SOIL PHYSICAL AND CHEMICAL ASPECTS OF TILLAGE

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Introduction

Tillage is performed for a variety of reasons in practical agriculture, but all reasons do not apply to each specific crop production system (Cooper, 1971).

- To move soil for seed insertion
- To modify topography
- To manage crop residues
- To change the physical condition of soil
- To reduce wind erosion
- To add and mix soil amendments
- To control insects and diseases
- To control weeds

"Plants respond to variations of soil water, soil air, soil temperature, and soil strength. The purpose of tillage is to alter the tilth or fabric of the soil so that water, air, temperature, and strength conditions in the soil are improved for plant growth and for long-term productivity of the soil" (Larson & Blake, 1966).

Soil physical properties can be expected to increase in practical importance as fertility limitations are removed in crop production. Even if a soil's physical characteristics are changed as needed, a tillage operation can be rendered agronomically ineffectual for chemical reasons, such as the presence of toxic Al.

Before a tillage system can be specified for optimum use under a specific field situation, it should first be known (a) what physical conditions plant roots require in the soil (which will vary according to plant species, soil series, climate, and management practice) and (b) how these physical conditions can be created in the soil by means of tillage. (Different soils, or the same soil in different conditions, may require unequal amounts and kinds of physical effort to create the required physical condition). "The design, selection, and management of tillage equipment and cropping systems must be directed toward producing the optimum state of compaction at the different positions in the soil volume throughout the period of crop production" (McKibben, 1971).

This paper is not intended as an extensive review of the literature, but simply presents a particular viewpoint of some basic aspects and considerations underlying tillage practices.

Plant demand for growth factors

The genetic constitution of a plant, together with the environmental conditions imposed upon it, determine the plant's demand for the essentials of growth. This can be expressed symbolically as

$$\text{Demand for plant growth factor} = f\,(\text{plant genes, environmental conditions}) \qquad (1)$$

In order to be of use under a specific situation, each of the elements in this function would have to be described in more specific component terms.

A plant's demand for a growth factor manifests itself over time, and varies with time from planting stage to eventual maturity, and also fluctuates in the short-term. If rate of demand for a factor were plotted as a function of time, the total requirement for the specific factor could be determined mathematically by integrating the function between the time limits of interest.

It is known intuitively, and from practical observation, that the growth rate of a particular plant is dependent on whether the supply rates of all growth factors are constantly matched to the variable needs of the plant during its whole growing period. The quantititative effect on final yield, of exceeding or under-supplying the demand, will be different at different growth stages and will also not be the same for all growth factors. This can be written as

$$YR_F = f\,(F\text{ stress}, S) \qquad (2)$$

where YR = yield reduction
F = growth factor
S = growth stage, and
F stress = (Demand for F – Supply of F)

It is not known how the interactive effects of stress and growth stage combine, multiply, or interact on total yield over all growth factors.

Although still insufficiently specific, a more useful function (in terms of the fundamental growth factors) would be

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$$\text{Plant growth} = f(\text{genes, light, heat, water, nutrients, } CO_2, O_2, \text{poisons, pests, diseases}) \quad (3)$$

Again, each element in function 3 would require more detailed component terms to include characteristics of the soil, the plant, the environment, and time. Once such an overall equation were available, it could be differentiated with respect to time to yield, amongst other things, the required flow rates in the soil for the various growth factors, especially in respect of heat, water, carbon dioxide, and oxygen. If it were further known how tillage affects a soil's properties regarding storage (water) and transmission (water, gas, heat), it would then be possible to predict the effects of various tillage options on yield. Attempts in agriculture to control the flow of gas, water, and heat through soils at rates which satisfy the dynamic needs of growing plant roots are primarily exercised by manipulation of soil physical properties, particularly soil structure and its effects on porosity characteristics (compare Taylor, Huck, & Klepper, 1972).

Function 3, in its general form, applies to both roots and shoots. The more detailed equation would distinguish between aerial and subterranean plant parts. For example, shoots require both light and CO_2, roots do not. A non-flow factor, not accounted for by function 3, would involve the soil strenth requirements for optimal root growth. However, soil resistance is unlikely to affect plant yield provided the plant's demand or repulsion for the fundamental growth factors can be fulfilled (see function 3).

Soil physical problems arising in mechanised crop production systems

Three types of soil physical problems can be expected to arise, to variable extents, in mechanised crop production. Not all of these problems will necessarily be absent in non-mechanised systems. These problems usually occur at the soil surface, within the soil profile at specific depths, or they may be of a general nature, such as overall compaction.

Surface problems

Soil porosity should be of a nature which allows the passage of gases and water at rates which ultimately satisfy the dynamic demands of plant roots. The kind and extent of soil pores depend on the soil's texture and its structural development. Structural breakdown is usually in favour of microporosity, mainly at the cost of macroporosity, but also to the detriment of totoal porosity (Laws & Evans, 1949).

Particularly vulnerable to structural deterioration and aggregate breakdown is the surface soil zone (tillage, traffic, raindrop action, scouring action of runoff). Such deterioration often results in the formation of a dense and relatively impervious surface crust, which in turn obstructs infiltration of water and free exchange of gas (when wet), and impedes seedling emergence.

Three sets of factors are relevant to the dynamics of soil aggregation: those responsible for aggregate formation, those which give aggregates stability once they are formed, and those which tend to destroy aggregates. The structural condition of a soil is determined by the relative intensities of the above sets of factors acting on the particular kind of soil material. Tillage markedly increases the intensity of the destructive forces acting on soil aggregates.

According to Russell (1957), the most desirable size for the surface crumbs or clods from the point of view of plant growth lies in the range of 1–5 mm, rather towards the smaller limit in dry conditions and the larger in moist (compare Larson, 1964).

Traffic pans

A traffic pan can be defined as any horizontal layer of soil which, due to the action of one or a combination of tillage operations, is at a level of compaction distinctly higher than the rest of the soil. The most common instance of a traffic pan is a plough sole.

When infiltration rate is profile controlled (which occurs when water supply rate is faster than infiltration), steady-state infiltrability is controlled by the soil layer of lowest hydraulic conductivity. This impediment is likely to be the ploughpan, unless the soil surface has developed a crust of even lower conductivity. If the ploughpan is destroyed by appropriate tillage, infiltration rate would increase, possibly even to exceed water application rate. This situation would obviously be desirable as surface runoff would then be minimised or eliminated.

Traffic pans in soils may act as physical barriers to root growth. When a plant root encounters a soil pan, depending on its strength, the root may continue to grow in the same direction but at a slower rate, it may grow into the layer a short distance and then stop further elongation, or it may divert horizontally (Taylor, 1971). "It seems probable that high-strength pans will reduce yields of nearly all crops if, and probably only if, the pans substantially increase plant stress for water or nutrients" (Taylor, 1971). The more arid the environment, or the closer to the surface the tillage pan, the greater the expected depressive impact on growth. Thus, depending on conditions, plant response is variable.

A buried compressed layer may give rise to a perched water table of variable duration following rain. Roots growing in this zone prior to formation of the water table are frequently killed if the condition persists for long. If these roots represent a large proportion of the root system, the crop can suffer or be almost entirely lost during periods of high transpirational demands (Trouse, 1971a).

Overall compaction

Compaction will generally reduce a soil's conductivity for water and air (but increase it for heat), as well as enhance soil strength. Diffusion of gas in soil is proportional to the volume of air-filled pores and, for the sizes encountered in soils, seems to be largely independent of pore size (Russell, 1957). Reduced air exchange with the atmosphere on compaction seems to be a problem only when the soil is very wet. Macroporosity is a casualty of compaction ahead of microporosity. Reduced macroporosity has a detrimental effect on saturated hydraulic conductivity, including infiltration. Since water flow is proportional to the fourth power of the radius of pores, halving pore size decreases saturated flow rate by a factor of 16.

Compaction reduces root proliferation and extent, not only by reducing the supply or exchange of water, oxygen, carbon dioxide, and other gases, but also by increasing soil strength. Tillage markedly influences the pore system in soils (Figures 1 and 2).

FIG 1 The pore system of a thin slice of uncompressed soil. The dark area represents the voids (Trouse, 1971b).

FIG 2 The pore system of a thin slice of tilled soil which was compressed by interrow surface traffic. Note the small isolated voids typical of the pore system of compressed surface soil (Trouse, 1971b).

Principles of machinery use to minimise compaction are given by Gill (1971). Except in rare instances, the enhancement of yield from loosening soil is not comparable to increases due to fertilising, land forming, irrigating, or other management factors (Gill, 1971).

Effects of tillage on soil properties and plant growth

Water

Tillage influences the availability of water to plants mainly through its effects on infiltration, temporary surface storage, rooting depth, weed growth, surface evaporation, and changes in the soil's water content-suction relationship. Any tillage-induced deterioration of soil structure will work in the direction of increasing the tension at which a given amount of water is held and consequently decreases its degree of availability to plants. Soil structural problems intensify the detrimental effects of excess water on plant root growth.

Properties of the soil surface determine the partitioning of rainfall between runoff and infiltration, the latter determining moisture recharge of the soil profile. If runoff is to be eliminated, the soil's surface characteristics must be managed so that cumulative infiltration plus surface storage capacity, at any time during a rain, at least equals cumulative rainfall. Formation of a surface crust, whether caused by tillage or rain, has a marked influence on infiltration (Figure 3). Note that a surface crust, acting as a hydraulic bottleneck, decreases both initial and final infiltrability of a soil.

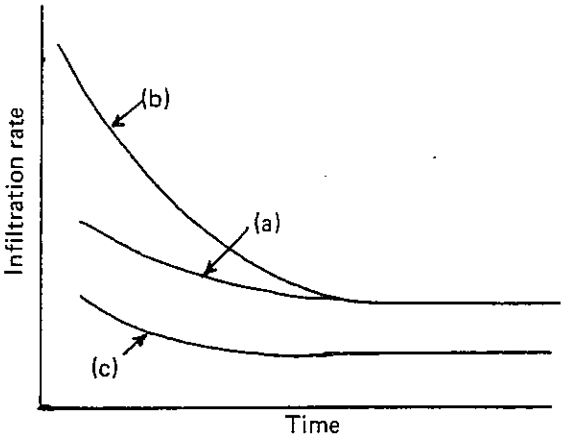

FIG 3 Infiltrability as a function of time: (a) in a uniform soil; (b) in a soil with a more porous upper layer; and (c) in a soil covered by a surface crust (Hillel, 1971).

Aeration

Water occupies pore space of a porous medium, such as soil, obviously at the cost of air. Water containing dissolved oxygen in equilibrium with air holds only 3 per cent as much oxygen per unit volume as does air. Furthermore, the diffusion coefficient of oxygen is of the order of 10 000 times as great in air as it is in water (Black, 1968).

Equal quantities (moles) of oxygen and carbon dioxide are, respectively, consumed and evolved during aerobic respiration. Carbon dioxide evolution exceeds oxygen consumption when respiration is partially anaerobic. No gaseous oxygen is consumed in completely anaerobic respiration (Black, 1968). The amount of oxygen that must be exchanged per day between soil and atmosphere is of the order of 25 per cent of the amount present in the soil (Black, 1968).

Curtailed root growth, decreased nutrient and water absorption, and formation of toxic compounds other than CO_2 (H_2S, ethylene, methane, H_2) are all expected under conditions of poor aeration in a soil. Root growth will generally cease if oxygen diffusion rate (ODR) falls to less than 20×10^{-8} g cm^{-2} min^{-1}. Satisfactory root growth can be expected if ODR is equal or greater than 30–40 x 10^{-8} g cm^{-2} min^{-1} (Stolzy, Letey, Szuszkiewicz & Lunt, 1961). A satisfactory ODR seems possible as long as air porosity does not fall below 10–12 per cent of soil volume. This aeration threshold is usually reached in productive soils only upon flooding. It may occur in poorly drained soils after each rain or for an extended period in severely compacted soil (Erickson & van Doren, 1960).

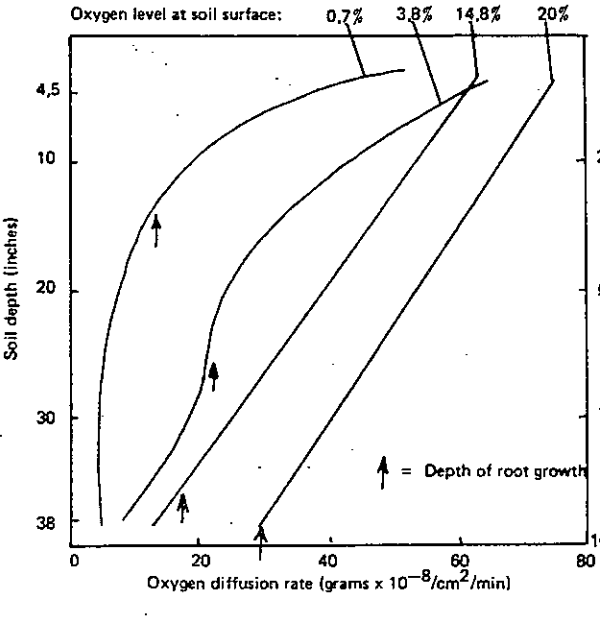

FIG 4 Effect of soil depth and oxygen concentration at the surface on the oxygen diffusion rate (ODR). Arrows indicate snapdragon root penetration depth (Redrawn from Stolzy et al., 1961).

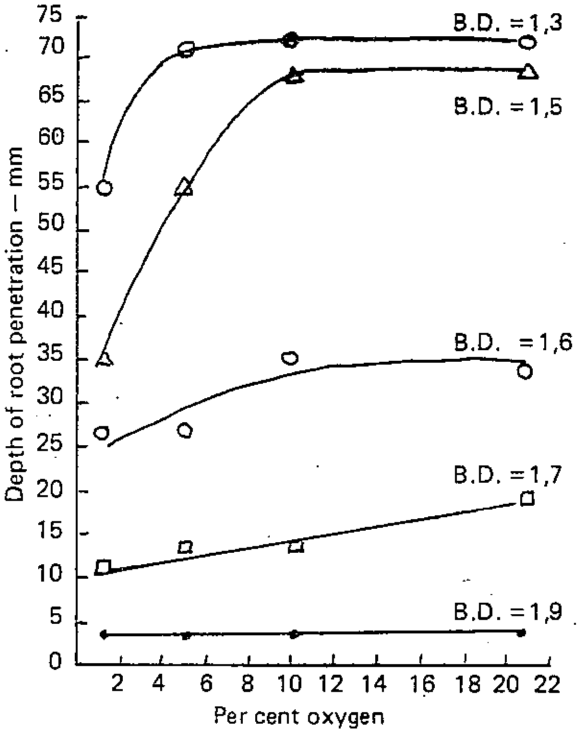

FIG 5 Effect of oxygen concentration and bulk density on depth of cotton seedling root penetration into compacted soil (Tackett & Pearson, 1964).

Depth of snapdragon root growth as a function of ODR is shown in Figure 4. Even when atmospheric air with 20 per cent O_2 was used, the ODR at 97 cm was less than half that at 11 cm. Root growth ceased when ODR dropped to about 20×10^{-8} g cm^{-2} min^{-1}. The rate of respiration, and hence oxygen requirement, is greatest in root tips (where most active growth occurs) and decreases with distance from the tip. Root elongation is thus particularly sensitive to aeration conditions (Black, 1968).

Although aeration of compact soil zones improves on drying, strength and consequent impedance to root penetration increases. The ability of maize and bean seedling roots to grow against applied pressure in a glass bead matrix depended on oxygen level (Gill & Miller, 1956). Similar results were observed for cotton radicles growing in a sandy clay loam soil at different levels of compaction and oxygen (Tackett & Pearson, 1964). Root penetration was reduced as much by increasing bulk density from 1,5 to 1,6g cm^{-3} as by decreasing oxygen concentration from 10 to 1,2 per cent (Figure 5).

Temperature

Soil temperature is a function of air temperature, type, amount, and duration of radiation, precipitation, soil water content, soil texture, structure, colour, thermal

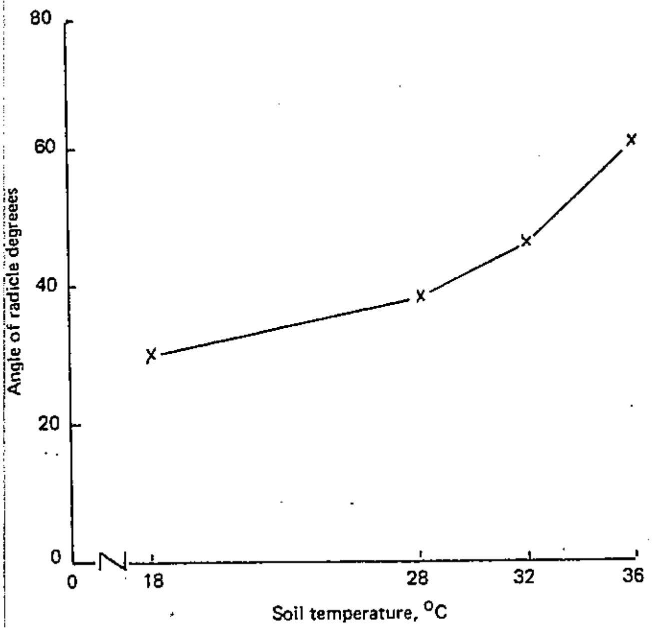

FIG 6 *Average angle of growth of maize radicles at different constant temperature (Mosher & Miller, 1971)*

conductivity, soil surface aspect, and the type and amount of soil cover (Willis & Amemiya, 1973).

Temperature affects various root functions, such as nutrient and water absorption, metabolite production, and action as a sink for carbohydrates produced in aerial plant parts. All of these functions will have an optimum temperature, not necessarily the same, above and below which the particular function will decrease in rate and effectiveness. Generally, as temperature increases towards the optimum, there will be an increase in germination and rate of emergence, as well as increased yield, top weight, and height (Willis & Amemiya, 1973). If ODR is low, high soil or aerial temperature is more detrimental to shoot growth than is low temperature. Oxygen demands of the root, and its sensitivity to CO_2, seem to increase for most plants as temperature increases (Russell, 1961).

Friend (1966) reported optimum aerial temperatures for maize to be 30 to 35°C (day) and 25°C at night. Optimum soil temperature at the 10 cm depth appears to be about 24°C (Willis & Amemiya, 1973).

Soil temperature influences the direction of root growth in maize (Fig. 6).

Onderdonk (1972) established that the primary root of a maize plant will grow closest to the horizontal at 17°C. Above or below this temperature it grows more towards the vertical, reaching about 45° at 10 and 30°C.

The above information is potentially very important in designing fertilizer band placement relative to seed. Since the maximum of temperature fluctuations was found to determine root behaviour, soil temperatures would only need to reach 30°C for short periods to result in a 45° root angle. A fertilizer band would then be most effective if placed equal distances below and to the side of the seed. Uptake of surface broadcast fertilizer might thus be improved by reducing soil temperature maxima (by means of mulch) and thereby encourage a more horizontal growth of roots (nearer to surface).

When soil is tilled, its specific heat capacity and thermal diffusivity are altered (Taylor, 1967). These changes will be reflected in soil temperature measurements. Tillage may also alter the quantity of heat generated internally within a soil volume by influencing respiration of roots and micro-organisms.

Nutrient supply

The effect of soil compaction on nutrient supply to plant roots can be both detrimental and beneficial (Kemper, Stewart & Porter, 1971). Compaction increases the rates at which most nutrients move to roots by diffusion and mass flow (Table 1). Mass flow of nutrients in the transpiration stream is influenced by compaction only as water movement is affected (Parish, 1971). On the other hand, compaction of soil usually results in a decrease in the amounts of nutrients mineralised from soil organic matter (Kemper *et al.*, 1971).

If compaction increases runoff and this reduces soil water content, the cross-sectional area available for diffusion decreases while diffusion path tortuosity increases, thereby reducing diffusive flux. However, moderate compaction should not be detrimental to plant nutrient status, provided infiltration and fertilizer application remain satisfactory (Kemper *et al.*, 1971).

TABLE 1 *Uptake of P and water by simulated roots at three bulk densities (Kemper* et al., *1971)*

Bulk density (g/cc)	Relative P uptake[1]		Average bulk flow rate of soil solution[2] (cc/cm of root/day)
	Diffusion	Diffusion plus bulk flow	
1,10	0,79	0,86	0,50
1,35	1,00	1,10	0,72
1,60	1,16	1,31	0,89

[1] Relative uptake rates were all calculated as decimal fractions of the uptake rate by diffusion alone from a soil of 1,35 g/cc bulk density.

[2] Data from several field and greenhouse studies on maize, where both root length and transpiration could be estimated, indicate that flow rates of soil solution into roots is generally between 0,01 and 0,15 cc/cm of root per day.

Soil strength

Bulk density and moisture tension interact strongly in their influence on soil impedance to a root or probe (Figure 7).

"This interrelation of soil bulk density and matric pressure, which possibly occurs in all soils, renders the resistance behaviour of soils to be unpredictable unless related to both these parameters simultaneously" (Mirreh & Ketcheson, 1972). On the other hand, Taylor & Gardner (1963) show a progressive decline in root penetration with increasing strength obtained with various combinations of moisture and compaction (Figure 8). Taylor & Burnett (1964) reported no apparent difference among several plant species in ability to penetrate high-strength layers and confirmed an earlier conclusion that root penetration was controlled by impedance. A soil strength of about 30 bars may be a generally applicable critical value for root penetration of soils (unpublished data of C R Camp & Z F Lund, Auburn University, as quoted by Pearson, 1965). This is corroborated by the data in Figure 8. The same figure seems to show that soil strength must be somewhat less than 10 bars to allow relatively successful root penetration of soil.

$$Y = 450 - 845X_1 - 13{,}3X_2 + 385X_1^2 - 1{,}60X_2^2 + 23{,}4X_1X_2$$

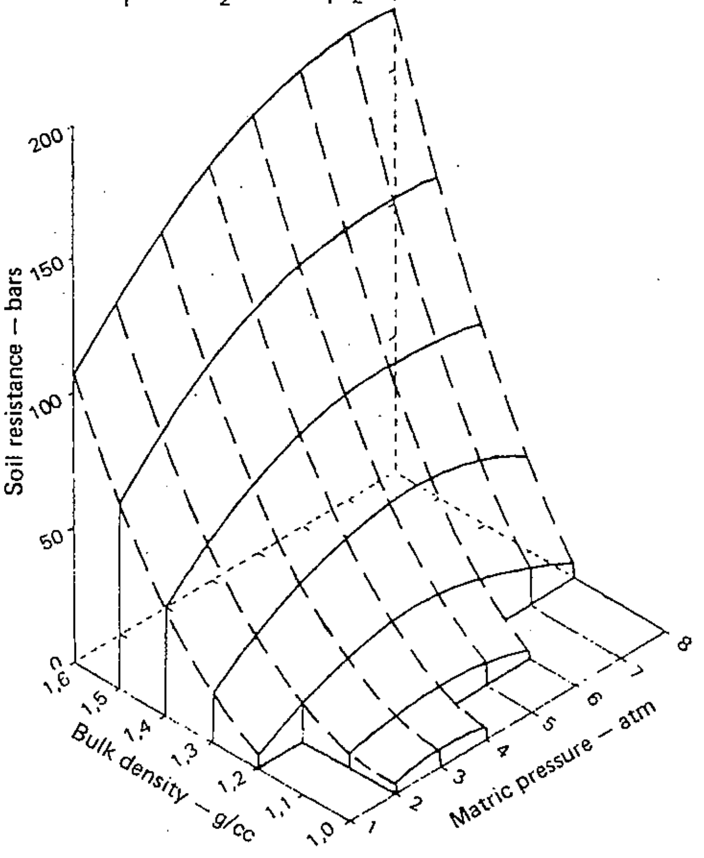

FIG 7 *Three-dimensional plot of generated soil resistance values, bulk density; and matric pressure for a Conestoga clay loam soil (Mirreh & Ketcheson, 1972)*

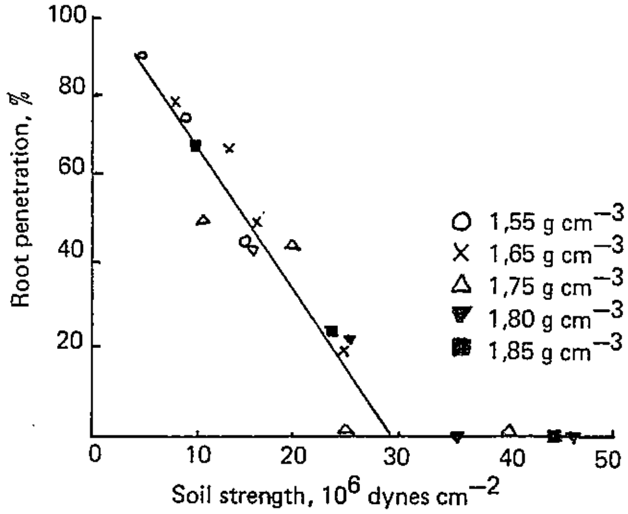

FIG 8 *Effect of soil strength as measured by a penetrometer on cotton seedling root penetration of Amarillo fine sandy loam (Taylor & Gardner, 1963).*

Pearson, Ratliff & Taylor (1970) developed an equation, accounting for 68 per cent of the variation, relating cotton root length at 100 hours after planting to levels of soil penetrometer resistance, soil temperature, and soil solution Al activity. Any of the three variables exerted the greatest effect when the other two were at optimum conditions. When any variable was at or critically near a limiting value, the other variable exerted only a slight effect on elongation rate.

It should be kept in mind, however, that an increase in root proliferation is not necessarily associated with an increase in yield (Larson & Blake, 1966). The entire environment — physical, chemical, and biological — must be assessed to forecast tillage effects on root growth and yield (Taylor, 1967). "In arid or infertile environments, root growth and root absorption capacity frequently limit top growth, but in humid, fertile environments, the plant's photosynthetic capacity or metabolic balance controls production" (Taylor, 1967).

Tentative soil physical specifications regardless of tillage system

1 $\Sigma I + SSC \geq \Sigma R$ (slope $\neq 0$)

where ΣI = cumulative infiltration
SSC = surface storage capacity
ΣR = cumulative rainfall

SSC = f (slope, volume of surface depressions)
ΣI = f (macroporosity, pore stability, initial soil wetness, temperature, impeding layers, mulch, time from rain onset)

2 Air porosity ≥ 10–12% of soil volume (between field capacity and saturation)

3 Soil temperature (maize) = $24^\circ C$

4 Soil strength < 10 bars (at wilting point)
If soil strength ≥ 30 bars, root penetration stops

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