ALVARO - SOLOS

apisilva@ecologia.ufrj.br

comut

Relationship between Soil Physical Properties and Crop Production

J. Letey*

Contents

I.	Introduction	277
II.	Factors Directly Affecting Plant Growth	278
III.	Factors Indirectly Affecting Plant Growth	281
IV.	Interrelationships of Soil Physical Factors	283
V.	Relationships between Soil Physical Conditions and Management	286
VI.	Soil Erosion and Productivity	292
VII.	Conclusions	293
References		293

I. Introduction

Having been labeled a soil physicist, I have received inquiries during my professional career concerning relationships between soil physical properties and plant growth as well as questions on what constitutes good soil physical properties. Most inquiries could be put off by a recitation of generalities such as a loam soil having intermediate bulk density, good aggregation, good infiltration rate, and no impedance to drainage represented a soil with good physical conditions, and good production could be expected on such soil if chemical factors were not limiting. Generalities are not always acceptable as verified by the following three examples.

The golf industry puts high priority on having good putting greens and issued a real challenge. Usually entirely new "artificial" profiles are constructed from mixtures of various materials such as soil, sand, and amendments like peat or wood chips. They desire specific information on

*Department of Soil and Environmental Sciences, University of California—Riverside, Riverside, California 92521

© 1985 by Springer-Verlag New York, Inc.
Advances in Soil Science, Volume 1

what constitutes the "best" soil physical conditions because they can arrange for it and generalities were not very helpful to them.

A second challenge was encountered when I spent several weeks as a Food and Agriculture Organization consultant to a soil science institute in an Eastern Europe country with a centralized national government. Prediction of crop yields was important to the government. Data books were filled with values of bulk density, texture, aggregate stability index, etc., for soils throughout the country. The soil physicists were "obliged" to develop quantitative relationships between these soil physical properties and crop yield so that appropriate yield predictions could be made.

A National Workshop was held in 1981 at Madison, Wisconsin, with the goal to identify national research priorities regarding the uses, management, and conservation of our soil and water resources. An executive summary of that workshop was published (Larson *et al.*, 1981) and one of the six most important research priorities for the nation was stated as follows.

> One-third of the cropland and much of the range and forest lands of the nation are eroding rapidly. Research is needed to quantify the relationship between plant growth and those soil attributes affected by erosion. Once we understand this relationship, we can evaluate periodically the nation's continuing ability to produce food and fiber.

Physical properties are some of the important soil attributes affected by erosion so again a call is recognized for quantifying the relationship between soil physical conditions and plant growth, and generalities won't suffice.

This report represents a viewpoint and not a literature review on the topic. Some references will be cited to document certain points but the cited references will, in most cases, only be examples of several references which could be quoted.

II. Factors Directly Affecting Plant Growth

In considering soil physical properties which are important in crop production, it is necessary to separate factors which directly affect plant growth from those which indirectly affect plant growth. Water, oxygen, temperature, and mechanical resistance impairing seedling emergence or root growth all directly affect plant growth.

Plants cannot grow without water. The important parameter which links soil water to plant growth, however, is not soil water content but soil water potential. Water potential refers to the energy with which water is retained by the soil and consequently to the energy necessary for water to be removed from the soil by plant roots. Different types of soil contain different water amounts at a given potential. There is a relationship between soil water content and potential for a given soil, and thus it is possible to measure soil water content and infer the water potential value if the appropriate

relationship between the two is known. The relationship between soil water content and potential is often determined in the laboratory and very commonly on disturbed soil samples. The measured relationship in the laboratory and the existing relationship in the field may be different.

Plant roots respire thus consuming oxygen and producing carbon dioxide. An adequate exchange of gases between the root and aerial atmosphere is required for optimum plant metabolism, and this exchange has frequently been called aeration. Although both O_2 and CO_2 are involved, measurements are more frequently made on O_2 with the assumption that CO_2 exchange is adequate when O_2 exchange is adequate. Plant metabolism is not impaired if oxygen supply rate to the respiration site equals the oxygen consumption rate under optimum respiration. Oxygen is supplied to the respiration site through diffusion, the rate of which depends on the concentration gradient and diffusion coefficient. Oxygen concentration measurement in soil pores provides information concerning the concentration gradient, but very little or no information on the diffusion coefficient which may be the limiting factor in O_2 supply to the respiration site. The rate of oxygen diffusion to a platinum wire electrode (Lemon and Erickson, 1952) in the soil is quantitatively affected by factors which also affect oxygen diffusion to the respiration site; thus a measurement of this type conceptually allows for a better correlation to plant response than does merely measuring O_2 concentration in soil pores. Redox potential measurements are useful in identifying reducing conditions in the soil, but most agronomic and horticultural field crops are sensitive to oxygen supply before strong reducing conditions exist in the soil.

Metabolic processes are definitely temperature dependent so that soil temperature is an important factor in crop production. Soil temperature would obviously be measured and reported in units of degrees.

Plants can be directly affected by a factor frequently referred to as mechanical resistance of the soil. This has reference to the difficulty that a root encounters in growing into a dense compact soil layer or the difficulty a seedling encounters in emerging through the soil surface. Since both cases are approximately represented by a "probe" being extended through soil, penetrometers have been used to measure soil mechanical resistance as it might affect plants (Taylor, 1971).

An obvious question now arises. What is the optimum value for each of these parameters relative to crop production? A simple answer to this question is not possible. One chief difficulty arises from the fact that these soil physical parameters vary both with respect to time and position in the soil profile. Water content, for example, is constantly changing because of evapotranspiration and precipitation or irrigation. Water is not extracted uniformly throughout the root zone, so differences in water potential occur at different positions in the root zone. No single value of water potential can describe the condition to which a plant is exposed.

The change in oxygen diffusion rate (O.D.R.) with time following irrigation shown in Figure 1 illustrates time and depth variation. The first

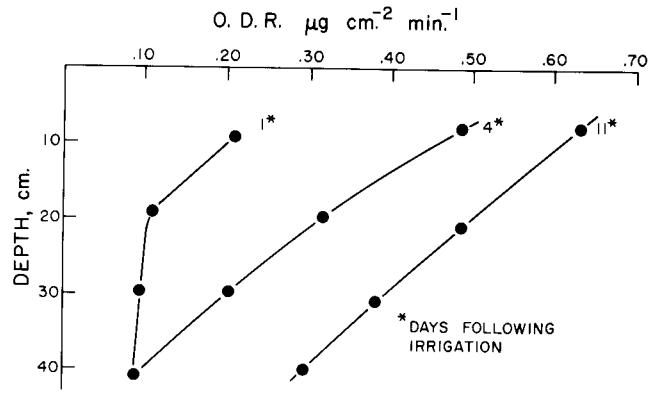


Figure 1. Oxygen diffusion rate as a function of depth for various days following irrigation.

day following irrigation, O.D.R. is below a value which is considered adequate for root growth of several plants (Stolzy and Letey, 1964) at depths of 20 cm or greater. By the fourth day after irrigation, water had been extracted and O.D.R. increased at all depths except 40 cm. The O.D.R. had increased and was well above any limiting level at all depths by the eleventh day following irrigation. Note that for any day, O.D.R. differs with respect to depth within the soil profile and also changes with time at any given depth. The plant integrates the temporal and spatial variations, but quantifying the integral relationships through experimentation is difficult.

Another complication arises from the fact the four soil physical factors being considered are interrelated and never independent of each other. It is impossible under natural conditions to change the value of one soil physical factor without also changing the value of one or more of the other factors. Thus two or more variables are always involved. For example, optimum water status for plant growth may be zero potential or water-saturated soil. Oxygen supply to roots would obviously be limiting for most crop plants under this condition. A balance between the various soil physical properties is desirable.

Furthermore, the relationship between crop production and soil physical condition depends on several plant variables. First, plant species differ in their response to physical properties. Thus the answer will differ depending on the plant species. Second, different phases of plant growth may be affected by soil physical parameters differently. For example, the water potential corresponding to maximum leaf growth may be different from the water potential corresponding to maximum seed production. Third, response to changes in soil physical properties may differ depending on stage of plant growth. Fourth, the relationship between a given soil physical property and plant growth is often dependent upon the climate. For example, allowing the

water potential to reach relatively low values (dry) before adding water was found to be more damaging to the plant under hot as compared to cool climate conditions (Letey and Blank, 1961). Similar observations have been made in experiments with soil aeration (Letey *et al.*, 1962).

Despite these difficulties in relating water potential, O.D.R., mechanical resistance, and temperature to plant growth, several studies have been conducted on soil physical properties and plant production for various plant species and these have been the subject of reviews such as Cannell, 1977; Armstrong, 1979; Taylor, 1971; and Jordan, 1983. It is not the purpose of this discussion to give detailed relationships between soil physical properties and plant growth, but rather to develop a conceptual framework concerning soil physical properties and crop production.

III. Factors Indirectly Affecting Plant Growth

One might consider that thus far some important soil physical properties have been completely overlooked. After all, aren't bulk density, texture, aggregation, aggregate stability, and pore size distribution important soil physical properties and aren't these the properties commonly measured and also most likely to be altered by erosion? Yes, but their relationship to crop production is through their effect on water, aeration, temperature, and mechanical resistance. In other words, the effect is indirect rather than direct.

This point is demonstrated by results of a study on the effect of soil bulk density on the growth of tomatoes (Rickman *et al.*, 1965). A greenhouse study was conducted where the lower parts of containers were packed with a soil to different bulk densities ranging from 1.32 to 1.76 g/cm^3. The upper part of all containers had soil packed to a bulk density of 1.32 g/cm^3 to allow good root growth. This would represent a "loose" top layer of soil over a compacted subsoil in the field.

The results of plant top and root growth for the various bulk densities are shown in Figure 2. Note the general trend for both plant top and root growth to decrease with increased bulk density.

Oxygen diffusion rates were measured in these containers and results are presented in Table 1. In the "loose" surface soil, O.D.R. was well above values considered to limit root growth. In the compacted layers below the "loose" surface, O.D.R. decreased. Lower O.D.R. values were found in the soils with higher bulk densities. Previous experiments provided evidence that an O.D.R. of about 0.20 μg/cm^2 min was required for root growth (Stolzy and Letey, 1964). The stars (**) in the table represent depth to which roots grew for a given treatment. Note that there was no root growth when O.D.R. dropped greatly below 0.20. This suggests that the effect of increased bulk density was to decrease oxygen supply, but the results were not conclusive because O.D.R. was not the only variable. Mechanical resistance was not

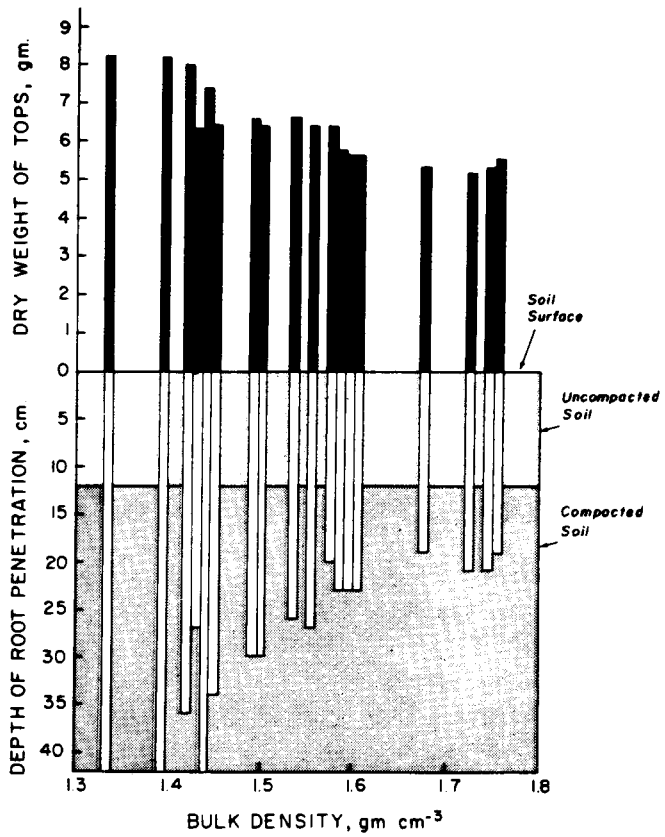


Figure 2. Top and root growth of tomatoes grown in soils with layers compacted to various bulk densities.

measured, but resistance surely increased with increased bulk density of a given soil at comparable water contents.

The next question is would roots grow into the higher bulk density soil if O.D.R. was not limiting? A study was set up to answer this question (Rickman *et al.*, 1966). Special containers were constructed for the study. Four treatments were imposed. Half of the containers had very compact soil and the other half had less compact soil. Under "natural" conditions the low bulk density soil would have high O.D.R. and the high bulk density soil would have low O.D.R. Artificial conditions were used to produce high O.D.R. in high bulk density soil and low O.D.R. in low bulk density soil. The results are summarized in Table 2. The average top growth for plants grown under low O.D.R. was the same regardless of bulk density. Likewise the average under high O.D.R. was the same regardless of bulk density. Therefore, one of the main effects of high bulk density under these conditions was to restrict oxygen supply and thereby reduce plant growth. Under the

Table 1. Oxygen Diffusion Rates at Various Depths of Soils Packed to Different Bulk Densities and Depth of Root Penetration

Bulk density (gm/cm³)					
1.33	1.39	1.44	1.55	1.59	
Oxygen diffusion rate μg/cm² min					
.50	.44	.47	.47	.52	Above Compacted Layer
.34	.51	.42	.55	.61	
.43	.45	.48	.52	.66	
.40	.52	.42	.65	.81	
.35	.43	.24	.28	.26	Below Compacted Layer
				**	
.27	.34	.21	.14	.09	
.33	.22	.15	.13	.05	
			**		
.28	.25	.18	.10	.09	
		**			
.28	.39	.10	.13	.19	
.22	.33	.05	.06	.10	
**	**				

conditions of this experiment, mechanical resistance was not a primary factor in plant growth under the imposed bulk densities.

IV. Interrelationships of Soil Physical Factors

Of the four physical conditions directly related to plant growth, water is the dominant controlling factor. The other three are affected by water content as schematically illustrated in Figure 3. Bulk density and pore size distribution affect the relationship between water and both aeration and mechanical resistance. The relationship between water and aeration is opposite to that between water and mechanical resistance. Increasing water content decreases aeration which is undesirable but decreases mechanical

Table 2. Average Dry Weight of Tops in Grams for Different O.D.R. and Bulk Density Levels

	Low O.D.R.	High O.D.R.
Low bulk density	1.76	3.54
High bulk density	1.92	3.35

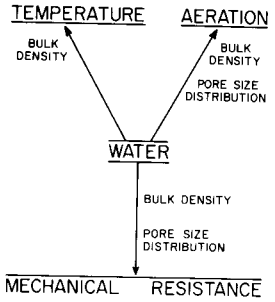


Figure 3. Schematic representation of the relationship between water and other soil physical parameters which directly affect plant growth.

resistance which is desirable. The effect of water on both of these parameters is intensified by increase in bulk density and/or presence of small unisize pores. The optimum range of water content for plant growth has generally been assessed on the basis of plant water availability per se. The upper limit is usually associated with field capacity and the lower limit is associated either with permanent wilting point or lowest water potential which will not reduce plant growth. However the *non-limiting water range* (NLWR) may be affected by aeration and/or mechanical resistance, particularly in poorly structured soils with high bulk density. Possibly O.D.R. is limiting for root growth at field capacity and a lower water content is required for adequate O.D.R., or on the other end of the scale, mechanical resistance which restricts root growth may occur at a water content higher than the value which would be considered limiting to plants on the basis of water availability determination. In other words, the NLWR can be reduced by poor aeration and/or high mechanical resistance in some soils. As bulk density increases and/or poor structure occurs, the NLWR becomes narrower, as illustrated in Figure 4.

These relationships were demonstrated in a field study conducted by Phene and Beale (1976). Their investigation was done on a shallow-layered Varina sandy loam soil of the Coastal Plains in South Carolina. Generally the A_2 horizon of this soil is compact (bulk density equal to 1.7 g/cm^3) restricting root growth so that most of the roots exist in the 25-cm A_1 layer. The authors determined for the A_1 layer that mechanical resistance would restrict corn root growth at soil matric water potential values less than -0.4 bar. The O.D.R. would be inadequate for maximum plant growth at soil matric water potential values greater than -0.08 bar. Ideally water in the A_1 layer would be maintained within the NLWR of -0.08 to -0.4 bar. The NLWR for the A_2 layer was reported as being less than 0.2 bar, but the limit values were not reported.

High-frequency irrigation was imposed in an attempt to maintain the matric potential within the desired range. Porous tube trickle, furrow, and sprinkler irrigation systems were used. There were no statistically significant (95% confidence level) differences between furrow and sprinkler irrigation systems in marketable corn ear weight or amount of applied water. The

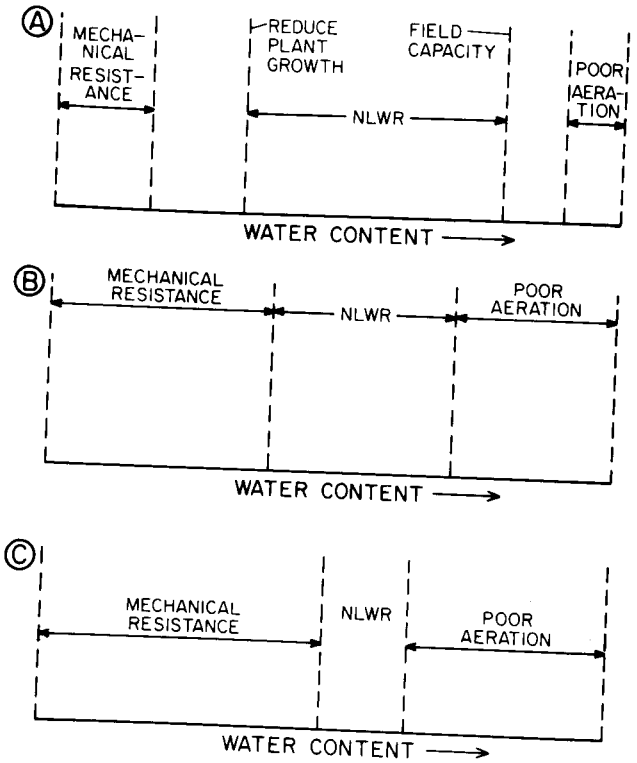


Figure 4. Generalized relationships between soil water content and restricting factors for plant growth in soils for soils with increasing bulk density and decreasing structure in going from case A to C.

trickle irrigation treatment resulted in significantly higher yield and lower applied water than furrow and sprinkler. All irrigation systems were operated to keep soil water potential within NLWR, but the trickle system required less water per irrigation than the other two systems and was better suited for high-frequency irrigation. The lower yields obtained with furrow and sprinkler irrigation as compared to trickle irrigation may have resulted from rainfall which created excessive wetness (deficient aeration) under furrow and sprinkler irrigation.

The photograph in Figure 5 illustrates root distribution under no irrigation and high-frequency trickle irrigation treatments from Phene and Beale's study. The horizontal white lines represent 15-cm soil layers. The dense root system developed in all horizons under trickle irrigation demonstrates that, with careful water management, conditions can be maintained that allow good root growth even where a small NLWR occurs.

Figure 5. Corn roots developed under no irrigation (left) and high-frequency trickle irrigation (right) in study by Phene and Beale (1976). Horizontal white lines represents 15-cm soil layers. The bulk densities of the A_1 horizon varied between 1.5 and 1.6 g/cm^3 and those of A_2 between 1.7 and 1.9 g/cm^3. Photograph by courtesy of C.J. Phene.

V. Relationships between Soil Physical Conditions and Management

Soils classified as having poor physical conditions are those which require very careful management to maintain conditions favorable for plant growth and generally have a small NLWR. Soils with good physical conditions require less careful management and generally have large NLWR. For example, a deep soil of intermediate texture and bulk density with good structure will often provide favorable conditions for plants. If water is applied in excess, it simply drains through the profile without causing low O.D.R. Yet sufficient water is retained in the profile so that plants can grow for a period without suffering from water deficiency. The pores between aggregates allow root growth with low resistance.

The key point is that traditional soil physical properties (texture, bulk density, structure, etc.) affect the *management* practices required to maintain water potential, oxygen diffusion rate, temperature, and mechanical resistance in a range suitable for good production. This relationship is charted in Figure 6. Good soil physical conditions are those which do not require

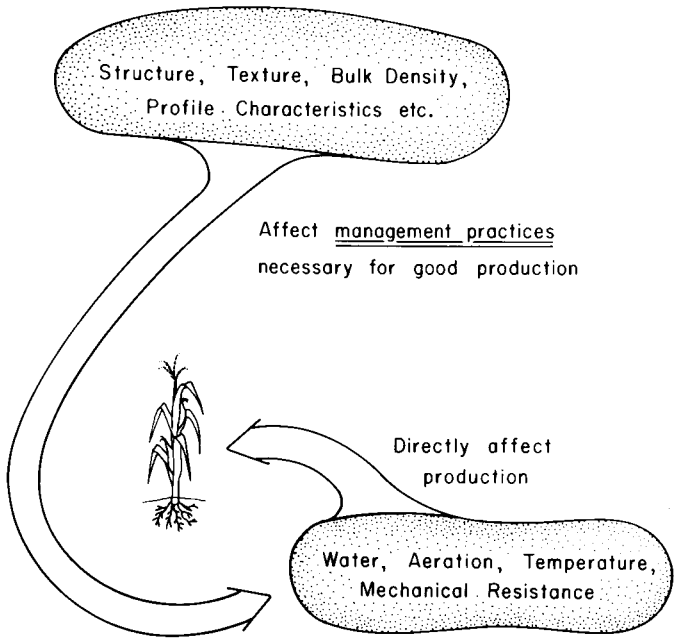


Figure 6. The relationship between various soil physical conditions and crop production.

unusually good management for good production, while poor physical conditions are those which do. Indeed soil physical conditions may be so bad (very small NLWR) that it is generally impossible to manage them sufficiently for good production.

The relationship between soil physical properties and management can be illustrated by results of another study designed to gain information useful for the golf industry. Construction of putting greens provides a challenge and an opportunity to soil physicists to prescribe the "best" soil physical conditions. A greenhouse experiment was set up to investigate the effects of various physical amendments and management practices on the production of grass (Morgan *et al.*, 1966; Letey *et al.*, 1966). Soil with no amendment and soil separately mixed with peat, lignified redwood, and calcined clay were used. (Lignified redwood is redwood chips treated with sulfuric acid so that the remains are mostly lignin. Calcined clay is clay that has been baked at high temperatures and forms stable sand size aggregates.) Two management treatments were applied—one based on irrigation and the other on compaction. One irrigation treatment consisted of adding 1.2 cm of water three times a week which is comparable to some grower irrigation practices, and the other was irrigation as guided by tensiometer readings. Half of the soil

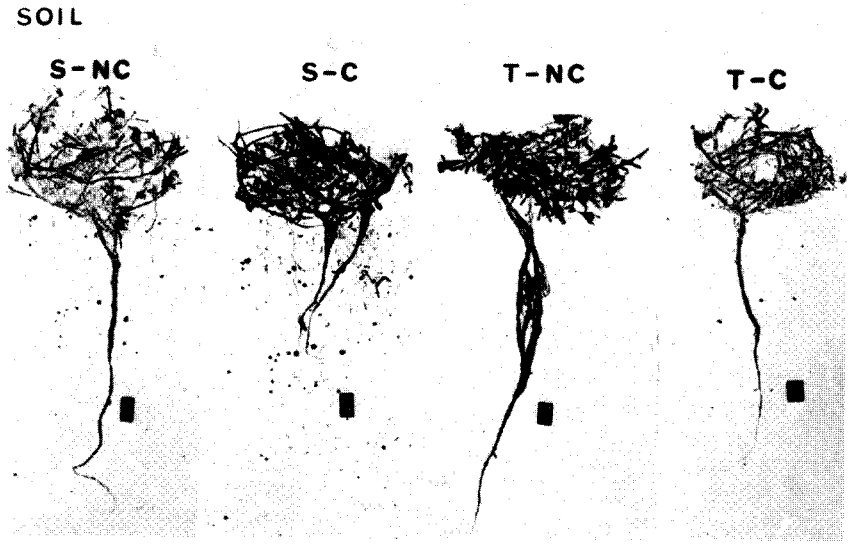


Figure 7. Root growth in unamended soil under various management treatments. S–NC is regular irrigation schedule and no compaction. S–C is regular irrigation schedule and compaction. T–NC is tensiometer-guided irrigation and no compaction. T–C is tensiometer-guided irrigation and compaction.

mixes had compaction applied at the surface periodically whereas the other half had no further compaction after column packing.

Figures 7 through 10 show comparative root growth for various treatments. Note that the root growth on unamended soil (Figure 7) was greatly affected by management of irrigation and compaction whereas root growth of lignified redwood-amended soil was relatively unaffected by management (Figure 8). The roots (Figure 9) grown in various soil mixes under the management practice of irrigation on a set scheduled basis and compaction differed greatly depending upon the soil mix. On the other hand, the soil mix had relatively little effect on root growth in the case of no compaction and with the use of a tensiometer to guide irrigation management (Figure 10).

There were many more results from the experiment, but all lead to the same conclusion. The effect of soil physical conditions on plant growth was dependent upon management factors. There was not one single physical amendment which gave the best results under all management conditions. In other words, the "universal best physical condition" does not exist. Nevertheless the unamended soil would normally be considered as having poorer physical properties than the amended soil and grass growth in the unamended soil was affected by management to a far greater extent than in amended soil.

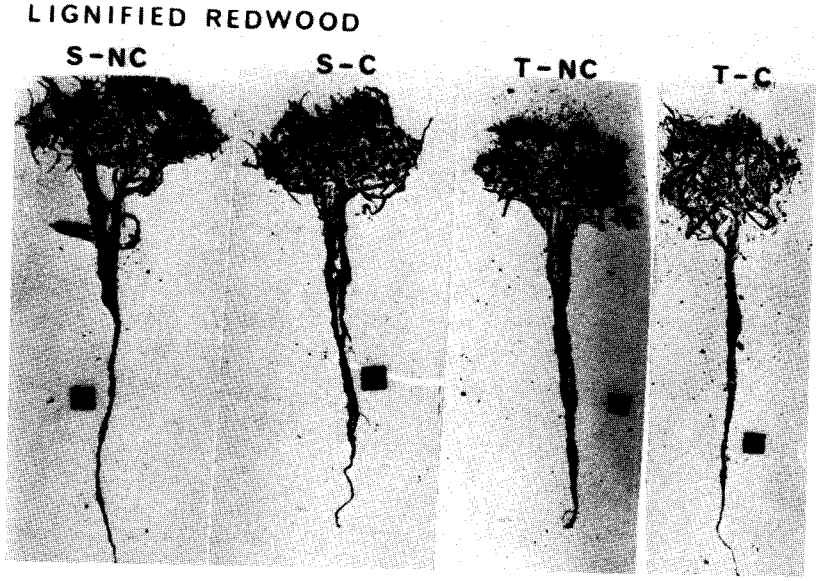


Figure 8. Root growth in soil amended with treated redwood chips. (See legend of Figure 7 for meaning of symbols.)

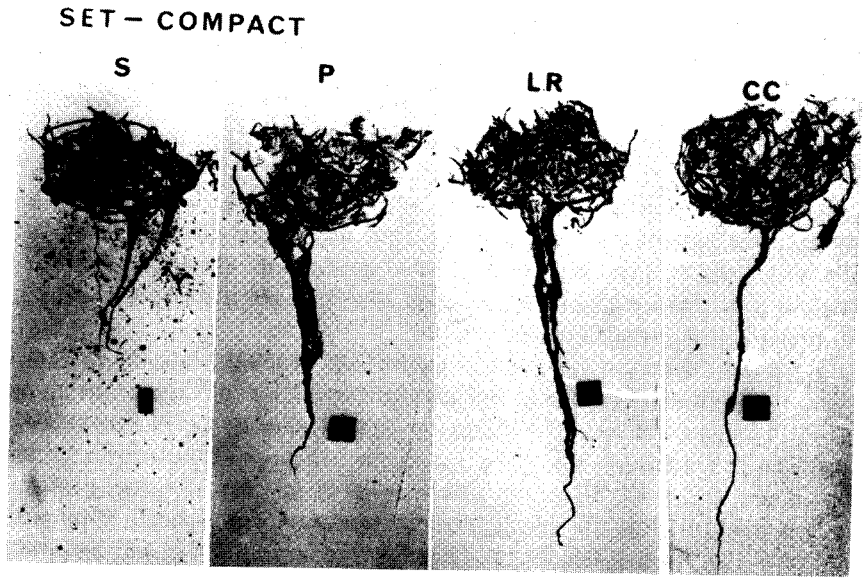


Figure 9. Roots grown in unamended and amended soil under a regular irrigation schedule and compaction. S is unamended soil. P is peat-amended soil. LR is soil amended with treated redwood chips. CC is calcined clay-amended soil.

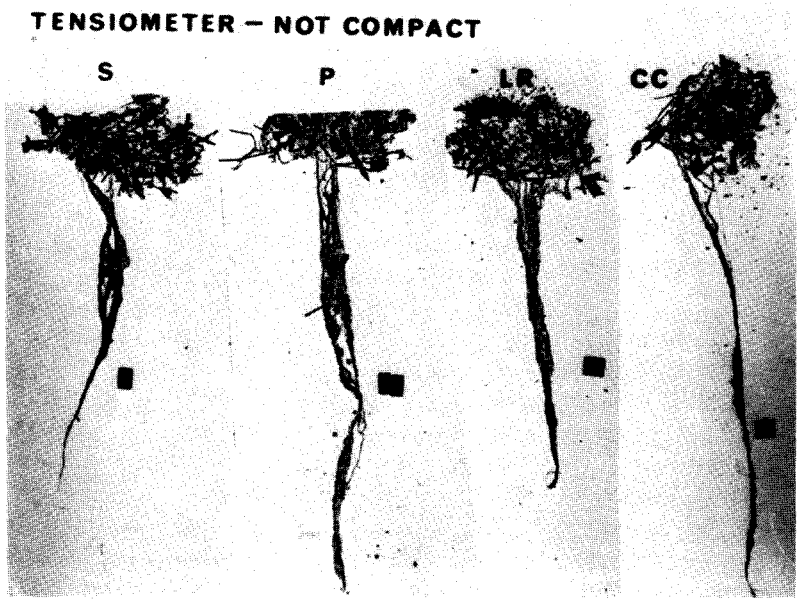


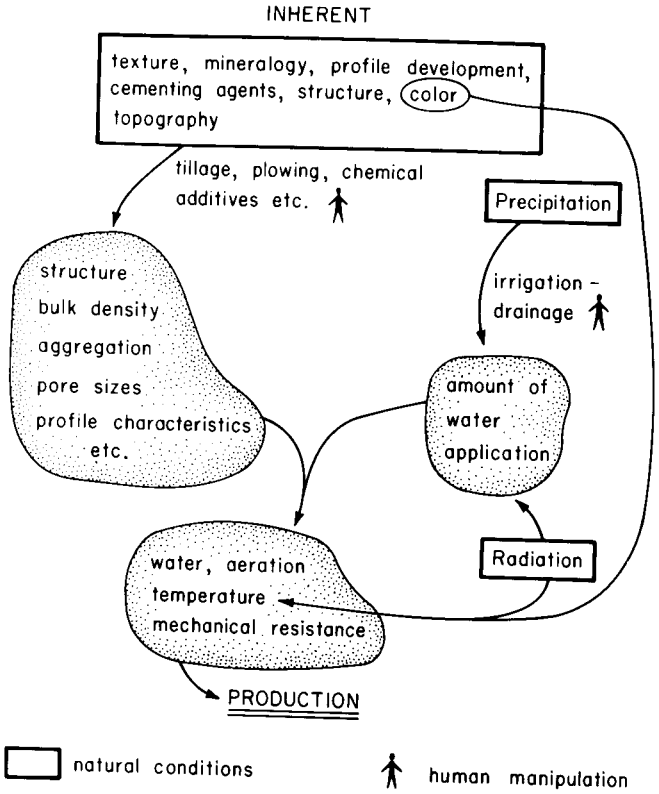
Figure 10. Roots grown in unamended and amended soil under tensiometer-guided irrigation and no compaction. (See legend of Figure 8.9 for meaning of symbols.)

No correlation between plant growth and soil physical properties such as texture, structure, and bulk density will occur except for special management practices. Yield predictions from tabular data on soil physical properties is not possible.

An attempt to put all the factors together in an overall picture is illustrated in Figure 11. The chart is restricted to soil physical conditions and no consideration is given to chemical or fertility factors. The inherent soil system has various physical and chemical properties and soils have been classified and mapped on the basis of these factors. Other natural factors include precipitation and solar radiation. Amount, intensity, and distribution of precipitation are also important.

With these inherent conditions, humans try to manipulate the system to obtain maximum productivity. Soil structure and bulk density may be altered through plowing, tillage, and cultivation. In some cases profile characteristics are altered by deep plowing or other mechanical manipulation. A comprehensive review on tillage effects on soil physical properties and processes was published in an American Society of Agronomy Special Publication edited by Unger and Van Doren (1982).

Natural precipitation provides water to the system. Radiation provides energy for evaporation and removal of water from the system. Humans may try to manipulate the water status through irrigation and/or drainage. Complete control of water content is not possible because soil factors affect



S. A. "LUIZ DE QUEIROZ"
Divisão de Biblioteca e Documentação

Figure 11. Relationship between natural conditions and human manipulation in affecting soil physical conditions directly related to crop production.

the movement of water into or out of the soil. For example a soil may have too much water so that aeration is restricted. Installing a drainage system can correct the problem if the hydraulic conductivity of the soil allows reasonably rapid water movement. A soil with very low permeability is difficult to drain.

As previously stated, water is the key variable of the soil physical parameters directly related to plant productivity. Water application combined with the soil physical properties will affect water potential, oxygen diffusion rate, and mechanical resistance which subsequently have a direct relationship to production. Soil temperature is not only affected by water content and bulk density, but also by solar radiation. Soil color also is an important factor in temperature because color influences how much energy is reflected or absorbed by the soil.

Although the quantitative aspects of crop production from a given soil are subject to management alternatives, there are physical and economic

constraints on management. Different potential yields are to be expected from different soils based upon physical properties. The traditionally measured soil physical properties such as bulk density, aggregate stability index, texture, etc., may not be the most helpful in judging the productivity potential of a soil. Information on NLWR at different depths is proposed as being the most useful method of characterizing the physical properties of a soil when crop production is being considered. This information also provides management guidelines.

VI. Soil Erosion and Productivity

Because of concern about soil erosion, some of the concepts presented will be discussed in the context of soil erosion. The discussion will be limited to soil physical factors while chemical factors will be ignored except for acknowledging that they are important and must be included in a complete analysis of soil erosion effects on productivity.

Soil erosion alters the inherent soil properties with potential consequences for crop production. Because of the network of interacting factors relating the inherent soil properties and crop production, as illustrated in Figure 8.11, a general simple quantitative relationship between soil erosion and crop production is not possible. Nevertheless some analysis of the problem is possible considering interactions illustrated in Figure 8.11 and discussed in this paper.

Soil erosion causes a change in the soil profile and the effect of this change on production must, among other factors, be dependent upon the initial soil profile characteristics. For example, loss of a given amount of soil would have less effect on a "deep" soil than the same loss on a "shallow" soil. Clearly a first consideration in discussing soil erosion is that the analysis must be site specific.

An important consideration is whether the land is to be irrigated or non-irrigated. Non-irrigated lands potentially present the more serious problems because one important management alternative is not available. The fact that soil water is the one component that influences other soil physical conditions which directly affect plant growth makes the matter critical.

A vital function of the soil, particularly under non-irrigated conditions, is to provide a water storage reservoir for the plants. In this regard infiltration rate is important in determining how much water enters the soil. Infiltration rate is largely controlled by soil pore size distributions and is, to some extent, subject to management alternatives. Sufficient water must infiltrate and be stored in the soil to provide for crop evapotranspiration between precipitation events or otherwise growth reduction results. In determining effective water storage capacity of a soil, the plant rooting pattern must be considered. Establishing the NLWR at various zones in the soil profile as done by Phene and Beale (1976) would be most useful in estimating the rooting depth and

available water holding capacity. The projection of effects of erosion could be accomplished by estimating rooting depth and available water holding capacity for a given soil profile and making new estimates after removing various layer depths from the soil surface.

Irrigation expands the opportunity to overcome poor soil physical properties through management. The use of soil as a water storage medium can be reduced if frequent irrigation is possible. The key then is to manage water within the NLWR. Special irrigation systems such as drip may be necessary for soils with a small NLWR.

Typically the NLWR tends to decrease with increased soil depth. Erosion which results in surface soil removal contributes to an overall profile of lower NLWR than before erosion. Decreasing NLWR requires more careful management to maintain productivity and so a consequence of erosion is increasing management constraints. Management options on eroded non-irrigated land may not be sufficient to maintain productivity. More management options are available on irrigated land to compensate for erosion, but the costs of management must be considered as well as the opportunity to maintain productivity in assessing erosion damages. Economic optimization is required to truly evaluate consequences of erosion.

VII. Conclusions

In conclusion, attempts should be to manage so that water potential, aeration, mechanical resistance, and temperature are in a balanced range to provide good productivity. Soils with so-called "good soil physical conditions" are easier to manage than "poor soil physical condition" soils. Because management and weather are integral factors, no meaningful correlation between texture, bulk density, or structure and crop productivity is possible. Relationships between water potential, O.D.R., temperature, and mechanical resistance and plant growth can be established for given plants for a given climatic zone. Determination of NLWR at different depths is proposed as being the most useful method of characterizing physical properties of a soil when crop production is being considered.

References

Armstrong, W. 1979. Aeration in higher plants. *Adv. Bot. Res.*, 7:225–332.

Cannell, R.Q. 1977. Soil aeration and compaction in relation to root growth and soil management. *Appl. Biol.* 2:1–86.

Jordan, W.R. 1983. Whole plant response to water deficits. An overview. In: *Limitations to efficient water use in crop production.* ASA-CSSA-SSSA, 677 So. Segoe Road, Madison, WI 53711. pp. 289–317.

Larson, W.E., L.M. Walsh, B.A. Stewart and D.H. Boelter (Editors). 1981. *Soil and water resources: research priorities for the nation*, Executive Summary, Soil Science Society of America, Inc., Madison, Wisconsin.

Lemon, E.R., and A.E. Erickson. 1952. The measurement of oxygen diffusion in the soil with a platinum microelectrode. *Soil Sci Soc. Am. Proc.* 16:160–163.

Letey, J., and G.B. Blank. 1961. Influence of environment on the vegetative growth of plants watered at various soil moisture suctions. *Agron. J.* 53:151–153.

Letey, J., W.C. Morgan, S.J. Richards, and N. Valoras. 1966. Physical soil amendments, soil compaction, irrigation, and wetting agents in turfgrass management. III. Effects on oxygen diffusion rate and root growth. *Agron. J.* 58:531–535.

Letey, J., L.H. Stolzy, N. Valoras, and T.E. Szuszkiewicz. 1962. Influence of oxygen diffusion rate on sunflower growth at various soil and air temperatures. *Agron. J.* 54:316–319.

Morgan, W.C., J. Letey, S.J. Richards, and N. Valoras. 1966. Physical soil amendments, soil compaction, irrigation, and wetting agents in turfgrass management. I. Effects on compactability, water infiltration rates, evapotranspiration, and number of irrigations. *Agron. J.* 58:525–528.

Phene, C.J., and O.W. Beale. 1976. High-frequency irrigation for water nutrient management in humid regions. *Soil Sci. Soc. Am. Proc.* 40:430–436.

Rickman, R.W., J. Letey, and L.H. Stolzy. 1965. Soil compaction effects on oxygen diffusion rates and plant growth. *Calif. Agr.* 19(3):4–6.

Rickman, R.W., J. Letey, and L.H. Stolzy. 1966. Plant response to oxygen supply and physical resistance in the root environment. *Soil Sci. Soc. Am. Proc.* 30:304–307.

Stolzy, L.H., and J. Letey. 1964. Measurement of oxygen diffusion rates with the platinum microelectrode. III. Correlation of plant response to soil oxygen diffusion rates. *Hilgardia* 35(20):567–576.

Taylor, Howard M. 1971. Effects of soil strength on seedling emergence, root growth, and crop yield. In: *Compaction of agricultural soils*, an ASAE Monograph, Publ. American Society of Agricultural Engineers, 2950 Niles Road, St. Joseph, Michigan 49085. pp. 292–305.

Unger, P.W., and D.M. Van Doren, Jr. (Co-editors). 1982. *Predicting tillage effects on soil physical properties and processes. ASA Special Publ.* No. 44. American Society of Agronomy, 677 So. Segoe Road, Madison, WI 53711.