Soil Stability and the Architecture of Root Systems

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Project Objectives

In the first year of the project we have characterized saturated soil shear strength in fallow soil (controls) and in soil planted with *Avena fatua* as a function of several key variables: depth from soil surface, plant developmental stage, and soil compression. Root tensile strength was measured as a function of distance from the root apex in well-watered and water-stressed roots. Root growth analysis revealed the spatial pattern of expansion producing the root elongation in the soil. Root architecture was characterized to correlate with the soil shear strength measurements. We addressed management implications by networking with Andrew Simon and Danny Klimetz of the USDA-ARS National Sedimentation Laboratory and Alison Berry of Plant Sciences Dept. UCD. Importance of plant cover for soil stability and riparian habitat was taught in two undergraduate courses at UCD.

Approach and Procedures

The experimental plan has been to monitor root development and relevant properties (morphological and mechanical plant attributes relevant to soil strength) in conjunction with the evolution of soil shear resistance and erodibility. Results are interpreted in terms of existing engineering models for stabilization of soil by root systems.

Plants and Soil

Avena fatua (wild oat, producing a fibrous root system) and *Daucus carota* (garden carrot, producing a taproot) were used, as they proved easier to collect than the species (with similar root morphologies) originally proposed. Soil was collected from the UCD site for Long Term Research in Agricultural Systems (LTRAS), dried at 60 ^{o}C for 4-5 days, ground and sieved to 2-mm particle size. The soil was a productive agricultural soil managed with an organic tomato/corn/legume cover crop rotation and characterized as Yolo silt loam, a fine-silty, mixed, nonacid, thermic Typic Xerorthent (Burger 2003). Seeds were planted two per square inch in five gallon pots filled with soil made to a bulk density of 1.51 Mg m^{-3} with 15 % water corresponding to drained field conditions. Plants were cultivated in a Conviron growth chamber at 13 h day (26 ^{o}C) / 11 h night (19 ^{o}C). Soil cores were collected at one, three, and seven weeks after planting. Coring was with a Geoprobe hydraulic push / hammer system fitted with a galvanized steel, thin sampler head from Boart Longyear. Soil cylinders were extruded onto flexible, transparent plastic sheets that were wrapped to maintain a soil cylinder of 5-cm diameter for transport to the soil testing machine. For mechanical testing and subsequent architectural analysis the plastic wrapped cylinders were sliced into five-cm lengths located at 3-8 cm, 11-16 cm and 19-24 cm from the soil surface.

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Soil Shear Strength

Soil shear forces and displacements were measured with a modified interface direct shear device in the laboratory of Prof. DeJong (Fig.1) Sensors were in direct contact with the shear box and soil specimen. Only saturated soil properties were measured. Desired duration for saturation time was determined empirically. Since all settlement occurred roughly 30 minutes into the saturation time, a duration of two hours was set. The cylindrical sample was placed inside the shearing device made of two parts. The lower part is held still and the upper part is moved at a constant velocity, 0.0254 mm/h, until it is displaced by 1.27 cm. The shearing velocity of 0.0254 mm per minute was used to ensure that all excess pore pressure generated during shearing had ample time to dissipate.

Fig. 1A Moist soil sample after trimming. **Fig. 1B** Soil sample mounted in the shearing device.

Root Tensile Strength

The force required to break roots was measured by subjecting clamped roots to progressively larger tensile force. Roots were clamped in metal clips lined with foam and sandpaper. An increasing traction force was applied by hanging a plastic bottle at one end of the root segment and slowly adding water with a squeeze bottle until the root broke (Fig. 2). The water was weighed and root diameter was measured with an ocular micrometer. Root tensile strength *T* (in MPa) is calculated as shown in the figure.

$T = B\,g/A$ where T is the root tensile strength, B is the weight (kg) required to break the clamped root, g is the gravitational constant, and A is the area of the root cross-section (m^2).

Fig. 2A Force application **Fig. 2B** Root segment in clamp

Root Architecture

Existing engineering theory emphasizes the importance of the cross-sectional area of roots per area of soil (Waldron, 1977; Wu, 1998; Bengough, 2009). The "root area ratio" was determined using calculations based on output of a WINRHIZO root measurement system (www.regentinstruments.com). The slices of soil were washed gently to remove the soil. Then dissected roots were placed on the slide of a high-resolution flat bed scanner and the root images were analyzed. The root length density output provided by Winrhizo was converted into numbers of roots crossing a fictional shear plane for each diameter class.

Fig. 3A Winrhizo image of dissected root system)

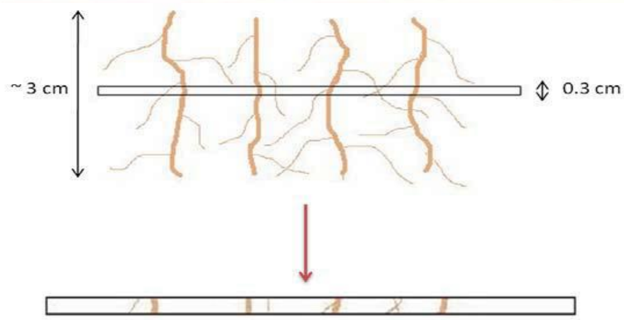

Fig. 3B Narrow horizontal slice used to measure the number of roots crossing a fictional shear plane.

Results

Root tensile strength increases with distance from tip for more than 40 cm (Fig. 4). This trend is related to developmental age of the tissue. Because the root elongation rate is a bit less than one mm h^{-1}, the results show that root tensile strength increases for over 400 hours of development. Root tensile strength is also greater in roots grown in dry soil (Fig. 4, yellow and blue symbols).

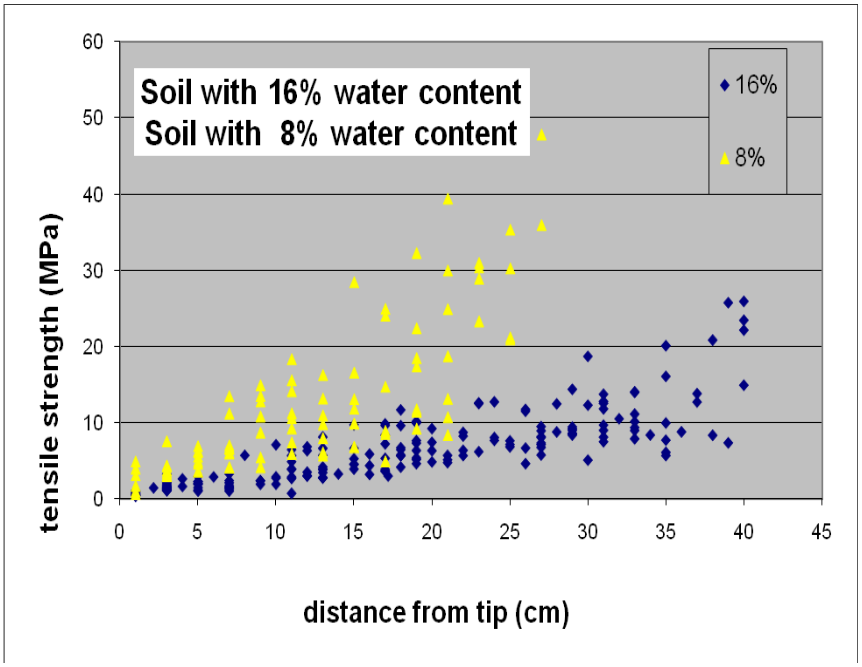

Fig. 4 Root tensile strength as a function of distance from the root tip (tissue developmental stage) in moist and dry soils

The distance effect, related to tissue age, does not involve diameter changes. The water stress effect is largely explained by thinning of roots under water stress (Fig. 5). Roots increase soil shear strength in the upper soil stratum, but this does not occur until plants are seven weeks old (Fig. 6).

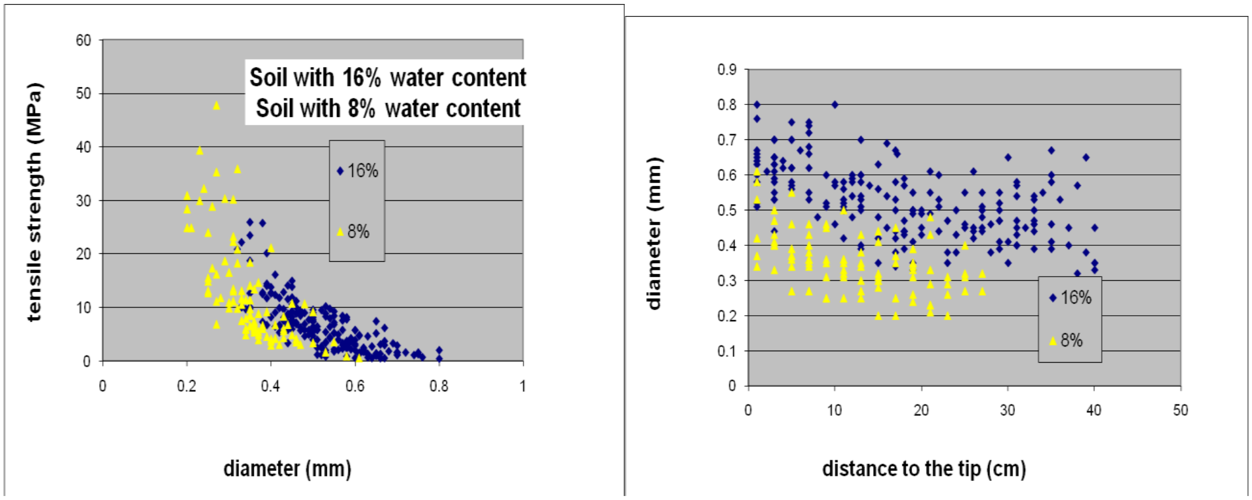

Fig. 5 (left) Decrease in root tensile strength with diameter **(right)** Invariance of diameter with distance from tip (developmental age)

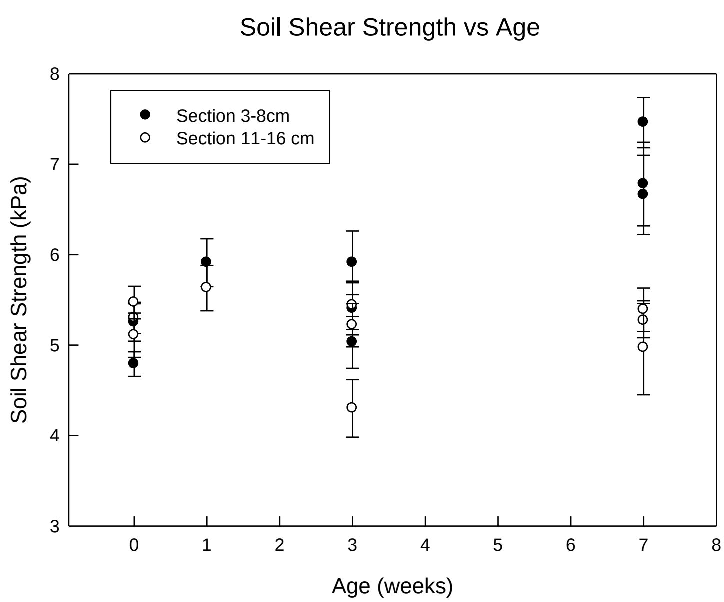

Fig. 6. Soil shear strength in fallow soil and at one, three and seven weeks after planting.

The root area ratio increases between one and three weeks after planting in the upper 16 cm of soil, but root area ratio (RAR) is not greater at seven than at three weeks (Fig. 7).

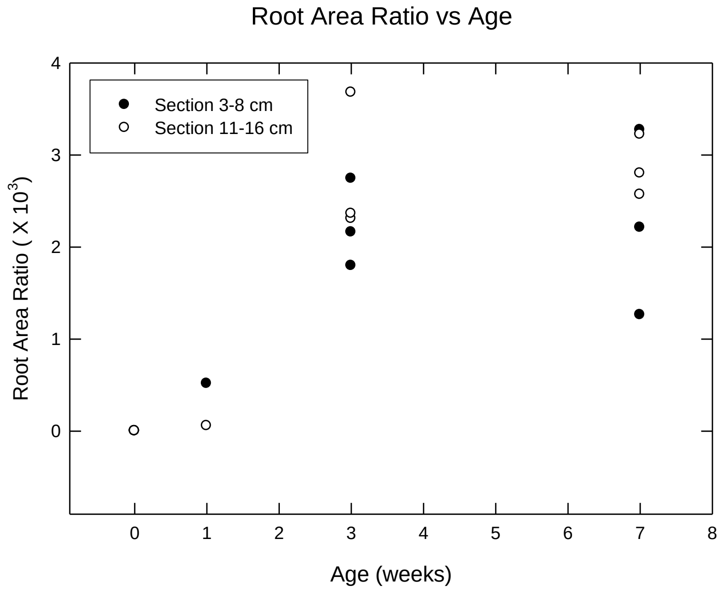

Fig. 7. Root area ratio in fallow soil and at one, three, and seven weeks after planting

Discussion

Engineering models predict a causal relationship between root area ratio (RAR) and soil shear strength (Waldron, 1977; Wu, 1998; Mickovski, 2009). Studies in the literature show a correlation between RAR and soil shear strength although the effect is smaller than expected with the classical models. Fiber bundle models are able to explain some of the discrepancy between observation and theory (Pollen 2005; 2007). Most studies show a large effect of roots on soil strength after months or years of plant growth (Waldron, 1981; Mickovski, 2009). We found a smaller strengthening of soils by oat roots seven weeks after planting. This effect was not correlated to an increase in root area ratio. The increase in soil strength could be explained by the observed increase in root tensile strength with developmental age. If the roots are resisting soil shear until the roots break, the increased tensile strength is the beneficial mechanism. However, if the roots are resisting soil shear by pulling out of the soil rather than by breaking, then the increased soil strength may be due to soil strengthening compounds released by roots between three and seven weeks after planting. Experiments are in progress to test the occurrence of breaking and pullout and to measure the protective effects against erosion.

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