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Mawodza, T., Burca, G., Casson, S. et al. (1 more author) (2020) Wheat root system architecture and soil moisture distribution in an aggregated soil using neutron computed tomography. Geoderma, 359. ISSN 0016-7061

https://doi.org/10.1016/j.geoderma.2019.113988

Wheat Root System Architecture and Soil Moisture Distribution in an Aggregated Soil using Neutron Computed Tomography.

Tinashe Mawodza[1*], Genoveva Burca[2], Stuart Casson[1], Manoj Menon[3]

[1]Department of Molecular Biology and Biotechnology, The University of Sheffield, Western Bank, Sheffield S10 2TN, United Kingdom

[2]STFC, Rutherford Appleton Laboratory, ISIS Facility, Harwell, OX11 0QX, UK

[3]Department of Geography, The University of Sheffield, 9 Northumberland Rd, Sheffield S10 2TN

* Corresponding author E-mail address: tmawodza1@sheffield.ac.uk

Non-invasive techniques are essential to deepen our understanding of root-soil interactions in situ. Neutron computed tomography (NCT) is an example of such techniques that have been successfully used to study these interactions in high resolution. Many of the studies using NCT however, have invariably focused on lupine plants and thus there is limited information available on other more commercially important staple crop plants such as wheat and rice. Also considering the high neutron sensitivity to hydrogen (e.g. water in roots or soil organic matter), nearly all previous in-situ NCT studies have used a relatively homogeneous porous media such as sand, low in soil organic matter and free from soil aggregates, to obtain high-quality images. However to expand the scope of the use of NCT to other more commercially important crops and in less homogenous soils, in this study we focused on wheat root growth in a soil that contained a considerable amount of soil organic matter (SOM) and different sized aggregates. As such, the main aims of this research were (1) to unravel wheat (Triticum aestivum cv. Fielder) root system architecture (RSA) when grown in an aggregated sandy loam soil (<4 mm) with 4% SOM content, (2) Map in 3D, soil water distribution after a brief drying period and (3) to understand how the root system interacts with soil moisture

distribution brought about by soil structural heterogeneity. To achieve these, wheat seedlings were grown for 13-days in aluminium tubes (100 mm height and 18 mm diameter) packed with soil and imaged for the first time at the IMAT neutron beamline (in the Rutherford Appleton Laboratory, UK). To the best of our knowledge, this is also the first study to use NCT to study wheat root architectural development. Our study proved that NCT can successfully be used to reveal wheat RSA in a heterogeneous aggregated soils with moderate amounts of SOM. Lateral root growth within the soil column was increased in regions with increased finer soil separates. NCT was also able to successfully map water distribution in a 3D and we show that large macro-aggregates preferentially retained relatively higher soil moisture in comparison to the smaller soil separates within our samples (Fig. 1). This highlights the importance large macro-aggregates in sustainable soil management as they may be able to provide plants water during periodic dry spells. More in situ investigations are required to further understand the impact of different aggregate sizes on RSA and water uptake.

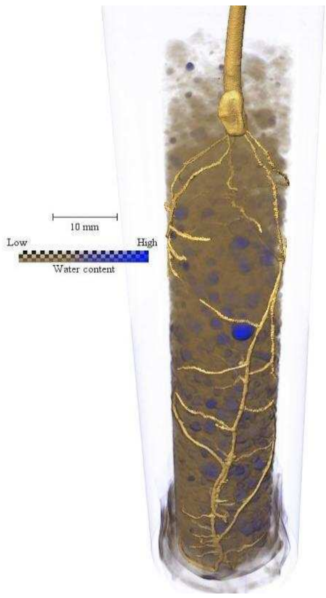

Figure 1: NCT image of a 13-day old wheat seedling root growing in an aggregated sandy loam soil. The colour map indicates water distribution within the soil column.

Key Words: Wheat, Root architecture, Neutron Computed tomography; Water dynamics

1. Introduction

The seemingly insurmountable task of feeding a growing global population with increasingly limited natural resources is one of the greatest challenges facing humanity in the 21st century (Borlaug and Dowswell, 2003; Lal, 2016). With the effects of climate change threatening to further disturb global production patterns across the world, it is imperative for the research community to devise possible strategies to increase global crop productivity in the forthcoming decades (IPCC, 2007; Knox et al., 2012). This will require a deeper understanding of factors affecting crop production systems using contemporary technologies. One such area of research that has received increased attention of late is that of belowground root-soil interactions. These interactions are a vital part of the crop production system as plants acquire the majority of the resources they use for production via these associations and thus increasing our understanding of these interactions may hold the key for a 'second green revolution' required to feed a rapidly growing population (Gewin, 2010; Lynch, 2007; Rich and Watt, 2013).

Understanding root-soil interactions especially amongst the worlds' major cereal crops (maize, wheat, rice) is of paramount importance for the attainment of sustainable global food security as these crops provide more than two thirds of all human dietary energy (Cassman, 1999; FAOSTAT, 2019; Khoury et al., 2014). This understanding is crucial for wheat in particular as it is arguably the worlds' most important staple food crop. It accounts for more than 15% (220 million ha) of global arable land use, (the highest for any cultivated plant) and often yields in excess of 700 million metric tonnes of grain per annum globally (FAOSTAT, 2019). In spite of its great importance however, yield gaps in wheat production still exist, often as a result of poor adaptation of its root system to varying edaphic conditions (Senapati and Semenov, 2019; Waines and Ehdaie, 2007). As such increased research into root-soil interactions in wheat to tailor its root system for different soil environments is pivotal for improving wheat yields especially in marginal areas (Alahmad et al., 2019; Figueroa-Bustos et al., 2018; Waines and Ehdaie, 2007).

Traditionally these root-soil interactions have been investigated using either inference root health from the development of above ground parts (shoots) or by the more labour intensive invasive soil excavation methods (Pierret, et al. 2005). These observations however, although useful, lacked critical root developmental detail required to make conclusive inferences into how best to improve plant productivity (Mooney et al., 2012). Even when elements of the root-soil interactions were deduced, high throughput measurements were often very difficult to obtain which limited research into subterranean interactions.

The advent of non-invasive soil imaging in the late 70's marked a significant step forward in the study of plant-soil interactions with technologies such as X-Ray Computed Tomography (X-Ray CT) (Crestana, et al, 1986; Keyes et al., 2013; Tracy et al., 2013; Ahmed et al., 2016; Blunk et al., 2017; Burr-Hersey et al., 2017; Koebernick et al., 2017), Magnetic Resonance Imagery (MRI) (Metzner et al., 2015; Pflugfelder et al., 2017; Stingaciu et al., 2013), Nuclear Magnetic Resonance imaging (NMR)(Bačić and Ratković, 1987; Brown et al., 1991; Southon, et al, 1992) and Neutron imaging (NI) (Willatt, et al, 1978; Furukawa, et al. 1999; Menon et al., 2007; Tötzke et al., 2017) being used to answer a multitude of questions about root-soil interactions in great detail. Of these technologies NI has been the most effective non-invasive soil imaging technique used when studying water dynamics and root growth within the soil due to its high sensitivity to hydrogen which is abundant in water (Robinson, et al. 2008). Willatt. et al, (1978), demonstrated the use of this method for the first time, successfully imaging roots of different plants (soya bean and maize) growing in soil. Subsequently this technology was used by in many studies including Willatt and Struss (1979), Couchat et al., (1980), Bois and Couchat, (1983), (Nakanishi, et al 1992) as well as Furukawa, et al. (1999). Two papers by Menon et al (2007) and Moradi et al., (2009) also provided a comprehensive, accurate description of NI that subsequently led to even more insightful studies using NI.

Initial plant experiments with NI involved the use of 2 dimensional neutron radiography (NR) to study the root architectural properties in situ (Bois and Couchat, 1983; Couchat et al., 1980; Willatt and Struss, 1979) using thin slabs made of aluminium. The most extensively used plants in NI have been maize (Zea mays L.) pioneered in experiments by Willatt, et al. (1978) and lupine (Lupinus albus L.) first used by Nakanishi, et al. (1992) with the majority of papers being published on NI in plant-soil interaction mainly focusing on them. Research in soil NI has since moved on to the study of more complex root-soil processes such as dynamics of water flux and the extent of rhizosphere which had previously been difficult to study using other techniques (Carminati et al., 2010; Oswald et al., 2008). Visualisation of water movement coupled with the ability to use tracers such as heavy water (D_2O) in NI has led to a better understanding of water uptake and transport in specific roots with Zarebanadkouki, et al. (2013) showing that most of the water uptake in 3 week old lupine plants is carried out by the lateral roots with the tap root mainly acting as a conduit for upwards water movement.

Unlike NR, there have been fewer studies that have used neutron computed tomography (NCT) to study soil-root water dynamics despite the fact that computed tomography has the potential to provide even more detailed 3D visualisation of plant-soil systems as compared to NR. Its uptake may have been limited by the size of the specimen that can be successfully imaged in detail (usually no more than 20mm in diameter) as well as the time required for such images to be taken, which is much longer than that for individual neutron radiographs (Warren et al., 2013). The initial work done by Tumlinson et al., (2008) and Esser et al., (2010) with maize seedlings and lupine seedlings showed that visualisation of root and water distribution dynamics in soils can be visualised successfully in 3D using NCT with improved root-soil contrast as compared to other non-invasive imaging techniques. Moradi et al., (2011) went a step further in their study with lupine plants showing that water dynamics at the microscale can be accurately observed in 3D and thus can be used in complex and precise modelling operations explaining rhizosphere water flux. Recent advancement in NCT by Zarebanadkouki et al., (2015) who visualised 3D water dynamics of lupine plants in real time, provide great prospects of the use of NCT in further plant-soil interaction studies.

Regardless of the recent advancements in NCT in plant-soil interaction studies, there are some important limitations for this technique. For example, all of the previous studies utilising NCT have used soils containing no less than 90% sand, which are mostly devoid of organic matter or macro-aggregates. Therefore, for a wider application of this method it will require testing further using a variety of soil textures and structures. Also conspicuous in many NI studies to date is the absence wheat root architectural investigations using this technology despite the crop being major contributor to global food security. As such it is important to test the feasibility of the use of NI on wheat plants, with the aim of enhancing knowledge on wheat roots and their interactions with soil moisture.

In this paper, we thus aimed at determining the 3D root architecture of wheat seedlings grown in an aggregated sandy loam soil with 4% organic matter content using NCT. Our specific objectives were to use NCT to: a) Map 3D wheat root architectural distribution within an aggregated sandy loam soil b) Visualise in 3D, soil water distribution after a brief drying period and (c) to understand how the root system architecture interacts with soil moisture distribution as brought about by soil structural heterogeneity within an aggregated soil.

2. Materials and methods

2.1 Sample preparation and plant growth

The soil used in this experiment was a sandy loam soil (70% Sand, 17% Clay, and 13% Silt) obtained from Cove farm (53°30'03.7"N 0°53'57.2"W) and had an organic carbon content of 5.59%. This soil was air dried and mechanically sieved through a 4mm sieve to eliminate large clods and aggregates. The sieving produced a dry aggregate size distribution of 24% for particles <250µm, 36% for 250-500µm, 13% for 500-1000 µm, 13% for 1000-2000µm and 14% for 2000-4000µm with 4% SOM. This was then packed into specially designed, closed bottom, cylindrical aluminium tubes (18mm internal diameter × 100mm height) to ensure a bulk density of 1.2g cm^{-3} within the tubes. A single wheat (Triticum Aestivum. L cv. Fielder) seed was sown about 1cm underneath the surface of the soil and the tubes were watered to a volumetric moisture content (θ) of 16.0±3.0% which was experimentally determined (using gravimetric methods) to be the field capacity of our growth tubes. This water content was maintained during the course of this experiment by daily surface irrigation to the predetermined weight corresponding to the above mentioned θ for each tube. The wheat seedlings were grown for 13 days (starting from date of planting) in a growth chamber maintained at a temperature of 22°C (day)/18°C (night) and a relative humidity of 55% with light intensity averaging 400µmol m^2 s^{-1} with an 8-hour day length. Watering was stopped 4 days before neutron imaging was carried out to enhance the contrast between the root and soil.

2.2 Neutron computed tomography set up

Neutron CT imaging was carried out at the IMAT neutron imaging beamline of the ISIS Neutron and Muon Source at the Rutherford Appleton Laboratory, UK. A more detailed description of the IMAT imaging station can be found in (Burca et al., 2013); Kockelmann et al., 2013 and Burca et al., 2018). For these experiments the neutron beam was shaped to the field of view of 112.7 mm × 112.7 mm accompanied by a multiaxial tomography stage allowing for 2 simultaneous scans. The neutron radiographies were acquired with an optical camera box equipped with Andor Zyla 4.2 PLUS sCMOS with 2048×2048 pixels, an 85mm lens and 100 µm 6LiF/ZnS: Ag scintillator. The images produced had a pixel and voxel size of 55µm with 30s being the exposure time for each projection and an L(10000mm) /D (40mm)= 250. The time taken for a single scan of the plants was almost 6 hours with 654 radiographs being recorded using a rotation step of 0.55°. This was the best set up achievable on IMAT, suitable for our experiment (Mawodza et al., 2018).

2.3 Image reconstruction, root segmentation and analysis

The images were reconstructed using the commercial available Octopus 8.9 software (Octopus, 2019), and images were corrected for neutron beam variation and camera noise using the flat images and dark images taken before and after image acquisition (Dierick et al., 2004; Vlassenbroeck et al., 2006). We did not use an scattering correction when processing our images. The final reconstructed stack of images were imported into Avizo ® 9.0.1 for root segmentation and analysis (FEI, 2015).

We attempted to use automated root segmentation algorithms RooTrack (Mairhofer et al., 2012) and Root1 (Flavel et al., 2017) but due to the great heterogeneity in water content both the soil and within roots, these proved unreliable for our samples. To get the best results, roots were manually segmented using the limited range paintbrush editor in the segmentation module in Avizo software. The segmented roots obtained from this process were then used to calculate root lengths, thickness, surface area and volume for each root scan. Segmentation of the larger seminal roots was primarily done using automated thresholding techniques available in Avizo as there was a clear attenuation contrast between the soil and these roots.

This was however not done universally throughout the whole root system as most of the smaller lateral roots as well as some sections of the larger seminal roots had attenuation values that poorly contrasted or were even lower than that of moist soil and aggregates surrounding them as shown in Figure 2. Time consuming manual segmentation based on a combination of localised differences in attenuation and the connectivity of circularly shaped pixel groups (as roots are usually circular in shape) enabled the segmentation of the outstanding lateral roots and seminal root sections throughout the soil columns. Calibration for water content was done using the same soil used in our experiments with known volumetric water contents similar to what was done in Moradi et al., (2011). We then used this calibration to relate the relative neutron attenuation to the moisture content for all the images we acquired.

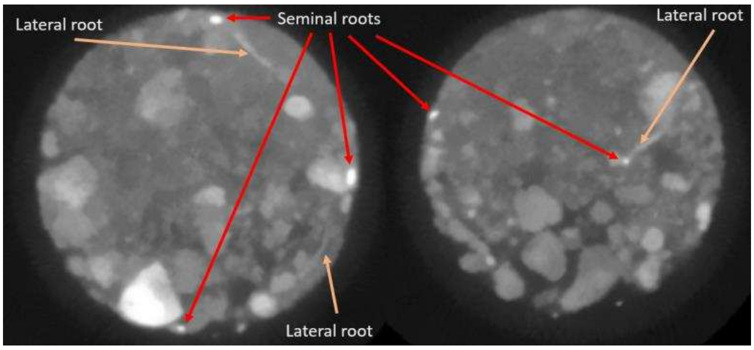

Figure 2: Grayscale images used to segment out roots showing how the different root types contrasted with the soil.

2.4 WinRhizo® root analysis

As segmentation was a subjective process, we compared the root properties obtained from our analysis with those obtained from flatbed scanning results analysed using WinRhizo ® (Regents Instruments, Inc.). Therefore, after CT scanning, the soils columns were destructively sampled and the soil was washed off from the roots over a 250µm sieve. The washed roots were then placed in a specially designed water tray and scanned using an Epson

Expression 10000XL Pro at 600dpi resolution. This scan obtained 2D images of the plant roots which were then analysed using WinRHIZO® 2016a software to determine the root properties (Wang and Zhang, 2009). These roots alongside their shoots were then dried at 65°C for 48 hours to obtain their dry biomass.

2.5 Statistical analysis

All graphs and statistical analysis for these experiments was performed using GraphPad Prism 8.0.1 (https://www.graphpad.com/) with a two tailed paired T tests used to separate means.

3. Results

3.1 3D wheat root architecture from NCT

Three-dimensional root architectural properties of the 13-day old wheat seedlings rendered from neutron scanning were successfully mapped with images in Fig 3. illustrating the different root systems of the six plants that were grown.

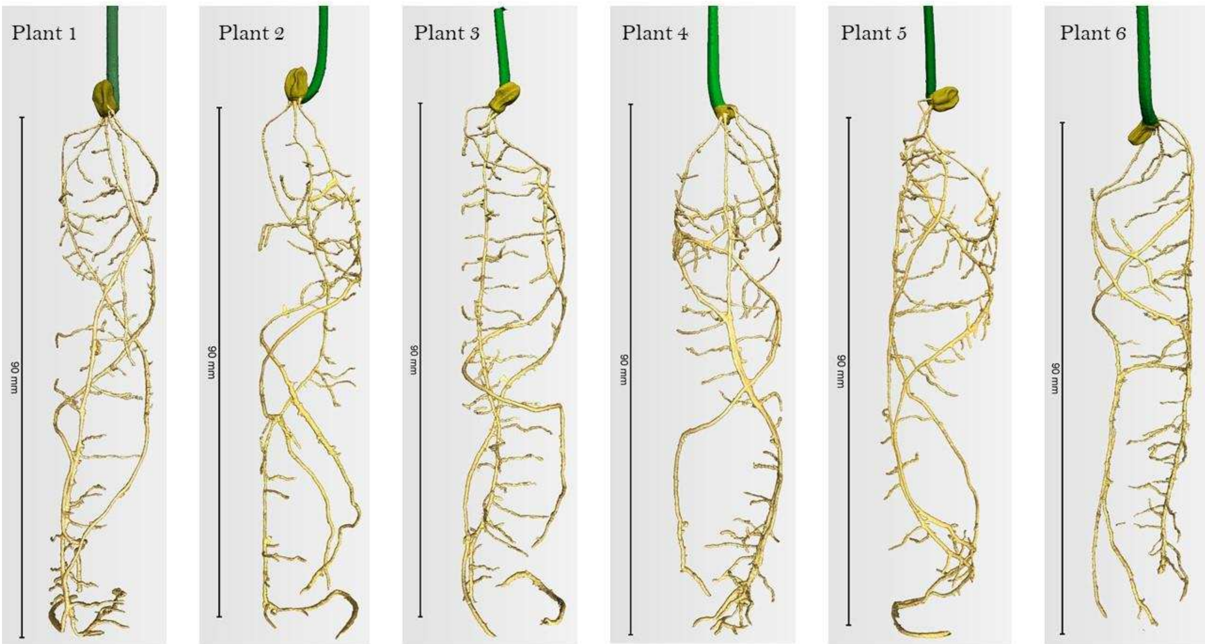

Figure 3: Images revealing the root architecture of the 6 different plants grown

The root architecture of the plants was broadly similar with an average total root length of 89.775 cm ±4.418 (SEM). The plants had 3-5 seminal roots at the time of imaging with least one of the roots (mainly the primary root) having grown to reach to the base of the growth tube they were growing in. Lateral roots of the different plants extended throughout the soil column with visible differences in lateral root growth especially in regions where the seminal roots were in close proximity to larger aggregates (1-4mm) that had large pores in-between them. Lateral roots growing in these regions tended to be fewer and longer whilst those growing in finer soil particles were more numerous but visibly shorter. This can be seen in Figure 4 where due to the random segregation of particles when packing, larger aggregates settled on one side of the column. Roots in some of the columns (plant 1, 4 and 6 in Figure 3) also coalesced together and grew side by side in their downwards trajectory, only disentangling lower down the soil column.

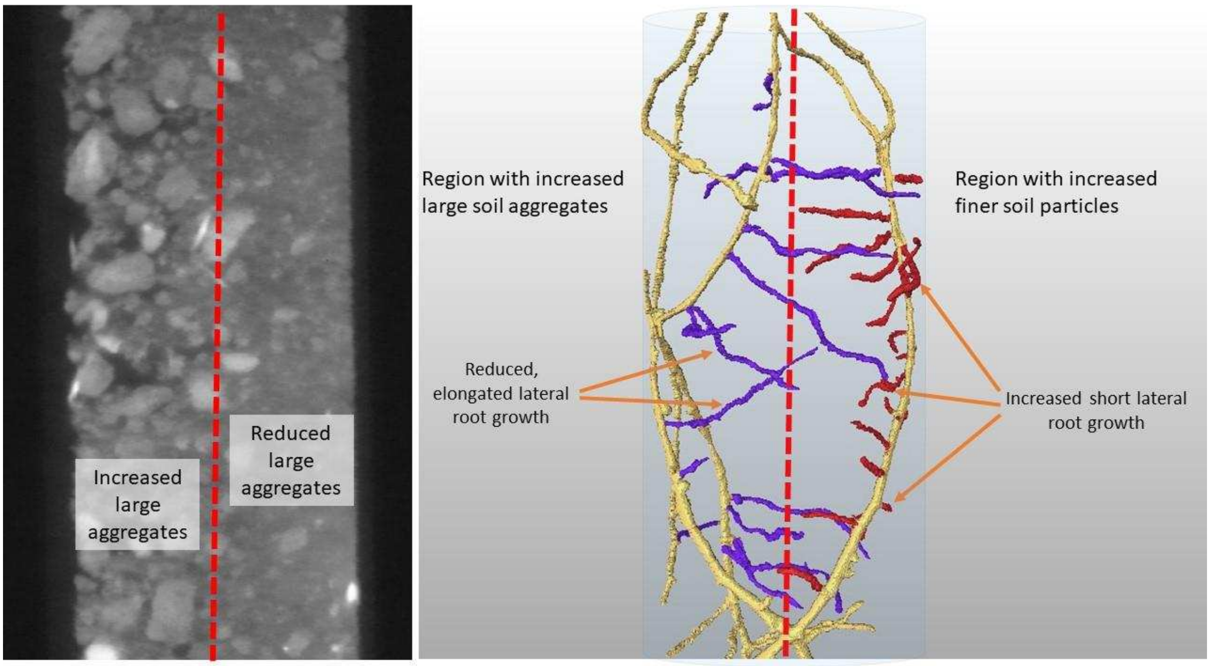

Figure 4 (Left)Greyscale image of a growth tube showing a segregation of large aggregates towards the left side of growth tube. (Right) increased shorter lateral root growth in regions with finer soil particles whilst lateral roots growing in regions with increased larger aggregates are reduced and longer. The red line demarcates an arbitrary boundary between regions dominated by large aggregates or finer particles. Longer lateral roots are shown in purple whilst short lateral roots are shown in red.

3.2 Comparison between 3D and 2D root properties

Root properties calculated using WinRhizo ® from the flatbed scanning and 3D NCT enabled the correlation of the two methods thus ensuring the validity of the method we used to segment out the roots. Visual comparison between images obtained using the two methods as shown in Figure 5 showed great similarities between them.

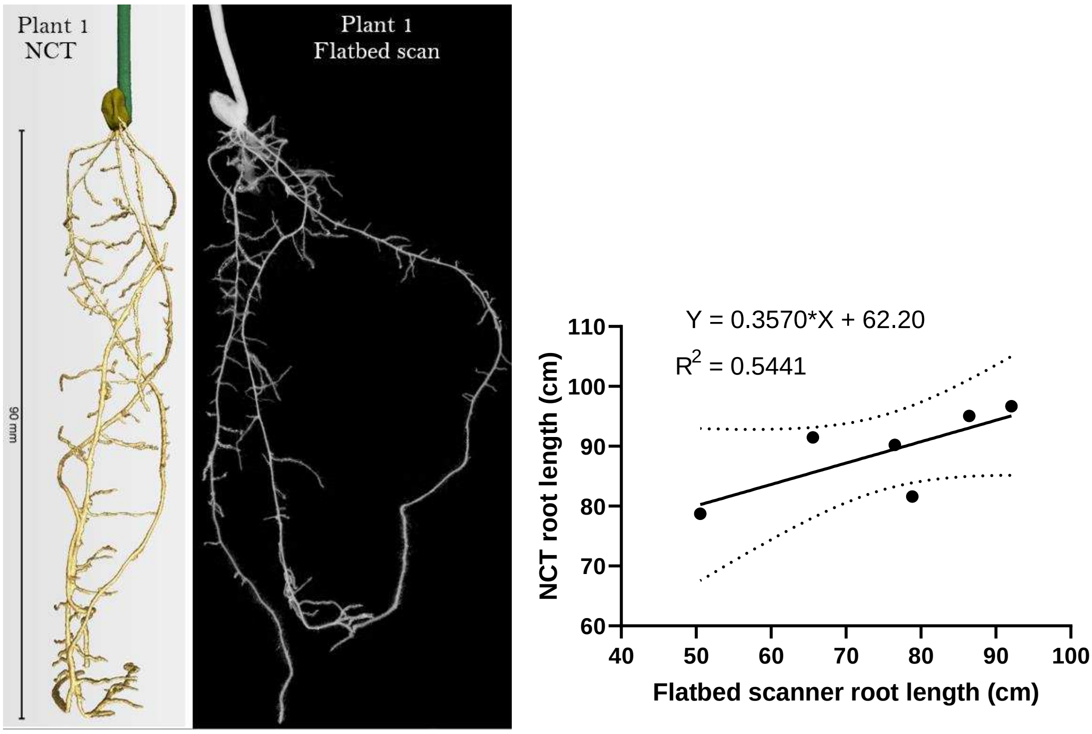

Figure 5: Side by side comparison of the same plant imaged using NCT and flatbed scanning

There was also a moderately strong linear relationship (R^2= 0.5441) between the root length estimated by the two methods as given in Figure 5. As shown in Figure 6, estimates of root length and surface area from neutron scans were significantly ($P<0.05$) higher than those from flatbed scanning whilst root volume and thickness did not vary between the two methods. The thinnest roots we could detect were around 110µm (2 voxels) in diameter which corresponds to double our image pixel size according to Nyquist–Shannon theorem.

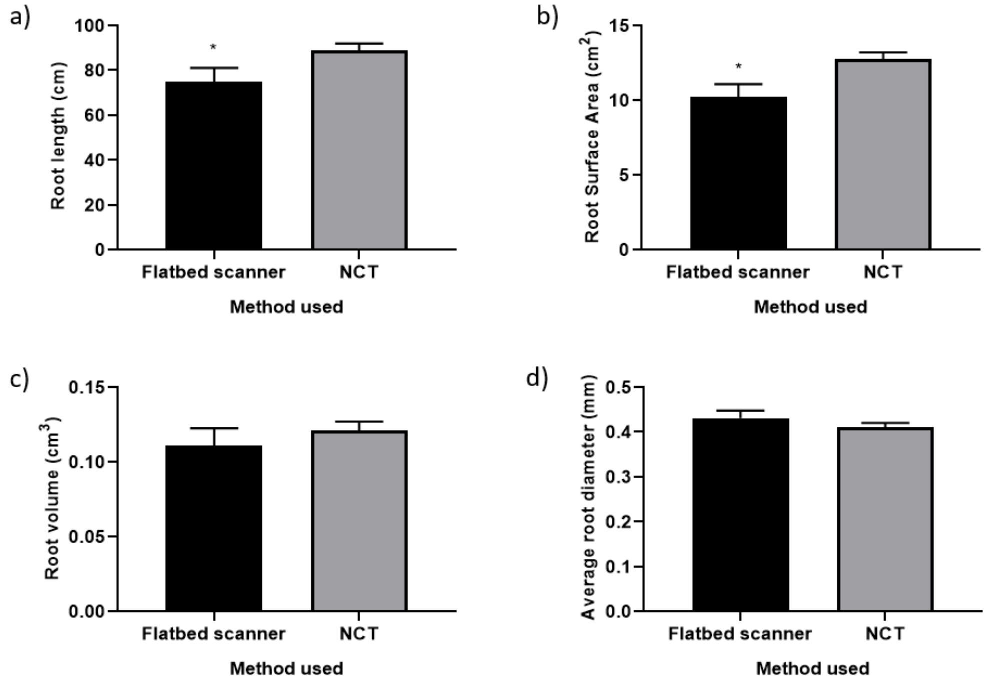

Figure 6: Comparison of root architectural properties as estimated by flatbed scanning and NCT. a) Root length (P= 0.0250), b) Root surface area, c) Root volume and d) Average root diameter. The error bars indicate Standard Error of the mean and * indicates significant differences (P< 0.05)

3.3 Soil moisture distribution

Similar to root architecture, the visualisation of soil moisture distribution was possible in 3D NCT as illustrated in Figure 7 with neutron attenuation being used as a proxy for θ using calibrated estimates of water content. These were calibrated by a series of scans of dry soil samples similar (but not identical) to those used for plant growth. It is worth noting however that our estimation of moisture content may encompass an add on effect with the high organic matter which increases neutron attenuation.

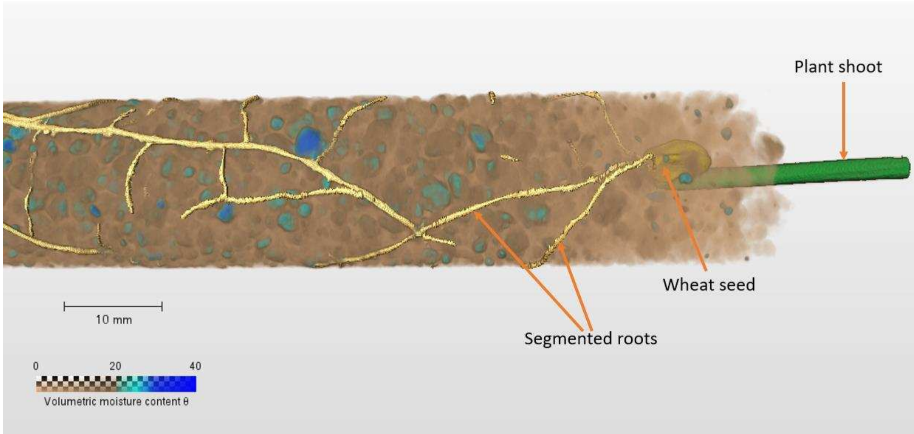

Figure 7: 3D NCT rendering of water distribution in aggregated soil where wheat seedling is growing

Water distribution within the columns was sporadic with regions of increased moisture localisation and depletion throughout the different tubes. Water depletion was greatest in the top 20mm of the soil with soil moisture gradually increasing between 20-60mm from the top of the column until it reached its greatest extent at the base of the tube. Water was largely localised in regions with nearly spherically shape regions within the soil as shown in Figure 8. Upon further analysis, it was discovered that this moisture accumulation was mainly associated with the heterogeneously distributed soil aggregates within the soil. As compared to finer particles, all or parts of aggregates have a θ >20%.

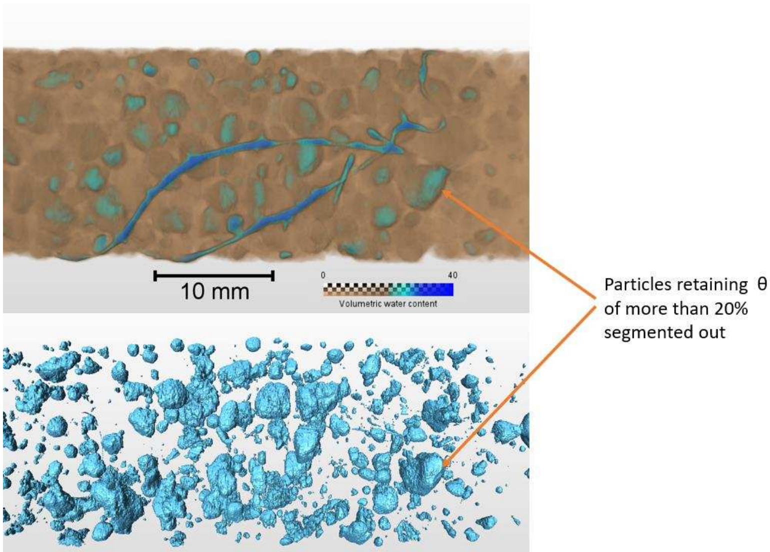

Figure 8: Showing segmenting out of particles retaining greater *θ >20%*

3.4 Root interactions with soil moisture

Wheat roots did not preferentially grow in regions of increased θ (blue regions with θ >20). Many of the roots that were observed did not penetrate into water rich aggregates but rather grew around them. Roots that were in direct contact with aggregates with a higher θ exhibited an increase in their internal θ. In large pores in-between soil aggregates, roots had reduced θ which was especially true in smaller lateral roots as opposed to the much larger seminal root network. Some seminal roots however also showed this unexpected internal θ decrease when growing through larger inter-aggregate pores. The rhizosphere around the roots as shown in Figure 10, did not show great differences in θ as compared to the rest of the soil with delineation of the extent of the rhizosphere being difficult decipher.

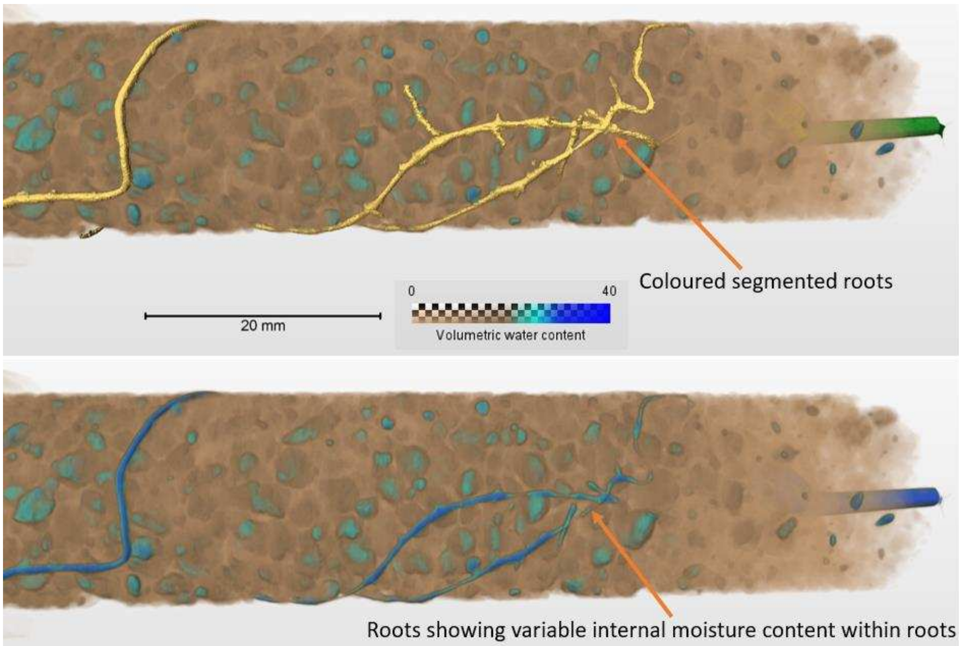

Figure 9: Variations in internal water content within roots growing through soil. The top image shows segmented root indicated in yellow whilst in the bottom image, only root moisture content can be visualised

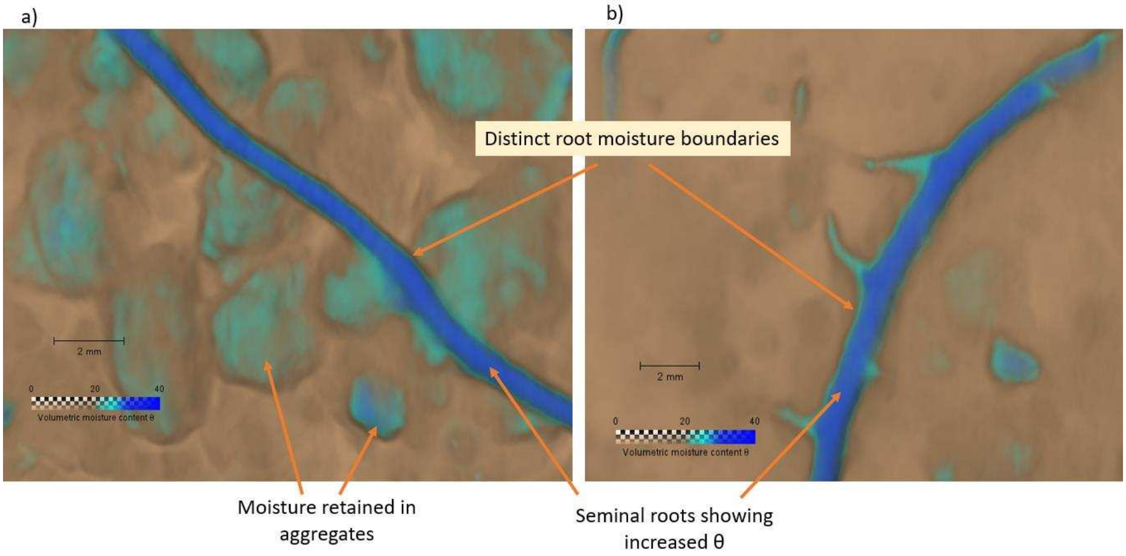

Figure 10: Close up view of the water-map in around seminal roots at a) 3cm and b) 5 cm below the soil surface showing distinct boundaries around the roots

4. Discussion

4.1 3D NCT wheat root architecture

The results presented show that detailed 3D root architectural properties of wheat growing in an aggregated soil with a moderately high organic matter content can successfully be visualised using NCT. To the best of our knowledge, this is the first study to use NCT to study root architectural development in wheat plants in detail. This research also represents a significant step away from many of the previous NCT root architectural studies such as those done by Nakanishi et al., (2005), Moradi et al., (2011), Warren et al., (2013) and Tötzke et al., (2017) that have used predominantly sand soils (with >90% sand). The sand soils used in the previously mentioned studies are more or less homogeneous and often lack aggregation. This study thereby seeks to break with convention by using a heterogeneous, aggregated soil with increased SOM. We recognise however, that the use of an aggregated soils as in this study presents a potential challenge when attempting to segment out wheat roots. This difficulty is brought about by the heterogeneity in soil properties with isolated regions retaining increased moisture and/or being high in organic matter (e.g. soil aggregates) that are highly neutron attenuating due to their increased hydrogen content (Robinson, et al. 2008). As a consequence of such features, there is a reduction in the clear attenuation difference between the soil and plant root matter that is characteristic in sand soils thus complicating segmentation as simple thresholding would yield inaccurate results. In this study we were able to overcome such difficulty by both localised thresholding using the increased attenuation and interconnectivity between roots as well as intuitive manual segmentation techniques.

This study represents a move away from the use of the leguminous dicotyledonous plant lupine (Lupinus albus. L) that has been popularly studied in many NCT and neutron radiography experiments ever since the pioneering work of (Nakanishi, et al. 1992) and then Menon et al., (2007) who established this plant as a 'model' for non-invasive neutron imaging studies in plant-soil systems (Zarebanadkouki et al., 2012; Rudolph-Mohr, et al. 2014; Ahmed et al., 2017). Our use of the monocotyledonous graminae family plant, wheat represents one of the first attempts at visualising the RSA of a staple food crop using NCT. Many of the non-invasive imagery done on wheat plants has been carried out exclusively using X-Ray CT (Flavel et al., 2014, 2012; Jenneson et al., 1999; Mooney et al., 2006; Tracy et al., 2012). This study thereby demonstrates the feasibility of using NCT to study the RSA of not only wheat plants but also other staple monocotyledonous crops such as rice and maize.

4.2 Comparison between 3D and 2D root properties

As the manual segmentation methods we used to reveal root architecture from NCT scans could be subjective, a comparison between the results obtained from NCT scanning and flatbed scanner scanning was done. This is the first time results from NCT have been compared to images flatbed scanning results. Similar correlations have previously been done in on X-Ray CT scan root measurements such as those by Tracy et al., (2015) and Flavel et al., (2012). In this study, here was moderately good correlation (R^2 = 0.54) between the two methods with respect to key essential root characteristics, root length and volume with estimates from flatbed scanning being significantly lower in root length. This could be explained by the fact that some roots are inevitably lost during washing with literature estimating a loss of about 20-40% of dry matter during storage and washing operations for wheat roots (van Noordwijk and Floris, 1979; Grzebisz. et al, 1989). These losses though, may be partially compensated for by the inability of our NCT to measure and quantify roots less than 110 µm (55µm pixel size ×2) which is 2 times each voxel size that is widely regarded as the effective spatial resolution limit of CT images (Moradi et al., 2011). Roots of this thickness can be picked up by flatbed scanning provided they are not lost during the washing process.

4.3 Soil moisture distribution

Similar to root system architecture, visualisation of soil moisture distribution was possible in 3D with the greyscale intensity acting as a proxy for θ. The high soil moisture heterogeneity within the scanned tubes was as expected since soil heterogeneity often results in variable hydraulic conductivity throughout the soil which has a direct bearing on the θ in unsaturated conditions. As plants were surface irrigated, θ was lowest at the soil surface increasing steadily towards the base of the growth tube. This accumulation of water at the base of the tubes may have been brought about by the lack drainage as they were sealed at the base to allow for accurate determination of the gravimetric water content. Localisation of water as shown in Figure 8, which was presumed to be as a result to the preferential retention of water in aggregates. This preferential water retention was presumed to arise from the pore size distribution within soil aggregates which is often comprised of multiple micro-pores with the ability to store water at higher suctions as opposed to the inter-aggregate pores referred to in literature as structural pore spaces that are characteristically bigger and thus can freely transmit water. This preferential water retention however was not universal as some aggregates were also relatively dry at the time of imaging with some parts of the moist aggregates also being relatively drier as compared to the rest of the aggregate. This may suggest that that some aggregates may have pores large enough to drain freely at lower suction levels.

Inference of soil moisture status using NCT and neutron radiography is not new with several scholars having shown soil moisture distribution in sand soils. This study builds on their findings adding further complexity by looking at an aggregated soil that has an increased organic matter content. This introduces inaccuracies with the estimation of water content as in such a soil, water is not the only highly neutron attenuating substance as organic matter has increased hydrogen atom content as compared to soil (Robinson, et al. 2008; Tumlinson et al., 2008). This thus means the total attenuation of each voxel is dependent on the water content as well as the organic matter content for the particular volume of soil under review. In this study we calibrated for water content using the same soil at varying levels of θ, however in doing this we assumed that the organic matter content throughout the soil was constant and variation in attenuation was primarily due to increased soil moisture content. This estimation would be inaccurate especially in regions with localised elevated level of soil organic matter. As such our interpretation of soil moisture distribution should be taken with this in consideration.

4.4 Root interactions with soil moisture

As roots did not seem to grow preferentially in regions of relative high θ (are not highly hydrotropic), it is clear that many other factors such as gravity, pore size distribution and nutrient status of the soil may have also contributed to root growth patterns (Kar, et al. 1979;

Niu et al., 2015; Sato et al., 2015). As roots grew around different aggregates probably as a consequence of trying to find the path of least resistance, many of the roots had good contact with the surface of the moist aggregates. Roots in contact with moist aggregate surfaces seemed to be able to extract water from these aggregates as more often than not, these roots exhibited an increased in θ. It was striking however that roots growing though large air spaces within the soil in some cases seemed to exhibit a reduction in θ as they passed through the pore space. This is thought to be as a result of increased evaporative water loss from the root surface within these large air spaces. Such large inter-aggregate pores may thus act as a hindrance to internal root hydraulic conductivity and thus limiting the functionality of roots growing through them. This finding could in part explain some of the observations seen by (Passioura and Stirzaker, 1993) as well as Alexander and Miller (1991) who noticed a general reduction in plant growth when artificial holes are introduced or when plants are grown soils with large aggregate sizes.

Another unexpected result from our study was the absence of a distinct region of increased θ around the roots demarcating rhizosphere soil around the roots as shown in Figure 10. This is contrary to what has been observed in many neutron studies such as those done by (Moradi et al., 2011) who noticed this distinct feature in all the plants they studied. This variation could be as a result of our use of a different textured soil that may not produce such distinct features as soil moisture was heterogeneously distributed within the soil. Differences in plant species difference i.e. wheat used in this study as compared to maize or lupins mainly used in previous studies could also be a contributory factor to our observed differences. Another plausible explanation for this could be in the difference of root segmentation protocols that were used in the different studies. In this case where semi-automatic and manual segmentation was employed based on the roots distinct increased attenuation properties, the edges of the roots could be mistaken to lie within the rhizosphere. This is however unlikely as the root thickness as estimated NCT compare well to that found by flatbed scanning. Questions may also be asked about the demarcation of root boundaries in the previous studies as many of these studies did not compare the thickness of the roots found in their scans to those obtained by manual measurement.

5. Conclusion

NCT was found to be able to reveal root architecture of wheat plants grown in an aggregated sandy loam soil with appreciable amounts of organic matter and inherent heterogeneity. This marks a step forward from the use of predominantly sand soils in NCT, albeit with new challenges of its own. Macro-aggregates increased water storage within the soil with their heterogeneous distribution determining the water distribution patterns across the soil after a period of drying which could help plants water acquisition in times of limited water supply. Lateral root growth was found to be reduced in regions with increased macro aggregates with roots growing through large inter-aggregate pores exhibiting loss of moisture that could potentially limit root function. Our work highlights how soil heterogeneity may affect water distribution and plant-soil interactions thus encouraging the further use of NCT technology to answer questions related soil water distribution in heterogeneous media for better modelling of soil water movement.

Funding and Acknowledgements

This research was funded as part of a PhD studentship by the Grantham Centre for Sustainable Futures at the University of Sheffield. Neutron imaging beamline grant (RB1820361) was provided by STFC ISIS Facility from Rutherford Appleton Laboratory, UK (Mawodza et al., 2018).

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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