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Soil Compaction and Root Growth: A Review

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ABSTRACT

Adverse effects of soil compaction on crop production have been recognized for many years. The objectives of this report were to briefly review the early literature, review the contributions of Dr. Howard M. Taylor (1924–1991) and co-workers, examine the current status of soil compaction and root growth research, and identify research needs related to soil compaction and root growth. Early in his career, Dr. Taylor and co-workers established relationships among soil strength, soil water content, and seedling emergence and root growth. These studies showed that root growth and distribution were altered to the point that water and nutrient uptake, and, hence, plant growth and yield, were reduced when soil strength reached critical levels due to natural or induced compaction. That research formed the basis for our current knowledge concerning the effects of compaction on root growth and the alleviation of compaction through soil and tillage management. Usually, not all parts of a root system are equally exposed to compaction under field conditions. Hence, because of compensatory growth by unimpeded parts of the system, only the distribution and not the total length of roots may be altered. Even if compaction limits root growth, weather events sometimes enhance or diminish the effect of root limitation on crop growth. To reduce risks in dry years and to use applied nutrients efficiently, managing soils through the use of tillage and related practices and growing of deep-rooted crops in rotations will help avoid or alleviate compaction, thus improving root distribution and increasing rooting depth.

ADVERSE EFFECTS of compact soil horizons on plant root growth and concomitant poor plant growth and yields have been recognized for many years. Cato the Elder (234–149 B.C.) wrote that the first principle of good crop husbandry is to plow well and the second principle is to plow again (Weir, 1936, cited by Bowen, 1981), presumably to provide for a "mellow" seedbed. King (1895, cited by Bowen, 1981), was more explicit when he wrote that "a mellow seedbed with its many well-aerated pores allows roots to grow unhindered in any and every direction and to place their absorbing surfaces in vital touch with the soil grains and soil moisture. In this way, nourishment in the seed provides the maximum root surfaces in the shortest time."

Compact horizons that impede root growth may be naturally dense layers or fragipans, or result from the forces applied to the soil by implements or animals. Examples of the latter are compacted layers resulting from traffic on the soil surface or tillage pans resulting from repeated tillage performed at the same depth. To alleviate these adverse conditions, many studies involving practices such as deep plowing, chiseling, and dynamiting were conducted from the late 1800s to the mid-1900s. Those studies, however, often gave inconsistent and inconclusive results, because the soil conditions causing the problems and the soil environment resulting from use of the problem-alleviating practices were not measured or fully understood.

Intensive research to better understand soil compaction and its alleviation were started in the late 1940s and early 1950s. Bowen (1981) attributed the intensification of this research to (i) the finding by Veihmeyer and Hendrickson (1948) that conclusively showed that increases in soil bulk density reduced root growth even where soil aeration should not have been a problem, (ii) the emphasis by Lutz (1952) that major gaps existed in knowledge about mechanical impedance (compaction) and plant growth, and (iii) the review by Gill and Bolt (1955) of Pfeffer's (1893) root growth pressure studies that showed that plants can exert pressures up to 2500 kPa during growth. In general, these factors pointed to complex interrelationships among soil compaction, density, strength, water content, aeration, root growth, and plant growth and yield.

This renewed emphasis on soil compaction occurred at about the time Dr. Howard M. Taylor (1924–1991) started his research and teaching career. Dr. Taylor published extensively on the subject, and many of his early papers are still considered definitive in the field. His early research continues to influence the direction of soil compaction research and is the basis for many current management practices on soils susceptible to compaction. The objectives of this report, in addition to the brief review above, were to review the contributions of Dr. Taylor and co-workers, to examine the current status of soil compaction and root growth research, and to identify research needs related to soil compaction and root growth.

EARLY STUDIES BY HOWARD M. TAYLOR

University of California, Davis

Dr. Taylor earned his Ph.D. degree at the University of California, Davis, in 1957. The research for his degree was on soil–plant–water relations, mainly the effects of various additives or treatments on soil compressibility, bulk density, and hydraulic conductivity. He also developed a pneumatic soil compression device to help study relationships between applied loads and soil compression, between soil water content and soil compression, and between soil treatments and soil compression (Taylor, 1958).

When various organic substances [sucrose, ground ladino clover (*Trifolium repens* L.)] or the half-amide ammonium salt of isobutylene maleic anhydride copolymer (a polyelectrolyte) were added to Yolo silt loam (fine-silty, mixed, nonacid, thermic Typic Xerorthent), compression treatments caused greater differences in hydraulic conductivity than in soil bulk density (Taylor and Henderson, 1959). The polyelectrolyte was most effective in maintaining a high hydraulic conductivity of the soil at various levels of compression.

Taylor and Vomocil (1959) evaluated the compressibility of Yolo silt loam and Columbia loam (coarse-loamy, mixed, nonacid, thermic Aquic Xerofluent) treated with the polyelectrolyte at a 0.1% rate. Soil samples having water

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contents ranging from oven-dry to 0.0067 MPa matric potential (1/15 bar) were compressed at air pressures up to 345 kPa (50 pounds per square inch). Due to their initially greater specific volume, polyelectrolyte-treated soils were more compressible than untreated check soils. However, treated soils retained greater specific volumes than untreated soils at all water contents and applied pressures. Differences in specific volumes between treated and untreated soils decreased with increases in water content at the time of compression or in compression pressure.

Bushland, Texas

Soil compaction is a major problem on some soils of the southern Great Plains. Early in his research career at Bushland (from 1957 to 1965), Dr. Taylor recognized that the ability of plant roots to penetrate compacted soils determines how effectively the plant makes use of soil water and nutrient supplies for growth and productivity (Taylor and Gardner, 1960a). He and his co-workers subsequently conducted numerous studies to determine relationships among factors such as plant type, rooting media, soil density and strength, and soil water content on plant root penetration and growth.

In growth chamber studies with wax substrates, which simulated plastic pressure pans in soils, Taylor and Gardner (1960a) found that the ability of roots to penetrate the wax depended on wax rigidity, plant type, and soil density above the wax. Corn (*Zea mays* L.) seedlings developed more roots than cotton (*Gossypium hirsutum* L.) or pinto bean (*Phaseolus vulgaris* L.) seedlings within the wax substrate. Advantages of using wax rather than soil in penetration studies include (i) resistance to root penetration is not affected by water content changes in the substrate, (ii) the substrates are nonporous, (iii) the substrates are uniform and can be reproduced easily, and (iv) the substrates can be characterized easily. Hence, use of wax can eliminate the confounding effect of a changing substrate, which may occur with plant rooting in soil.

By using wax substrates, Taylor and Gardner (1960b) showed that the penetrating abilities of legume roots were not significantly greater than those of nonlegumes. These studies discounted earlier reports that attributed improvements in soil physical conditions to the ability of legume roots to penetrate soil horizons that could not be penetrated by roots of other crops.

The presence of soil pans that restricted plant rooting was recognized for many years before Dr. Taylor and his co-workers began extensive research on the problem in the late 1950s. To gain information on why root-restricting pans occur, Taylor et al. (1964) studied the pans in 17 southern Great Plains soils. They concluded that the root-restricting pans in less than half the cases could be attributed to the genetic nature of the soil or to the effect of soil manipulation. In the remaining cases, root restriction was caused by excessive soil strength that occurred largely as a result of soil drying. Taylor et al. (1964) also showed that mineral soils gain strength when they are compacted, and that the compacted soils gain additional strength when they lose water (become drier) (Fig. 1). This confirmed the results of Taylor and Gardner (1963), which showed that soil strengths great enough to critically limit cotton root penetration could be attained by increasing soil bulk density or decreasing soil water matric potential (Fig. 2 and 3). Cotton root penetration stopped when strength of Amarillo fine sandy loam (fine-loamy, mixed, thermic Aridic Paleustalf), as determined with a static penetrometer, reached 296 N cm^{-2} (Taylor and Gardner, 1963). At strengths that did not prevent root penetration, cotton root elongation rates decreased as soil strength increased (Taylor et al., 1967).

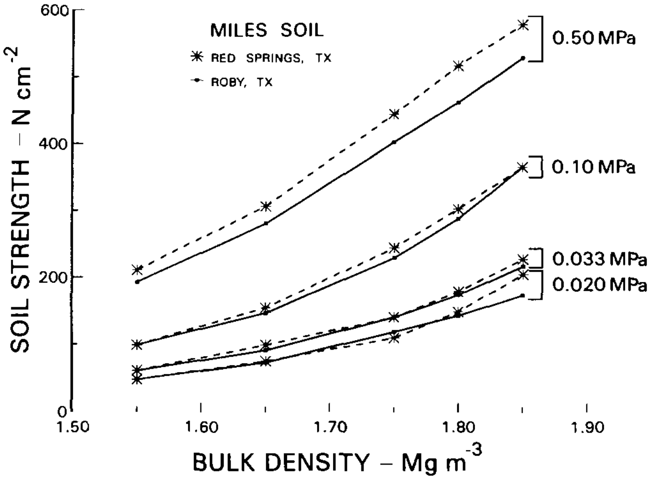

Fig. 1. Soil strength as affected by soil bulk density and soil water matric potential (MPa) (redrawn from Taylor et al., 1964).

SOIL BULK DENSITY, SOIL STRENGTH, AND PLANT ROOT GROWTH RELATIONSHIPS

In addition to soil water content and bulk density, other factors that affect soil strength include soil clay concentration and exchangeable cations (Mathers et al., 1966). For briquettes of Amarillo fine sandy loam, unconfined compression strength was maximum at 3 to 6% soil water content, and strength depended on clay concentration. Strength was greater with 282 than with 128 g kg^{-1} clay in soil, provided other factors remained unchanged. Maximum strength was attained at about one monolayer of water molecules on the total surface area, which suggests that H-bonding contributed to soil strength. Additional reductions in water content further reduced soil strength. Minimum strength occurred at about one-half monolayer of surface water. Then as the soil approached complete dryness, strength increased again. Sodium-saturated soils had greater dry strengths than Ca- or Al-saturated soils.

Pearson et al. (1970) studied the effects of soil temperature, pH, and strength on cotton seedling root elongation in glass-fronted boxes in a growth chamber. Root elongation rates gradually increased with increases in soil temperature until a maximum of 32 °C, then decreased sharply as temperatures increased further. The temperature effect was greatest at low levels of soil strength (0.5 N cm^{-2}) and at high pH (6.2). Temperature interacted with soil strength and pH on root elongation rates, but the effects of strength and pH were independent of each other.

For plants to derive benefits from water and nutrients in soil, plant roots must be able to reach them. Hence, soil strengths that prevent root penetration or reduce root

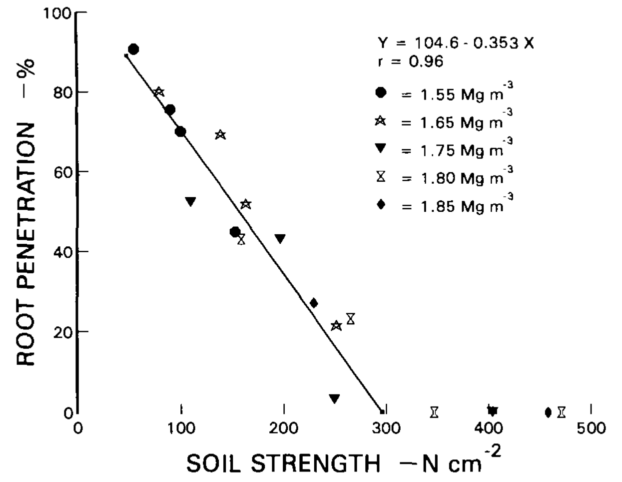

Fig. 2. Effect of soil strength resulting from different soil bulk densities on root penetration (redrawn from Taylor and Gardner, 1963).

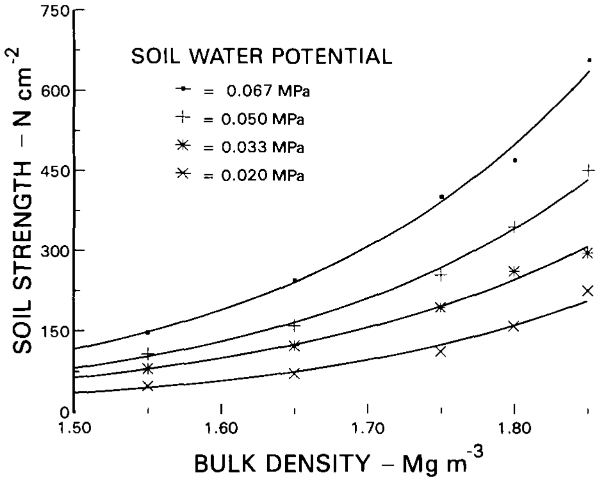

Fig. 3. Soil strength as affected by soil bulk density and soil water matric potential (MPa) (redrawn from Taylor and Gardner, 1963).

elongation rates may reduce plant development and yields, because water and nutrients beneath the restricting zone essentially are unavailable to the plants. The degree of reduction depends, to a large extent, on the depth at which the restrictive zone occurs in the soil.

A compact zone at a shallow depth that prevents root penetration is highly detrimental to plant growth and yield when plants depend only on precipitation for their water supply, especially when precipitation occurs infrequently, as in semiarid and subhumid regions. Under such conditions, plants rapidly deplete the plant-available soil water above the restricting zone, which results in severe plant water stress unless timely precipitation occurs (Barton et al., 1966). Plants may die in extreme cases when timely precipitation does not occur. A restrictive zone at a shallow depth may also severely limit plant growth and yields in more humid regions when short-term droughts occur (Campbell et al., 1974; Unger et al., 1988). As depth to the restrictive zone increases, usually more water is available to plants, thus resulting in less opportunity for development of severe plant water stress.

A compact zone at a shallow depth that reduces root penetration may be less detrimental to plant growth and yield than one that prevents root penetration. Where some roots penetrate the layer, some water from beneath the restrictive zone should be available to plants. In some cases, however, the restrictive zone essentially prevents radial growth of roots, thus resulting in root girdling (Mathers, 1967; Mathers and Welch, 1964; Taylor et al., 1964) and limited potential for water uptake at a rate sufficient to supply the plant's need. Under extreme root girdling conditions, plants may even die (Mathers and Welch, 1964).

Most plant nutrients have limited mobility in soils. Hence, roots must grow to the nutrients before they can be absorbed, and nutrient availability to plants may be limited by a soil zone that restricts root growth. In contrast to water deficiencies, nutrient deficiencies usually do not cause plant death, but may severely limit plant growth and yield.

Limited water and nutrient availability to plants due to compaction are major constraints to plant growth and yields in many soils, but compaction also affects plant growth and yields by affecting water infiltration, aeration, plant diseases, and yield quality. Compacted zones drastically affect the rate of water infiltration and, hence, soil water storage for subsequent use by plants. On Pratt fine sandy loam (sandy, mixed, thermic Psammentic Haplustalf) at Woodward, OK, water infiltration in 6 h was 71 mm on plots that had a distinct pan and 118 mm on plots that were moldboard plowed deep enough to destroy the pan (Taylor and Burnett, 1963). On Norfolk (fine-loamy, siliceous, thermic Typic Kandiudult) soil having a sandy clay loam B horizon at Florence, SC, water remained ponded on the surface of shallow-tilled plots 12 h after a rainy period, but no water was on the surface of chiseled plots (Campbell et al., 1974). Deep plowing also increased rainwater infiltration rate on Commerce silt loam (fine-silty, mixed, nonacid, thermic Aeric Fluvaquent) in the cotton growing area of the Mississippi River Delta Plains in Louisiana (Saveson et al., 1961). Greater infiltration more readily refilled the soil water storage reservoir, which increased cotton lint yields in years with limited rainfall. Yields were not affected by deep plowing in years with adequate rainfall.

Adequate soil aeration (O_2) is essential for plant roots to function properly. When compacted zones occur in clay or clay loam soils, O_2 flow to plant roots may be too low to fully meet plant needs, even if a water table is not present (Mathers et al., 1971; Taylor and Burnett, 1963). Other effects of poor aeration include the accumulation of CO_2 and other substances in soil, which may cause root death or interfere with water uptake, N_2 fixation, and microbial activity (Cannell and Jackson, 1981). Sandier soils usually have no aeration problems, even when a compacted zone is present within the root zone (Taylor and Burnett, 1963).

Waterlogging, which may occur when a compacted zone interferes with drainage of excess water from soil, may promote or inhibit plant disease development. Disease development depends on whether the particular organism can develop under anaerobic conditions and in the presence of other competing microorganisms, and whether changes (if any) occur in the susceptibility of the host plant to the organism (Cannell and Jackson, 1981). For example, some fungi are favored by wet, poorly drained soils, whereas others (e.g., actinomycetes) thrive in dry alkaline soils (Lyda, 1981). Root rot of sugar beet (*Beta vulgaris* L.) was reduced when Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) was deep plowed (>0.40 m) (Mathers et al., 1971). The soil is slowly permeable due to naturally dense B horizons.

Total yield is of primary concern for most crops, but yield quality is of major importance for some crops, especially root crops. A restrictive zone in soil may deform root crops, thus lowering their market value. This is especially true for tap-rooted crops, for which the restrictive zone results in short, odd-shaped roots (as shown for sugar beet by Mathers et al., 1971).

RECENT STUDIES OF SOIL COMPACTION AND ROOT GROWTH

Uniform Wheel Traffic Compaction

Surface Compaction

Several researchers (Raghavan et al., 1979; Willatt, 1986) have examined the effect of uniform soil surface compaction on crop growth and yield. Compaction treatments in such experiments generally are imposed by completely covering the soil surface with wheel tracks of the assigned contact pressure and number of passes. In an experiment with corn, Raghavan et al. (1979) found that rooting depth and root density were greatest in plots without traffic and decreased with number of passes (Fig. 4). For example, root density in the top 20 cm of soil dropped from 5.7 mg g^{-1} with no traffic to <2 mg g^{-1} with 15 passes of a 62-kPa tire track. Rooting depth decreased from 90 cm in control plots to 37 cm in plots with 15 passes. Similarly, Willatt (1986) observed that barley (*Hordeum vulgare* L.) root length density in the upper 30 cm of soil and rooting depth decreased as the number of tractor passes increased from zero to six.

Subsurface Compaction

Compaction below the depth of normal tillage operations is generally called subsoil compaction. Voorhees et al. (1989) examined effects of uniform subsoil compaction on root growth indirectly by examining water uptake patterns for corn. An 18-Mg axle load was applied to the entire plot surface of treated plots. This traffic caused significant changes in bulk density to a depth > 60 cm (Voorhees et al., 1986). Before planting, the upper 25 cm was tilled intensively, which left a compacted layer between the 25- to 60-cm depth. In the first 2 yr after compaction, the 18-Mg per axle treatment reduced plant water uptake and reduced the amount of water extracted from below the 45-cm depth as compared with the control (<4.5 Mg axle load). These water extraction differences reflect differences in root distribution, rooting depth, and root density caused by subsoil compaction.

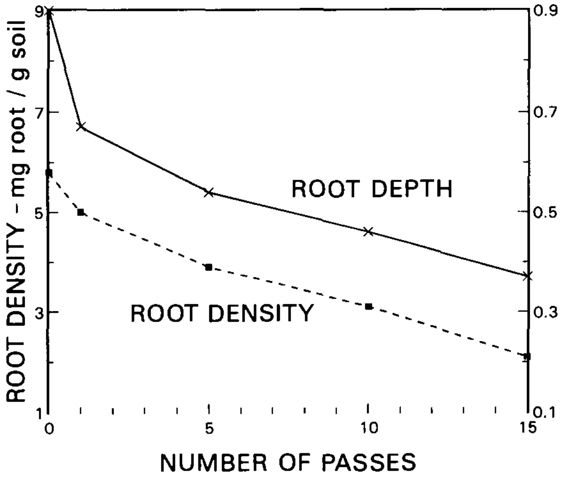

Fig. 4. Corn root density in the upper 20 cm of soil and maximum depth of root penetration for plots uniformly compacted by 0 to 15 passes of tires with a 62 kPa contact pressure (redrawn from Raghavan et al., 1979).

Nonuniform Traffic Compaction

Traffic on One Side of Plant Rows

In typical row-crop management systems, soils are not uniformly compacted by machinery traffic. Because the direction of travel for many field operations is parallel to the crop row, wheel traffic tends to be concentrated in interrows, and some interrows are compacted while others are not. As a result, wheel traffic can cause dramatically different soil physical conditions in traffic and nontraffic interrows. Bulk density and soil strength on the traffic side of a plant row can be much greater than those on the nontraffic side of the same row (Fausey and Dylla, 1984; Gerik et al., 1987; Kaspar et al., 1991; Voorhees, 1992). This positional variation of soil properties with respect to the crop row can alter root growth and distribution.

Kaspar et al. (1991; Table 1) found that wheel traffic consistently reduced corn root growth in the upper 30 cm of traffic interrows for no-tillage, ridge-tillage, and chisel-plow systems. The 0- to 15-cm layer of nontraffic interrows had three times more root length than traffic interrows. Other researchers also reported reductions in corn root growth in wheel-traffic interrows (Bauder et al., 1985; Chaudhary and Prihar, 1974; Hilfiker and Lowery, 1988), but the effect was not always consistent across tillage systems or soils.

Wheel-traffic compaction overshadowed any tillage effects in traffic interrows in the Kaspar et al. (1991) study.

Table 1. Three-year average root length of corn at the sixth-leaf stage at two depths in trafficked and nontrafficked interrows of three tillage systems (data from Kaspar et al., 1991).

Tillage	Soil depth	Root length		
		Nontrafficked	Trafficked	Avg.
	cm	km m^{-3}		
No-till	0–15	4.32†	1.24	2.78
	15–30	2.39‡	1.61	2.00
Ridge-till	0–15	3.60	1.50	2.55
	15–30	2.13	1.89	2.01
Chisel plow	0–15	3.73	1.07	2.40
	15–30	4.50	1.86	3.18
Avg.	0–15	3.88	1.27	2.58
	15–30	3.01	1.79	2.40

† LSD (0.05) for the 0- to 15-cm layer: Tillage (T) = nonsignificant; Interrow (I) = 0.97; T × I = 1.69.

‡ LSD (0.05) for the 15- to 30-cm layer: Tillage (T) = nonsignificant; Interrow (I) = 0.71; T × I = 1.23.

In contrast, Bauder et al. (1985) reported that tillage had a greater effect on root growth than wheel traffic. They found that root length in the 0- to 30-cm layer averaged across traffic and nontraffic interrows was greatest for ridge-tillage and similar for no-tillage and chisel-plow treatments. Similarly, Lal et al. (1989) found that corn root length density in traffic interrows with continuous no-tillage was ≈41% less than with continuous moldboard plowing. Hilfiker and Lowery (1988) observed that the magnitude of the reduction in corn root growth caused by wheel traffic depended on both tillage system and soil type.

Wheel traffic can also influence root growth below the depth of compaction in some soils. Tardieu (1988) observed that compaction of the upper 28 cm of interrows reduced corn root growth below 28 cm. He surmised that this occurred because roots normally enter these soil volumes from above and not laterally.

Traffic on Both Sides of Plant Rows

Whereas the above studies compared traffic and nontraffic interrows on opposite sides of a single plant row, Voorhees (1992) compared corn and soybean [*Glycine max* (L.) Merr.] root distributions when interrows on both sides of a row were either trafficked or nontrafficked. Wheel traffic on both sides of a row increased total corn root growth in the profile by 24% in a reduced-tillage (chisel-plow or disking) system and decreased total length by 22% in a moldboard-plow system. Wheel traffic reduced the percentage of total root length of corn in the upper 30 cm in the reduced-tillage system and in the 15- to 30-cm layer in the moldboard-plow system. As compared with no wheel traffic, total root length and percentage of roots of soybean in the upper 30 cm were increased by wheel traffic in the moldboard-plow system and decreased in the reduced-tillage system.

Managing Soil Compaction

Soil Management

If a soil has become compacted to the point that root and plant growth and yields are impaired, the compaction must be alleviated through management to achieve satisfactory growth and yields. Until recently, soil freezing and thawing were assumed to eliminate compacted soil layers in most of the U.S. Corn Belt (Gill, 1971) and no special management was required. However, Voorhees et al. (1978, 1986) have shown that subsoil compaction can persist for many years after the initial loading in spite of annual freezing to the 90-cm depth. Thus, compaction must be managed even on soils with freeze–thaw cycles.

One of the most direct methods for avoiding compaction is the concept of controlled traffic (Taylor, 1983; Gerik et al., 1987). A controlled-traffic system restricts wheel traffic to specific lanes or interrows. As a result, more of the soil area remains uncompacted than when a random or uncontrolled traffic pattern is used. Gerik et al. (1987) found that soil strength and bulk density were higher and that root densities of cotton, grain sorghum [*Sorghum bicolor* (L.) Moench], and wheat (*Triticum aestivum* L.) were lower in traffic lanes than in nontraffic lanes. Kaspar et al. (1991) found similar results for a controlled traffic system in Iowa.

Compacted zone strength is strongly influenced by soil bulk density and water content (Taylor and Gardner, 1963). Thus, it may be possible through management to circumvent the adverse effects of compaction by growing crops when the soil is sufficiently moist due to timely precipitation or applied irrigation water, so that soil strength does not seriously hamper root penetration. Diverting runoff to or irrigating the cropped area increases the water supply for crops directly and indirectly by allowing roots to penetrate the compacted zone, thus resulting in water extraction from a greater soil volume (Bowen, 1981). Another way to manage soil strength is through the addition of organic matter to the soil. This can be accomplished through the use of no-tillage, crop rotations, or additions of manure or other organic materials. Ohu et al. (1985) showed that adding organic matter decreases the penetration resistance of a soil when it is compacted.

If a compacted zone can be penetrated by plant roots, the channels and macropores formed by these roots may provide sufficient pathways through the compacted zone, so that subsequent plant rooting is not greatly impaired. Of course, recompaction must be prevented. Alfalfa (*Medicago sativa* L.), sweet clover (*Melilotus alba* Medik.), and guar [*Cyamopsis tetragonoloba* (L.) Taubert] have been touted for their pan-shattering abilities, but the mechanism of their effect on yield increases is not clear (Bowen, 1981). However, bahiagrass (*Paspalum notatum* Flügge cv. Pensacola) roots penetrated soil layers that impeded cotton roots, and cotton grown where bahiagrass was plowed under still showed a response after 3 yr (Elkins et al., 1977). Radcliffe et al. (1986) found that surface-applied gypsum improved subsoil root activity of alfalfa on soils with acid subsoils and high subsoil strength. Increased alfalfa root activity in gypsum-treated plots decreased penetrometer resistance below the 30-cm depth. Penetrometer resistance did not decrease in plots that received gypsum, but did not have alfalfa grown on them.

Another technique for encouraging macropore formation in a compacted soil is to manage the crop production system in a manner that promotes earthworm activity. When adequate organic matter is in the soil or organic materials are on the surface, earthworms will burrow to 2-m depths. Earthworm burrows increase water infiltration and provide for root growth through soil zones that might otherwise reduce or prevent root penetration (Bowen, 1981; Ehlers et al., 1983; Logsdon and Allmaras, 1991).

Tillage Management

Whereas circumventing soil compaction by plants or soil animals is relatively slow, rapid and often complete alleviation of soil compaction can be achieved with tillage. According to Gill and McCreery (1960), the moldboard plow is the most efficient tool for loosening a soil to a 0.30-m depth. Thus, if the compacted zone is within 0.30 m of the surface, satisfactory disruption should be possible by using a moldboard plow. Although moldboard plows are efficient for loosening a soil, their use requires large amounts of energy. Also, moldboard plowing buries most crop residues, which may leave the soil in a condition that renders it highly susceptible to erosion.

Various types of disk implements have potential for soil loosening. Standard disk plows can operate to depths similar to those of a moldboard plow, but the disk plows are less efficient. Also, disk plows are forced into the soil by their weight and, therefore, may add to soil compaction. Vertical disk plows (also called disk tiller, wheatland, or one-way plows) are operated at shallower depths than standard disk plows, but they also result in a compacted layer immediately below the tillage depth (Bowen, 1981). As with moldboard plows, most crop residues are covered by use of disk plows, which could lead to increased soil erosion. Disk harrows have little value for loosening subsurface compacted layers in soil. In fact, their use often is the cause of the compacted zone.

A variety of tined implements are available for disrupting compacted soil layers. These include various types of chisels, rippers, and subsoilers. The degree to which tined implements loosen a soil is affected by tine spacing and working depth, share type and width, and soil condition (Bowen, 1981). In general, tine spacing should not be >1.5 times the working depth. Tine implements cause a shattering action in the soil, with soil conditions having a considerable effect on the amount of shattering that occurs. Shattering generally is greater in a sandy soil of low plasticity than in a clay soil of high plasticity. Also, shattering generally is greater for a dry than for a wet soil, but the rough, cloddy condition created in the dry soil may require several secondary operations to break down the clods to achieve a satisfactory seedbed. In general, successful shattering can be achieved when the soil water content is suitable for moldboard plowing (Bowen, 1981): namely, at or near a soil water matric potential of -1.5 MPa. At such potential, the water content is 0.35 to 0.40 $cm^3\ cm^{-3}$ for a clay, 0.22 to 0.25 $cm^3\ cm^{-3}$ for a sandy clay loam, and 0.08 to 0.10 $cm^3\ cm^{-3}$ for a loamy sand (Gupta and Larson, 1979).

Tillage Management of Soils with Dense Soil Horizons

Many soils have naturally dense horizons relatively deep in the profile that, under some conditions, reduce water infiltration rates and restrict root penetration and proliferation. One of these is the Pullman series (fine, mixed, thermic Torrertic Paleustolls) that occurs extensively in the Southern High Plains (Taylor et al., 1963). Winter wheat and sunflower (*Helianthus annuus* L.) may root deeply (>2.0 m) in this soil (Johnson and Davis, 1980; Jones, 1978). In contrast, grain sorghum rooting generally is limited to the upper 1.2 m. To improve water infiltration, plant rooting depth, and water-use efficiency, Eck and Taylor (1969) modified the profile of Pullman clay loam to 0.9- or 1.5-m depths with a large ditching machine. Over a 3-yr period, modification to both depths increased water-use efficiency an average of 41% and total dry matter production an average of 25% for grain sorghum grown under limited irrigation (preplant only) conditions. It increased grain yield an average of 66% with 0.9-m-deep modification and 80% with 1.5-m-deep modification. These increases were attributed to changes in amount and distribution of water in the profile and to changes in plant rooting patterns (Fig. 5). With adequate irrigation, modification increased water-use efficiency in two of three seasons, but had little effect on sorghum grain or stover yields. Initially, water infiltration was greatly increased by the modification treatments (Eck and Taylor, 1969), and water infiltration has continued to be much greater on modified than on unmodified plots (Unger, 1970, 1993).

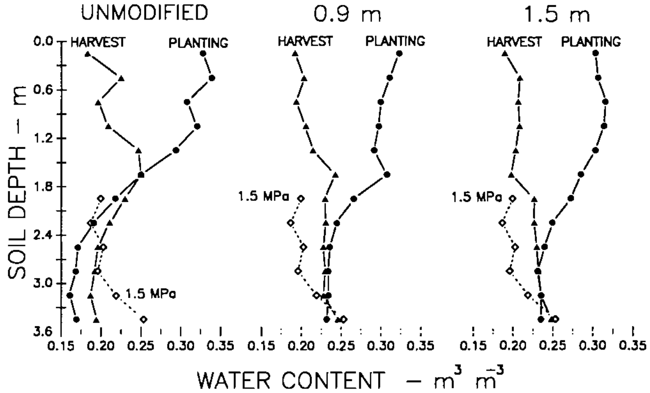

Fig. 5. Soil water content at planting and harvest of grain sorghum as affected by soil profile modification, limited water phase, 1967 (redrawn from Eck and Taylor, 1969).

Musick and Dusek (1975) measured water infiltration, retention, and depletion on furrow-irrigated Pullman clay loam that was moldboard plowed 0.2, 0.4, 0.6, or 0.8 m deep. Infiltration rates and water retention in the profile increased with depth of plowing, and grain sorghum yields were increased under limited-irrigation conditions. Tillage to depths > 0.2 m increased 4-yr average yields from 3.39 to 5.65 Mg ha^{-1} with one preplant and one seasonal irrigation and from 4.66 to 5.94 Mg ha^{-1} with one preplant and two seasonal irrigations. With still more irrigation, tillage at the 0.4-m depth was as effective as tillage at greater depths for achieving yield increases. Musick and Dusek (1975) recommended deep tillage for use with limited irrigation where increased soil water storage was important, but not where frequent irrigation was practiced for high yields, except for crops that responded to reduced soil density and improved aeration associated with deep tillage.

Freeman silt loam (fine-silty, mixed, mesic Mollic Palexeralf) in eastern Washington and northern Idaho has a B horizon beginning at a 0.46-m depth that is almost impervious to roots (Mech et al., 1967). Root proliferation and water extraction were increased and wheat grain and alfalfa hay yields were almost doubled when this horizon was loosened and mixed (Cary et al., 1967). Water use by wheat to a 1.5-m depth was 114 mm with conventional tillage; 145 mm with soil mixed to 0.46 m; 290 mm with topsoil and subsoil removed to 1.2 m, mixed separately, and replaced in the original positions; and 250 mm with topsoil and subsoil mixed together to a 1.2-m depth.

Many coarse-textured soils in the southeastern Coastal Plains have dense layers that restrict root proliferation and water use. Two of these are the Norfolk series (fine-loamy, siliceous, thermic Typic Paleudults) and the Wagram series (loamy, siliceous, thermic Arenic Kandiudults), which have a tendency to form a dense genetic E-B horizon that is known to restrict the growth of corn, tobacco (*Nicotiana tabacum* L.), and soybean roots (Campbell et al., 1974; Kamprath et al., 1979; Vepraskas et al., 1986). In-row subsoiling has proven to be effective for alleviating the effect of this dense layer in these soils. Vepraskas et al. (1986) found that the number of tobacco roots below the compacted layer was greater in plots that were in-row subsoiled than in plots that were not subsoiled. Similarly, Vepraskas and Wagger (1990) and Kamprath et al. (1979) found that in-row subsoiling of Norfolk and Wagram soils increased corn and soybean rooting depth and yield.

RESEARCH NEEDS

Major advances have been made in our understanding of the relationships between soil compaction and plant root growth in recent decades due to the efforts of Dr. Taylor and co-workers, as well as numerous other scientists. Although advances have been made, these advances have also helped to identify gaps in our knowledge regarding soil compaction and root growth. In addition, changing crop production technology is leading to new areas of concern regarding soil compaction and root growth and activity. The following are some areas where research is needed.

1. Improved understanding of the effect of nonuniform soil compaction on root growth patterns and water and nutrient uptake by roots. Nonuniform compaction occurs when wheel traffic after planting is confined to interrows. With no-tillage or ridge tillage, plant rows are reestablished at similar locations each year and they must not be compacted by harvesting or by off-season operations. Interrow compaction may limit root extension into surface soil zones, thus limiting water and nutrient uptake from these compacted zones, especially when fertilizers are applied in these compacted zones. At present, our knowledge regarding root response over time and the response of different crops to such conditions is limited. Also, such research often has involved only a few soils and few levels of compaction, and was limited to one or two growing seasons.
2. Determination of soil compaction alleviation by plant roots. Roots of some plants are known to grow into or through compacted soil zones that prevent root growth of other plants. Also, some producers using no-tillage have no problems with compaction after the transition to no-tillage has occurred, even though they move the row position each year or drill plant their crops. One hypothesis is that roots extend throughout the compacted zone, thus resulting in macropores that are explored by roots of the next crop.
3. Improved understanding of the interactions among weather conditions (precipitation and temperature), soil compaction, and volume of soil explored by roots. Such understanding may explain why compaction decreases crop yields in some years on some soils, but not in other years or on other soils. Eventually, this research should lead to modeling of the volume of rooted soil as a function of compaction, soil water content, and plant development, then prediction of plant growth and yield as a function of rooted soil volume, weather conditions, and available water and nutrients. Long-term climatic data could then be used to predict (model) the risk to crop yields associated with a given level of soil compaction.

SUMMARY

Research by Howard M. Taylor and co-workers established the foundation for our knowledge concerning the effects of soil compaction on root growth, aboveground plant growth responses to root zone compaction, and the alleviation of compaction through soil or tillage management. Generally, compaction is considered to be detrimental to crop root growth; however, usually not all parts of a root system are exposed to the same degree of compaction under field conditions, and the capacity of unimpeded parts of the root system for compensatory growth may result in only the distribution of roots being changed and not the total length. As a result, effect of compaction on plant growth may be important only when the altered root distribution limits the supply of water or nutrients. For example, surface compaction of interrows may limit uptake of fertilizer applied on or near the surface of these interrows. Additionally, weather conditions through the effect of soil water on soil strength can enhance or diminish the effect of compaction on root growth. Even if compaction limits root growth, subsequent weather events may either enhance or diminish the effect of the root limitation on crop growth. From the viewpoint of risk reduction in dry years and efficient utilization of applied nutrients, managing soils by using appropriate tillage and related practices and growing of deep-rooted crops in rotations will help avoid or alleviate compaction, thus improving root growth and distribution and increasing rooting depth.

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