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J. Bornstein

W. E. Hedstrom

F. R. Scott

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by

J. Bornstein, W.E. Hedstrom,
and F.R. Scott

Life Sciences and Agriculture Experiment Station
University of Maine at Orono

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OXYGEN DIFFUSION RATE RELATIONSHIPS UNDER THREE SOIL CONDITIONS

J. Bornstein[1], W.E. Hedstrom[2] and F.R. Scott[3]

The design of agricultural drainage systems includes the formulation of design criteria to meet the desired drainage intensity. But information about crop yield response to drainage intensity is generally lacking (4). By better understanding the agronomic requirements of drainage, we could formulate a more rational design procedure, a fact that several authorities have pointed out (4, 11).

The primary reason for draining agricultural land in humid areas is to improve soil aeration, or the exchange of oxygen (O_2) and carbon dioxide (CO_2) between the atmosphere and the soil and plant roots (2). Other related benefits include improved trafficability, the lengthening of the growing season, and the ability to get onto land safely soon after precipitation, as well as more rapid warming of the soil in the spring (5). Most of the supply of O_2 moves to the roots by diffusion through the soil — first, through the air-filled pores and then through the water films surrounding both the soil particles and the root hairs. The O_2 diffusion coefficient in water equals 2.4×10^{-5} versus 1.8×10^{-1} cm^2/sec in air. The O_2 diffusion rate (ODR) is primarily affected by the thickness of water film around the roots and to some extent by the composition of soil air — the CO_2 in relation to O_2, nitrogen (N), and inert gases (2). Characterizing soil aeration is complicated by the heterogeneity of soil and root systems, the uncertainty about what should be measured, the variation in the soil atmosphere with location and time, and the difficulty of correctly obtaining the desired information i.e., the rate of oxygen movement to the root zone.

Measurements of the gas phase of the soil atmosphere have not proved adequate to precisely predict plant response. However, measurement of ODR by the platinum electrode method does include the factors which influence O_2 supply to the root (8). The method, introduced by Lemon and Erickson (7) and developed by Letey and Stolzy (9) depends on the reduction of O_2 at the surface of the electrode under the influence of an electrical potential. The microelectrode becomes a localized sink for O_2 and simulates a small respiring root. The initial electrical current decreases rapidly as the O_2 adjacent to the electrode in

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[1] Agricultural Engineer, U.S. Department of Agriculture, SEA-AR, N.E. Plant, Soil and Water Laboratory and Faculty Associate in Agricultural Engineering, University of Maine at Orono 04469.

[2] Associate Professor of Agricultural Engineering, Department of Agricultural Engineering, University of Maine at Orono 04469. Supported in part with Hatch funds.

[3] Engineering Associate, N.E. Plant, Soil and Water Laboratory, University of Maine at Orono 04469.

the surrounding pores is depleted. In time, a steady-state condition is approached in which the current flowing to the microelectrode is governed by the rate at which O_2 diffuses to the electrode surface from the air through the surrounding soil (6). To measure O_2 diffusion, we used a modified (3), commercially available, Jensen Model B Oxygen Diffusion Ratemeter, which consists of a ratemeter, a silver-silver chloride (Ag-AgCl) reference cell, an anode and 10 platinum electrodes[4] The instrument operates at a current of up to 25 MA at applied potentials up to 1 volt.

Although the platinum microelectrode method has been used extensively in studies of the effects of soil aeration, it has inherent limitations because of the electrochemical and physical principles governing its behavior (10). Because of problems in using this method, we questioned its value as the standard for characterizing soil aeration under field conditions.

Our objective was to determine the ODR — soil moisture relationship for three sieved, root-free soils to determine if there are basic ODR-soil characteristic differences that might influence data at different soil water contents in the presence of plant roots. Advanced knowledge of ODR-soil moisture relationships would also help scientists to evaluate the effect of variation in the water table on plant growth.

PROCEDURE

Our ODR-soil water content measurements started with oven dry soil and proceeded through increased water contents to saturation. All soil was sieved and root free.

We determined the relationships among ODR, soil moisture content, and soil density for three soils — bank run sand, subsoil from a site classified as Stetson (frigid Typic Haplorthods) fine sandy loam, a somewhat poorly drained silt loam Ap and subsoil horizons that would fall between Buxton (frigid Aquic Dystric Eutrochrepts) and Scantic (frigid Typic Haplaquepts). Samples of each dry soil were mixed with water to obtain a prescribed uniformly distributed moisture content and then samples were placed into plastic containers. This procedure was repeated for each water content. We were able to establish five water contents for each top and subsoil and nine for sand. Simply adding water and mixing worked well for sand. However, silts and clays rolled into small balls that resulted in nonuniform moisture distribution. Adding water as crushed ice solved this problem. It gave the rapid, uniform water distribution needed by gradually melting during the mixing pro-

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[4] Mention of trade names in this paper does not constitute a recommendation for use by U.S. Department of Agriculture.

cess. We then allowed each container of wetted soil to stand covered overnight to complete the dispersion process.

We inserted 10 platinum microelectrodes into the soil to a depth of 15 cm±3 cm. The ODR meter readings, the current in microamperes, were taken three times for each water content. Table 1 is a sample of the ODR data collected at specific water contents. Because we recognized the microheterogenity of the soil, we took 10 readings, one for each electrode, and averaged them. After the three sets of readings were taken at a particular moisture content, we removed the soil from the container. An increment of water was added to the soil to give the next desired water content. We replaced the soil in the container and proceeded as before. We repeated this procedure for each of the three soils. Then we plotted the ODR data to obtain a representative soil water content-ODR relationship. The equations generated, one for each soil, and the curves thus plotted were fitted to all points generated from each soil type (Figure 1).

Table 1. Soil Water Content vs ODR

	Trial No.	Soil Water % Dry Wt.	ODR $g\ cm^{-2} min^{-1} \times 10^{-8}$ *
Topsoil	1	6.9	15.5
	2	13.7	60.8
	3	18.2	76.7
	4	23.5	57.8
	5	28.5	23.6
Subsoil	1	2.7	2.4
	2	6.3	21.9
	3	10.4	16.7
	4	15.2	33.2
	5	22.6	30.2
Sand	1	1.6	3.0
	2	6.5	22.7
	3	9.8	33.9
	4	12.6	30.7
	5	16.0	31.4
	6	16.6	31.5
	7	17.1	33.9
	8	18.2	23.9
	9	18.6	18.5

*Each value is the average of 10 electrode readings.

As a part of our study, we began an experiment in the greenhouse to determine the effects of soil moisture on aeration near plant roots and on the quantity of alfalfa growth. Twelve concrete cylinders, each containing a mass of silty clay loam soil, a Mesic Aeric Haplaquepts, 61 cm in diameter and about 152 cm in height planted to alfalfa, were used. The treatments imposed at 42-day growth cycles of alfalfa were 1) three constant water table depths — 15, 45 and 76 cm; 2) a falling water table series — first saturating the soil surface for 3 days, then lowering the water tables, to the three depths listed above; and 3) a three sequence falling water table series — thrice during the crop-growth cycle, saturating the soil surface, followed by lowering the water table again to the three depths. We measured the ODR values weekly for several 42-day crop cycles in each of the cylinders for each water regime. Additional measurements of soil water content, water table, plant water use, and crop growth, yield, and quality parameters have been made and are presently in preparation for publication. We noted clearcut ODR response to saturation (decreased ODR values) and to lowered water table (increased ODR values).

RESULTS AND DISCUSSION

An ODR-soil water content experiment described herein should serve as a basic reference for application of ODR measurements to greenhouse and field studies. It could help others who need to know the relationship between soil characteristics, soil water content, and oxygen diffusion rate.

The ODR values measured in this laboratory study generally agreed with those published by other investigators for the type of soil we used. Also, we noted some of the peculiarities of our method. The usual data scatter was observed, especially at high moisture contents, as shown in Figure 1. The ODR values, as determined by averaging values from 10 electrodes placed in the soil at a given soil water content, usually decreased at a steady rate with time, as shown in Figure 2. Occasionally, the ODR would increase slightly, possibly due to a change with time of the configuration and thickness of the water films around individual electrodes. Before starting each trial, we checked battery voltage to assure it was adequate. The trend line of decreasing ODR varied considerably. The percentage decrease tended to be much greater at higher moisture contents.

Measurements at low moisture content, where aeration is not a problem, are not accurate indications of ODR's. Although aeration is good, conductance between anode and electrode declines. Birkle et al. (1) explained that this is caused by disruption of the moisture film around the electrode. A root would thus continue to receive a flow of air but the ODR meter-platinum electrode system does not measure this type of O_2 movement.

Typical ODR values as a function of water content, expressed as a percentage of the bulk soil volume for several soils and soil densities, are shown in Figure 3. Another method of expressing this same basic relationship is shown in Figure 4, where ODR values are plotted against air-filled porosity; i.e. the volume of air-filled voids, divided by the total pore space of soil, expressed as a percentage for each water content. This figure shows directly the effect of soil air. As the soil voids become filled with water within the range where the meter works well, ODR values clearly decreased for all three soils. Here, different curve shapes describe the relationship for each soil. However, in the future, we must determine whether these relationships are characteristic and whether drainage and cultural practices will modify them and thereby provide us with a way of measuring improved root environment.

Also in Figures 3 and 4 we made an effort to relate ODR values to soil density. Average dry soil densities measured were 1.26, 1.82 and 1.39 g/cm^3 respectively for topsoil, sand and subsoil. Topsoil had the highest peak ODR values while those for sand were second and those for subsoil were last. Although ODR values were not in the order of increasing density, they were, at least, in logical order. The silty clay loam subsoil would have the smallest pores, although probably greater total porosity than the sand.

We also measured soil ODR values above the water table in silt loam in the presence of growing alfalfa in the 61-cm-diameter × 152-cm deep cylinders previously mentioned. A sample of these data, taken at 10 to 15 cm soil depth, is plotted in Figure 5 for a falling water table. The variation in ODR values with time for each treatment illustrates that soil aeration conditions change with time. As the water table depth increased to 45 and 76 cm, the ODR values increased steadily. However, the ODR values at the 15 cm depth water table steadily decreased. This was due in part to maintenance of a capillary fringe.

CONCLUSIONS

Our data showed that each soil has a characteristic ODR-soil water-content relationship. At a low water content, we would expect to have the highest actual O_2 diffusion but it is not measurable with the meter because of discontinuous moisture contact between electrodes, cathode, and anodes. As the soil approached field capacity and saturation, we have very limited O_2 diffusing to the electrode tips (the potential root zone) and, thus, low ODR meter readings.

Usually for all soils, repeated readings of ODR at the same moisture content taken at 20-minute intervals, gave decreasing ODR values. The differences among readings were small. We used the first value from each series in our analysis.

We also found a definite variation in the distribution of ODR data points with changes in moisture content for each of the three soils studied. Topsoil, higher in organic matter than the sand and subsoil, had higher ODR values. Sand has the lowest porosity but its open structure seemed to permit greater O_2 diffusion than subsoil at moisture levels optimum for plant growth.

We acknowledge the contribution of Robert Ofoli, former Agricultural Mechanization student, who carried out the experimental procedures and compiled the basic data.

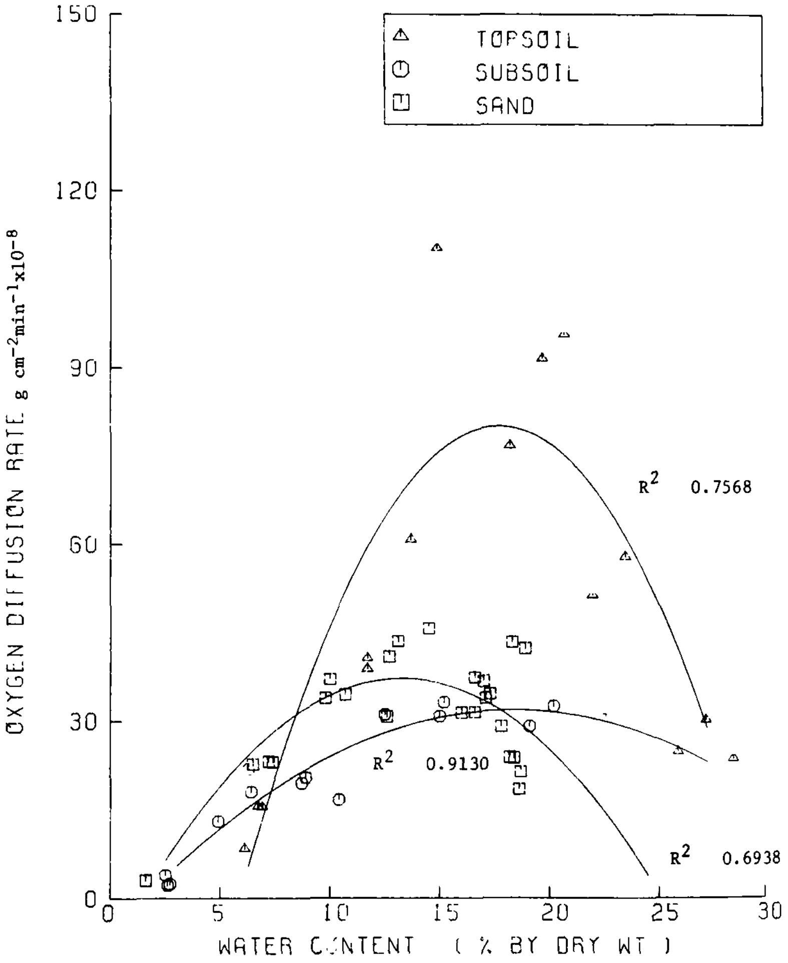

Fig. 1 Oxygen diffusion rate vs. soil water content for three soil materials — dry wt. basis

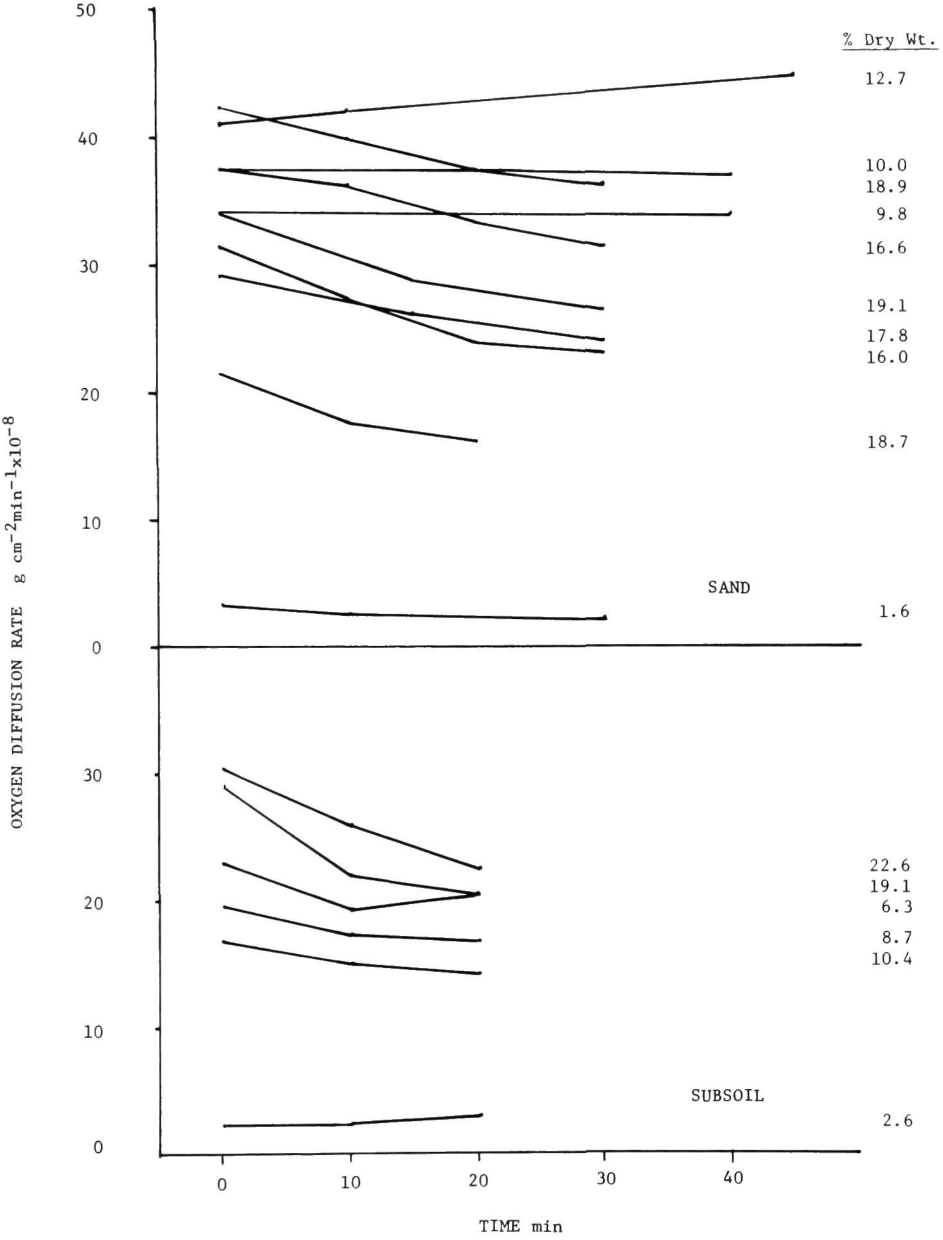

Fig. 2A Oxygen diffusion rate change for selected moisture levels

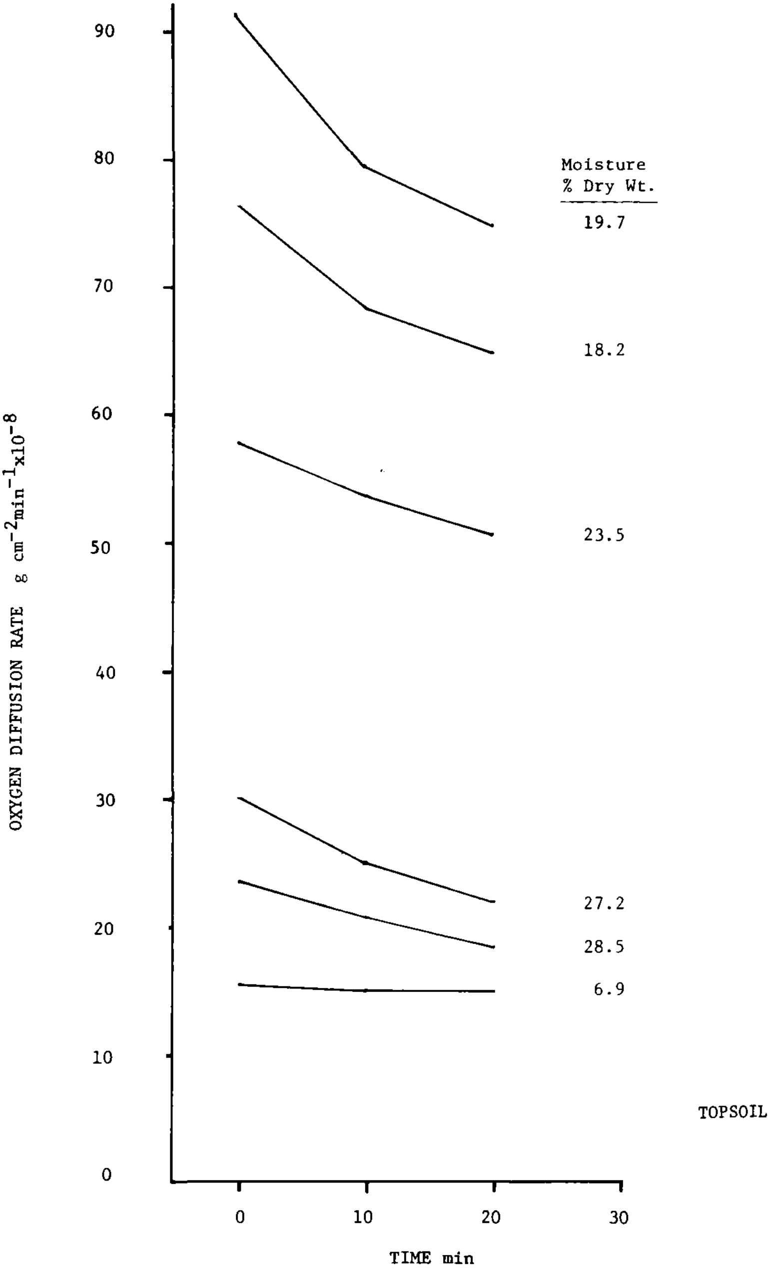

Fig. 2B Oxygen diffusion rate change for selected moisture levels

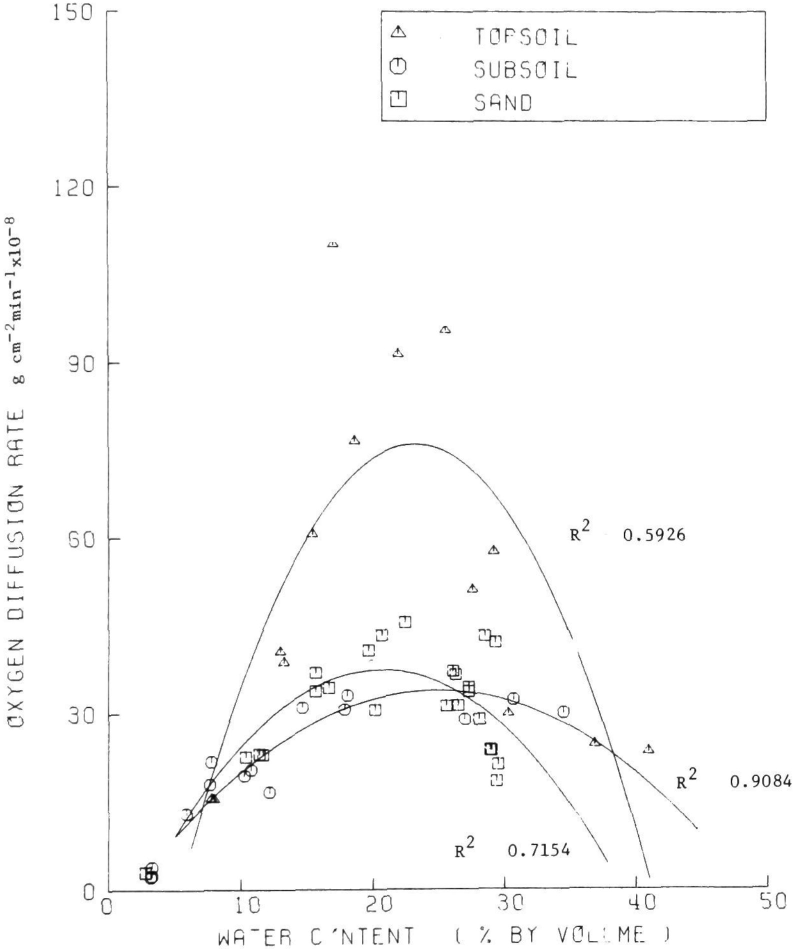

Fig. 3 Oxygen diffusion rate vs. soil water content by volume

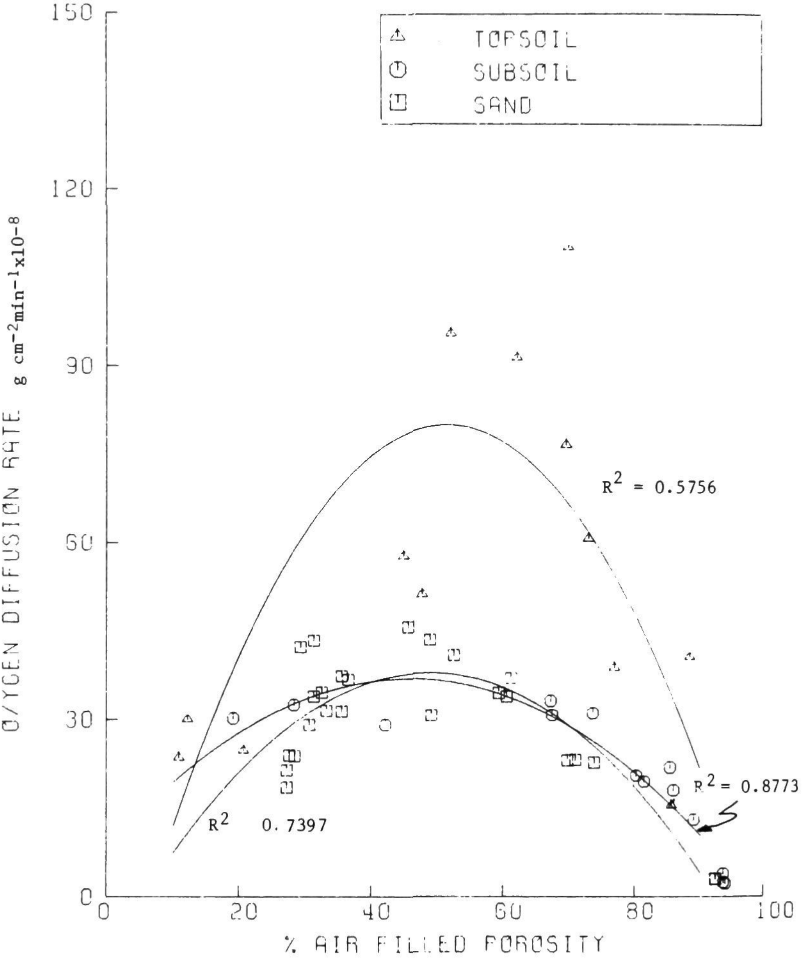

Fig. 4 Oxygen diffusion rate vs. air-filled porosity

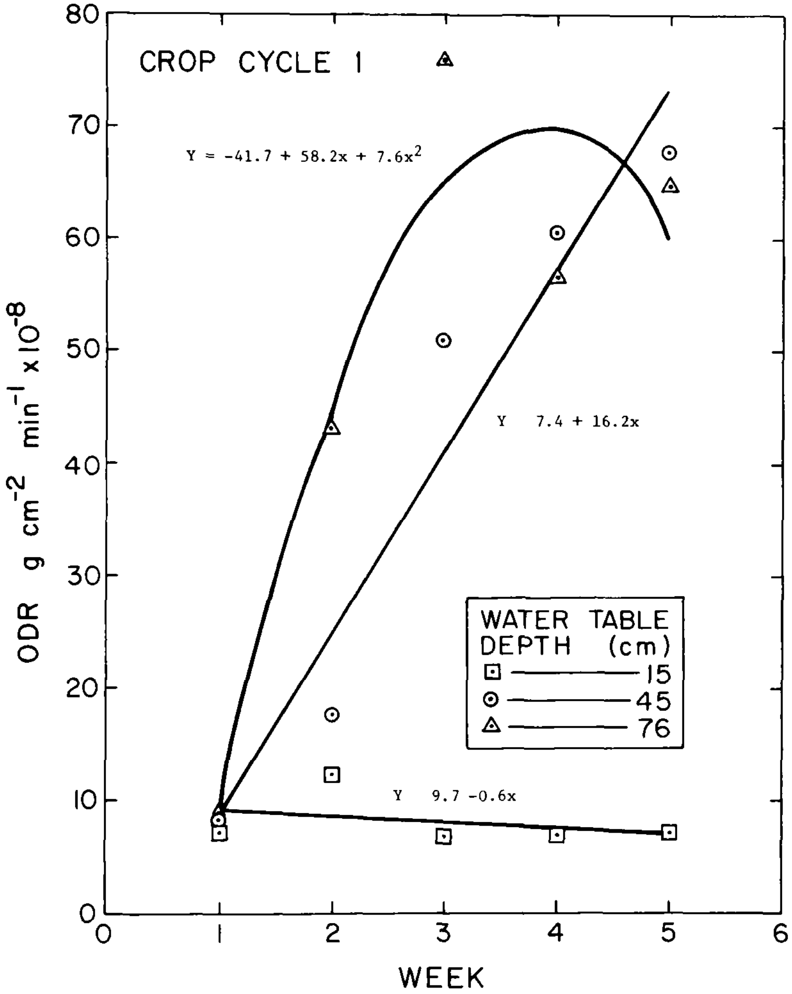

Fig. 5 Oxygen diffusion rate changes by weeks in a silty clay loam with a falling water table

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