Soil Physical and Morphological Properties and Root Growth

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Soil provides the physical space and the resources to support root growth. The water and nutrients needed for the growth of both roots and the aerial portions of the plant are housed in soil pores. The size and distribution of pores in a soil determine its ability to store and transmit these entities to the roots. Other physical properties of soil, such as texture, structure, temperature, aeration and water content, also influence root growth.

Roots elongate in the soil when root pressure exceeds soil mechanical impedance. Root elongation is affected by the nature of the soil profile. Roots proliferate in the biopores made by soil fauna, such as earthworms, or in old root channels made by previous crops. On the other hand, a hardpan layer in the soil profile or a high water table restricts root growth. Soil management practices modify soil physical properties and significantly impact root growth. Tillage can alter soil porosity by loosening soil particles and breaking up aggregates. Heavy machines used for tillage, harvesting, and other cultural practices can compress soil pores by compacting the soil.

The purpose of this paper is to discuss the various physical and morphological properties of soil that influence root growth. Soil and crop management practices that alter these properties in relation to root growth are also analyzed.

SOIL PHYSICAL PROPERTIES

Bulk density and porosity

Bulk density and porosity are interrelated. As bulk density increases, total porosity decreases. Lateral or horizontal variation in bulk density results from changes in soil texture, structure, organic matter concentration and management practices, whereas vertical variation is the result of soil morphology. Seasonal changes in bulk density can result from freezing and thawing, raindrop impact, soil settling and biological activities (Cassel, 1982).

Bulk density or porosity is altered by tillage, traffic or the addition of organic matter. Kaspar et al. (1991) obtained higher bulk density in the surface soil in no-till than in chisel-plow or ridge-till system. Kaspar et al. (1995) found a bulk density of $1.36 \text{ Mg}\cdot\text{m}^{-3}$ in trafficked vs. $1.09 \text{ Mg}\cdot\text{m}^{-3}$ in nontrafficked interrows. Taylor (1983) observed that 75% of

the increase resulted from the first traffic pass, although subsequent passes also increased bulk density. Zhang et al. (1997) reported a negative linear relationship between the amount of organic matter added and bulk density. Sainju and Good (1993) observed lower bulk density in the surface soil than in subsoil in an undisturbed forest because of the plant litter (organic matter) deposit on the surface.

Both high bulk density and low porosity restrict root growth. Rosolem and Takahashi (1996) reported a 10% and 50% decrease in soybean [*Glycine max* (L.) Merr.] root growth when the bulk density of a dark red Latosol (70% sand and 22% clay) was increased from $1.06 \text{ Mg}\cdot\text{m}^{-3}$ to 1.45 and $1.69 \text{ Mg}\cdot\text{m}^{-3}$, respectively. Foil and Ralston (1967) found that root growth of loblolly pine (*Pinus echinata* Mill.) was severely restricted when bulk density was $>1.4 \text{ Mg}\cdot\text{m}^{-3}$. Shierlaw and Alston (1984) observed that bulk density equal to or $>1.2 \text{ Mg}\cdot\text{m}^{-3}$ reduced root growth in corn (*Zea mays* L.) seedlings. As soil bulk density increased, root length decreased and root diameter increased in corn seedlings (Logsdon et al., 1987b) (Fig. 1). Sainju and Good (1993) found a negative relationship between root length density and bulk density and a positive relationship between root length density and porosity.

Aeration and water content

Soil should contain more than 10% air-filled pores to maintain aeration (Box, 1996; Grable and Siemer, 1968). Pores not filled with water are filled with air. Intensity of rooting is restricted by deficient aeration. Gardner and Danielson (1964) found a high correlation ($r = 0.998$) between soil penetration by cotton (*Gossypium hirsutum* L.) roots and percentage of aeration porosity. Root elongation is more sensitive to oxygen diffusion rate (ODR) than to oxygen concentration. When ODR in the soil falls below $58 \text{ mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, root growth is restricted (Erickson and Van Doren, 1961). Compacted soil may have ODRs of $<33 \text{ mg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Erickson, 1982). Therefore, in compacted soil, even air-filled pore space $>10\%$ can limit root growth. Asady et al. (1985) reported that root penetration of compacted layers decreased linearly as air-filled porosity decreased from 30% to 0%.

Drought conditions result in deeper root penetration and higher root distribution in the subsoil than in the surface soil. Box et al. (1989) found that drought decreased root counts in corn by 37% in the 0- to 20-cm depth, but at 60- to 150-cm depth, root counts were 50 times higher after an 18-d drought period in comparison with well-irrigated plants. Similarly, plants growing on xeric and subxeric (dry) sites have higher root densities than those

growing on mesic (moist) site (Kalisz et al., 1987; Parker and Van Lear, 1996; Sainju and Good, 1993). However, soil drying increases mechanical resistance and can restrict root growth. On the other hand, soil wetting decreases interparticle attraction and increases particle mobility, which, in turn, decreases the pressure needed for soil deformation (Bennie, 1996). Details of soil water effects on root system is the topic of an accompanying paper of this workshop proceedings.

Temperature

Temperature at the soil-atmosphere interface controls soil temperature. However, it is moderated by soil color, surface random roughness, surface residue, and soil moisture content (Box, 1996). Soil temperature influences root biomass (Voorhees et al., 1981; Walker, 1969), elongation rate (Logsdon et al., 1987b), and rate of branching (Box, 1996). The maturation zone occurs closer to root apex and root orientation becomes horizontal at low temperature (Box, 1996). As temperature increases, root angle from the vertical decreases (Sheppard and Miller, 1977). Soil temperature is discussed comprehensively in another paper of this workshop proceedings.

Organic matter

Besides supplying nutrients to plants, organic matter also improves soil physical condition. It reduces bulk density, improves soil aggregation and infiltration capacity, and increases water-holding capacity. Soil containing adequate amounts of organic matter is less prone to compaction (Zhang et al., 1997). Unger and Kaspar (1994) reported that soil organic matter promoted earthworm activity; when organic matter was adequate, earthworms burrowed to a depth of up to 2 m, thereby forming macropores in the compacted soil. Earthworm burrows increased water movement and penetration of roots through otherwise less amenable soil horizons.

Organic matter promotes root proliferation. Root density is greater in horizons of the soil profile with higher organic matter accumulation (Davis et al., 1983; Kalisz et al., 1987; St. John, 1983). Sainju and Kalisz (1990) observed that, in eastern Kentucky's undisturbed forest soils, there were more roots in weathered coal seam (coal bloom) subsoil horizons containing higher organic matter concentrations than in adjacent colluvium horizons at the same depth. Similarly, Sainju and Good (1993) found higher root density in the soil horizon that contained a higher concentration of organic matter than in the horizons above and below it.

Received for publication 19 Dec. 1997. Accepted for publication 13 Mar. 1998. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

Fig. 1. Root length and diameter of 6-day-old corn seedlings as affected by bulk density (After Logsdon et al., 1987b).

Mechanical strength and impedance

Mechanical strength of a soil protects its pore space from collapse under the overlying weights. However, it also impedes root growth. Roots must apply a force greater than the mechanical strength of the soil matrix to elongate. Mechanical impedance depends on adhesive and cohesive forces of soil particles, that, in turn, depend on water content, texture, porosity or bulk density, pore size distribution, organic matter content, aggregate size, overburden pressure and degree of confinement, exchangeable cations, degree of cementation, orientation of soil particles, and surface roughness of sand particles (Bennie, 1996). Soil impedance increases from excessive animal grazing, use of heavy farm and tillage equipment, vehicular traffic, saturation of sandy topsoil during flood irrigation, and settling of soil particles. As bulk density of soil changes seasonally, mechanical impedance also changes (Cassel, 1982).

After reviewing the literature, Unger and Kaspar (1994) concluded that root growth of most species slows considerably or completely

ceases at soil impedance above 2.0 MPa penetrometer resistance. Root elongation rate or root length varies inversely with, whereas mean root diameter is directly proportional to, mechanical impedance (Bennie and Krynanuw, 1985; Greacen, 1986; Misra et al., 1986b). Mechanically impeded roots are shorter, thicker, and more irregularly shaped than are roots growing under low strength condition (Dexter, 1986a, 1986b; Richards and Greacen, 1986). They also have significantly fewer second- and third-order lateral roots (Sauerbeck and Helal, 1986). Bennie and Burger (1981) found that relative root length (root length per pot/maximum root length) in maize, cotton, wheat (*Triticum aestivum* L.), and groundnut (*Arachis hypogaea* L.) decreased curvilinearly with increasing soil strength (Fig. 2).

The relationship between soil impedance and root growth has been described by Klepper and Rickman (1990) as:

$$(1/L)(dL/dt) = \phi (P - Y - M)$$

where L is root length (m), ϕ is wall extensibility ($S^{-1}MPa^{-1}$), P is turgor pressure of root

cells for extension (MPa), Y is the minimum turgor pressure required for expansion (MPa), and M is the resistance of soil to root penetration (MPa).

Dexter (1987) proposed the following exponential equation to describe the effect of impedance on root elongation:

$$R = R_{\max}(e^{-0.6931})(Q_p/Q_{0.5})$$

where R is the root elongation rate ($m \cdot d^{-1}$), $R_{\max}$ is the maximum root elongation at very low impedance ($m \cdot d^{-1}$), Q_p is the penetrometer resistance (MPa) and $Q_{0.5}$ is the penetrometer pressure corresponding to $(R/R_{\max}) = 0.5$.

The ability of roots to penetrate impeding soil layers varies among plant species. Wolfe et al. (1995) compared the root growth of cabbage (*Brassica oleracea* L. Capitata group), cucumber (*Cucumis sativus* L.), snap bean (*Phaseolus vulgaris* L.), and sweet corn at low (<1 MPa) and high (>2 MPa) penetrometer resistance soil strengths. Root growth of all species was slower in high strength than in low strength soil. However, the reduction ranged from 43.6% in sweet corn to 77.9% in cucumber. Winter wheat and sunflower (*Helianthus annuus* L.) roots can penetrate >2.0-m depth in Pullman series soil (fine, mixed, thermic Torrertic Paleustolls), while grain sorghum [*Sorghum bicolor* (L.) Moench] roots are mostly confined to the upper 1.2 m (Eck and Taylor, 1969; Johnson and Davis, 1980; Jones, 1978). Elkins (1985) found that bahiagrass (*Paspalum notatum* Flugge var. Pensacola) roots penetrated soil layers that were impermeable to cotton roots. Alfalfa (*Medicago sativa* L.), sweet clover (*Melilotus alba* Medik), and guar [*Cyamopsis tetragonoloba* (L.) Taubert] roots also have the ability to penetrate compact soil layers (Bowen, 1981).

Once a root penetrates through the compacted soil, it makes channels and macropores that facilitate subsequent rooting. Elkins et al. (1977) observed cotton root growth through the compact soil horizon for three consecutive years when planted after bahiagrass.

SOIL MORPHOLOGICAL PROPERTIES

Soil profile

Soil profile varies with location because of the differential effects of various factors of soil formation, such as parent material, vegetation, climate, and time. Not only does the depth of a horizon in the profile change within a few meters, but the physical, chemical and biological properties of the soil also vary. As a result, root distribution differs with location. Root development and distribution differ not only among plant species (Kasperbauer, 1990; Klepper, 1992; McMichael, 1990; Zobel, 1992), but also within species because of the differences in soil environmental conditions where roots grow (Jung, 1978; Kasperbauer, 1990). Some of these soil conditions are soil structure, mineral stress, temperature, gases, drainage, and availability of nutrients and water. All or some of these conditions may

Fig. 2. Effect of soil impedance on relative root length of 70-day-old maize, cotton, wheat, and groundnut plants (After Bennie, 1996). Regression equation based on combined data for all four species.

interact with the genetic character of the plant (Box, 1996). Root elongation and branching may be extensive in a favorable environment, whereas growth is substantially reduced in an unfavorable environment (Hamblin, 1985). These variations in soil environment and root growth occur not only from one soil layer to another but also within a given layer (Box, 1996).

Root density usually decreases with depth (Kalisz et al., 1987; Klepper and Rickman, 1990). The highest concentration of roots, especially fine roots, occurs near the soil surface where conditions are more favorable for root growth. These layers are usually rich in organic matter, nutrients, cation exchange capacity, and porosity, and low in bulk density (Sainju and Good, 1993). Fine roots constitute a large proportion of total root biomass and are therefore important in water and nutrient absorption (Parker and Van Lear, 1996). On the other hand, large roots, such as tap and sinker roots, penetrate deeper into the profile to access moisture when the surface layer dries, and also to support aboveground plant biomass. Kalisz et al. (1987), Sainju and Good (1993), and Sainju and Kalisz (1990) found an exponential decline in root density with soil depth, reflecting declining fertility, reduced organic matter concentration, and decreasing aeration.

The presence of a hard layer, such as fragipan, duripan, argillic or alluvial horizons, within a soil profile severely restricts root growth. These layers are formed by settling of sand and clay particles and cementation between them during soil formation. Such layers can occur at any depth in the soil profile. Root growth in these layers depends on water flux and water content, as well as on the frequency of cracks, planar voids, biopores, and packing voids, and on pedal properties (Box, 1996). Sainju and Good (1993) found reduced root density in the B horizon of New Jersey Pineland forest soils whenever a firm argillic layer was present in this horizon. On the other hand, when the B horizon was higher in nutrient

concentrations and cation exchange capacity than adjacent horizons, it promoted greater root density than layers immediately above and below it.

Biopores

Biopores are formed by decaying plant roots, mesofauna (such as earthworms), or cracks within the horizon when the soil dries during the drought condition. These pores are usually filled with loose surface soil or decaying organic matter or both, allowing easier root penetration (Parker and Van Lear, 1996). Soils in the biopores are often characterized by enhanced fertility, and better aeration and moisture conditions that promote vigorous root growth (Lutz and Chandler, 1955; Van Rees, 1984). In addition, biopores form as avenues for water and air flow in heavy-textured subsoils that have restricted permeability (Anderson and Bouma, 1976; Quinsberry et al., 1993).

Parker and Van Lear (1996) reported that there were 0 to 8 old root channels/m² soil profile area in mature loblolly pine stands in Piedmont soils, with size ranging from 69 to 105 cm². They also noted that density of fine roots in old root channels was 17 times as high as in the adjacent soil matrix. Therefore, although biopores constitute a small area of the soil profile, they are important avenues for root growth, especially in dense layers, because of the high concentration of roots in them. Biopores often extend more deeply into the soil than do cracks (Van Stiphout et al., 1987).

Soil-rock interface

Rocks may act as loci for water films that promote root proliferation in the soil-rock interface. They also may contain macropore spaces from prior biological activity that allow root penetration. Parker and Van Lear (1996) found that the number of rock-soil

interfaces were as high as 13/m² soil profile area and that root density in the interface was significantly higher than in the adjacent soil matrix.

Water table

The presence of a shallow water table in the soil profile restricts root growth unless roots can grow in anaerobic conditions, and limits the volume of the soil available for exploitation by roots. In such a case, roots grow profusely above the water table (Gary, 1962; Oliver 1978). Sainju and Good (1993) found higher root density in the soil layer just above the water table than in higher layers in pine-oak lowland forests in New Jersey.

SOIL AND CROP MANAGEMENT PRACTICES

Tillage

Tillage can alter soil bulk density, porosity, aggregation, and mechanical impedance and therefore affect root systems. It can mix and granulate the soil, eradicate or control plants, incorporate plant residues and chemicals, and establish desired surface configuration and degree of compactness for root growth (Gill and Vanden Berg, 1967). Kaspar et al. (1991) found that a no-till system produced higher bulk density than chisel-plow or ridge-till systems. According to Bauder et al. (1981), reduced or no-till systems could lead to an increase in the development of root-restricting soil layers in a clay loam soil. Voorhees (1983) hypothesized that increased bulk density in a no-till system could be an effect of incomplete amelioration of compacted soil over the winter.

The effect of tillage on root distribution system is variable. Kaspar et al. (1995) observed no significant differences in root length density between no-till, ridge-till, and chisel-plow systems. Baligar et al. (1996) obtained greater root length per plant and root density in silage corn in a no-till system than in a conventional-till system. In contrast, Bauder et al. (1985) observed that root length density in the 0- to 30-cm depth was higher in a ridge-till system than in no-till or chisel-plow systems. Bhagat and Acharya (1987) also found higher root density in the root-restricting soil layer with mulched conventional tillage than with nonmulched conventional tillage or no-tillage systems in a monsoonal climate. Rasse and Smucker (1996) reported maximum root growth for alfalfa and corn in the upper B₁ and B₂ soil horizons under no-till and conventional-till, respectively.

In our study on the effect of tillage on tomato (*Lycopersicon esculentum* Mill.) root distribution in a Dothan sandy loam soil (Plinthic Paleudult) in Georgia, the number of roots/cm² soil profile from 19.5- to 58.5-cm depth was 65% higher in a moldboard-plowed system than in no-till (Fig. 3); the higher root number was attributed to less soil impedance. However, Merrill et al. (1996) found that in dryland cropping, root length density of spring

Fig. 3. Tomato root distribution at various soil depths 90 d after transplanting as affected by no-till and conventional-till. *Differences between systems significant at $P = 0.05$.

wheat was 40% to 112% higher in a no-till than in a conventional-till system. They attributed this to superior moisture conservation and cooler soil temperature in the near-surface zone in no-till under dryland farming conditions.

Tillage management assumes special importance in soils with naturally dense horizons. Bowen (1981) recommended plowing at or near a soil water potential of -1.5 MPa to shatter a compacted soil layer. The water contents for clay, sandy clay loam, and loamy sand at this water potential are in the range of 0.35 to 0.40, 0.22 to 0.25, and 0.08 to 0.10 $\text{cm}^3\cdot\text{cm}^{-3}$, respectively (Gupta and Larson, 1979). In coarse-textured southeastern Coastal Plains soils, corn and tobacco (*Nicotiana tabacum* L.) formed more roots below the compacted layer with in-row subsoiling than without subsoiling (Vepraskas et al., 1986; Vepraskas and Waggoner, 1990). Cary et al. (1967) obtained increased root number and water extraction, and doubling of alfalfa hay yields, as a result of loosening and mixing of B horizon of Freeman silt loam (Mollic Palexeralf). Rosolem and Takahashi (1996) obtained a quadratic decrease in the soybean root growth by increasing the subsoil bulk density of a dark Latosol (70% sand and 22% clay) soil column from 1.06 to 1.71 $\text{Mg}\cdot\text{m}^{-3}$. However, the root growth was not completely inhibited even at the highest bulk density. Once roots penetrated the compacted layer, growth was completely restored.

Traffic

Use of heavy farm machinery for tillage, cultural operations, harvesting, and transport causes soil compaction. The soil properties and processes affected by soil compaction include increased bulk density and mechanical resistance, disruption of pore continuity, and altered exchange of water, heat and gas (Assouline et al., 1997; Linn and Doran, 1984; Wierenga et al., 1982). Large pores conducting water at lower tension are more easily destroyed than smaller ones conducting water

at higher tensions (Ankeny et al., 1990). Small aggregates are less compacted by traffic than are large aggregates (Logsdon et al., 1987a; Misra et al., 1986a, 1986b).

Bauder et al. (1985) and Gerik et al. (1987) found that the bulk density and soil strength on the trafficked side of a row was much greater than on the nontrafficked side of the same row. Kaspar et al. (1995) observed that the hydraulic conductivity near saturation in a Webster silt clay loam (Typic Haplaquoll) was 39.4 and 104.7 $\text{mm}\cdot\text{s}^{-1}$ in trafficked and nontrafficked interrows, respectively. Soil compaction from traffic is a serious problem in no-till and ridge-till systems (Karlen, 1990). Limiting traffic to permanent traffic lanes is suggested as a way of reducing compaction (Taylor, 1983). Raghavan et al. (1979) observed maize root densities of 5.7 vs. <2 $\text{mg}\cdot\text{g}^{-1}$ in the upper 20 cm of soil with no traffic vs. 15 passes of 62-kPa tire track, respectively. Root length density in barley (*Hordeum vulgare* L.) in the top 30 cm of the soil decreased as the number of tractor passes over the field increased from zero to six (Willatt, 1986). Voorhees et al. (1989) reported that compaction of the subsoil with an 18-Mg axle load decreased root growth of corn below 45 cm more than did a <4.5 -Mg axle load. Dolan et al. (1992) observed that compaction of the subsoil of Webster clay loam (Typic Haplaquolls) reduced corn P and K uptake as much as 22% when June and July rainfall was less than average.

Kaspar et al. (1991) found that root length and root mass of corn in the 0- to 15-cm layer of trafficked interrows was one-third and one-half, respectively, of that in nontrafficked interrows. Traffic also reduced root growth in the 15- to 30-cm soil layer, but the differences between trafficked and nontrafficked interrows were not as large as those for 0- to 15-cm layers. Kaspar et al. (1995) reported that root length density in a particular interrow was also affected by traffic pattern in the adjacent interrows. Chaudhary and Prihar (1974) noted that interrow compaction resulted in downward movement of roots because of inhibition

of lateral root elongation. Hilfiker and Lowery (1988) observed that the response of root growth to wheel tracks depended on both soil type and tillage system. Bauder et al. (1985) reported that tillage had a greater effect on root length than did wheel traffic.

Crop rotation

Crop rotation can improve soil physical condition by adding more biomass residue to the soil in comparison with a continuous single crop (Bullock, 1992; Havlin et al., 1990; Hussain et al., 1988; Juma et al., 1993). Incorporation of biomass results in improved soil structure (Kay, 1990) and aggregation (Raimbault and Vyn, 1991; Van Bavel and Schaller, 1950), lower soil bulk density (Bullock, 1992; DeKimpe et al., 1982; Hageman and Shrader, 1979), increased water infiltration (Jordahl and Karlen, 1993; Logsdon et al., 1993), higher water retention capacity (Hudson, 1994; Jamison, 1953), improved soil aeration and reduced soil erosion (Bezdicsek, 1984; Reganold, 1988; U.S. Dept. of Agriculture, 1980). The effects of physical properties on root proliferation have already been described.

Elkins (1985), Kay (1990), and Merrill et al. (1994) observed that including a deep-rooted crop in the rotation increased biopores in the soil that facilitated proliferation of the roots of the succeeding crop. Merrill et al. (1996) found that spring wheat planted after sunflower had greater root density in no-till than in conventional-till. Since the soil was not disturbed in no-till, in all probability, biopores made by the deep roots of sunflower remained intact for the succeeding wheat roots to recolonize, thus facilitating formation of more roots than was the case for conventional-till. Rasse and Smucker (1996) reported that in a corn-alfalfa succession, alfalfa roots recolonized 14% and 21% of corn root-induced macropores in B₁ horizon under conventional-till and no-till, respectively. Root recolonization in the B₂ horizon was 17% and 18% for conventional-till and no-till, respectively.

SUMMARY

Root development in the soil is influenced by soil physical properties as well as the nature of horizons in the soil profile. Soils vary widely in their physical properties, and hence in their ability to support root growth. The presence of a hardpan or water table in the root zone impedes root growth. Roots proliferate in the soil horizons with favorable conditions, such as high organic matter content and abundant biopores. Roots of different crop species as well as of cultivars within species differ considerably in their ability to penetrate through hard soil layers. Management practices, such as tillage, traffic, and crop rotation can influence root growth by altering soil properties.

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