly higher under non-trafficked tillage treatments when compared to DTCP, STCP and ZTCP (Figure S4~~.~~3b).

Table 5: WinRhizo results of Tillage, traffic and Tillage x Traffic interactions with root traits at HAU during tillering (GS25) and anthesis (GS61). P values represent level of significance and 'NS' indicates non-significance. d.f. = degrees of freedom.

Root trait	Term	d.f.	GS25	GS61
Root length mm				
	Tillage	2	NS	< 0.01
	Traffic	2	NS	< 0.000
	Tillage x Traffic	35	NS	NS
Surface area mm^2				
	Tillage	2	NS	< 0.05
	Traffic	2	NS	< 0.000
	Tillage x Traffic	35	NS	NS
Root diameter mm				
	Tillage	2	NS	NS
	Traffic	2	NS	NS
	Tillage x Traffic	35	NS	NS
Root volume mm^3				
	Tillage	2	NS	NS
	Traffic	2	NS	< 0.05
	Tillage x Traffic	35	NS	NS
RLD mm^3				
	Tillage	2	NS	< 0.01
	Traffic	2	NS	< 0.000
	Tillage x Traffic	35	NS	NS

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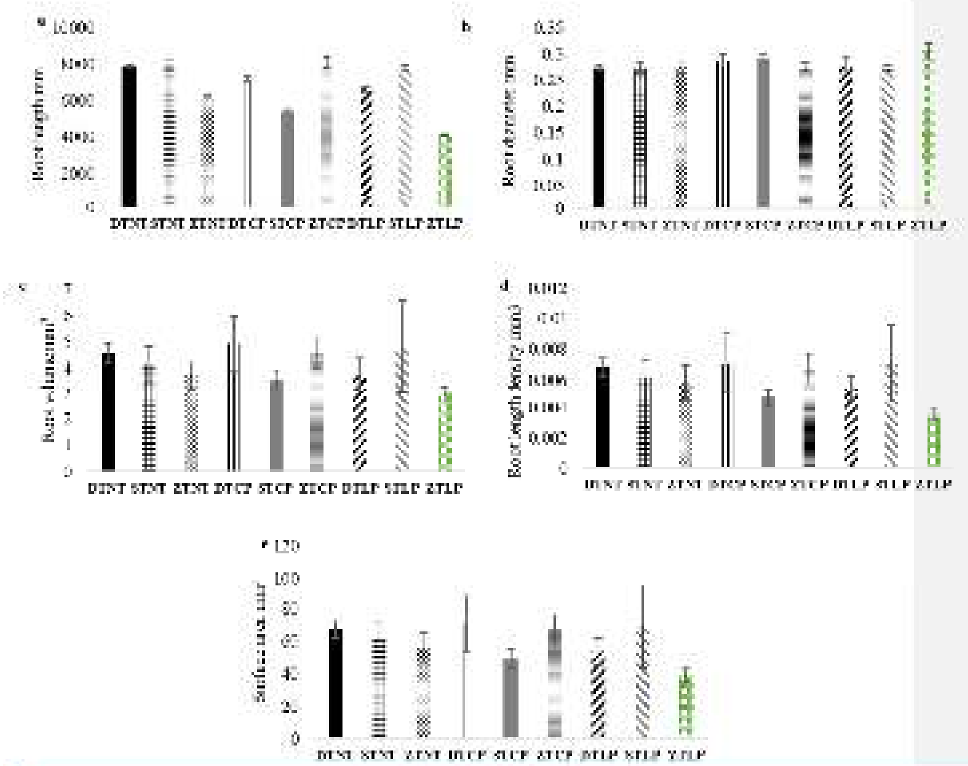

Figure 4.3~~: Tillering (GS25) root system architecture using destructive root method. (a) Root length (mm), (b) Root diameter (mm) (c) Root volume (mm3), (d) Root length density (mm3), (e) Root surface area (mm2).~~

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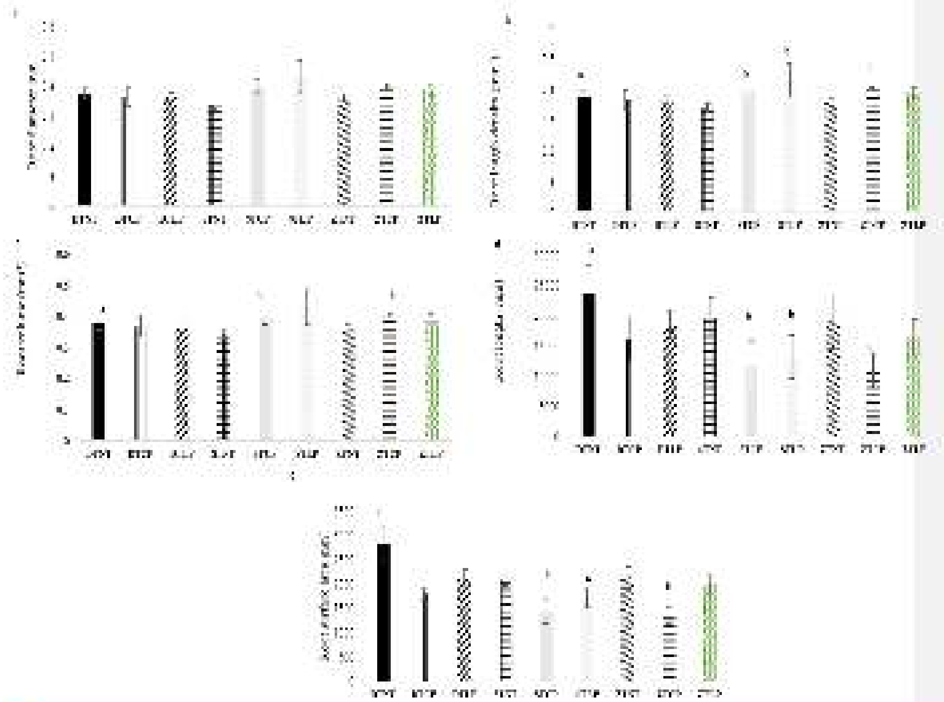

Figure 4.4~~: Flowering growth stage 61 root system architecture using destructive root method. (a) Root diameter, (b) Root length density (mm3), (c) Root volume (mm3), (d) root length (mm), (e) Root surface area (mm2).~~~~**Table 4.6:** WinRhizo results of Tillage, traffic and Tillage x Traffic interactions with root traits at HAU during tillering (GS25) and anthesis (GS61). P values represent level of significance and 'NS' indicates non-significance. d.f. = degrees of freedom.~~

3.3.2~~4.4.5~~ X-ray CT root analysis results

Significant differences were found between trafficking treatments at GS61 for RLD and vertical root depth using non-destructive VGStudioMax 3.2 (Table 4~~.3~~). The X-ray CT scans revealed significantly longer vertical rooting (measured via the Z axis in VGStudioMax®) in ZTNT (112.7 mm) compared to DTCP (60.44 mm), DTLP (66.96 mm), STLP (65.39 mm) treatments (P<0.001). ZTNT showed significantly greater RLD (0.000098 mm/m^3) over DTCP (0.000052 mm/m^3), DTLP (0.000058 mm/m^3), STLP (0.000058 mm/m^3) and ZTCP (0.000060 mm/m^3) treatments (P<0.001). Root volume and surface area showed no significant difference using X-ray CT. However, similar trends were found to the conventional WinRHIZO™ method. Trafficking had more of an influence on rooting than tillage method which did not have any significant effect on root parameters. As RLD is an important root trait commonly measured to estimate water uptake (White et al., 2015), linear regression was used to verify the relationship between root depth and RLD. A significant relationship (P < 0.001) was found with a coefficient of determination $R^2 = 0.54$ (Supplementary Fig. S4~~2~~).

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Table 6~~4.3~~: Root system architecture using non-destructive method.

	Root system Architecture flowering growth stage			
Tillage x traffic	Root volume mm3	Root surface area mm2	Length (Z) axis (mm3)	Root length density (mm/m3)
DTNT	3900.00	23448	96.1 **ab**	0.000083 **ab**
STNT	2648.00	17350	88.4 **abc**	0.000077 **ab**
ZTNT	3048.00	17907	112.7 **a**	0.000098 **a**
DTCP	2276.00	12114	60.44 **c**	0.000052 **b**
DTLP	3525.00	20269	66.96 **bc**	0.000058 **b**
STCP	2900.00	18052	67 **abc**	0.000058 **ab**
STLP	2358.00	14211	65.39 **bc**	0.000057 **b**
ZTCP	2533.00	15040	69.43 **abc**	0.000060 **b**
ZTLP	4480.00	25104	97.89 **ab**	0.000085 **ab**
P value	NS	NS	0.001	0.001

*Significant differences between means are represented by different letters.

Figure 3~~4.5~~ shows root biomass results for GS25 and GS61. No significant differences between treatments at GS25 (P<0.848) were found. However, root biomass was significantly different for tillage x traffic with high confidence level (P<0.001) at GS61. DTNT (0.829 g) showed significantly (P<0.001) greater root biomass, than STCP (0.437 g) and ZTCP (0.4530 g) treatments. DTNT did not significantly differ from ZTLP (0.7992 g), ZTNT (0.7939 g), DTLP (0.6837 g), STNT (0.4991 g) and STLP (0.4923 g). The results show that, DTNT, ZTLP and ZTNT resulted in nearly 50% greater root biomass over STCP and ZTCP treatments. Tillage treatments (center line where there was no traffic effect) did not differ significantly with respect to root biomass.

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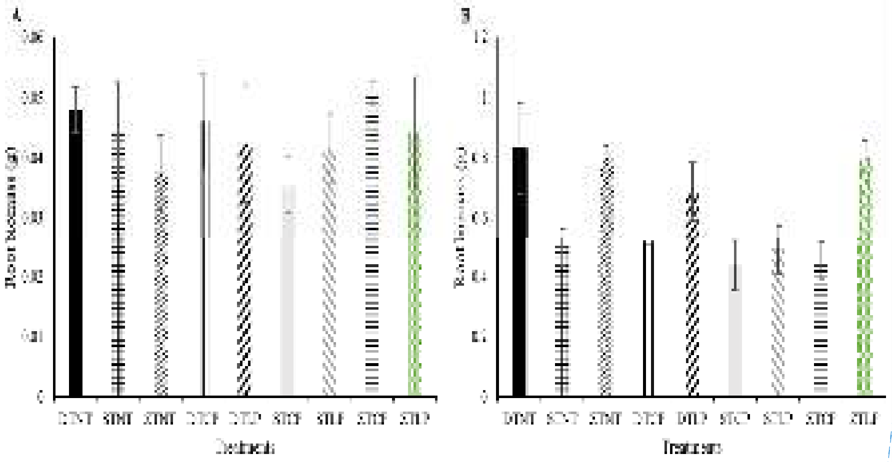

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Figure 3~~4.5~~: Root biomass at tillering (GS25) and flowering (GS61) for traffic and tillage treatments. Treatments represented by initials (Tillage: D = Deep, S = Shallow, Z = Zero), (Traffic: NT = No traffic, LP = Low pressure tyre, CP = Conventional pressure tyre).

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3.4 ~~4.4.6~~ Crop yield

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Crop yield was highly significant between trafficking treatments and tillage (P<0.01) shown in Figure. 4~~6~~. ZTLP had the highest yield (11,385 kg ha-1) and was significantly greater than DTLP (10,757 kg ha-1), STCP (10,700 kg ha-1), STNT (10,678 kg ha-1), STLP (10,638 kg ha-1) and DTCP (10,613 kg ha-1). All three zero tillage treatments trended higher than deep tillage and shallow tillage treatments. ZTLP showed a 500 kg ha-1 yield advantage over DTNT (NS) and between 628 - 772 kg ha-1 over trafficked treatments and STNT with high significance. In general, this study did not show a trend in yield between conventional and low tyre pressure treatments. For deep tillage, conventional tyre pressure reduced crop yield compared to low tyre pressure by 144 kg ha-1) (1.34%). When compared to the no traffic sample, conventional tyre pressure consistently reduced yield by 272 kg ha-1) (2.5%) in deep tillage. Although not significant, trafficking trended towards improving yield by 30 kg ha-1) (0.03%) using conventional tyre pressure and 340 kg ha-1) (3.07%) using low tyre pressure. No trends were found in shallow tillage treatments. Linear regression of root depth using X-ray CT showed a significant relationship to crop yield (P < 0.001) and positive correlation (r = 0.54). However, the coefficient of determination was low R2 = 0.3094 (Figure S5~~4.12~~). Moreover, regression analysis also showed a significant relationship between root biomass and crop yield (P < 0.01). However, the correlation between the two variables was weaker (r = 0.43) (coefficient of variance R2 = 0.1859. This indicates that root depth is a stronger predictor of crop yield.

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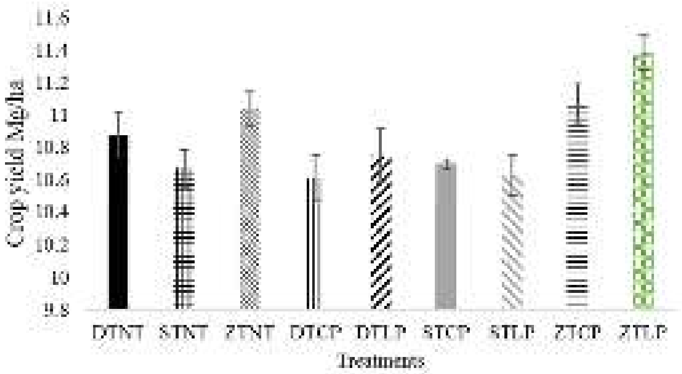

Figure 4~~.6~~: Crop yield in Mg/ha for traffic x tillage treatments.

4.~~5.~~ Discussion

4.1~~5~~.1 Soil physical responses to tillage ~~& trafficking~~

~~In line with this papers hypothesis, trafficking effects were more influential on crop and root performance than tillage system. The presence of wheeled areas in both zero and deep cultivation treatments increased soil bulk density significantly in deep tillage treatments (Figure 4.1).~~ Previous studies have shown that zero tillage systems increase in bulk density, penetration resistance and reduce in porosity in the early years of adoption from conventional tillage systems (Christian and Ball, 1994; Six et al., 2004; Mangalassery et al., 2014b; Smith, 2016). ~~Vogeler et al., (2009) showed that bulk density is higher under conservation tillage methods in the top 100 mm layer during the first five years of adoption from conventional systems.~~ Indeed, Soane et al., (2012) reported that significant regeneration of soil structure requires a three-year period from tillage depending on previous historic land management practice. Moreover, values decrease in the long term with multiple benefits including improved saturated conductivity, soil organic matter and air permeability in lower soil horizons. Arvidsson, 1998 showed that soils with <30 g kg^{-1} of organic matter were likely to suffer 11% higher crop yield loss due to compaction using uniaxial compression tests. It is plausible that the actions of soil fauna such as earthworms and old root channels could have reduced bulk density over time (Figure 5~~4.7~~) as identified by (Angers and Caron, 1998). Roots promote soil structural formation through increasing soil aggregation. Root mucilage production, root hair formation, and localised wetting and drying cycles encourage a reduction in soil bulk density (Bengough, 2012).

4.1.2 Soil porosity in response to tillage

Sandy soils due to their adhesive and coarse grain nature, have reduced porosity, including lower levels of micropores compared to loamy soils (Arvidsson, 1998). The aggregation potential in this sandy loam soil is low. In the presence of plants, porosity and pore connectivity as shown to reduce further compared to clay cohesive

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soils which tend to increase in porosity through flocculation and aggregation (Bacq-Labreuil et al., 2018). Here, we found soil porosity to be low in general across all treatments. When comparing cultivation systems, we found that shallow tillage in the 0-100 mm layer had significantly lower porosity (10.58%) compared to deep tillage (22.72%). Although zero tillage recorded low porosity values also (10.72%), it was not significantly different to the other two systems.

A key characteristic of zero tilled soils is a change in soil pore architecture with vertically orientated fissures connected down through the soil profile created by biopores (Figure 5~~4.7~~). Similar findings have resulted in reduced CO_2 fluxes and increased saturated hydraulic conductivity by surface-connected porosity (Cooper et al., 2021). The same study found similar soil porosity levels between conventional and zero tillage with zero tillage total porosity ranging from <5%, 10% and 12% on average over 1-5, 6-10 and 11-15 years respectively. The significant increase in deep tillage soil porosity substantially increases soil respiration, resulting in up to 13.8 times higher CO_2 emissions through increased oxidation and carbon breakdown (Reicosky et al., 1999). The lower porosities in zero and shallow tilled soils reduces space for gas exchange, reducing soil respiration and supporting carbon sequestration, thus increasing recalcitrant levels of carbon in soil. Mangalassery et al., (2014) found similar porosity results using X-ray CT methods to measure the effect of tillage method on greenhouse gas emissions, finding significantly higher porosity in tilled soil (13.6%) compared to zero tilled soil (9.6%) in the top 0-100 mm layer. However, in deeper soil horizons, no difference could be found between tillage system. The findings in this experiment agree with that study, showing both tillage methods did not differ significantly in the 100-200 mm layer with lower soil porosities recorded.

4.1.3 Root system architecture responses to tillage

The ‘hidden half’ (i.e. roots) of plants are difficult to interpret in field studies (Lynch and Brown, 2001). A large root system is characterized by large biomass, root length and root length density (Ehdaie et al., 2010; Hamblin and Tennant, 1987). Root biomass was an important indicator of root size, showing treatment effect at anthesis compared to the tillering stage. In general, root biomass had a positive relationship with grain yield. Zero tillage treatments both untrafficked and trafficked at low pressure had greater root biomass over all shallow tillage treatments and deep till trafficked at conventional pressure. Although deep tillage treatments had the highest root biomass by GS61, it did not achieve the highest yield. No significant difference in root biomass was found between tillage treatments, confirming that roots are more sensitive to trafficking than tillage method. RLD in shallow tillage treatments and zero tilled treatments trafficked at conventional pressure. RLD is an important parameter for characterizing root growth (Doussan et al., 2006) and has been used in previous studies as a key root parameter for modelling water uptake (Tinker and Nye, 2000; Javaux et al., 2013). Munos-Romero et al., (2010) and Chakraborty et al., (2008) results indicate that RLD is a positive predictor of crop yield. Although RLD had a positive correlation with crop yield in this study, root depth (using X-ray) displayed a much stronger relationship with crop yield (Figure S5).

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4.2.1 Soil physical responses to traffic

In line with this papers hypothesis, trafficking effects were more influential on crop and root performance than tillage system. The presence of wheeled areas in both zero and deep cultivation treatments increased soil bulk density significantly in deep tillage treatments (Table 2~~Figure 4.1~~). Our data shows similar findings with zero and deep tillage significantly reduced bulk density values in untrafficked zones. However, in trafficked treatments, high tyre pressure combined with deep tillage treatments resulted in higher bulk density values due to the loss of inherent strength by tilled soil, resulting in compression of soil particles (Raper, 2005; Soane, Godwin and Spoor, 1986). Chan et al., (2006) observed that trafficking after deep tillage increased bulk density values from 1.27 Mg m^{-3} to 1.54 Mg m^{-3}, emphasizing the effect of trafficking on the reduced bearing capacity of the deep tilled soil. The optimum soil density has been reported to differ between soil types in previous studies. Indeed, Czyż, (2004) established a soil type interaction between crop yield, bulk density and root mass concluding with sandy loam soils (similar to this study) having an optimum bulk density value of 1.54-1.66 Mg m^{-3}. Yet, in this study, root biomass was significantly reduced with treatments displaying similar soil density values to that reported optimum. Although conventional pressure tyres significantly affected zero tillage in the 100 – 200 mm layer, trafficking affected the 0 – 200 mm later under deep tillage. In shallow tillage treatments, the top 0- 100 mm layer was considerably impacted by high tyre pressure.

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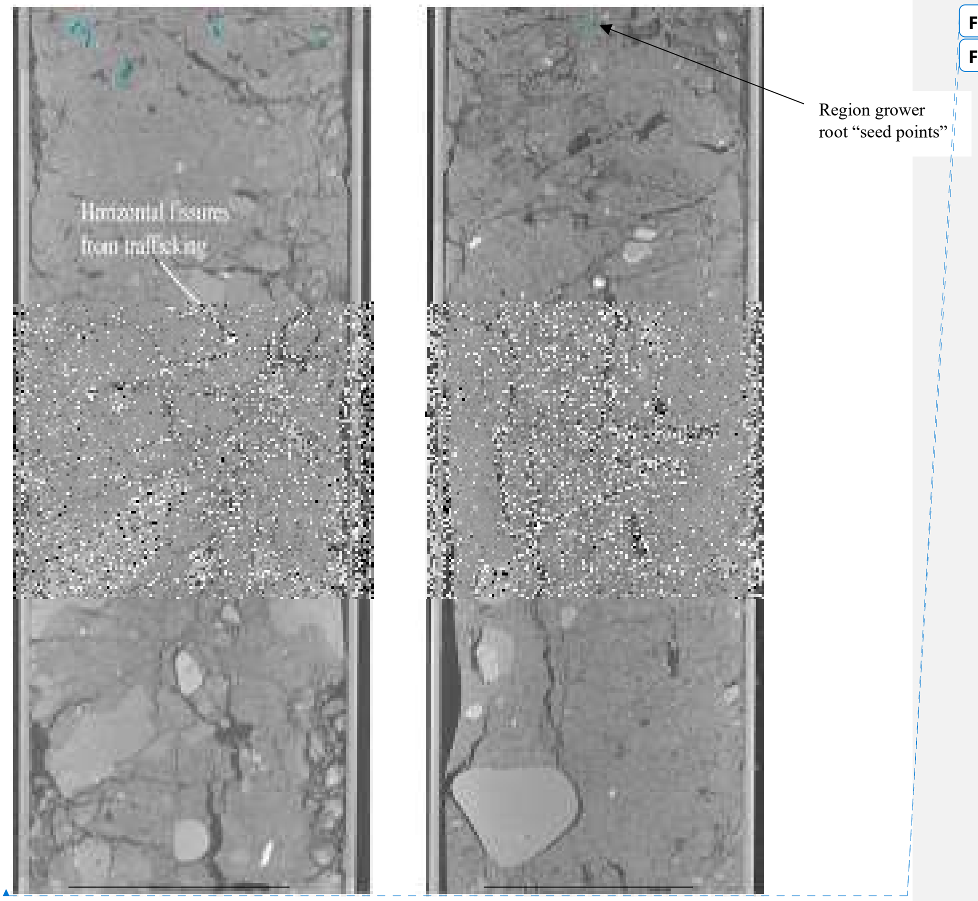

(a) **(b)**

Figure 5~~4.7~~: Vertical view of X-ray CT images through centre of soil core using VGStudioMax® software for (a) Shallow tillage conventional pressure (b) Zero tillage low tyre pressure. Scale bar = 50 mm.

4.2~~5~~.2 Soil porosity in response to ~~trafficking & ~~t~~illage~~raffic

~~Sandy soils due to their adhesive and coarse grain nature, have reduced porosity, including lower levels of micropores compared to loamy soils (Arvidsson, 1998). The aggregation potential in this sandy loam soil is low. In the presence of plants, porosity and pore connectivity as shown to reduce further compared to clay cohesive soils which tend to increase in porosity through flocculation and aggregation (Bacq-Labreuil et al., 2018). Here, we found soil porosity to be low in general across all treatments. When comparing cultivation systems, we found that shallow tillage in the 0-100 mm layer had significantly lower porosity (10.58%) compared to deep tillage (22.72%). Although zero tillage recorded low porosity values also (10.72%), it was not significantly different to~~

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~~the other two systems.~~ Compared to non-trafficked treatments, trafficked soil in general caused a sharp decline in soil porosity in the top 0-100 mm layer. Tyre inflation pressure is one of the key contributors to soil stress in the 100 to 1000 mm layer (Botta et al., 2008). The effect of re-compaction from trafficking after cultivation was often worse in deep tillage treatments, with a lower percentage porosity than in zero and shallow tillage (Table 4~~2~~ for DTLP and DTCP treatments). In deeply cultivated soils, water infiltration rates can be reduced by up to 82% after a single wheeling's (Chyba, 2012), which has agronomic implications such as reduced water and nutrient use efficiency by up to 22% thus, potentially resulting in crop yield penalties of up to 38% (Ishaq et al., 2001). Yield effects by trafficking were modest in our study due to low soil moisture conditions during sowing in autumn 2018 (Met office, 2019). Dry soil has increased soil strength, reducing the effects of soil compaction as the soil load support capacity would have increased thus, increasing permissible ground pressure (Hamza and Anderson, 2005).

~~A key characteristic of zero tilled soils is a change in soil pore architecture with vertically orientated fissures connected down through the soil profile created by biopores (Figure 4.7). Similar findings have resulted in reduced CO_2 fluxes and increased saturated hydraulic conductivity by surface-connected porosity (Cooper et al., 2021). The same study found similar soil porosity levels between conventional and zero tillage with zero tillage total porosity ranging from <5%, 10% and 12% on average over 1-5, 6-10 and 11-15 years respectively. The significant increase in deep tillage soil porosity substantially increases soil respiration, resulting in up to 13.8 times higher CO_2 emissions through increased oxidation and carbon breakdown (Reicosky et al., 1999). The lower porosities in zero and shallow tilled soils reduces space for gas exchange, reducing soil respiration and supporting carbon sequestration, thus increasing recalcitrant levels of carbon in soil. Mangalassery et al., (2014) found similar porosity results using X-ray CT methods to measure the effect of tillage method on greenhouse gas emissions, finding significantly higher porosity in tilled soil (13.6%) compared to zero tilled soil (9.6%) in the top 0-100 mm layer. However, in deeper soil horizons, no difference could be found between tillage system. The findings in this experiment agree with that study, showing both tillage methods did not differ significantly in the 100-200 mm layer with lower soil porosities recorded.~~

4.2~~5~~.3 Penetrometer responses to ~~tillage~~ traffic~~and traffic~~

Penetrometer resistance (PR) is a useful parameter for evaluation of soil physical resistance to root growth (Otto *et al.*, 2011). In general, trafficking had a considerable influence on soil PR in this study as depicted in F~~f~~igure 6~~.8~~. The greatest contrast in soil penetration resistance was between trafficked and un-trafficked soil with zero tillage showing the highest resistance under conventional tyre pressure. Recent studies have shown that roots can exploit pores and bypass layers of strong soil (Atkinson et al., 2020). Axial pressure from repeated trafficking in ZTCP resulted in the highest PR values. However, root depth was less affected in contrast to STCP and DTCP. This might explain why roots could exploit existing pore networks in undisturbed soils compared to tillage treatments. In the middle layer examined, shallow till conventional pressure treatments suffered from a tillage pan effect shown in Figure 6~~4.7~~. In fact, all trafficked zero and shallow tillage systems resulted in PR values beyond

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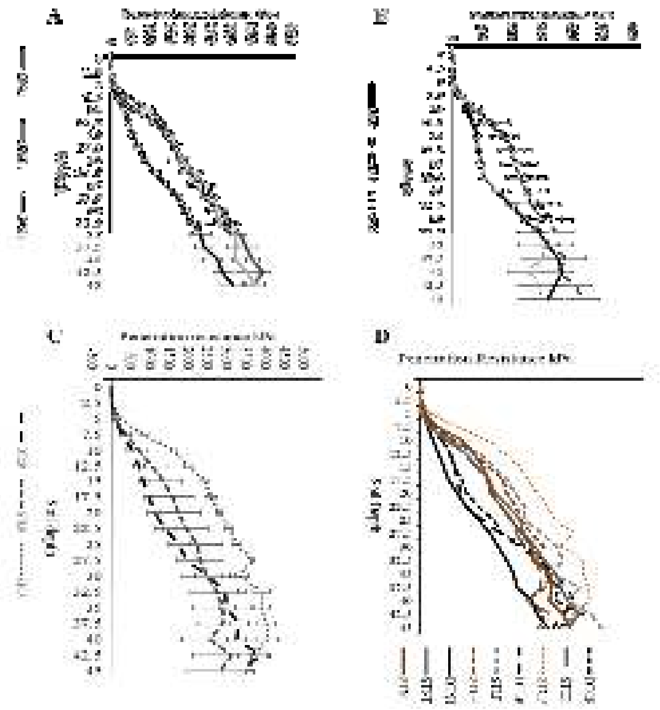
2,000 kPa, a threshold level which several studies show there is a reduction in root growth (da Silva et al., 1994; Lapen *et al.*, 2004; Tormena, da Silva and Libardi, 1999). A compact zone at shallow depths is detrimental to plant growth and crop yield in rainfed temperate climates when short term droughts occur (Campbell, Reicosky and Doty, 1974).



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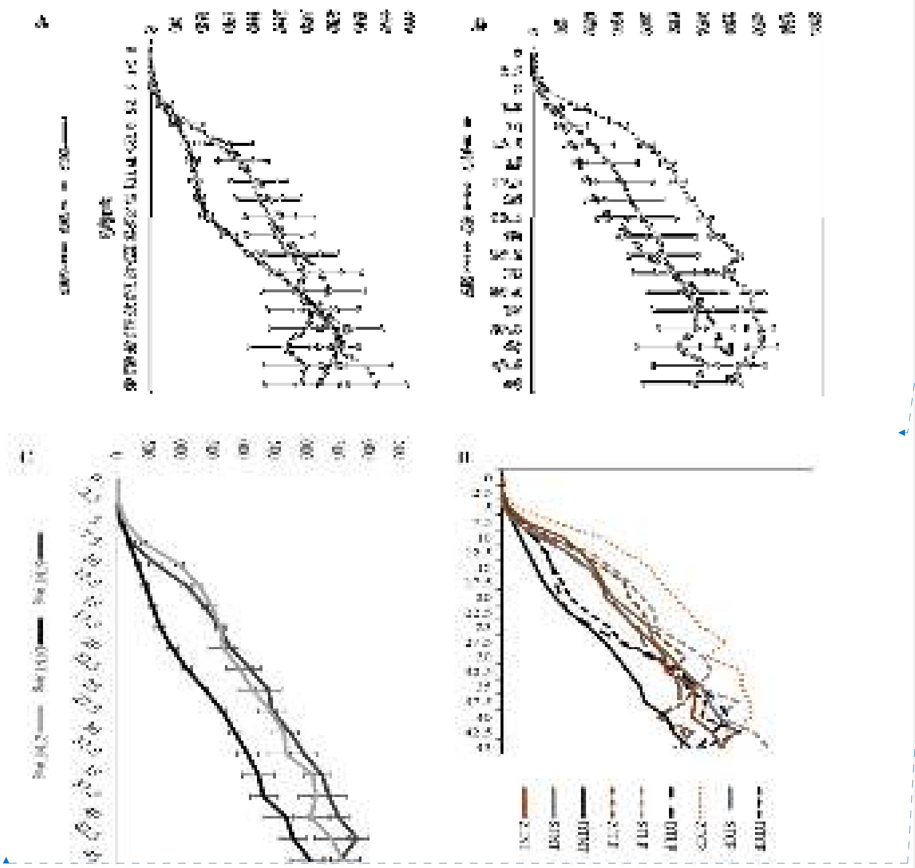

Figure 6~~4.8~~: Penetration resistance (kPa) for tillage and traffic treatments at soil depths of 0 - 450 mm. X axis depicts soil depth. Y axis depicts Soil penetration resistance (kPa). Treatments represented by initials (Tillage: D = Deep, S = Shallow, Z = Zero), (Traffic: NT = No traffic, LP = Low pressure tyre, CP = Conventional pressure tyre). **A** ~~low tyre pressure~~no traffic, **B** ~~conventional~~ low tyre pressure, **C** conventional tyre pressure~~no traffic~~ and **D** traffic x tillage treatments combined.

~~4.5.4 Root system architecture responses to tillage and traffic~~

~~The 'hidden half' (i.e. roots) of plants are difficult to interpret in field studies (Lynch and Brown, 2001). A large root system is characterized by large biomass, root length and root length density (Ehdaie et al., 2010; Hamblin and Tennant, 1987). Root biomass was an important indicator of root size, showing treatment effect at anthesis compared to the tillering stage. In general, root biomass had a positive relationship with grain yield. Zero tillage treatments both untrafficked and trafficked at low pressure had greater root biomass over all shallow tillage treatments and deep till trafficked at conventional pressure. Although deep tillage treatments with no traffic had the highest root biomass by GS61, it did not achieve the highest yield. No significant difference in root biomass was found between tillage treatments in untrafficked samples, confirming that roots are more sensitive to~~

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~~trafficking than tillage method. The compaction effects of trafficking on soil structure exacerbated the impact on rooting in general. Typically, studies report shallower rooting, increases in root diameter and decreased axial and lateral rooting (Grzesiak et al., 2014). Due to the high moisture deficits depicted in (Figure 4.10) experienced during April and May 2019, it is likely that the deeper vertical rooting in zero tillage treatments retained more moisture at depth compared to other establishment methods.~~

4.2.4 Root system architecture responses to traffic

Traffic significantly affected root volume, root surface area, root length and ~~RLD in shallow tillage treatments and zero tilled treatments trafficked at conventional pressure. RLD is an important parameter for characterizing root growth (Doussan et al., 2006) and has been used in previous studies as a key root parameter for modelling water uptake (Tinker and Nye, 2000; Javaux et al., 2013). Munos-Romero et al., (2010) and Chakraborty et al., (2008) results indicate that RLD is a positive predictor of crop yield. Although RLD had a positive correlation with crop yield in this study, root depth (using X-ray) displayed a much stronger relationship with crop yield (Figure 4.12).~~ w~~W~~hen comparing the highest root biomass (under deep tillage with no traffic) and bulk density results in the 100-200 mm layer, we found a reduction in root biomass when trafficked under conventional pressure by 28% in deep tillage under conventional pressure (BD = 1.66 g cm^{-3}), 37% in shallow till conventional pressure (1.437 g cm^{-3}) and 39% in zero tillage conventional pressure (1.583 g cm^{-3}) treatments. The compaction effects of trafficking on soil structure exacerbated the impact on rooting in general. Typically, studies report shallower rooting, increases in root diameter and decreased axial and lateral rooting (Grzesiak et al., 2014). ~~Colombi and Walter, (2017) observed decreased shoot dry weights in pot studies by 19 and 82% under moderate (1.45 g cm^{-3}) and high (1.6 g cm^{-3}) soil strength conditions. In the same study root dry weight was also reduced by 36 and 87% under the same soil strength conditions.~~ Shallow tillage had the lowest root biomass in both trafficked and untrafficked treatments. Shallow tillage treatments suffered from visible horizontal fissures or “tillage pan” in Figure 5~~10~~, causing significantly reduced rooting compared to deep tillage treatments. Moreover, a combination of <10% porosity and PR reaching >2,000 kPa in the 100-200 mm layer, it is likely that roots may also have suffered from anaerobic conditions due to poor infiltration rates through the tillage pan during heavy rainfall events. Conversely, root impedance may have occurred during drought periods through May and June (Batey, 2009). Alameda, Anten and Villar, (2012) proposed that axial growth suffers more than radial root growth. These effects of increased PR and soil bulk density were observed underin the current study. However, the increase in root diameter reported by several authors was not detected here (Chen et al., 2014; Lipiec et al., 2012; Tracy et al., 2012a; Alameda et al., 2012).

4.2.5 Tillage and trafficking effects on rooting and crop yield

In the present study, it was found that long term zero tillage plots under low tyre pressure increased yield by up to 0.772 Mt ha^{-1} compared to the deep tillage conventional tyre pressure treatments. All zero tillage treatments yielded over 11 Mt ha^{-1} compared to deep and shallow tillage treatments (10.71 Mt ha^{-1}mean). Evidence using data collected from the X-ray CT scans showed deeper vertical rooting in zero tillage plots compared to shallow and deep tillage treatments (Figure 7). Coupled with deeper rooting, zero tillage no traffic treatments had significantly lower bulk density than deep tillage conventional pressure plots. Munoz-Romero et al., (2010) reported a yield increase of 0.5 Mt ha^{-1} in zero tillage compared to conventional tillage which was associated with

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greater water use and increased water use efficiency, similar to (Chakraborty et al., 2008). Improvements in moisture retention, soil pore structures and reduced soil compaction under zero-tillage, may also have contributed to a yield increase over conventionally tilled treatments.

It is possible that the lower levels of porosity found in zero tillage aided with water retention during drought periods on the highly sandy soil in this trial. Coupled with the development of vertically oriented soil structural characteristics attributed to earthworm activity and old root channels (Figure 5), the zero tillage treatments may also have had increased access to water by roots at lower soil horizons. Indeed, biopores benefit root growth by altering the surrounding chemical, physical and biological properties of soil (Stroud et al., 2017; Banfield et al., 2017). Thus providing macropore pathways with lower mechanical resistance in which deeper rooting preferentially grow towards (Zhou et al., 2021). In contrast, deep cultivation created a porous structure which has shown to increase respiration of aerobic microorganisms, improving the flow of air and water thus increasing CO_2 emissions (Mangalassery et al., 2014a). Crop yield was influenced less in zero tillage treatments by trafficking than the other tillage treatments. The lower sensitivity to compaction in zero tillage is attributed to an elastic behavior or increase in bearing capacity, with soil acquiring similar structural properties to grassland soil (Ehlers and Claupein, 1994).

4.3~~5.5~~ 2D & 3D imaging for studying root-soil relationships

Due to the complexity of measuring root systems, two methods were conducted to provide comprehensive analysis. Important topology (root networks) and geometrical (physical positions) characteristics of wheat rooting using X-ray CT were found in this study. A strong significant relationship between RLD (WinRHIZO™) and root depth (X-ray CT) was found (Figure S4~~4.11~~) validating the suitability of image analysis methods in field studies. Further, root depth showed the strongest correlation with crop yield compared to root biomass and RLD (Figure S5~~4.12~~). Moreover, the large environmental variance (low r number) in root relationships may have been caused by spatial effects reported in previous studies (Guo et al., 2020; Zhou et al., 2021). ~~Compared to traditional 2D WinRHIZO™ analyses, the significant difference found with *in-situ* root depth between treatments using X-ray CT was not detected by destructive WinRHIZO™ analysis (i.e., it involves the washing of soil from root material, thus losing important architectural data). Destructive root analysis showed evidence of superior rooting properties under deep tillage treatments (e.g., root length density and root volume).~~ Visualizing important behaviors of wheat rooting in field scale trials, highlights the ~~importance~~ significance of root depth to sustain high yields in drought conditions. Figure 7~~4.9~~ depicts significantly longer root length in zero tillage treatments compared to trafficked deep and shallow tillage, with trafficked treatments roots were generally confined to the top 0-50 mm of soil. In general, root length rarely surpassed 100 mm in depth. This was partly due to insufficient resolution available with the X-ray CT scanner to capture finer root materials (Pfeifer et al., 2015).

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In general, both root analysis methods showed agreement in the results. Zero tillage treatments had significantly deeper rooting over shallow tillage and deep tillage trafficked treatments. Using the WinRhizo™ method, untrafficked deep tillage treatments showed superior root length. Similar disagreements in findings between methods could be explained by the difference in methodology between the two imaging approaches as X-ray CT is 3D and scans roots in soil whilst, WinRhizo™ is 2D and scans washed roots (Tracy et al., 2012a). Root volume and surface area were also examined using X-ray CT. In contrast to the WinRhizo™ analysis, no significant differences could be detected between treatments. The root volumes obtained by the WinRhizo™ were much greater than the volumes attained from the X-ray CT scan. The difference can be attributed by much clearer contrasts between air and root material with the destructive method compared to limitations with resolution and density differences between soil, root and organic materials (Mooney et al., 2012) in the X-ray CT scan images.

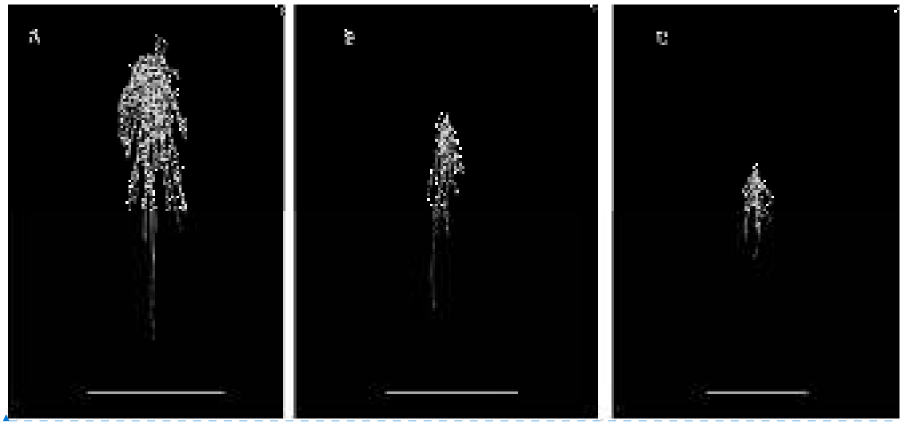

Figure 7~~4.9~~: Root system architecture of winter wheat during anthesis for (a) Deep tillage no traffic, (b) Zero tillage low tyre pressure and (c) deep tillage conventional tyre pressure. (a) and (b) showed significantly longer root length on the primary axis compared to (c) deep tillage trafficked treatments. Scale bar = 70 mm.

~~*4.5.6 Traffic and tillage effects on rooting and crop yield*~~

~~In the present study, it was found that long term zero tillage plots under low tyre pressure increased yield by up to 0.772 Mt ha^{-1} compared to the deep tillage conventional tyre pressure treatments. All zero tillage treatments yielded over 11 Mt ha^{-1} compared to deep and shallow tillage treatments (10.71 Mt ha^{-1} mean). Evidence using data collected from the X-ray CT scans showed deeper vertical rooting in zero tillage plots compared to shallow and deep tillage treatments (Figure 4.9). Coupled with deeper rooting, zero tillage no traffic treatments had significantly lower bulk density than deep tillage conventional pressure plots. Munoz-Romero et al., (2010) reported a yield increase of 0.5 Mt ha^{-1} in zero tillage compared to conventional tillage which was associated with greater water use and increased water use efficiency, similar to (Chakraborty et al., 2008). Improvements in~~

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~~moisture retention, soil pore structures and reduced soil compaction under zero-tillage, may also have contributed to a yield increase over conventionally tilled treatments.~~

~~It is possible that the lower levels of porosity found in zero tillage aided with water retention during drought periods on the highly sandy soil in this trial. Coupled with the development of vertically oriented soil structural characteristics attributed to earthworm activity and old root channels (Figure 4.7), the zero tillage treatments may also have had increased access to water by roots at lower soil horizons. Indeed, biopores benefit root growth by altering the surrounding chemical, physical and biological properties of soil (Stroud et al., 2017; Banfield et al., 2017). Thus providing macropore pathways with lower mechanical resistance in which deeper rooting preferentially grow towards (Zhou et al., 2021). In contrast, deep cultivation created a porous structure which has shown to increase respiration of aerobic microorganisms, improving the flow of air and water thus increasing~~ ~~CO_2~~ ~~emissions (Mangalassery et al., 2014a). Crop yield was influenced less in zero tillage treatments by trafficking than the other tillage treatments. The lower sensitivity to compaction in zero tillage is attributed to an elastic behavior or increase in bearing capacity, with soil acquiring similar structural properties to grassland soil (Ehlers and Claupein, 1994).~~

~~4.~~5. Conclusion

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The results from this research highlight the importance of traffic management for improving crop productivity. Physical and visual implications of soil compaction on the soil profile were demonstrated in this study, signifying the implications of tyre pressure on root growth. ~~High tyre pressure~~Traffic significantly reduced root development in all tillage treatments with tyre pressure having no significant effect on mitigating compaction effects on soil and roots. ~~However~~Moreover, deep, and shallow tillage systems were more influenced by compaction than zero tillage with roots confined to the top 0-60 mm thus, reducing primary vertical rooting and inhibiting roots access to deeper soil moisture reserves. The highly significant impact on crop yield was highlighted by the strong relationship between root depth and crop yield. The visible effects of trafficking on the soil profile depicted through X-ray CT, provides evidence of the damage modern farm machinery can cause for root resource capture, leading to potential increased drought stress and yield loss in crop production. This long-term trial site has shown that zero tillage does not affect root growth, in fact, reduced bulk density, improved grain yield and rooting depth significantly through deeply connected vertical soil pore fissures created by earthworms and old root channels, allowing roots to access deeper soil moisture reserves. These findings suggest that scientists and farmers should focus on designing improved zero tillage cropping systems, managing field trafficking protocols with controlled traffic farming. Moreover, further investigation on tracks and dual radial tyres are required to quantify practical compaction mitigation measures. Furthermore, this research shows that the combination of X-ray CT scanning along with traditional destructive methods provide a robust method for assessing in field rooting for future crop breeding initiatives and soil management practice. This research concludes that trafficking has more profound effects for root growth and crop yield than tillage method~~little differences were found between deep tillage and zero tillage methods in the absence of traffic in terms of overall physical root growth~~.

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~~However, in abundance of biopores and increased soil bearing capacity to withstand machinery traffic in in zero tillage systems increased rooting depth and moisture retention during the growing season.~~

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Supplement. The supplement related to this article is available in a separate word file as per submission.

~~4.7 Supplementary tables and figures~~

~~HAU~~	~~Deep~~	~~Shallow~~	~~Zero~~	~~Mean~~
~~Traffic/ Tillage 0 – 100 mm~~				
~~No traffic~~	~~0.971~~	~~1.099~~	~~0.994~~	~~1.058_b~~
~~LP~~	~~1.351~~	~~1.625~~	~~1.230~~	~~1.401_a~~
~~CP~~	~~1.661~~	~~1.444~~	~~1.282~~	~~1.462_a~~
~~$P < 0.01$~~				
~~Traffic/Tillage 100 – 200 mm~~				
~~No traffic~~	~~1.079~~	~~1.406~~	~~1.353~~	~~1.279_b~~
~~LP~~	~~1.389~~	~~1.509~~	~~1.552~~	~~1.483_a~~
~~CP~~	~~1.637~~	~~1.437~~	~~1.583~~	~~1.553_a~~
~~$P < 0.01$~~				
~~Traffic/Tillage 200 – 300 mm~~				
~~No traffic~~	~~1.429~~	~~1.466~~	~~1.404~~	~~1.433~~
~~LP~~	~~1.593~~	~~1.787~~	~~1.619~~	~~1.666~~
~~CP~~	~~1.537~~	~~1.548~~	~~1.548~~	~~1.544~~

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~~**Table 4.5:** Analysis of variance table for penetration resistance x tillage, traffic and tillage x traffic interactions between 0 – 150 mm, 150 – 300 mm and 300 – 450 mm.~~

	0 – 150 mm 2019	150 – 300 mm 2019	300 – 450 mm 2019
Traffic			
No traffic	432.3$_{b}$	1848$_{b}$	3028.5$_{b}$
CP	538.8$_{a}$	2614$_{a}$	3753.6$_{a}$
LP	626.7$_{a}$	2422$_{a}$	3655.7$_{a}$
P value	< 0.001	< 0.000	< 0.000
Tillage			
Deep	240$_{c}$	1366.3$_{b}$	3135.2$_{b}$
Shallow	488.4$_{b}$	2811.4$_{a}$	3800$_{a}$
Zero	869.4$_{a}$	2706.7$_{a}$	3502.7$_{a}$
P value	< 0.000	< 0.000	< 0.000
Tillage x traffic	0.001	0.067	NS

~~*Significant difference between means is represented by different letters~~

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~~Root trait~~	~~Term~~	~~d.f.~~	~~GS25~~	~~GS61~~
~~Root length mm~~				
	~~Tillage~~	~~2~~	~~NS~~	~~< 0.01~~
	~~Traffic~~	~~2~~	~~NS~~	~~< 0.000~~
	~~Tillage x Traffic~~	~~35~~	~~NS~~	~~NS~~
~~Surface area mm^2~~				
	~~Tillage~~	~~2~~	~~NS~~	~~< 0.05~~
	~~Traffic~~	~~2~~	~~NS~~	~~< 0.000~~
	~~Tillage x Traffic~~	~~35~~	~~NS~~	~~NS~~
~~Root diameter mm~~				
	~~Tillage~~	~~2~~	~~NS~~	~~NS~~
	~~Traffic~~	~~2~~	~~NS~~	~~NS~~
	~~Tillage x Traffic~~	~~35~~	~~NS~~	~~NS~~
~~Root volume mm^3~~				
	~~Tillage~~	~~2~~	~~NS~~	~~NS~~
	~~Traffic~~	~~2~~	~~NS~~	~~< 0.05~~
	~~Tillage x Traffic~~	~~35~~	~~NS~~	~~NS~~
~~RLD mm^3~~				
	~~Tillage~~	~~2~~	~~NS~~	~~< 0.01~~
	~~Traffic~~	~~2~~	~~NS~~	~~< 0.000~~
	~~Tillage x Traffic~~	~~35~~	~~NS~~	~~NS~~

~~**Table 4.6:** WinRhizo results of Tillage, traffic and Tillage x Traffic interactions with root traits at HAU during tillering (GS25) and anthesis (GS61). P values represent level of significance and 'NS' indicates non-significance. d.f. = degrees of freedom.~~

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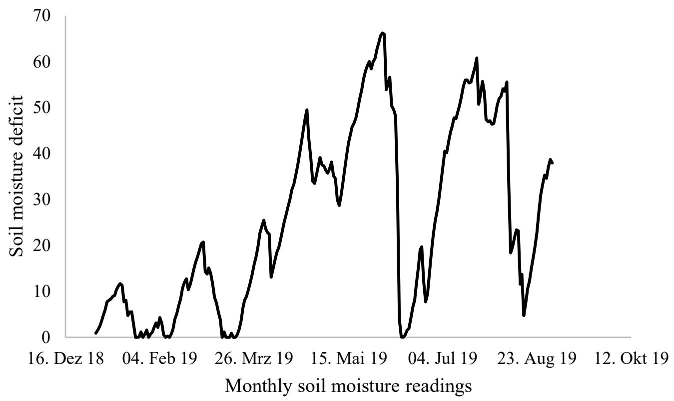
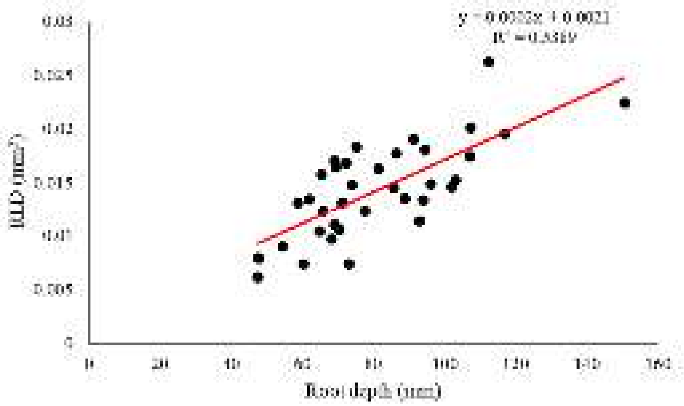


~~Figure 4.10:~~ ~~Soil moisture deficit model during the growth period (January-August) in Harper Adams University.~~



~~Figure 4.11:~~ ~~Linear regression measuring the relationship between RLD (mm3) (destructive analysis) and root depth (mm) (X-ray CT).~~

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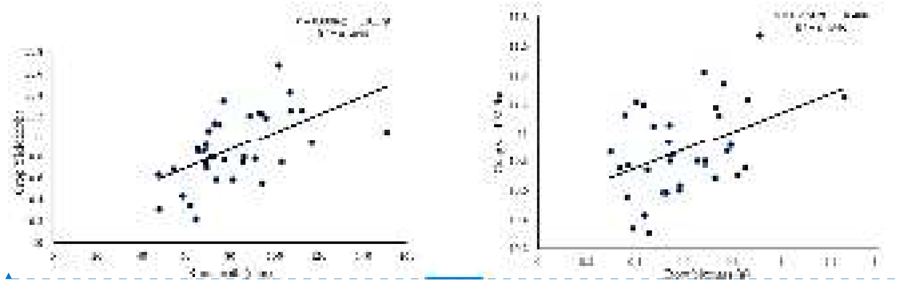

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~~**Figure 4.12:** Linear regression between crop yield (Mt/ha) and (a) Root depth and (b) root biomass as predictors of crop yield.~~

Author contributions. KMc and ST conceived the experiment. DH & MH carried out sampling and soil analysis. DH processed and analysed all samples. DH analysed and interpreted the data and wrote the manuscript. All authors contributed to the data, providing interpretation and comments to the manuscript.

Competing interests. The authors declare that they have no conflict of interest

Disclaimer.

Acknowledgements. This research took samples from a long term tillage and traffic experiment site in Harper Adams University. Long term crop rotation treatments at the Large Marsh site on the University grounds are managed and maintained by the agricultural staff at the university.

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