Soil Stability and the Architecture of Root Systems

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Project Objectives

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 area per unit of soil area was characterized to correlate with the soil shear strength measurements. Soil erodibility is being characterized as a function of plant developmental stage.

The PI put some effort into studying the water relations sustaining elongation. Mathematical models and automated time lapse growth studies led to increased understanding of the path of water from soil through the plant to enable root elongation and thereby soil stabilization at deeper layers.

We addressed management implications by networking with Andrew Simon, Danny Klimetz, and Natasha Pollen of the USDA-ARS National Sedimentation Laboratory, Michelle Watt of CSIRO in Australia, 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. Results were communicated to experts in plant-soil relations at an international meeting of the Functional and Structural Plant Modeling group and at an international workshop on plant modeling supported by the National Science Foundation.

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. Ongoing studies of growth-sustaining water relations provide deeper understanding of the mechanism of root elongation through soil.

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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°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 and Jackson 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°C) / 11 h night (19°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 5-cm lengths located at 3-8 cm, 11-16 cm and 19-24 cm from the soil surface.

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 of 0.0254 mm/min until it is displaced by 1.27 cm. The shearing velocity of 0.0254 mm/min was used to ensure that all excess pore pressure generated during shearing had ample time to dissipate.

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 Figure 2.
Fig. 1A A moist soil sample after trimming.
Fig. 1B Soil sample mounted in the shearing device.

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

\[ T = \frac{B}{gA} \]

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\(^2\)).
Root architecture

Existing engineering theory emphasizes the importance of the cross-sectional area of roots per area of soil, or “RAR,” as a quantitative measure of root density (Ennos 1989, Mickovski et al. 2009, Waldron 1977, Wu 1998). The RAR 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 (Fig. 3). The root length-density output provided by Winrhizo was converted into numbers of roots crossing a fictional shear plane for each diameter class.
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Results

Effect of roots on soil strength

Roots increase soil shear strength in the upper soil stratum, but this does not occur until plants are between three and seven weeks old (Table 1).

\[ \text{Table 1. Mean shear strength of fallow soil and planted soil following one, three, and seven weeks of root development.} \]

<table>
<thead>
<tr>
<th>Age of Root System</th>
<th>Shear Resistance (kPa)</th>
<th>3-8 cm depth</th>
<th>11-16 cm depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fallow Soil</td>
<td>4.81 ± 0.09</td>
<td>5.13 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>Planted one week</td>
<td>4.91 ± 0.22</td>
<td>5.15 ± 0.29</td>
<td></td>
</tr>
<tr>
<td>Planted three weeks</td>
<td>4.96 ± 0.27</td>
<td>4.89 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>Planted seven weeks</td>
<td>6.48 ± 0.22(^a)</td>
<td>5.22 ± 0.14</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\) only statistically significant difference from the other means (P<0.01)

Components of soil strength, root tensile strength and root area ratio

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 greater in roots grown in dry than moist soil (Fig. 4, yellow and blue symbols).

\[ \text{Fig. 4 Root tensile strength as a function of distance from the root tip (developmental stage) in moist and dry soils} \]
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The distance effect, related to tissue age, occurs over a length characterized by uniform diameter. In contrast, the water stress effect is associated with thinning of roots under water stress (Fig. 5).

Fig. 5 (above) Decrease in root tensile strength with diameter (below) Invariance of diameter with distance from tip (developmental age)

Root area ratio increases throughout the seven week period in both upper and lower soil strata (Fig. 6). The increase is particularly large in the upper stratum between three and seven weeks, when branch roots are seen to grow extensively. At seven weeks the root area ratio in the 11-16 cm depth is similar to that found at three weeks in the 3-8 cm layer.
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![Bar chart showing root area ratio in two soil depths at one, three, and seven weeks after planting. Significant differences among means are indicated by different letters.]

**Fig. 6.** Root area ratio in two soil depths at one, three, and seven weeks after planting. Significant differences among means are indicated by different letters.

**Related work of PI supported by other funding sources—Water relations for root growth**

Root stabilization of soils requires root elongation and is affected by root radial growth. The primary process in growth is osmotically driven water uptake generating hydrostatic (turgor) pressure to inflate the cell, stretching the rigid cell walls. Thus water relations of growing tissue are basic to the growth process and thereby the process by which roots can stabilize soil. During the grant period, ongoing theoretical and empirical studies of water relations have contributed to our understanding of root-soil interactions.

*Mathematical modeling* (Wiegers, Silk and Cheer 2009). Growth is characterized by cell expansion facilitated by water uptake. The multiple source theory of root growth hypothesizes that root growth involves transport of water both from the soil surrounding the growth zone and from the mature tissue higher in the root via phloem and protophloem. We assumed protophloem water sources as boundary conditions in a three-dimensional model of growth-sustaining water potentials in primary roots. Our model predicts small radial gradients in water potential, with a significant longitudinal gradient. The results improve the agreement of theory with empirical studies for water potential in the primary growth zone of roots of maize (*Zea mays*). A sensitivity analysis quantifies the functional importance of apical phloem differentiation in permitting growth and reveals that the presence of phloem water sources makes the growth-sustaining water relations of the root relatively insensitive to changes in root radius and hydraulic conductivity. Adaptation to drought and other environmental stresses is predicted to involve more apical differentiation of phloem and/or higher phloem delivery rates to the growth zone.
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**Time lapse experiments** (Boyer, Silk and Watt 2010). Wheat (*Triticum aestivum*) roots were followed by automated time lapse photography in soil, from soil into air, and after excision from the plant body. The time lapse experiments show that in moist soil phloem provides 26 to 45% of the water for rapid root growth, while the rest comes externally from the soil surrounding the growth zone. The mathematical theory of Wiegers et al. (above) shows that the phloem could supply 64% of the total water for growth. This indicates that phloem water can be used to sustain growth when root tips cannot access external water, such as in cracks or pores or regions of dry soil. The distribution of phloem-delivered water for root growth should be considered in whole-plant modeling of root systems and their ability to stabilize soil.

**Discussion**

**Low correlation between shear strength and RAR in our system**

In agreement with all theoretical models, most studies in the literature report strong correlations between root density (RAR) and soil strength (Mickovski et al. 2009, Pollen & Simon 2005, Waldron 1977, Waldron and Dakessian 1981, Wu and Watson 1998). In our Kearney study, root density increased with time in both shallow and deeper layers. Yet soil shear strength increased only in the shallow layer (3-8 cm) and only between three and seven weeks after planting. Furthermore, other studies found large increases in soil strength in root-permeated soil (compared to fallow soil) while we found a modest increase at seven weeks and only in the upper soil stratum. For instance, we find saturated soil is increased in shear strength over fallow soil by 1.67 kPa, or 33%. In contrast, a recent publication reports 100% increase in shear strength in field soil and 53% in greenhouse soil at five weeks after planting with barley, another fibrous root system (Loades et al. 2010). Another study reports more than 500% increase in soil strength conferred by grasses (Comino, Marengo and Rolli 2011). However, these soils were sheared at field capacity rather than at saturation. The small increase in measured shear strength provided by roots in our system is attributed partly to our characterization of saturated soil, while many of the studies in the literature characterize drained soil. Our results are relevant to the problem of shallow landslides and erosion after rainfall. We conclude that planting with wild oats will provide modest protection against soil sliding at two months after planting, and roots are well established at this time. Work remains to understand the factors causing the large variation in root reinforcement reported in the literature.

**Need for plant developmental properties in soil stability models**

Roots are widely known to improve the stability of soil, and over the last several decades considerable efforts have been made to develop models based on physical properties of roots that allow one to predict the strength conferred to the soil by the root system. The models hypothesize that root reinforcement is largely a function of the tensile strength of the individual roots and the area of roots crossing the shear plane. However, implementation of the models has ignored changes in root properties with development. In this study we monitored several root properties over time to provide a developmental perspective of root reinforcement on soils.

Root tensile strength was found to increase with distance from the root tip (Fig. 4). Tensile strength calculations are sensitive to the cross-sectional area of the root and root tensile strength decreased with root diameter, as other studies have shown (Figure 5; Mickovski et al., 2009; Pollen & Simon, 2005). However, root diameter was uniform with distance from root tip.
(between 2 and 40 cm), suggesting the increase in tensile strength was not associated with changes in diameter (Fig. 5). Rather, the increased tensile strength could be associated with developmental changes within the root. The exact mechanism for the increase in tensile strength is not known. Past studies have hypothesized a link between increased tensile strength and increased cellulose content (Genet et al. 2005), and it is possible the developmental changes we observed in root tensile strength reflect increases in cellulose content. We have begun looking at wall anatomy and biochemical components of the cell wall, particularly lignin, as possible contributors to the developmental increases in tensile strength.

The growth analysis can be combined with the information on spatial pattern of tensile strength to infer the progression of root-induced changes in soil properties. Since the tensile strength increases along the root axis for 40 cm, a growing root is predicted to increase strength in a particular moist soil layer during the 19 days (=400 mm / 0.9 mm per h) following initial appearance of the root tip in the layer.

The observation that root tensile strength increases under drought is interesting and worth exploring in future experimental work. Our work shows that in dry soil several growth attributes are affected. The increase in root tensile strength is five-fold greater (predicted to increase soil strength) while the diameter is reduced by one third (predicted to decrease soil strength). Since the elongation rate is slower in the drier soil, soil strength might increase more slowly, but for a longer time period following first appearance of the root tips in the soil layer. More experiments are needed to characterize effects of drought on both soil strength and root architecture.

Both the increase in root density and the increase in root tensile strength must contribute to increased soil strength. The increase in RAR at seven weeks is typically observed, but the changes in root tensile strength tell us that less conspicuous developmental changes occur and should be incorporated into structural and functional models for soil strength. Recently, root architecture models have made significant progress as computational power has improved (Dupuy, Gregory, and Bengough 2010; Leitner et al. 2010). Computer-assisted visualization technologies suggest the possibility to test and refine the comprehensive architecture simulation models (Iyer-Pascuzzi et al., 2010). Thus, with the development of complex three dimensional root architecture models, the opportunity exists to incorporate data on development of plant mechanical properties to create more predictive root reinforcement models that contain greater temporal data. The “waves of meristems” predicted by Dupuy et al. (2010) is a particularly intriguing concept that lends itself readily to including waves of developmental changes.

The wide variation in soil shear strength conferred by plants is intriguing and draws attention to the need to quantify other beneficial effects of developing roots on soil structure and function.

**References**


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This research was funded by the Kearney Foundation of Soil Science: Understanding and Managing Soil-Ecosystem Functions Across Spatial and Temporal Scales, 2006-2011 Mission (http://kearney.ucdavis.edu). The Kearney Foundation is an endowed research program created to encourage and support research in the fields of soil, plant nutrition, and water science within the Division of Agriculture and Natural Resources of the University of California.