

CHARACTERIZATION OF SOIL AERATION IN SITU WITH AUTOMATED OXYGEN DIFFUSION MEASUREMENTS¹

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ABSTRACT

The measurement of soil oxygen diffusion rate (ODR) with a platinum microelectrode was automated and used to characterize field aeration of a typical compact-layered sandy soil (Varina) under static and dynamic soil water regimes.

The yield of millet, grown in the field under wet soil conditions, doubled when the ODR at the 10-cm depth increased from 0.09 to 0.15 $\mu\text{g}/\text{cm}^2/\text{min}^1$ and was related to the ODR, which fluctuated according to the amount of water infiltrating the soil as rainfall and irrigations. After the initial irrigation, the ODR in the A2 layer was below 0.2 $\mu\text{g}/\text{cm}^2/\text{min}^1$, the adopted critical ODR level for sustaining root growth for certain crops. Although the ODR in the B layer was greater than that in the A2, it was usually below the critical level. The ODR measurements were used to determine field soil matric potential (ψ_M) levels critical to aeration of plant roots, and to develop functional relationships between soil ψ_M and ODR for the A1, A2, and B horizons. Soil ODR profiles were calculated from measured soil ψ_M and compared with measured ODR profiles.

Automating the ODR measurement procedure permitted frequent measurement of a sensitive and rapidly changing soil variable important to optimal plant growth.

INTRODUCTION

Crops, growing in shallow, compact-layered sandy soil, may be detrimentally affected by intermittent oxygen stresses. The importance of soil aeration to growth and yield of agronomic crops has been reviewed (Stolzy et al. 1975) and widely demonstrated, especially after rainfall and/or irrigations (Campbell et al. 1972; Gingrich et al. 1956; Grable 1966; Grechin 1963; Kramer et al. 1954; Williams 1963; Williamson et al. 1970). Brief soil oxygen deficiency can reduce root respiration and nutrient uptake by plants, and cause formation and accumulations of some toxic substances in soil and plants (Chang 1962; Grechin 1963; Iljin 1954; Kramer et al. 1954; Shalhevet et al. 1958; Shalhevet 1962; Williams 1963; Williamson et al. 1970). Persistent soil oxygen deficiencies generally increase cell permeability and cause death of roots (Campbell et al. 1972; Williamson et al. 1970).

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Rickman et al. (1966) have shown that compact subsoil layers can substantially decrease soil aeration and restrict root growth in the layers of noncompacted soil. Warnars et al. (1970) have demonstrated that mechanical impedance and aeration affect pea-, corn-, and grass-seedling root growth. Typically, root growth of plants with or without tap roots is confined to the A1 layer by a compact sandy A2 horizon (Campbell et al. 1974; Grable 1967; Phene 1974; Rickman et al. 1966). The dense A2-soil layer physically restricts root penetration, since soil strength increases as water content decreases (Campbell et al. 1974) and aeration decreases as water content increases. Soil drainage characteristics and aeration during critical periods of excess water can be improved by deep tillage that disrupts this A2 barrier (Grable 1967).

Poor soil aeration conditions can be partially ameliorated by surface or subsurface drainage or by controlled water application in a portion of the root zone that may reduce the probability of water saturation (Grable 1967; Phene et al. 1973; Phene 1974). Additional nitrogen fertilization of some crops at certain stages of develop-

ment may partially counteract the harmful effect of flooding and improve yields of crops growing in inadequately drained soils (Shalhevet et al. 1958, 1962).

Oxygen diffusion rate (ODR) to a platinum (Pt) micro-electrode is limited only by the diffusion of O_2 to the microelectrode. The electrode is designed to physically simulate a plant root and should measure a quantity of oxygen similar to that which a root might experience (Lemon et al. 1952; Letey et al. 1964). The electric current flowing in the system, for a given voltage potential, is proportional to the electrolytic reduction of oxygen at the platinum surface of the microelectrode (Kolthoff et al. 1952; Lemon et al. 1952, 1955; Letey et al. 1964) and can be expressed by the equation:

$$i = n F A f \quad (1)$$

where i is the electric current; n is the number of electrons required to reduce one molecule of oxygen ($n = 4$); F is the Faraday Constant; A is the surface area of the Pt microelectrode; and f is the flux of oxygen to the electrode surface or the ODR (Letey et al. 1964):

ODR ($\mu\text{g}/\text{cm}^2/\text{min}^1$)

$$= \frac{i \times 10^{-6} \times 60 \times 32 \times 10^6}{4 \times 96,500 \times A} \quad (2)$$

where the values 60 and 32×10^6 are used to obtain ODR in terms of units shown. This equation can be simplified to the form:

$$\text{ODR} = C \frac{i}{A} \quad (3)$$

where C represents all the constants. Theoretical treatments of polarography and its application to ODR measurement have been presented and discussed previously (Kolthoff et al. 1952; Lemon et al. 1952, 1955; Letey et al. 1964). The ODR to plant roots is influenced by the same soil factors affecting the diffusion of oxygen to the Pt microelectrode; i.e., soil metric potential (ψ_M), temperature, bulk density, texture, and structure (Lemon et al. 1955).

Organic matter, chemical amendments, and textural soil variability greatly affect micro-measurements in the field. Therefore, the ODR must be measured often at several locations to delineate and characterize the measurement under static or dynamic soil water regimes. When calibrated electrodes are operat-

ing properly, the measurement variability is more a function of soil variability than electrode variability (Lemon et al. 1955), which infers that precision could be increased by using permanently installed electrodes.

Our objectives in this paper are to describe the procedure for automatically measuring ODR in situ to define the soil ψ_M which limits ODR for a typical, layered sandy soil of the Coastal Plains and to evaluate the growth and nitrogen (N), phosphorus (P), and potassium (K) content of field-grown millet in response to different soil water regimes.

EQUIPMENT AND PROCEDURE

Soil is microscopically heterogeneous and to satisfactorily measure many physical properties, like ODR, requires averages of several measurements. Measurements cannot always be obtained manually when needed to characterize ODR under dynamic conditions. The ODR measurement was automated, tested, and used in the field to characterize soil aeration and to study the effect of high soil ψ_M on soil ODR and plant growth in the compact-layered sandy loam soil.

The ODR measurement system consists of a platinum (Pt) microelectrode, the Ag-AgCl half-cell, the KCl-Agar salt bridge, the electrical circuit required to apply the voltage potential, and the output voltage data acquisition system (DAS).

1. The microelectrode. Bare Pt microelectrodes (22 gauge) were constructed of 12-gauge single-strand copper wire. A vernier microscope was used to determine the proper electrode length. The construction and calibration procedures were those outlined by Letey et al. (1964). An electrical gold-plated pin connector (Winchester 2520S)² was soldered to each microelectrode to facilitate the installation and exchange of the microelectrodes, if necessary. Erratic electrodes were either discarded or corrected and recalibrated.

Of the 72 microelectrodes installed, 60 operated satisfactorily during the test period. However, after eight were replaced and four were cleaned with a metal polish and reinserted in the soil, no further problems developed. Figure 1 shows the position of the Pt microelectrodes in

²Trade names are used for identification purposes only the do not imply preference for this item by the U.S. Department of Agriculture.

the chamber with respect to the soil surface and the A1, A2, and B layers, and the oxygen diffusion path.

2. Microelectrode installation in situ. Holes were drilled and tapped at four radially equidistant points 15, 30, and 50 cm from the top edge of aluminum cylinders 21 cm in diameter and 59 cm high. The lower cylinders' edges were sharpened to facilitate their installation, and the cylinders were pressed into the sandy soil with their edge 15 cm from the row. The soil was removed from within the cylinder and a steel bottom plate was installed and sealed with silicone rubber cement. Each of the tapped holes had a O-ring vacuum fitting, 0.95 cm in diameter (Cajon Ultra-torr),² screwed into it. The soil surrounding the cylinder was saturated with water and the Pt microelectrodes were pushed through the O-ring vacuum fittings into

the saturated soil, which insured thorough electrode wetting. The O-ring vacuum fitting sealed the electrodes in place and prevented air exchange between the chamber and the soil. Each electrode was connected to the measuring bridge (Fig. 1). The measuring bridge, the half-cell and the electrical connections were stored inside the cylinder which was closed with a small wooden cover. Data were inspected and partially evaluated daily to determine normal electrode functioning or possibility of electrode poisoning. Installation of the Pt microelectrodes in the cylinder prevented loosening of the electrode in the soil during the experimental period and, possibly, the ensuing diffusion of oxygen along the body of the electrode. By this method of installation, the soil above the electrode was not disturbed, which was a more natural field environment for the electrodes and the plants.

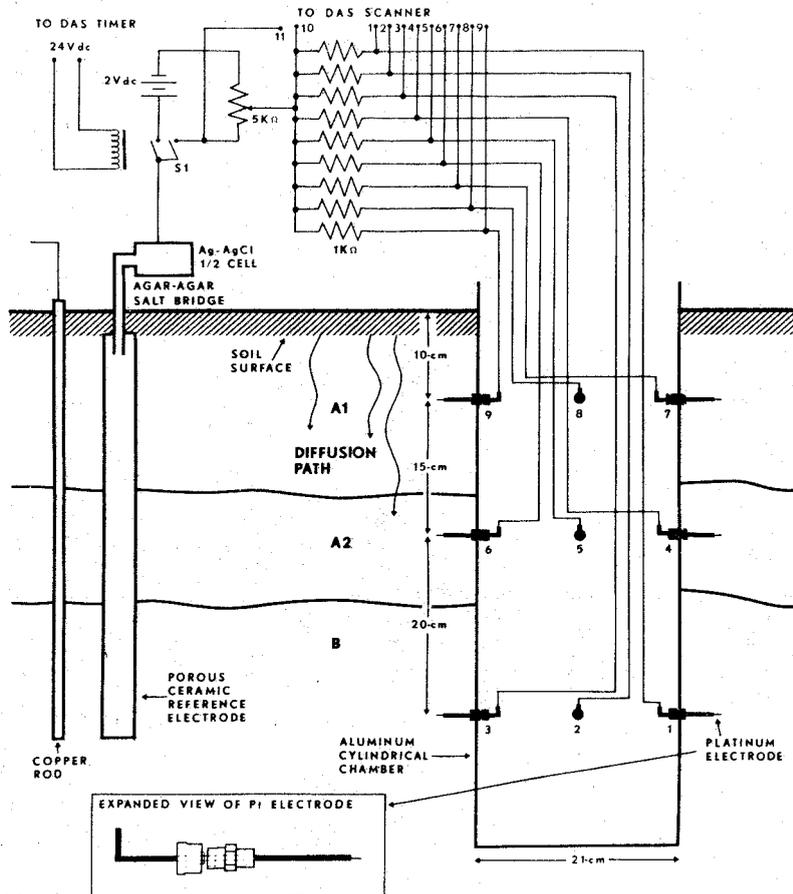


FIG. 1. Platinum (Pt) microelectrode installation and electrical circuitry for each plot ODR measurement station.

The diffusion path of oxygen from the atmosphere at the soil surface to the electrodes was confined to the soil above the electrodes.

3. The silver-silver chloride (Ag-AgCl) reference cell and electrode. The Ag-AgCl reference cell consisted of a Lucite² container which held the salt solution and approximately 2000 cm² of rolled Ag foil (0.0127 cm thick). A strip of silver foil was inserted through a slit in the Lucite container, and sealed with Epoxy cement² to provide electrical contact with the anode. A Lucite tube inserted into the container was connected to the reference electrode with a Tygon² tube (Stolzy et al. 1964).

The reference electrode consisted of a long, cylindrical, porous-ceramic cup filled with potassium chloride (KCl) saturated agar-agar gel, and connected to the Ag-AgCl reference cell with a Tygon tube filled with the gel. This cell was lowered into the cylinder to minimize the flow of KCl solution into the soil. The reference electrode remained in the soil continuously, until a recharge or replacement was indicated.

4. The electrical circuit. The soil ODR and the reference voltage were automatically measured every 6 hr with an electronic data acquisition system (DAS). The electrical circuit (Fig. 1), designed for automatically measuring ODR, is similar to that described by Letey et al. (1964). At 6-hr intervals the solenoid relay S₁ was closed, and the voltage drop across resistors 1 to 9 was measured after 4 min by scanning nine channels for each plot. The electrical current flowing between the two electrode when the relay S₁ was closed was equal to the voltage drop measured across the resistors (1 to 9) divided by their resistance and was used in Eq. (2) to calculate ODR (Fig. 1). The reference voltage between connectors 10 and 11 was initially adjusted to -0.65 v and was measured and recorded every 6 hr. The current flowing in the circuit is directly proportional to the voltage potential between the reference and microelectrode and the rate of oxygen diffusing to the microelectrode, and it is inversely proportional to the internal resistance of the circuit (Kristensen 1966). The internal resistance is the sum of the half-cell resistance (approximately 300 ohms), the resistance used to measure the voltage drop (1000 ohms), and the soil resistance which varies with soil water, texture, temperature, and salt content.

Measurement of the soil resistance may be required for qualitative work to permit correction of the voltage measurement to a standard applied potential (Kristensen 1966). The soil electrical resistance between the copper rod and each platinum microelectrode (Fig. 1) was measured at 5-day intervals with an AC bridge (Wayne Keer Auto Balance Universal Bridge Model B641)².

5. Electrode poisoning. The term *poisoning*, used in reference to Pt microelectrodes, indicates a decrease in electrode reaction, possibly caused by a chemical deposit on the Pt surface (Stolzy et al. 1964). Poisoning can be readily detected under drying soil conditions, because the current decreases when it should increase. Under dynamic soil water conditions, the complete soil water history must be analyzed to determine whether or not there was poisoning. In this experiment, we assumed there was poisoning if the current measurements were erratic. If we suspected poisoning, we pushed the electrode slightly further into the soil with a rotating motion so that the soil's abrasive action might purge the Pt tip (Stolzy et al. 1964).

6. Experimental field design and control. The ODR measurements were conducted on a Varina sandy loam soil in the conventionally tilled treatment of two replications. The split-plot field experiment involved two tillage practices (main plots) and four water control treatments (subplots). Main plots were 24 × 8 m and subplots were 6 × 8 m. The four water control treatments (M₁, M₂, M₃, and M₄) are described in Table 1. The ODR measurement stations, installed between rows, were not replicated. An ODR of 0.4 μg/cm²/min¹ was assumed the level at which aeration was insufficient to sustain vigorous root growth, and 0.2 μg/cm²/min¹ was assumed the ODR level critical to plant growth. These ODR values have been determined empirically for other crops (Stolzy et al. 1964).

The N, P, and K fertilizers were applied at rates of 129, 56, and 107 kg/ha, respectively. A hybrid pearl millet, Millex-23, was planted in 50-cm rows on May 12, 1971.

The water status of the soil profile was monitored by tensiometers and gravimetric samplings. Tensiometers were installed in two locations between the rows, at 15-, 25-, 30-, 36-, 45-, and 60-cm depths in each plot. Soil ψ_M was measured daily during the treatment period and

TABLE 1

Water control treatments

Treatment symbol	Initial water application	Apply additional 2.5 cm of water when ψ_M at 30-cm depth is equal to:	Method of water control
	(cm)	(mb)	
M_1	10	-70	Irrig. + rainfall impoundment
M_2	5	-150	Irrig. + rainfall with surface runoff
M_3	2.5	-200	Irrig. + rainfall with surface runoff
M_4	2.5	-500	Irrig. with plot shelter

on Monday, Wednesday, and Friday at other times and corresponded approximately to ODR measurements for the 15-, 25-, and 45-cm depths.

Rainfall on the M_4 plots was intercepted by automated shelters, which were activated by 0.05 cm of rain and opened within 15 min after the rainfall stopped. The M_4 plots were irrigated when the soil Ψ_M at the 30-cm depth was lower than -0.5 bar.

The experiment began with a pretreatment period (May 12 to June 16) during which all plots were irrigated when the soil ψ_M at the 30-cm depth was lower than -0.5 bar. Irrigation water was surface applied and ponded on the plots until it infiltrated.

Water control was initiated on June 16 (day 168) and terminated June 30 (day 183) when the millet was harvested. Plants were cut off at approximately the 6-cm height, dried, weighed, and their relative dry matter yield determined. During a posttreatment period the millet recovered and grew under natural rainfall conditions.

When the plant height was approximately 1 m, the millet was sampled. The samples were dried at 70°C and ground. The total N content of the samples was determined by the Kjeldahl method, and their P and K contents were determined spectrophotometrically.

RESULTS AND DISCUSSION

Figure 2 shows the mean of three ODR measurements, at three depths, for an M_1 plot, after an initial 10-cm water application. The irrigations and rainfall are shown on the upper horizontal axis. This plot was wetted with a total of 46.4 cm of irrigation water and rainfall during the 28-day period. After the initial 10-cm water irrigation, the ODR's at the three depths were low during the experimental period (days 169 to 195) and in the range determined deficient or critical for other crops. The ODR at the 10-cm depth (A1 layer) reacted quickly to water additions and showed that the soil at that depth would have soon become well aerated, if less water had been applied. Generally, the ODR in the A1 layer rose above $0.2 \mu\text{g}/\text{cm}^2/\text{min}^1$ within 24 hr after an irrigation, except when large quantities of water were applied.

The ODR at the 25-cm depth (A2 layer) decreased to less than $0.1 \mu\text{g}/\text{cm}^2/\text{min}^1$ after the initial irrigation, and, thereafter, ODR changed very slowly, indicating poor aeration. This was expected, because the A2 is a compact layer, with a bulk density ranging from 1.7 to $1.9 \text{ g}/\text{cm}^3$ (Campbell et al. 1974; Grable 1966).

The ODR at the 45-cm depth (B layer) apparently was not directly related to ODR measurements in the upper two layers and, although the measurements showed an ODR deficiency, ODR was slightly greater than that at the 25-cm depth. This might be due to entrapped air below the A2 layer diffusing upward.

In the A1 layer for the M_2 , M_3 , and M_4 treatments, ODR progressively increased as soil ψ_M decreased. In the M_4 plots, ODR was above $0.4 \mu\text{g}/\text{cm}^2/\text{min}^1$, except for brief periods after irrigation or when the soil ψ_M was too low to provide a continuous water film around the electrode. In the A2 and B layers, ODR varied between 0.2 and $0.4 \mu\text{g}/\text{cm}^2/\text{min}^1$ but seldom exceeded $0.4 \mu\text{g}/\text{cm}^2/\text{min}^1$.

The mean soil ψ_M in the M_1 plot, corresponding with the ODR profile measurements in the A1, A2, and B layers, are shown as a function of time in Fig. 3. During the irrigation treatment period (days 168 to 183) the soil ψ_M at the three depths remained above the predetermined -70 -mb level. After day 183, the soil desaturated slowly. Usually, the soil ψ_M at the 25-cm depth (A2 layer) was slightly higher than at the

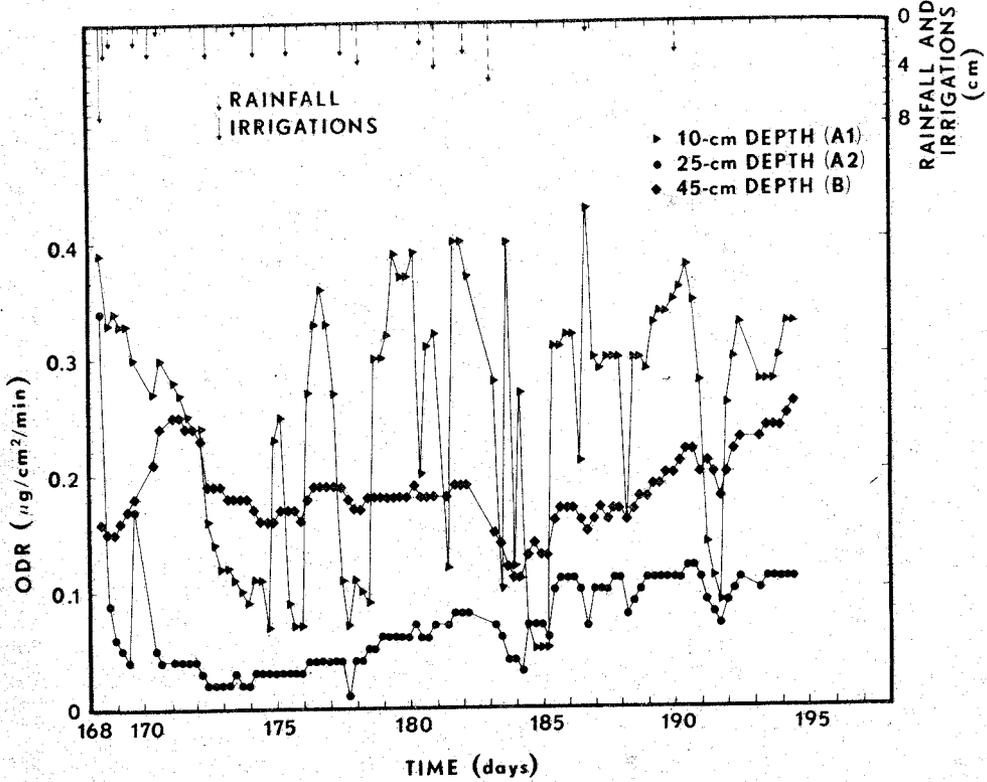


FIG. 2. Oxygen diffusion rate (ODR) at three depths, measured every 6 hr with a digital data acquisition system, in a plot irrigated when the soil matric potential (ψ_M) at 30-cm depth was -70 mb (M_1 treatment).

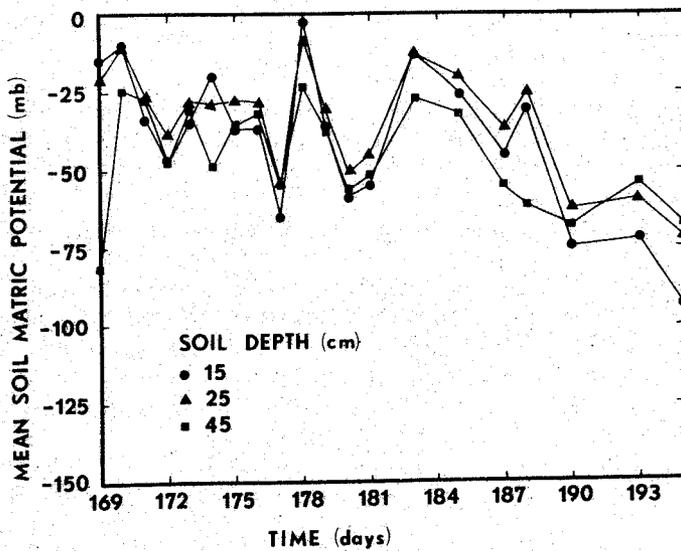


FIG. 3. Mean soil matric potential at three depths for a millet plot irrigated when the soil matric potential (ψ_M) at 30-cm depth was -70 mb (M_1 treatment).

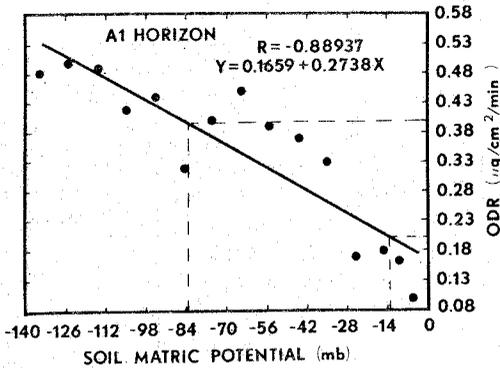


FIG. 4. Mean oxygen diffusion rate (ODR) at 10-cm depth as a function of soil matric potential (ψ_M).

other two depths, resulting in a lower ODR as shown in Fig. 2. Soil ψ_M measurements in the M_2 , M_3 , and M_4 treatment plots had similar patterns resulting in respectively higher ODR values and increases in plant yields.

The mean ODR values for the 10-, 25-, and 45-cm depths, respectively, are shown in Figs. 4, 5, and 6 as a function of soil ψ_M . The intercepts of the regression lines with the 0.2 and the 0.4 $\mu\text{g}/\text{cm}^2/\text{min}^1$ ODR levels determine respectively the ODR-critical and ODR-deficient soil ψ_M levels in the A1, A2, and B layers. In Fig. 4 (A1 layer) the regression line intercept with the 0.4 $\mu\text{g}/\text{cm}^2/\text{min}^1$ ODR at -85 mb and with the 0.2 $\mu\text{g}/\text{cm}^2/\text{min}^1$ ODR at -14 mb soil ψ_M , indicating that the soil at that depth could sustain plant growth under extremely high soil ψ_M .

The regression line for the A2 layer (Fig. 5) intercepts the 0.2 $\mu\text{g}/\text{cm}^2/\text{min}^1$ ODR level at -84-mb soil ψ_M and the 0.4 $\mu\text{g}/\text{cm}^2/\text{min}^1$ ODR at -136 mb. These data and those of Fig. 3 indicate that high soil ψ_M resulting from excessive irrigation and/or rainfall markedly affected aeration at the 25-cm depth.

The data of Fig. 6 show that a less severe aeration problem will develop at the 45-cm depth than at the 25-cm depth under high soil ψ_M levels. A root penetrating to the 45-cm depth could continue to grow, although aeration at the 25-cm depth may be critically low.

Linear and/or curvilinear regression equations and correlation coefficients of ODR as a function of soil ψ_M for the A1, A2, and B horizons are shown in Figs. 4, 5, and 6. The slope of each line is nearly equal but the intercepts are different, indicating the possibil-

ity of a significant difference between each of the ODR-soil ψ_M relationships. Analysis of variance indicates a significant difference (99 percent confidence level) between each regression line.

The aeration profile can be calculated from the soil ψ_M measurements in the three soil layers of the soil by using these equations. Figures 7a, 7b, and 7c show a comparison between the calculated and measured daily mean ODR for the A1, A2, and B layers during the treatment period. The mean ODR in the A1 layer was measured every 6 hr and showed rapid fluctuations in response to irrigation and rainfall. However, the mean ODR calculated from daily soil ψ_M measurements and the linear regression equation in Fig. 4 seems to average out these rapid fluctuations.

In the A2 and B horizons, ODR calculations

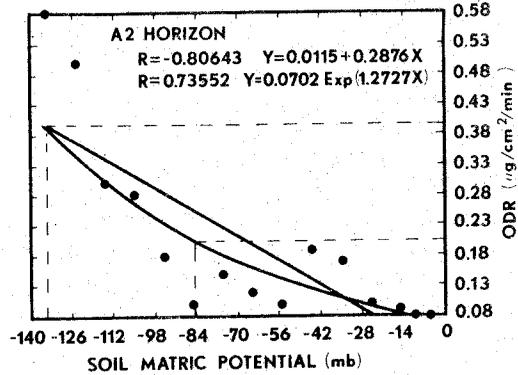


FIG. 5. Mean oxygen diffusion rate (ODR) at 25-cm depth as a function of soil matric potential (ψ_M).

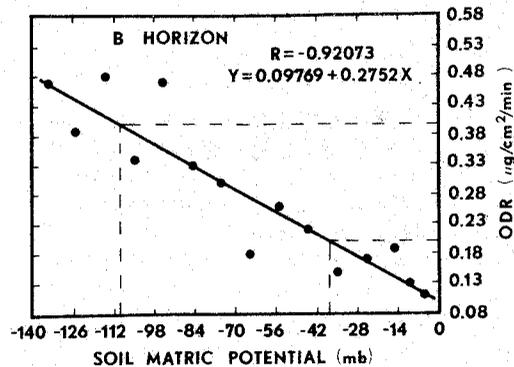


FIG. 6. Mean oxygen diffusion rate (ODR) at 45-cm depth as a function of soil matric potential (ψ_M).

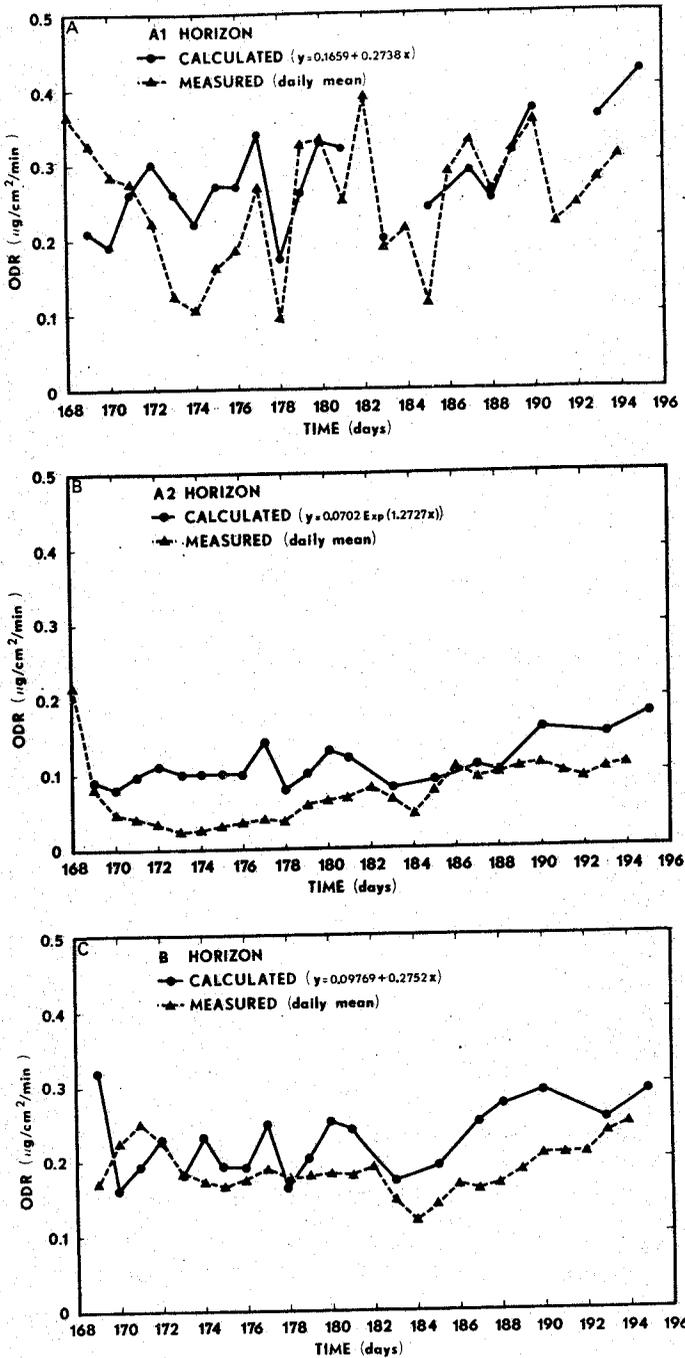


FIG. 7a. Measured (daily mean) and calculated ODR's for the A1 horizon of a millet plot irrigated when the soil matric potential (ψ_M) at 30-cm depth was -70 mb (M_1 treatment).

FIG. 7b. Measured (daily mean) and calculated ODR's for the A2 horizon of a millet plot irrigated when the soil matric potential (ψ_M) at 30-cm depth was -70 mb (M_1 treatment).

FIG. 7c. Measured (daily mean) and calculated ODR's for the B1 horizon of a millet plot irrigated when the soil matric potential (ψ_M) at 30-cm depth was -70 mb (M_1 treatment).

from daily soil ψ_M measurements follow the same general trends with varying differences in magnitude. Since the soil ψ_M and ODR measurements were obtained at three different locations in the plots and at different times of the day, complete agreement cannot be expected between measured and calculated ODR. The ODR prediction may have been better if we had measured ODR and soil ψ_M at the same time and location within the plots.

The electrical resistance of the soil varied between 1500 and 4500 ohms as the soil dried out. During the treatment period, the soil in the M_1 plots was kept at a high soil ψ_M with frequent irrigation and the electrical resistance of the soil was not measured often enough to permit daily accurate correction of the ODR measurements (Kristensen 1966). Soil electrical resistance measurement should be obtained simultaneously with ODR measurements, to make an accurate correction.

The dry matter yield of millet for the cutting period ending on June 30 is plotted as a function of ODR at the 10-cm depth (Fig. 8). These data are consistent with previously published results (Stolzy et al. 1964). The yield of millet was doubled when the soil matric potential control level was decreased from -70 (M_1) to -150 mb (M_2). The yield of millet for the M_4 plots could have been depressed by water stress so that the yield may have been maximum between the M_3 and M_4 plots (Fig. 8).

TABLE 2
Mineral content of millet

Water control treatment	N %	P %	K %
M_1	1.46 a*	0.19 a	2.44 a
M_2	1.53 a	0.29 b	3.19 a
M_3	2.00 b	0.35 b	4.16 b
M_4	2.42 c	0.32 b	4.47 b

* Means followed by the same letter are not significantly different at the 5 percent level.

The mean N, P, and K contents of millet for the treatments are shown in Table 2. The N, P, and K contents were significantly different (5 percent level of confidence) among the M_1 and the M_4 treatments. The N content of millet was more closely related to aeration deficiency than either its P or K contents, since the N contents of the M_1 and the M_2 plots were significantly different from that of the M_3 and M_4 (5 percent level of confidence).

The use of the automated soil ODR measurement showed the rapid responses of ODR to rainfall and irrigation in the A1 horizon and the slow response of ODR in the A2 and B layers. The ODR profile (Fig. 2) partially explains the lack of root proliferation at the A2 and B layers under normal tillage conditions and emphasizes the importance of precise soil-water management practices in these soils.

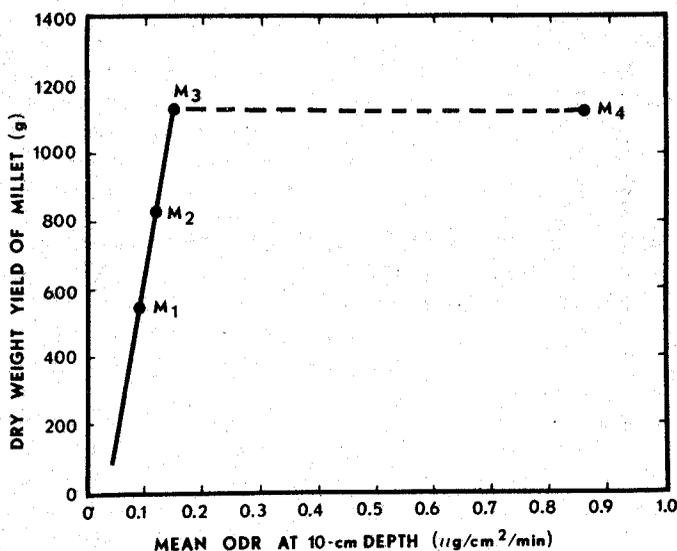


FIG. 8. Dry weight yield of millet as a function of oxygen diffusion rate (ODR) for millet harvest on June 30.

SUMMARY

The automated method of ODR measurement with a Pt microelectrode has been developed and tested in a field experiment. Its use enabled rapid characterization of the dynamics of soil aeration in situ and the determination of soil ψ_M levels which are critical to good aeration.

In field plots, the soil ODR increased rapidly at the 10-cm depth as the soil dried and decreased rapidly with each irrigation and rainfall. At the 25-cm depth, the ODR remained below the critical level (ODR $< 0.2 \mu\text{g}/\text{cm}^2/\text{min}^1$) after the initial irrigation. At the 45-cm depth, the ODR was higher but usually below the critical level. In the A1 layer of a Varina sandy loam soil, ODR was less than adequate (ODR $< 0.4 \mu\text{g}/\text{cm}^2/\text{min}^1$) for soil ψ_M greater than -85 mb. In the A2 layer, ODR was critically low (ODR $< 0.2 \mu\text{g}/\text{cm}^2/\text{min}^1$) for soil ψ_M greater than -60 and -84 mb, and was less than adequate for soil ψ_M greater than -136 mb. The ODR in the B layer was critically low for soil ψ_M greater than -40 mb and was less than adequate for soil ψ_M greater than -112 mb. These results are being used to establish water management criteria for humid regions (Phene 1974).

Soil ψ_M measurements were used with ODR-soil ψ_M regression equations to simulate the ODR profiles of a Varina sandy loam soil. Although the soil ψ_M measurements used in the calculations were made at plot locations different from those for the ODR measurements, calculated and measured ODR compared favorably.

Yields of millet grown in the field under wet soil conditions were related to the ODR which fluctuated according to the amount of water infiltrating the soil as rainfall and irrigations.

Yields of millet, grown at soil ψ_M greater than -70 mb at 15-cm depth, were significantly lower than yields from treatments with soil ψ_M of -120 and -150 mb or less.

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