Soils and Plant Roots

By Robert Mikkelsen

Sustaining agricultural productivity relies on maintaining a soil environment to support the growth of healthy roots. Because roots are not immediately visible, their importance is often overlooked. A number of biological, chemical and physical stresses in the soil can impair root function and have an immediate effect on plant growth. Boosting water and nutrient use efficiency by roots is an important key for enhancing sustainable agricultural production. A few important root and soil interactions are highlighted here.

Plant roots have many important functions, such as supporting plants, providing sufficient surface area to allow water and nutrient uptake, and serving as the synthesis site for a number of hormones and growth regulators. Despite their importance, plant breeding programs largely focus on increasing yield and pest resistance, without much attention on incorporating potentially valuable root traits. Some of these key traits might include early root vigor, a high root surface area, and deep rooting ability during times of moisture stress.

Plant roots grow in a complex soil environment densely populated with organisms, including bacteria, fungi, yeasts, protozoa, and insects feeding on multiple substrates. In the rhizosphere soil are a variety of interactions occurring between plant and soil organisms—interactions that can be positive or negative for the root.

A significant amount of the C fixed through photosynthesis is allocated to support growing root cells. For example, between 5 and 30% of the plant C is released into the soil as organic exudates, symbiotic associations with mycorrhizal fungi can use an additional 20% of the C fixed in the leaves. Nitrogen fixation also requires substantial C resources (5 to 10 grams of C for each gram of fixed N). Maintenance of healthy roots requires a large investment of the total plant C.

In times of stress (such as drought or nutrient deficiency), plants generally respond by increasing the C flow to the growth of roots at the expense of the aboveground portion of the plant. This root stimulation increases the likelihood of exploring and exploiting the scarce soil resources, but may reduce the aboveground yield.

Root Growth and Development

Soils must provide sufficient support to anchor the plant for months or years and supply adequate nutrients, water and air from the network of pores. When the physical properties of soil are damaged, the ability of roots to support plant growth is impaired.

Soil compaction can be a major impediment for normal root growth. Compaction from tractor and machinery traffic is significant; especially as the size of farm equipment increases. Soil compaction causes a compression of the large soil pores, resulting in slower water infiltration, air movement, and root growth.

Roots must force their way through soil and only grow in existing pores or soils that are compressible. In compacted soil, roots become stunted if they encounter much resistance. Roots in compacted soils often have shorter overall length, a higher concentration of roots in the top layer of soil (above a hardpan), and fewer roots than normal at greater depth. These smaller root systems can decrease the capacity for water and nutrient uptake, resulting in more susceptibility to stress during the growing season.

Abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; C = carbon; Al = aluminum.


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Since many plant nutrients have limited mobility in soil, roots must grow to the soil volume where the nutrients are located. Compacted soils result in reduced root growth and poor recovery of nutrients. For example, low root density in compacted soil results in a greater distance between neighboring roots, resulting in less opportunity to acquire nutrients.

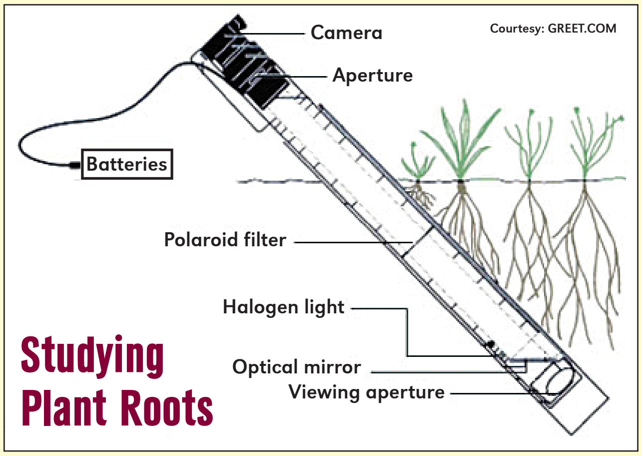
Subsoil tillage can help alleviate root growth limitations, but avoiding compaction is preferred to eliminating it after it occurs. Tillage equipment is available to disrupt existing compacted soil layers, and using controlled traffic patterns in the field keeps wheel compaction in specific areas. Deep-rooted crops can also help to begin to alleviate compacted soils. No-till practices may provide gradual, long-term improvement of compacted soils.

Nutrient Uptake by Roots

Roots develop in coordination with the overall vigor of the entire plant, as influenced by the soil environment. They invariably encounter environmental, chemical or biological stresses during the growing season causing them to rapidly adapt. For example, plants with root systems that are well suited to efficiently use resources in the surface layers of soil need to transform, through plasticity, to access soil moisture or nutrients from deep horizons to be successful during periods of drought.

Nitrogen: Nitrate is the dominant form of inorganic N taken up by most crop plants. One study found that 79% of N supply to maize roots came from mass flow, 20% by diffusion, and 1% by direct interception by roots (Watt et al., 2013). Early root vigor and a high root length density is a useful trait for intercepting nitrate as it moves with soil water before it might be leached below the root zone early in the growing season. When ammonium is a major N source, more soil exploration by roots may be advantageous since this N form is not highly mobile in soil water.

The important symbiotic relationship between roots of leguminous plants and N_2-fixing bacteria contributes to the N requirement of many important crops. A long-term goal for



Studying Plant Roots

Plant roots have been traditionally studied by extensive digging projects to extract roots from the soil. In the last 50 years, the use of non-destructive techniques has made root studies more convenient and rapid. For example, a variety of rhizotrons and mini-rhizotrons (root windows) have been developed to observe root activity in soil without destructive sampling. Early rhizotrons consisted of glass walls placed on the face of a soil. Minirhizotrons typically involve installation of a transparent tube into the root zone lowering an imaging device into the ground.

In addition to direct observation and root measurement, there are many noninvasive root measurements that can be made directly on growing roots using microsensors and optical sensors.

scientists has been to understand the genetic controls that prevent non-legumes from serving as host for N_2 fixation.

Phosphorus: There is continued interest in improving the recovery and short-term efficiency of applied P fertilizer. Various agronomic practices help achieve this goal, but it is also feasible to accomplish increased P recovery by modifying the plant root architecture.

The concentration of soluble P is quite low in the soil, but plant requirements are fairly high. Because of its strong reactions with soil components, P is principally supplied to plant roots by diffusion. Young root tips, continually expanding into fresh soil, are exposed to higher P concentrations found in the bulk soil solution. The abundance of root hairs and association with mycorrhizal fungi also enhances P uptake from the soil. As P uptake occurs at the root surface, a depletion zone of 0.2 to 1.0 mm develops surrounding the root. This depletion zone around the root is a major driver of rhizosphere chemistry and nutrient availability.

Potassium: Roots take up K directly from the soil solution, which is in equilibrium with the exchangeable K and in a slow quasi-equilibrium with non-exchangeable K. Plant roots have specific mechanisms to acquire K. For example, K transporters and channels facilitate uptake under low a K supply.

The Role of Root Hairs

Root hairs are a major organ for acquiring water and mineral nutrients from the soil. They consist of single, tubular-shaped root cells that can extend up to 80 to 1,500 µm into the soil (approximately the thickness of a credit card). Individual root hairs typically survive for a few days or as long as two weeks. While new root hairs are being produced behind the root tip, older root hairs are dying off.

Root hairs facilitate nutrient uptake primarily by increasing the root surface area in contact with the soil and decreasing the distance that P must diffuse to the root. It is through the additional surface area provided by root hairs that the greatest proportion of P uptake occurs. It has been demonstrated that root systems with root hairs absorbed 78% more P than those without (Barley and Rovira, 1970). Plants growing in P-deficient soil frequently respond by increasing root hair length and density. Increased colonization by mycorrhizal fungi, which can extend up to several centimeters in P-deficient soils also accomplishes a similar result by transferring P to the root. Root hairs are also important for K uptake as they increase the root surface area and the K depletion zone in the soil.

Soil Acidity and Salinity

Soil acidity is one of the most important constraints for global crop production. Impaired plant growth in acid soils is not caused by a single factor, but includes toxicities of Al, H^+ and various nutrient deficiencies (such as Ca and P). The effects of elevated Al concentrations on roots first appear as shortening and thickening. Roots often become brown and branching is reduced as Al is accumulated. Some plant roots can detoxify excessive Al by excreting various organic acids to chelate Al. The application of limestone is the most widespread practice to overcome plant growth constraints in acidic soils. Adding limestone reduces the concentration of soluble Al in the soil by raising the soil pH, and supplies more Ca, which limits root activity when low. Gypsum is also useful as a Ca amendment in acidic soils.

Excessive salt concentrations are also a major constraint to plant growth in many important agricultural soils. Plant nutrients must be dissolved in the soil water before roots can take them up. However when salt concentrations become excessive, the water potential becomes equal to or below the water potential in root cells. Some plants can adjust to these high salt conditions, but many crop plants are not tolerant to osmotic stress so root cells and membranes become permanently damaged. Salt stress is often more visible in the leaves than the roots. Differences in salt tolerance among crops are primarily due to the varying ability of roots to exclude salts from uptake into the plant. Soil salinity is managed by leaching soluble salts from the root zone with additional water and providing adequate drainage to remove dissolved salts from the field.

Summary

Maintaining soil conditions conducive to healthy roots is fundamental for sustaining a secure food supply and promoting environmental stewardship. Enhanced efficiency of water, nutrients and resources is achieved when healthy roots lead to better crop growth. Without healthy roots, the yield potential of plants cannot possibly be met. Recent attention to the importance of various root functions will lead to an improved ability to manage productive cropping systems. BC

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References

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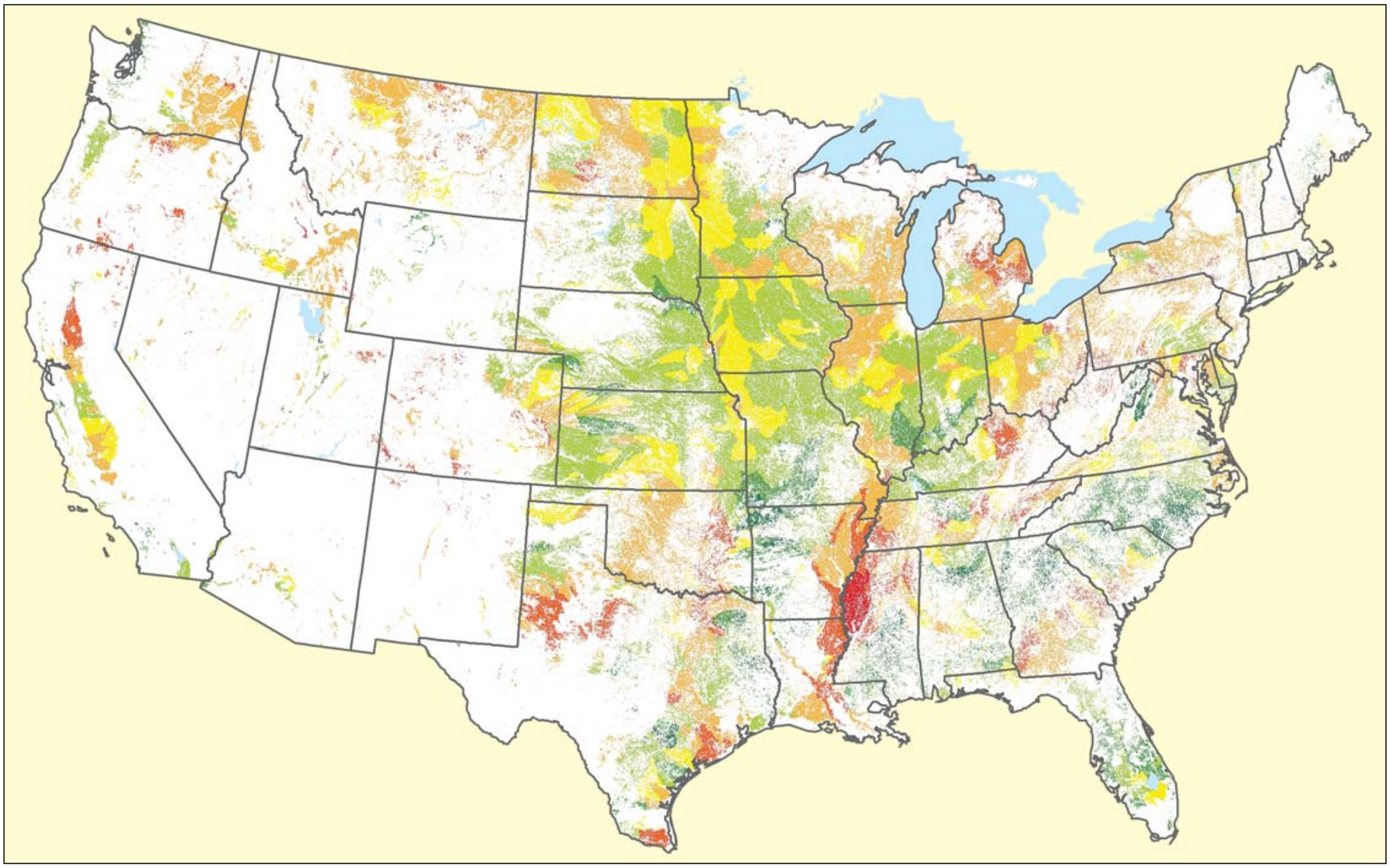
DATA UPDATE

U.S. Nutrient Use Geographic Information System (NuGIS)



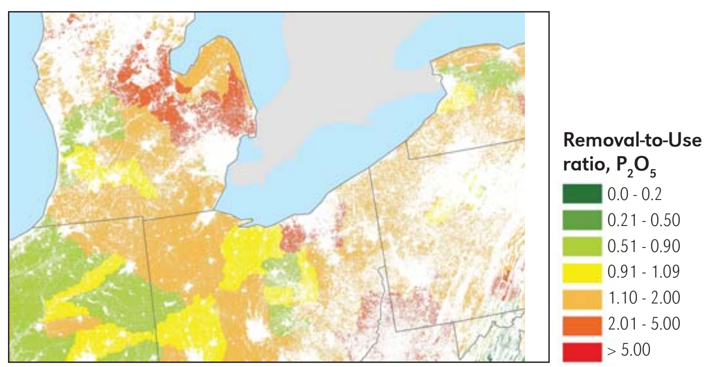
The two primary objectives of the NuGIS project are to assess nutrient use efficiency and balances for defined regions of crop production, and identify weaknesses in the balance estimation processes and the datasets used for these estimations. In the case of the U.S., the model predicts partial nutrient balance and nutrient removal-to-use ratios at county, state and watershed scales.

Sponsored and directed by the International Plant Nutrition Institute (IPNI), NuGIS integrates multiple tabular and spatial datasets to create county-level estimates of nutrients applied to the soil in fertilizer and livestock manure, and nutrients removed by harvested agricultural crops. Estimates coincide with the USDA Census of Agriculture years from 1987 to 2012. Geospatial techniques are used to estimate balances and efficiencies for 8-digit hydrologic units using the county-level data. The results are provided through interactive thematic maps and in tabular form.

In 2015, we added NuGIS analyses for more recent years, including non-Census years, and updated some previous years using improved input data.

Key improvements include:

- 2012 has been added as the most recent year of analysis
- Manure nutrient contributions have been updated based on recently released 2012 Census of Ag data. This currently affects 2010, 2011 and 2012 data. Data for 2008 and 2009 will be updated soon.



Estimated phosphorus removal-to-use ratio by watershed for 2012. Maps reflect Nutrient Removal by Crops / (Fertilizer + Recoverable Manure Nutrients + Legume N Fixation). Maps provided by PAQ Interactive.

- Higher resolution, recently updated land use maps for 2011 and 2012 are now being used to help fine-tune fertilizer input data for 2011 and 2012.
- For years 2010, 2011 and 2012, estimates of nutrient removal by crops are based on annual data rather than 3-year averages

NuGIS is freely available by registering at http://nugis.ipni.net/login

Comments and suggestions for improving this model or the web tool are welcomed and can be submitted by e-mail to nugis@ipni.net. BC