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Physical limitations to root growth: screening, scaling and reality

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ABSTRACT

Climate change predictions are for increased variability of rainfall in many regions worldwide, resulting in greater fluctuations in soil water regime. Crop root systems will be subjected to increased physical stresses – specifically the incidence of intermittent water stress, soil mechanical impedance, and hypoxia. We need to understand the relative importance of these stresses to target particular crop cultivars to soil physical conditions. Frequently, a single root system (and even a single root tip) experiences a combination of physical stresses, presenting a challenging fluctuating environment for root growth coordination. Our data suggest that water stress rarely acts in isolation from mechanical impedance, whereas mechanical impedance frequently limits root growth even in relatively wet soils, often increasing by an order of magnitude as the soil dries. We found that penetrometer resistance exceeded 2MPa in more than one third of arable topsoils that we examined, at water contents approaching field capacity.

Plant scientists are responding to these environmental threats with increased interest in screening crops for particular root phenotypes. However, there are three major difficulties: seedling root system properties may not scale to root system properties of more mature plants; root systems are very plastic in relation to environmental conditions; and different types of root system are required for particular soil stresses. The electrical capacitance techniques offer a rapid glasshouse or field-based method for estimating root mass. Good correlations were obtained for barley seedlings grown in soil, and mature wheat plants of 35 varieties grown in sand columns. More information is needed on how root mass distribution in soil contributes to root capacitance.

KEY WORDS: abiotic stress, drought, root growth, scaling, mechanical impedance, root-soil interactions

1. INTRODUCTION

Crop yield depends on extracting sufficient nutrients and water from the soil. The root system has to elongate to a root length density sufficient to extract resources quickly from a volume of soil that contains these resources. Rainfall is predicted to increase in variability due to climate change, resulting in greater frequency of drought and waterlogging, and this will increase soil physical limitations to root elongation.

Comparatively little is known about the relative occurrence of soil physical stresses limiting to root growth, despite their great potential importance in restricting root growth. It is important to develop methods for assessing the relative importance of these stresses in soil, so that targets for plant breeding can be appropriately prioritized. Similarly, methods for screening large numbers of plant root systems must be developed, that relate to both root growth of seedlings, and to root growth of more mature plants in the field.

In this paper we consider how water status influences the physical stresses experienced by plant roots, and how this fluctuates during a growing season. The mechanical impedance experienced by roots growing in arable soils throughout Eastern Scotland is inferred from penetrometer resistance measurements at known matric potential. The utility of root capacitance as a screening method for root mass is determined for both young and mature cereal root systems, and considered in relation to other screening methods.

2. METHODS

Measurement of soil strength at known matric potentials: 59 Arable fields (usually two per farm) throughout Eastern Scotland were sampled at a depth of 5-10 cm, using 56 mm internal diameter soil core rings (x 40 mm deep). Prior to testing cores were equilibrated to -20 kPa matric potential on a ceramic plate tension table. Penetrometer resistance was measured using a 1 mm diameter penetrometer probe at a rate of 4 mm/min, for 3 cores/field (readings averaged 5 mm to 15 mm depth). Further detailed experiments were performed on one sandy loam soil (Mid-Pilmore, at SCRI) equilibrated to -10, -25 , -50 or -200 kPa, to obtain the soil strength characteristic.

Water content variation in relation to the least limiting water range Volumeteric water content was monitored using soil capacitance sensors in Mid-Pilmore soil at SCRI site during spring and summer 2007, to determine the soil physical factors likely to be limiting root growth.

Root capacitance versus root mass as a screening method Root capacitance (1 kHz, 1V) was measured for spring barley (cv. Optic) grown for up to 1 month in tubes of repacked Mid-Pilmore soil (5 cm diameter x 50 cm long) to evaluate its the relation with root mass, using a similar method to (Dalton 1995). Further experiments evaluated root capacitance versus mass relations for 35 varieties of wheat grown in sand/gravel columns at crop maturity.

3. RESULTS

39% of soils examined had a penetrometer resistance greater than 2 MPa, indicating that mechanical impedance was potentially a major limitation to root elongation (Fig. 1a). In the Mid-Pilmore soil, a rapid increase in penetrometer resistance with decreasing matric potential shows how effective stress due to water surface tension greatly increases soil strength as the soil dries (Fig. 1b). Thus it is likely that many more of the soils examined would have penetrometer resistances greater than 2 MPa at matric potentials drier than -10 kPa.

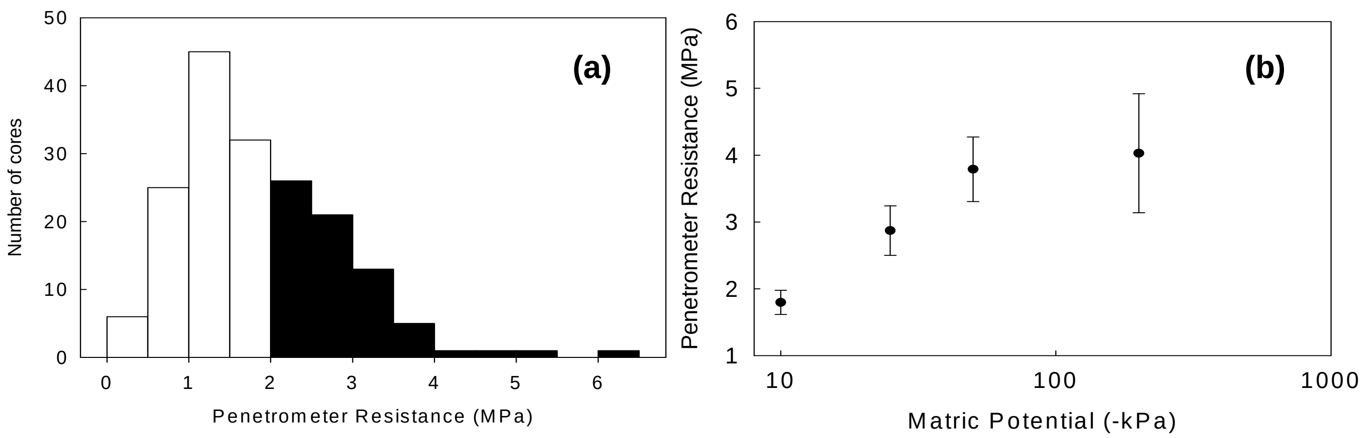

Figure 1. (a) Distribution of penetrometer resistances (b) Strength characteristic for sandy loam soil (5-10 cm depth under minimum tillage).

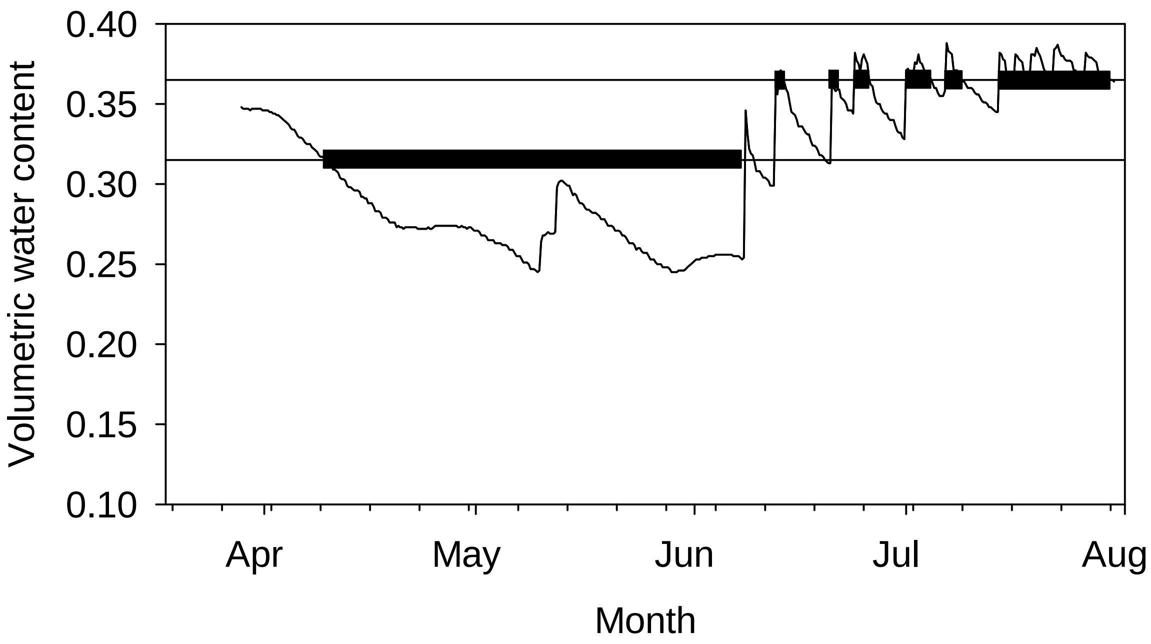

Figure 2. Volumetric water content vs time (25 to 30 cm depth, at single location in ploughed soil). Horizontal lines indicate least limiting water range (bars show outside LLWR).

In the example shown in Fig, 2, volumetric water content was outside the least limiting water range for 70% of the time between April and the end of July. Mechanical impedance limited root elongation during stem extension, with hypoxia limiting later in the summer.

Root capacitance was correlated strongly with root fresh mass (R^2=0.884) in barley, indicating its suitability for use in screening studies. Root capacitance was again correlated with root dry mass across 35 different varieties of wheat grown to maturity in sand columns (R^2 = 0.753, n = 67 plants).

4. DISCUSSION

Penetrometer resistances in excess of 2 MPa indicated that mechanical impedance to root growth would limit root growth in 39% of the samples tested, even when the soil was relatively wet (Fig. 1a). Given the strong increase in penetrometer resistance as soil dries (Fig. 1b), it is likely that strength would be an even greater limitation to root growth for much of the growing season (Fig. 2). These conclusions are broadly in agreement with the relatively few studies from the literature (daSilva *et al.* 1994; Topp *et al.* 1994; Bengough *et al.* 2006), that for many soils mechanical impedance is often the most important physical limitation to root growth. The strengths in the range indicated in Fig. 1b are sufficient to decrease root growth very substantially, and also decrease shoot growth via root-shoot signaling (Passioura 2002).

New methods are being developed and applied to screen for differences in root growth, both laboratory and field-based (McKenzie *et al.* 2009; Bengough *et al.* 2004). These methods concentrate at both the seedling, and mature plant scales. We need to better understand the effectiveness of these methods and how they can be used to screen for root growth traits. Root capacitance is of particular interest in screening for root mass in the field, and showed promising correlations in the laboratory, both in soil for young plants, and in sand/gravel for mature plants of a wide range of cultivars. Further experiments are planned to test the contributions of roots distributed at different depths in the soil profile.

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