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The Role Of Roots In Maximum Soil Productivity

A significant amount of production capital and labor are expended in an effort to provide an environment conducive to plant root growth. Don't ignore your investment, researcher advises.

Summary: With the advent of prescription application of nutrients and the potential to use biotechnology to engineer efficient root systems, research efforts directed toward the "hidden half" of the crop are now more important than ever. The first step in improving effectiveness of nutrient management practices is understanding how plant root systems interact with the soil. Basic knowledge will ensure that maximum soil productivity and profitability are sustained, and that the environmental impact of nutrient use is minimized.

Due to the complexity of the plant-soil system, much of the research addressing fertilizer responses by crop plants has taken somewhat of a "black box" approach—where crop responses to several increments of a soil amendment are measured. This approach is not without merit in that fertilizer recommendations have been developed for a range of crops grown under varying climatic conditions on many types of soil. However, if data are closely examined, significant scatter is readily apparent. The scatter can be attributed to variation in the growth and distribution of plant root systems. Nutrient uptake by plants growing in soil involves both soil and plant processes. Soil tests provide a measure of soil nutrient supply. If calibrated for individual crop species, soil tests can to some degree account for differences in the ability of plants to absorb nutrients. Nevertheless, we cannot expect a perfect fit because changes in root growth and function cause changes in crop response to fertilizer, even when the soil supply of nutrients remains at a constant level. With the advent of prescription application of nutrients and the potential to use biotechnology to engineer efficient root systems, research efforts directed toward the "hidden half" of the crop are now more important than ever.

The purpose of this discussion is to 1) provide a brief overview of environmental factors affecting root growth and development, and 2) discuss the relationship of root growth to nutrient availability and uptake.

What affects root growth

Since most of the elements essential for plants are absorbed by roots, an understanding of root system characteristics is important in determining the most effective method of nutrient management. Root systems of crops species are classified as being fibrous or taprooted, with each type occurring in annual and perennial species. The ability of the root system to extract nutrients and water from the soil depends on its morphological and physiological characteristics. Soil physical and chemical properties can affect root growth rate, root morphology, and ultimately, nutrient uptake.

Mechanical impedance, soil water content, and soil temperature often interact to affect root growth. When soils are compacted, bulk density increases and the number of larger pores decreases, leading to increased resistance (soil strength) to root growth. Roots growing into compacted soil must displace soil particles, so that the rate of root elongation decreases as soil strength increases. In soil without significant compaction, roots will grow

Figure 1. Corn root proliferation in a fertilizer band.

root growth (e.g., phenolics and short-chain fatty acids released by decomposing organic material) often accumulate in water-logged soils.

The effect of soil temperature on root growth varies with species. In general, optimum soil temperatures for root growth are in the range of 68 to 77^{o} F. Minimum temperature for root growth of species native to warm climates is in the range of 46 to 59^{o} F. When changing from cool, suboptimal conditions to conditions near optimum, root/shoot ratios decrease. In cold soils, relatively more roots are needed for the same increase in shoot dry weight. Decreased shoot growth in cold soils is the result of a decrease in water and nutrient uptake. This is the basis of starter use in the spring. Finally, research suggests that the angle of root growth also is affected by temperature, with lower soil temperatures giving more horizontal growth and higher temperatures more vertical growth.

When present in sufficiently high concentrations in soil, many elements can adversely affect root growth. Aluminum (Al), manganese (Mn), and hydrogen (H) often have a pronounced effect on root growth of agricultural crops. High H^+ concentrations (low pH) *per se* are usually not the main factor affecting root growth. At low pH, Al, Mn, other toxic metals come into solution and hinder root growth. Aluminum-injured roots are typically stubby because development of lateral roots is poor. Appreciable concentrations of Al usually are present when pH is below 5.2. Soluble Al in

through soil pores and rapidly extend into the profile. The effect on root distribution in a controlled-traffic system can be dramatic.

In some cases, soil water content affects root growth and, in turn, nutrient uptake more than soil bulk density (Table 1). Soil water contents above and below optimum both cause problems for roots. In dry soils, mechanical impedance is the dominant stress factor. Problems with loss of soil-root contact, as well as ion imbalance in rhizosphere soil solution, may also occur in dry soil. The effect of water deficit is less stressful for plants with root systems that easily and rapidly penetrate the subsoil where water content is usually greater. Nutrient availability can be a problem, however, given that subsoils are usually less fertile. In wet soils, loss of aeration and accumulation of phytotoxins are dominant stress factors. Oxygen (O_2) is necessary for root respiration, as well as the respiration of soil microorganisms. Unfortunately, critical O_2 concentrations are difficult to determine in soil, due to various interactive effects. While differences exist among plant species, O_2 concentrations of 10 to 15 percent are generally sufficient to provide uninhibited root growth and function. In addition to limited respiration, low molecular-weight solutes that inhibit

Table 1. Effect of soil bulk density and water content on corn root growth and K uptake.*

Bulk Density g cm^{-3}	Water Content %(w/w)	Root Growth inches d^{-1}	K Influx 10^{-9} lb inch^{-1} d^{-1}
1.2	10.7	3.40	3.43
	14.2	6.63	5.32
	19.0	8.27	6.37
1.4	10.7	4.22	3.71
	16.3	6.60	6.90
	19.0	7.62	8.54
1.6	10.7	3.81	4.09
	14.2	5.54	3.94
	19.0	7.89	6.82

* 18 days after planting Seiffert et al. 1995

Table 2. Average daily nitrogen, phosphorus, and potassium uptake by field-grown cotton.

Days after Planting	Nutrient uptake, 10^{-9} lb inch^{-1} d^{-1} N	P	K
37-49	4.14	0.51	2.47
49-64*	17.48	1.53	9.81
64-87	12.99	1.80	8.96
87-99[+]	6.14	2.47	11.26
88-112	7.43	0.43	0.17

* = first square [+] = peak bloom Schwab et al. 2000

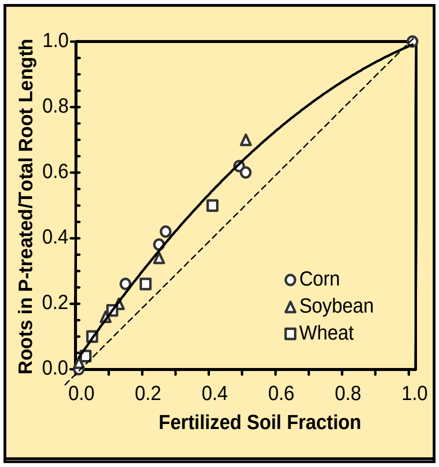

Figure 2. Stimulation of root growth by localized P placement (after Yao and Barber, 1986). Dashed line is in 1:1 relation, indicating no placement affect.

subsoils can be a challenge, since lime cannot be used to correct the problem. The toxicity of Al varies with plant species. For example, cranberry and blueberry tolerate high levels of exchangeable Al, whereas cotton and wheat do not. Manganese toxicity is not prevalent and tends to affect shoot growth more than root growth. It is most common when a combination of low pH and reducing conditions exist.

When supply of nutrients in the rooting zone is variable, plant roots often proliferate in areas where optimum concentrations exist, such as near fertilizer bands (Figure 1). Research has shown that phosphate, ammonium, and nitrate stimulate development of first- and second-order lateral roots. Therefore, when nitrogen (N) or phosphorus (P) is placed in some fraction of the root zone, root distribution between the fertilized fraction and unfertilized fraction is not proportional. This effect has been characterized for several economic species (Figure 2). The growth stimulation may be due to a competitive advantage that the roots with a more adequate supply of nutrients have over other roots on the same plant.

Root growth vs nutrient uptake

Nutrients move through the soil to root surfaces by mass flow and diffusion. Mass flow is associated with the convective flow of water to the root. Diffusion is driven by a concentration gradient that develops near the root surface when nutrients are removed from soil solution by roots. After nutrients arrive at the root surface, absorption can occur. For many essential nutrients, the uptake rate relative to nutrient concentration in soil solution can be described by a Michaelis-Menten relation (Figure 3). As solution concentration increases, influx rate increases until some root and/or nutrient-specific maximum (I_{max}) is reached. The affinity of root cells for a nutrient ion is reflected by the K_m value, the concentration at which influx is half that at I_{max}. When a root is absorbing at the maximum rate, further increases in the concentration of the nutrient in solution have little effect on the absorption rate. However, recent research with several perennial range species has shown that when the roots of these plants grow into nutrient-rich microsites, nutrient uptake rates per unit length of root significantly increase. This characteristic allows plants to take advantage of localized areas of fertile soil. Although data are limited, root systems of crop species may react the same way.

For many crop species, it is not clear which fraction of the plant's entire root system is active in nutrient absorption. In general, absorption and translocation of N, P, and potassium (K) occur in all parts of the root system, whereas calcium (Ca) tends to be absorbed in areas near root tips. Studies with winter wheat suggest that N and K uptake rates vary considerably among the seminal and nodal roots on the same plant. There also is evidence that some species have five or more types of roots, each with distinct developmental and physiological characteristics. Differences in root growth among cultivars or hybrids within a species also lead to differences in nutrient uptake. Genetic variation in both root length, and length and number of root hairs is common.

To further complicate the issue, some species rapidly accumulate nutrients early in the growing season, while others change the demand for nutrients throughout the season. For example, N, P, and K absorption rates peak early in the growing season for corn, but for cotton maximum P and K influx per unit root length occurs near peak bloom (Table 2). Maximum nutrient influx occurs later in the growing season for soybeans as compared to corn. Influx rates of both crops are significantly greater than those of cotton, suggesting that cotton roots are less efficient at extracting soil nutrients. These differences must be considered in developing an effective nutrient management program.

Exploiting root zone

An adequate supply of nutrients in the surface soil promotes greater top growth and encourages a more vigorous and extensive root system. Since plants absorb nutrients only from soil in which roots are active, fertilizer should be placed in the volume of soil where the roots will grow and where further stimulation of root growth is desirable. If the plant produces a vigorous taproot early in the season, the presence of nutrient-rich soil directly under the plant is desirable. Hence, fertilizer should be placed under or near the seed for optimum use. For plants with a fibrous root system, fertilizer placement to the side of the seed would allow developing lateral roots to take advantage of the added nutrients. In soils that frequently experience periods of drought, deep placement of fertilizer may be most effective. Within any specific crop production system, optimum fertilizer placement will necessarily depend on both the ability of the soil to supply nutrients and the ability of the root system to absorb the nutrients present.

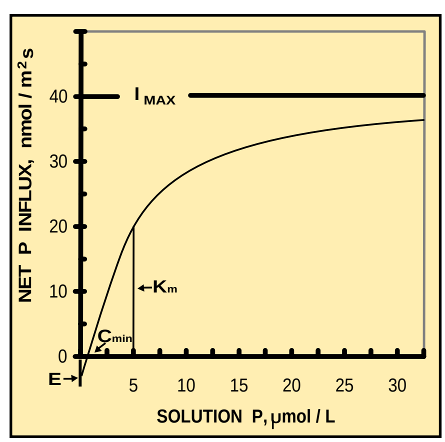

Figure 3. Relation of phosphorus in soil solution to root phosphorus absorption rate.

Timing is also a consideration. Nutrients must be available when plant demand is greatest. Cotton requires N early in the season and significant P and K later. Thus, an application of N as starter should benefit young cotton plants. The demand for nutrients by soybeans occurs later in the season, which suggests that fertilizer should not be banded close to the seed but rather mixed with more of the soil in the rooting volume. Although several interacting factors will affect plant nutrient content, nutrient accumulation during the growing season generally follows a typical growth pattern, with a rapid or exponential increase up to a maximum, followed by a general decline. Regardless of the exact shape of the curve, plants require significant quantities of nutrients during periods of exponential growth.

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