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Tillage, Matric Potential, Oxygen and Millet Yield Relations in a Layered Soil

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INTERPRETIVE SUMMARY

WET soils caused by intensive rain or a series of rainy days affect plant growth in the Southeastern Atlantic Coastal Plains. In this region, certain groups of soils with compact layers compound the effects of soil wetness by impeding downward gaseous diffusion, water flow, root growth and, thus, the development of plant root systems.

In a study of soil water, soil oxygen and plant growth relationships, millet growth was unaffected when the soil 0_2 concentration was greater than 15 percent. At 0_2 levels less than 15 percent in the soil, millet growth decreased as 0_2 concentrations of the soil were decreased. In a Varina loamy sand soil, 0_2 concentrations decreased as soil matric potential increased within the range of -2 to -80 mb. Below this range (< -80 mb), 0_2 did not vary with matric potential. These data suggest that the aeration status of this soil may be inferred from measurements of soil water status.

Deep tillage improved soil aeration, and deep-rooted plants in deep-tilled soil were less affected by poor aeration than were shallow-rooted plants in conventionally tilled soil.

INTRODUCTION

Compact layers of soil can impede movement of water, gas, and soluble salts, cause runoff to increase, and alter redistribution of water within the profile during wetting and drying (Burnett and Hauser, 1967; Duly, 1957a, 1957b; Hauser and Taylor, 1964). Many increases in crop yield associated with deep tillage have been ascribed to the physical alteration of these compact layers that also restrict plant-root development (Burnett and Tackett, 1968; Campbell et al., 1974; Doty et al., 1975; Raney et al., 1954; Saveson et al., 1961). Plants growing in shallow sandy or impermeable soils underlain by finer-textured soil or in soil compacted by mechanical implements are more susceptible to plant water and 0_2 stresses than plants grown in deep, uniformly developed soils Allmaras (1967). Introduction of small quantities of water into sandy soil, as compared with more-highly structured soil, rapidly decrease 0_2 diffusion rates Currie (1962). Pore-size distribution of aggregated soil is more complex than single grained materials. In a system of unsaturated aggregates, most of the water is held in the small pores of the aggregate, while most of the gas diffusion takes place in the large pores between aggregates. Surface soils of the southeastern Atlantic Coastal Plain are sandy and are usually single grained. Aeration may become critical when 0_2 stresses occur during periods of high rainfall. Sandy soils also tend to be droughty and create plant water deficits in a few days without rainfall (Campbell et al., 1974; Doty et al., 1975).

Low 0_2 levels found in soils of the Southeastern Atlantic Coastal Plain are not always associated with long-term, waterlogged conditions, but low 0_2 levels may occur 1 to 2 days after a heavy rain or after several successive days of moderate daily rainfall. Low 0_2 concentrations in soil under these condtions indicate that 0_2 sink requirements of plant roots and soil organisms are not being satisfied by downward 0_2 diffusion from the atmosphere. Soil has a limited air capacity, and the composition of its atmosphere will gradually change unless 0_2 is replaced and $C0_2$ removed. Under poorly aerated conditions, the net effect of low soil 0_2 levels on crop yield will depend upon 0_2 sink requirements of soil organisms, plant species, and crop maturity (Campbell, 1973; Williamson and Kriz, 1970). Surface and subsurface drainage can control water in soils but may not be economically feasible for field crop production for all crops on different types of soil. Deep tillage is an alternative for partially controlling the water and aeration status to improve internal drainage and to increase the rooting depth and is a means of coping with the effects of drought and excessive rainfall in soils with an impermeable layer in the root zone.

Since the cost of controlling and maintaining the aeration and water status of sandy soils with a compact subsurface layer s an important aspect of soil management, the objectives of this study were (a) to characterize the 0_2 status of a cropped field associated with natural rainfall events, and (b) to develop quantitative relationships between soil 0_2, matric potential, and forage yield at two tillage depths, four water regimes, and two harvesting sequences.

PROCEDURE

The soil at the experimental site was classified as a Varina sandy loam, Plenthic Paleudult with a 12-cm-thick compact layer beginning at the 17-cm depth, as described by Campbell et al., (1975). In 1969, rainfall, soil under matric potential, and 0_2 concentration in soil pores were measured during the growing season in irrigated and nonirrigated plots of millet to establish 0_2 deficits that may occur as a consequence of rain and also of rain superimposed upon an irrigation water regime. In 1971, a more detailed experiment was designed to study quantitative relationships between soil matric potential, soil 0_2 concentration, and the millet growth in plowed and chiseled soil. Millet was chosen as the indicator plant to evaluate the effects of soil physical factors on yield because Williamson et al., (1969) previously demonstrated that millet was more

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TABLE 1. EFFECT OF AMOUNT OF WATER AND RAINFALL ON SOIL OXYGEN AND MATRIC POTENTIAL.

Treatment symbol	Mean soil oxygen	Mean soil matric potential	Rainfall plus irrigation
	percent ± s	mb ± s	cm
Very wet (M_1)	5.5 ± 3.4	- 45 ± 14	31
Wet (M_2	9,8 ± 2.6	- 57 ± 8	16
Mod wet (M_3)	13.2 ± 4.2	- 87 ± 27	10
Mod. Dry	18.7 ± 0.5	- 296 ± 100	8

*Mobile plot shelters activated by rain were used to intercept rainfall on the M_4 treatment. Sufficient water was applied by surface irrigation to satisfy evapotranspiration requirements.

sensitive to poor aeration than many other grasses and exhibited moderate recovery after flooding.

In 1971, the field was divided into four blocks consisting of eight plots each 6.1 x 7.6 m (20 x 25 ft). Each block was divided into two subblocks, one of which was chiseled to a 38-cm depth before planting the previous year (1970), and the other was plowed to a 17-cm depth. In 1971, the entire experimental site was spring-plowed to a 17-cm depth. Four water regimes, referred to as M_1, M_2, M_3, and M_4, were imposed on the four plots of the subblock, making a total of 32 plots arranged in a split-plot randomized-block experimental design. Water applied during the 14-day treatment period (6/16 to 6/30), soil 0_2 concentrations, and the range of soil matric potential values are shown in Table 1.

All plots were limed with 2576 hg/ha of dolomite, plowed, and smoothed to a slope of about 0.5 percent. Fertilizer was applied before planting at a rate of 118, 52, and 98 kg/ha of N, P, and K, respectively. Supplemental N was applied in the irrigation water in approximate proportion to the water applied to avoid N loss by leaching. The amount of N applied was 196, 56, 56 and 84 kg/ha on the M_1, M_2, M_3, and M_4 treatments, respectively. A hybrid Pearl millet variety, Millex-23 (Pennisetum glaucum (L.) R. Br.), was planted in rows 51 cm apart on May 12, 1971.

Soil matric potential was measured at the 10- and 25-cm depth with mercury manometer-type tensiometers but only the 25-cm depth is reported. Measurements were recorded before 9:00 AM daily during the 14-day treatment and thrice weekly thereafter. Stainless steel, gas diffusion chambers, 1 cm high x 6 cm in diameter, were placed at 10- and 25-cm depths, and gas was sampled daily during the treatment period and thrice weekly during post-treatment, or until the final harvest. The diffusion chambers were buried in the soil in 8-cm diameter holes drilled into the soil, which were backfilled, and the soil tamped tightly to minimize gaseous diffusion from the region directly above the chamber base. The 25-cm depth chamber was installed in undisturbed soil in the middle of the A_2 layer. The soil 0_2 concentration was determined from gas samples removed with a gas-tight syringe through a septum covering a 1-mm inside diameter tube leading to gas diffusion chambers. The 0_2 content of each 5-ml sample was determined with a commercially available polarographic electrode probe system (Chemtronics model LP-10 mounted in a curvette and scaled with a septum)*. Oxygen diffusion rates measured in the soil at the same time were reported by Phene et al., (1976).

The voltage output of the 0_2 probe was measured with a portable d.c. voltmeter in a temperature-controlled trailer near the experimental site. With this system 20 to 30 analyses/hr could be made.

Two harvesting sequences, referred to as regrowth, C_1, and continuous growth, C_2, were adopted to distinguish treatment effects between regrowth and continuous growth of millet within the treatment period. All C_1 plots were cut at the beginning of treatment on June 16, 1971, at a height of about 20 cm above ground level to retain the growing point (apical meristem). The C_2 plots were not harvested, and millet continued to grow during the treatment period when the water regimes were imposed. On June 30, the C_1 and C_2 plants were both harvested. This was the first harvest for the C_2 treatment and the second for the C_1 treatment.

*Trade names are used for identification purposes only and do not imply reference for this item by the US Department of Agriculture.

Growth of the C_2 treatments during the 14-day period was determined by weighing the forage from each C_2 plot harvested on June 30 and subtracting the average weight of forage from C_1 plots harvested on June 16. Growth for the C_1 treatment during the 14 days was determined as the difference between the two successive cuttings. After June 30, the post-treatment period, each plot was irrigated when its soil matric potential, M, at the 25-cm depth reached -500 mb. The final harvest for the C_1 plots was July 22, and July 15 for the C_2 plots. All yield data are reported on a dry weight basis.

RESULTS AND DISCUSSION

Soil 0_2 in Irrigated and Nonirrigated Soil, 1969

In the summer of 1969, a daily time-log of soil 0_2 content was maintained for the 10-, 25-, 45-, and 66-cm depths. These data, plus the rainfall and water potential measurements, enabled us to compare 0_2 levels under rainfall with those under irrigation plus rainfall in shallow-tilled plots. In 1969, the irrigation water was applied in 2.5-cm increments, based upon estimated potential evapotranspiration measurements. Deep-tilled plots were included in the experiment in 1969 but were not instrumented for 0_2 determinations. However, the soil matric potential data for deep-tilled plots showed a greater rate of internal soil water drainage. This result suggests that soil aeration was better in the deep-tilled plots than in the shallow-tilled plots.

Oxygen concentration measurements for the shallow-tilled plots (Figs. 1 and 2) showed an envelope of 0_2 between the 10- and 66-cm depths. Values for the 25- and 45-cm depths were measured and were intermediate between the 10- and 66-cm depths. At the 10-cm depth, 0_2 levels were lower in the irrigated plot than those in the rainfall plot. Also, 0_2 levels were lower at the 66-cm depth in the irrigated plot, as indicated by the expanded envelope of data (Fig. 2). The lower 0_2 levels for the irrigated plots suggest a possible hazard of irrigation, if proper drainage preparations are not considered as part of the farming practice. That tensiometric measurements may offer a means of predicting 0_2 levels is indicated in the lower section of Figs. 1 and 2. At matric potential values, M, less than -70 soil 0_2 levels essentially

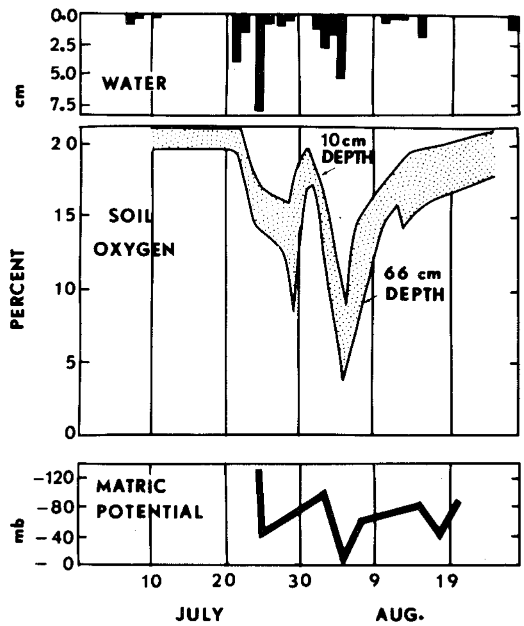

FIG. 1 Soil water matric potential and oxygen content of a nonirrigated field soil during a period of moderately high rainfall.

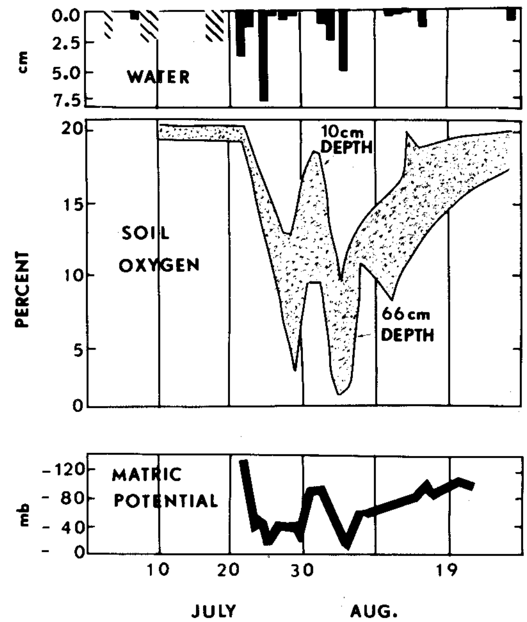

FIG. 2 Soil water matric potential and oxygen content in an irrigated field soil followed by a period of moderately high rainfall.

did not vary with M, and at M values between 0.0 and -70 mb, O_2 levels decreased rapidly with increasing M as a result of decreased O_2 diffusion rates. Once rainfall substantially wetted the soil, subsequent small amounts of rain further decreased O_2 levels. Soil O_2 levels decreased very rapidly 1 to 2 days after substantial rain, suggesting that O_2 retained in soil pores was gradually utilized by plant roots and soil microorganisms, until it was exhausted within 2 days after the initial wetting.

Soil O_2 and Matric Potential Relationships, 1971

Daily O_2 and M values obtained from each plot were averaged for the 14-day treatment period and were plotted in Figs. 3 and 4 for the C_1 and C_2 harvest methods, respectively. The set of data presented in each graph was fitted with two linear regression lines with intersections at 17.3 percent O_2 and -82 mb M for the C_1 harvest treatment (Fig. 3), and 17.8 percent O_2 and -88 mb M for the C_2 treatment (Fig. 4). For M values between 0 and -85 mb, O_2 concentrations of the soil varied with the soil water content. From -20 to -85 mb, downward O_2 diffusion was less than that of the respirational demand of plant roots and microorganisms in a summer climate. Under those conditions the soil is partially anaerobic with some of the soil pores filled with water and some with air. This is an unfavorable soil condition for plant root growth. Figs. 3 and 4 show that O_2 is largely independent of M for M values less than -82 and -88 mb. In this range of soil water content, the soil O_2 downward diffusion rate equaled or exceeded the O_2 respiration demand of plant and soil microorganisms, creating a favorable environment for root growth. Values of M for the chiseled plots for the M_3 and M_4 water regimes were displaced to the right, indicating lower M values (more negative) than those for the plowed plots. These data reflect the rapid change in soil water content, and the higher rate of downward O_2 diffusion as water drains from the soil in the early stages of drying in the chiseled plots.

Soil O_2 and Millet Yield

Soil O_2-matric potential-yield correlations reflect a balance between O_2 sinks and O_2 diffusion processes in the soil, but they do not uniquely imply causation in decreasing crop yield. Water at excessively high levels cause low soil O_2 levels that affect the respirational functions of the plant-root system. High correlations between yield, matric potential, and soil O_2 are useful because the matric potential can be readily measured in the field, partially controlled, and/

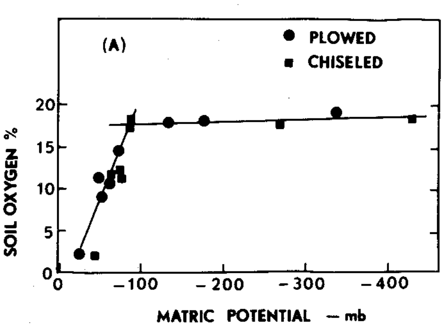

FIG. 3 Average soil oxygen content plotted against soil water matric potential for the regrowth C_1 haravest method during a 14-day (6/16 to 6/30/71) period.

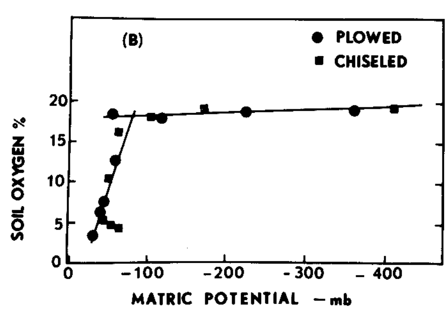

FIG. 4 Average soil oxygen content plotted against soil water matric potential for the continuous growth C_2 harvest method during a 14-day (6/16 to 6/30/71) period.

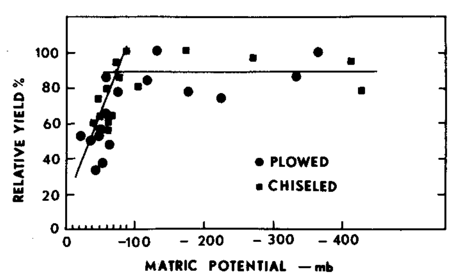

FIG. 5 The relative yield of millet plotted against the average soil water matric potential for a 14-day treatment period (6/16 to 6/30/71).

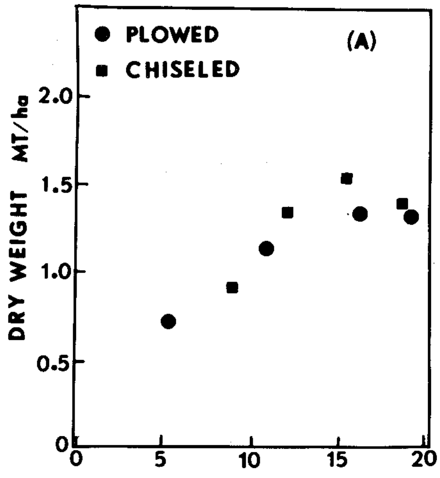

FIG. 6 Relative millet yield and average soil O_2 content at the 10- and 25-cm depths for the regrowth C_1 harvest method during a 14-day (6/16 to 6/30/71) period.

or managed to improve aeration and enhance crop growth (Phene et al., 1974; Raney et al. 1954). The form of the curve for the yield-M relationship (Fig. 5) resembles that for the 0_2-M functional relationships (Figs. 3 and 4). The matric potential value at the intersection of the two linear function in Fig. 5 is -72 mb, the approximate M value at which millet growth decreased. Decreased 0_2 levels at -82 and -88 mb (Figs. 3 and 4) represent the M level at which the 0_2 diffusion rate decreased rapidly with increasing M. These data corresponded with critical 0_2 levels, confirmed by 0_2 diffusion-rate measurements made in the same field and reported by Phene et al., (1976).

Soil 0_2, Tillage Effects, and Millet Yield

Data demonstrating the correspondence of millet yield to soil 0_2 concentration for the plowed and chiseled treatments are shown in Figs. 6 and 7. For the C_1 harvest method, millet regrowth during treatment decreased as soil 0_2 levels decreased below 15 percent. Within 0 to 15 percent 0_2, millet yields from chiseled plots were greater than those from plowed plots. At 0_2 levels greater than 15 percent, the yields from the chiseled and plowed areas were almost equal within each cutting treatment. Averaged 0_2 levels in the C_2 harvest method were nearly identical at both the 10- to 25-cm depths in chiseled and plowed plots, but millet yields of the chiseled treatment were slightly higher. This result suggests that roots in the chiseled soil were more extensive and not confined to the region where 0_2 was measured (Campbell et al., 1974). Studies conducted in this field in 1969 (data not shown) indicated that 0_2 can diffuse upward to the bottom of a deep root system when the surface soil is very wet. However, root distribution observations in the C_1 plots showed that regrowth developed from roots largely confined to the surface soil layer.

Total Yield, Water Regime, Cutting Method, and Tillage

The total, seasonal, millet dry matter production, consisting of the total of three cuttings for the C_1 harvest method and two cuttings for the C_2 method (Fig. 8), shows the effects of tillage methods for each of the four water regimes, M_1, M_2, M_3, and M_4. Millet yields were essentially independent of soil 0_2 levels and tillage method for the M_3 and M_4 water regimes. Plots harvested by the C_2 harvest method produced consistently more dry matter for both tillage method and within each water regime than those harvested by the C_1 method. The yield effects, ascribed to the chiseled treatment, was most significant under the M_1 and M_2 water regimes. Chiseling soil caused a 33 percent increase in millet yield in the C_2 plots over that of the plowed plots for the M_1 water regime, and a 16 percent increase for the M_2 water regime. For the C_1 harvest method, chiseling increased yield by 16, 5 and 10 percent over plowing for the M_1, M_2, and M_3 water regimes, respectively. Chiseling had a pronounced effect on yield for both the C_1 and C_2 harvest methods under wet soil water conditions. These data indicated that the more mature plants were able to survive the wet period better than could those plants that were cut before the start of the wet period.

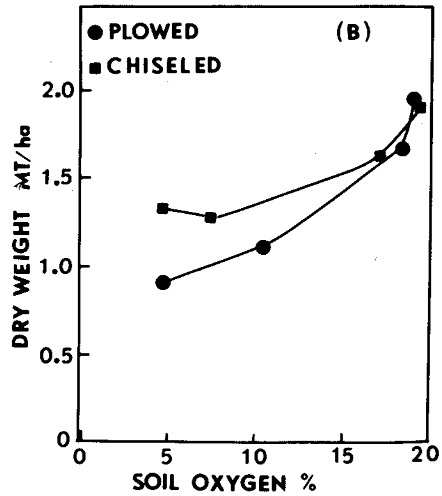

FIG. 7 Relative millet yield and average soil O_2 content at the 10- and 25-cm depths for the continuous growth C_2 harvest method during a 14-day (6/16 to 6/30/71) period.

SUMMARY

A unique relationship was found between soil 0_2 content and soil water matric potential, from which the 0_2 content may be estimated from soil matric potential data. From -20 to -85 mb matric potential, the 0_2 content of soil pores depended on soil water content. Soil 0_2 concentration increased about 0.27 percent per mb change in matric potential. At matric potential values less than -85 mb, the 0_2 content of the soil was independent of soil water content.

Yield of millet increased with increasing soil 0_2 content within a range of from 2 to about 15 percent. At soil 0_2 levels greater than 15 percent, the growth of millet was independent of soil 0_2 content; i.e., aeration was adequate for normal crop growth.

Two, rather than three, harvests during the growing season that in-

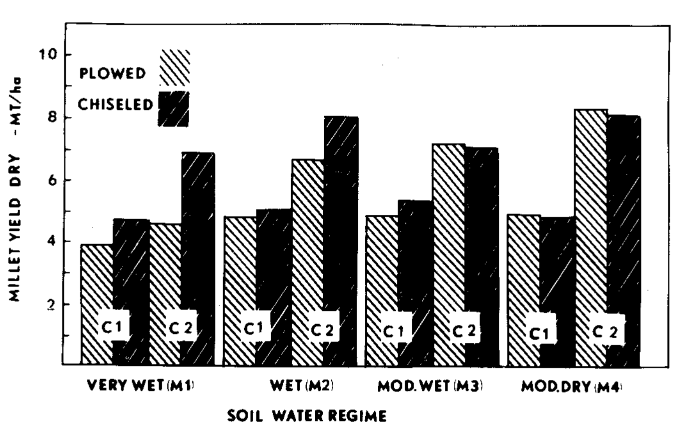

FIG. 8 Total dry yield of millet as influenced by depth of tillage, number of cuttings and soil water regimes.

cluded the 14-day wet period clearly produced greater yields.

Under simulated rainfall sufficient for crop use, in which the soil matric potential did not decrease more than -400 mb and with the adequate soil aeration, millet yield was unaffected by tillage depth. Under high matric potential conditions, -45 to -87 mb, chiseling partially alleviated 0_2 stresses associated with wet soil.

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