SPATIAL AND TEMPORAL VARIABILITY IN SOIL PHYSICAL CONDITIONS FOR ROOT GROWTH: INTERACTIONS BETWEEN SOIL, WATER AND ROOT GROWTH FOR SUSTAINABLE AGRICULTURE.

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Abstract

Plants and hence crops grow best when their roots are able to proliferate through soft stable soil. Crops with prolific root systems use water and nutrients efficiently, generally have greater yields and are best placed to resist or minimise disease. For most plants, physical constraints including mechanical impedance, water stress and oxygen deficiency limit root proliferation. However these constraints differ with location in the soil and change with time. Roots may exploit structural cracks and biopores in the soil and by so doing gain access to water and other resources at depth, but to fully exploit the soil resources roots must not be confined to these largest of pores and must explore the soil matrix. A range of sensors are available to quantify the physical constraints for roots, but penetrometers of similar dimensions to a root and with a relieved shaft to limit friction between the shaft and the soil are best able to described the condition of the soil matrix for root proliferation. To penetrate the soil matrix a root requires both to expand the cavity it is to occupy and to overcome the soil-root friction. While cavity expansion is determined solely by the soil, the soil-root friction involves both the plant and the soil. This paper will start at the scale of an individual root tip elongating into the soil matrix, consider how the physical environment changes that elongation, and the consequences of soil variability in space and time for the individual root. Using the understanding of the individual root-soil interaction it will draw inference for larger scales, comment on how the understanding informs sustainable soil management and finally emphasise the need to deploy plant genetics and soil management together to improve long-term productivity.

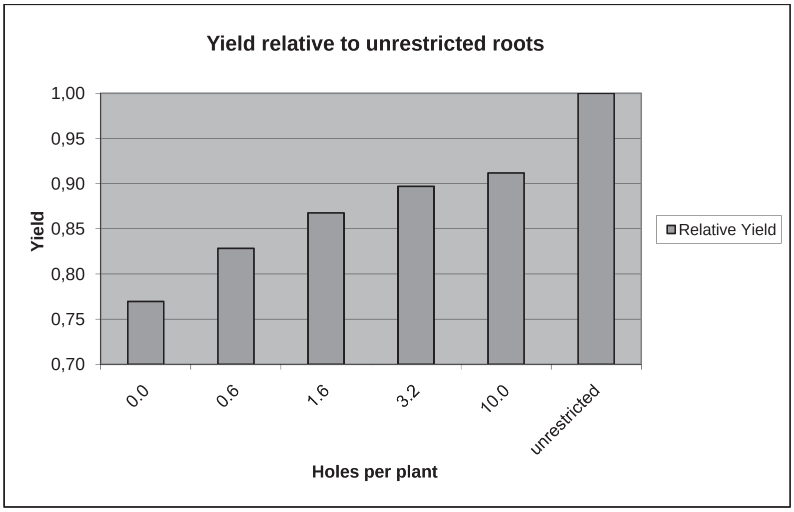
Keywords: root-soil; physical constraints; biopores; penetrometer; soil variability

Introduction

McKenzie et al 2009 clearly demonstrated that in a root restricting environment and under water limiting conditions the physiology of barley (Hordeum vulgare) responded positively to access of root systems to the subsoil. The methodology used to make this demonstration was to bury horizontal sheets of fluid-permeable membrane 20cm deep in the soil. Sections of the membrane had been punctured to provide access for a number of roots to the subsoil. Under water limiting conditions the physiological changes result in decreased crop yield (Figure 1).

Figure 1 Barley yield relative to crops with unrestricted access to the subsoil (Unrestricted yield 1.0 = 0.415 kg/m^2 LSD5%= 0.71kg/m^2). Access to the subsoil was controlled by burying horizontal sheets of fluid-permeable membrane at 20cm depth. Prior to burial the sheets had been differentially punctured with nails to create holes in the membrane that roots could penetrate. The number of holes is expressed as holes per plant based on the sowing rate of 300 seeds/m2. Mean yield for 5 cultivars.

While Figure 1 shows a clear yield response to subsoil access across 5 common spring barley cultivars, the response was not consistent across the cultivars. While 3 cultivars showed a statistically significant response to access to water in the subsoil, 2 others showed only non-significant trends. As differences exist between cultivars of the same crop, greater variation between crops might be expected, implying that the root systems of some crops may be more or less responsive to subsoil constraints.



Further, while the negative yield response to root restriction shown in Figure 1is for one season such responses do not occur in all seasons. If sufficient rain (or irrigation) supplies all the water needed by this crop at the times that it is needed then the yield penalty may be insignificant. This suggests that even where soil conditions are controlled, the response of crops to physical conditions is not straightforward. Re-visiting concepts such as potential yield (French and Schulz 1984) may help to explain crop responses to local conditions but greater understanding root-soil interactions and how these affect crop productivity, particularly how they vary in with time and location, is needed. Such information will be needed for crop breeding to improve root function or architecture to deliver improved productivity.

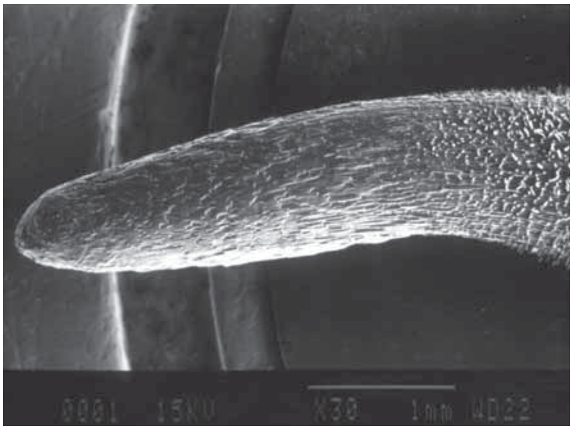
Roots and root-tips

To elongate through soil, a root must expand a cavity and overcome the friction necessary to elongate into the cavity. The penetration resistance, Q on an object penetrating the soil is:

$$Q = \sigma n + \sigma f \, , \qquad (1)$$

where σn is the stress normal to the surface of the object (which is also the pressure required to expand a cavity in the soil) and σf is the sum of frictional terms resisting penetration (Bengough 1992). Measurements have been made of the maximum turgor pressures generated by roots (e.g. Clark et al 2001), and these relate to the ability of roots to expand a cavity within soil. However there is still uncertainty of the relative magnitude of σn and σf.

Figure 2 is an scanning electron micrograph (SEM) of a pea root with some of the root tip mucilage removed exposing border cells covering the elongation zone back to the root hairs emerging 2-3mm behind the tip. The mucilage and border cells lubricate the tip to minimise soil-root friction.



The ability of a root to create a cavity is controlled by turgor and hence for a root in soil depends on the soil water status. Similarly in soil the extent of hydration of the mucilage covering the root cap will depend on the soil water status. There are differences between root tip shape and border cell type between crop species. For comparison, see Bengough and McKenzie (1997) which shows similar SEM's of maize roots. Recently Lipiec et al (2012) have compared the anatomy of the roots of a range of cereal crops that were grown in either compacted or un-compacted soil and found a number of changes – not only to the gross morphology but also to the vascular cylinder and cell shape.

While some roots may be able to penetrate deep into the soil by following cracks or biopores to fully explore the soil and to exploit the water and nutrients therein the roots need to leave these channels and penetrate the soil matrix (Hirth et al 2005). Roots will more easily leave a biopore if the biopore is aligned nearer to the horizontal and if the surface of the biopore is rough rather than smooth.

Soil physical properties and their relationships with root growth

Soil physical properties are interconnected and in summation create an environment that influences the growing root. There have been several recent reviews of the impact of soil physical conditions for root growth and crop production (e.g. Bengough et al 2011, Dodd et al 2011). A reason for the renewed interest in root-soil interaction results from advances in crop genetics that offers the possibility of crop breeding for improved root characteristics; however these reviews note that to exploit the available genetic information improved understanding of the interactions between roots, including root architecture, and the physical environment is needed. Commonly described and quantified soil physical properties that are directly related to root elongation include, water status, mechanical impedance, oxygen status and temperature. The importance of each of these will be now briefly described and their interconnection considered.

Water is vital for crop production and the relationships between root function and water availability has been long studied. Common definitions of field capacity and wilting point (and the volumetric water contents that these relate to: Θfc and Θwp) can be found in standard soil science or agrophysics texts (e.g. Hillel 1980, Encyclopedia of Agrophysics 2011). It is beyond the scope of this review to discuss the merits of the definitions but it is worth noting (as Hillel 1980 sets out) that to consider water held between these limits as equally available to the plant or that wilting is independent of evaporative demand lacks physical basis. They are however widely used and can serve as useful indicators. Root elongation rate decreases in response to decreasing soil matric potential (e.g. Veen and Boone 1990).

Penetrometers (metal cones on a relieved shaft that can be pushed into the soil) are the best method to approximate the mechanical impedance experienced by elongating roots. Typically the penetration resistance is between 2 and 8 times greater than the root penetration resistance. The differences are due to several factors including that penetrometers typically have much faster penetration rates, that the geometry of the root tip is different from a metal cone and that the root is able to influence the friction between itself and the soil (as described above). Bengough et al (2011) have summarised several studies that demonstrate that the rate of root elongation of roots is inversely correlated to mechanical impedance even when sufficient water is available. Typically root elongation decreases to less than half an unimpeded control in soil with a penetrometer resistance of 2MPa. This 2MPa (sometimes 2.5MPa) value is widely used as a standard above which soil strength is deemed to be restricting for root proliferation. For a given soil and soil condition, the greatest water content (Θmr) at which the penetrometer resistance does not exceed 2MPa has been defined as not restricting root proliferation.

For most crops, root system activity is adversely affected by oxygen deficiency associated with waterlogging, and with increased soil density decreased oxygen diffusion can contribute to decreased crop yield. (Czyz 2004, Dresbøll and Thorup-Kristensen 2012). Dexter (1988) suggested that 10% of the soil volume needs to comprise gas-filled pores and for at least 10% of that gas to be oxygen for the supply to roots to be adequate. The water content (Θafp) at which the air-filled porosity is at least 10% is a common standard for soil quality to be deemed acceptable.

When water and aeration are not limiting soil temperature is an important factor in the germination and emergence of seedlings (Addae et al 1991). As lower soil temperatures may delay seedling emergence, lower temperatures associated with reduced tillage has also been suggested to decrease crop shoot mass (Vakali et al 2011). Similarly high temperature stress has been shown to decrease biomass production in maize and change the interaction between roots and soil organisms (Zhu et al 2011).

Frameworks to combine soil physical conditions for roots

More than 20 years ago Boone (1988) proposed an envelope to account for the effects of the range of soil physical effects on root growth and crop production (Figure 3). In Figure 3 soil wetness and temperature are independent variables. These independent variables are deemed major determinants of the stresses on roots associated with drought, soil hardness and poor aeration. Boone considered this context as a way to consider the influence of soil management including soil tillage and traffic.

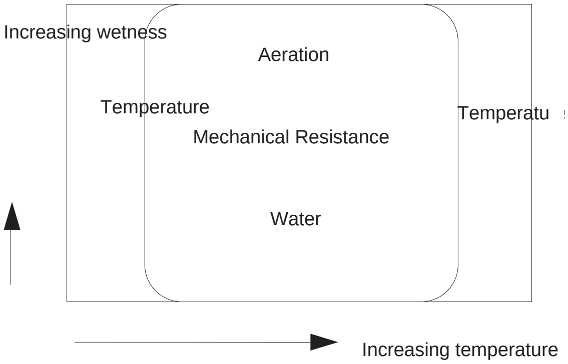


Figure 3 Representation of the least limiting water range llwr (after Boone 1988)

Letey (1985) introduced the concept of the non-limiting water range which while omitting temperature effects linked the separate effects that water, aeration and mechanical resistance have on root growth. This approach has been further developed into the least limiting water range (da Silva et al 1994) and extensively built on (e.g. Mohammadi et al 2010) and deployed (e.g. Olibone et al 2010).

Temporal variability in soil physical properties

Soil physical properties are interconnected with each other and in summation create the environment into which roots proliferate, the soil biology functions and the processes of filtering and buffering can take place. These properties will vary in time as well as in space. Within a stable soil structure it is the variables of soil wetness and temperature as Boone (1988) proposed that can be managed to provide an support crop growth. For example soil water content will increase with rainfall or irrigation and evaporation from the soil surface can be altered with the use of surface mulches. Soil temperature can similarly be modified by mulching and irrigation.

Figure 4 illustrates the changes that might occur in the soil environment over the growing season of an irrigated summer crop in the southern hemisphere. Here the water content is shown as discrete points (represented by stars) but could be quantified on a continuous basis using data-loggable water-sensors. The horizontal lines are set to the soil physical properties described above, but other water dependent standards be needed these could equally be deployed.

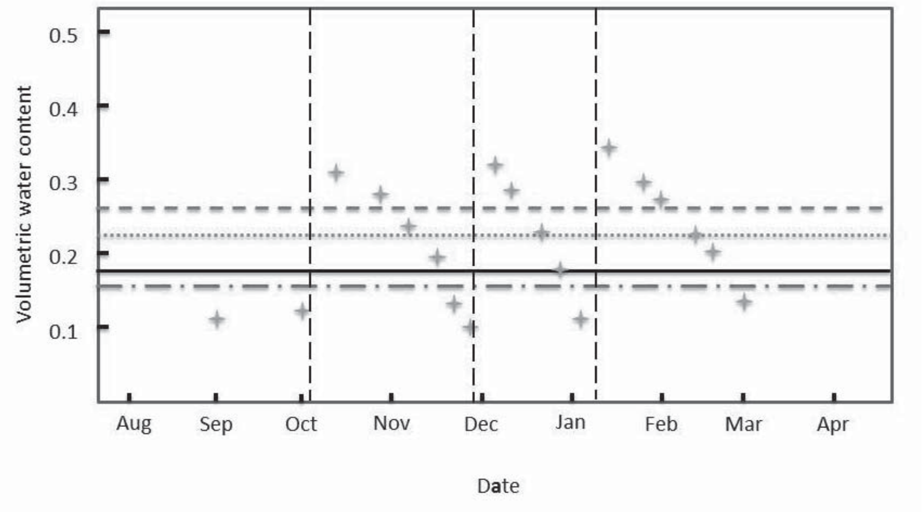


Figure 4 Measured volumetric water contents of a Red-Brown Earth soil at 0.2m depth. The laboratory determined values for the corresponding depth are (Θfc ….. green), wilting point (Θwp -.-.-.-. red), mechanical impedance (Θmr ------ black) and (Θafp - - - - blue) are shown as horizontal lines. Vertical dashed lines indicate irrigation. (After Vance 2002)

The example in Figure 4 is for a depth of 0.2m – in this case below the depth of cultivation. The limiting factors (aeration, drought or mechanical impedance) can be determined for any depth or horizon and hence other or multiple depths could be used. This offers the potential to target measurements at depths suspected of being limiting to root proliferation (e.g. where traffic-pans have been identified). Because the stresses are plotted against time it is possible to quantify the duration that any limiting factor is affecting the crop. In practical terms this can be presented as stress-time; e.g. number of days where the soil hardness limited root elongation. Management (e.g. irrigation) could be matched with known periods of sensitivity for any given crop.

Further the approach shown is Figure 4 identifies which stress (aeration, drought or mechanical impedance) is most likely to be detrimental to the crop and future management could be targeted to alleviate that stress. Maximum and minimum temperatures for root elongation of the crop use could be included by for example using the right hand axis.

Conclusions

An extensive root system is a major contributor for crops to achieve efficient use of water and nutrients. There are identifiable limits of wetness, aeration and soil strength for root growth outside which any crop will be stressed. Similar approaches could be applied for seedling emergence. By combining understanding of these standards in time and space the soil environment can be monitored for its suitability for productive use and where possible or necessary management may be deployed to deliver sustainable production.

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