

PREFERENTIAL MOVEMENT OF O₂ IN SOILS?

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Abstract

Plant roots and soil biota require O₂ to function normally. When the soil O₂ is depleted, it must be replaced by O₂ from the atmosphere. The transport occurs primarily by gaseous diffusion. Although O₂ diffusion has been researched in homogeneous soils, and in tight clay soils with cracks, little is known about the effects of macropores on O₂ transport in typical agricultural soils. In this study we examined the impact of large pores on O₂ concentration in a sandy loam soil. Experiments were carried out with homogeneous and simulated-macropore columns with a steady-state rainfall of 3 cm d⁻¹ in which the O₂ concentration in the soil matrix and in the macropore was measured at 15-cm vertical intervals. The diameter of each column was 20 cm and the height was 105 cm. Groundwater depth was systematically varied between 30 and 105 cm. Soil water content did not vary with distance above the water table for the 30-, 60-, and 90-cm groundwater depths. While both the soil water for the entire column and the O₂ concentration from the surface to the 30-cm depth was the same for the homogeneous and macropore columns, the O₂ penetrated deeper in the macropore column and was 4% greater below the 30-cm depth in the macropore column than for the homogeneous column.

THE AVAILABILITY OF O₂ to plant roots and microorganisms strongly depends on the transport rate of O₂ through the soil (Wilson et al., 1985; Refsgaard et al., 1991). In principle, O₂ in soil can be displaced by bulk movement of the soil air phase in response to differences in total air pressure, which can be induced by soil temperature changes, barometric pressure fluctuations, wind, and infiltration (Jury et al., 1991). According to a study by Romell (1922, quoted by Jury et al., 1991) advective transport due to these effects amounts to <1% of the total O₂ movement, with the possible exception of wind effects (Farrel et al., 1966). Although there are only a few studies concerning advective transport, O₂ is thought to be transported mainly by gaseous diffusion. Rates of O₂ diffusion are obtained by assuming that the soil is uniform and that the O₂ concentrations are equal in the horizontal plane (McIntyre and Philip, 1964; Wilson et al., 1985; Patwadhan and Nieber, 1987; Kanwar et al., 1989; Rolston et al., 1991). In an excellent study of CO₂ and O₂ transport by Ouyang and Boersma (1992a,b), many factors were considered, but only for a homogeneous soil. During the last 20 yr, solute transport field experiments have shown that macropores are the rule rather than the exception, possibly invalidating the above assumptions of homogeneity. Roseberg and McCoy (1990) found, for example, that a fine loamy soil core with macropores (>1 mm diam.) had a higher air permeability than with-

out macropores. This finding does not necessarily invalidate the assumption of homogeneity in the above-mentioned models because the air permeability refers to an advective O₂ transport for which the (pore) flux is related to the fourth power of the pore radius, while O₂ transport in the soil is considered to be diffuse and depends on water-free pore area. The radii of the pores only marginally affect the total porosity of the soil.

There are few experimental and simulation studies that have measured or calculated the O₂ distribution in heterogeneous soils. Hodgson and Macleod (1989) found that O₂ flux density was not affected by cracks in a Vertisol soil. Bronswijk et al. (1993) simulated O₂ diffusion in macropores, in a wet and tight clay soil, and showed that the formation of pyrite was directly related to the macropore network. Rappoldt (1990) developed models for the behavior of diffusion from macropores to soil aggregates and showed that for a clay soil, anoxic regions may be expected in the middle of soil crumbs.

Since the limited studies on diffusive O₂ transport in macropores were performed in clay soils, the emphasis in this study is on the effect of macropores on O₂ concentration in a soil with a well-conductive matrix. It is important to understand the relationship between O₂ status and macropores because modern agricultural practices greatly affect the macroporosity of the soil (Berry and Karlen, 1993). Considering the interest in the effect of water table height on the O₂ concentration for drainage design (Wesseling, 1974), we varied the water table and applied a low but steady-state rainfall rate. Artificial rain was used since under natural field conditions a rising water table is always associated with precipitation.

Materials and Methods

Laboratory experiments were carried out with three identical PVC columns 20 cm in diam. and 114 cm long filled with Fallsington sandy loam (fine-loamy, mixed, mesic Typic Ochraqult) taken from the upper 30-cm soil layer at the University of Delaware Experiment Station. A round 1.3-cm-thick PVC plate, with 0.3-cm holes drilled 1 cm apart, covered with glass fiber matting and filter paper (Cole Palmer G-02913-40, Chicago, IL), was glued to the bottom of each column. A cap was glued over the bottom plate (Fig. 1) and a flexible, adjustable, Nalgene overflow tube (1-cm diam.) connected to the cap regulated the groundwater in the column. The column was checked for leaks by filling it with water.

The air-dried Fallsington sandy loam (moisture content = 0.013 cm³ cm⁻³) was sieved (2 mm) and put into the three PVC columns by hand. The center macropore was made by placing a vertical 0.95-cm-diam. and 113-cm-long stainless steel bar in the middle of the column during filling. The soil was packed by adding 10-cm layers of air-dried soil and pressing it uniformly to a bulk density of 1.35 g cm⁻³. The soil was prewetted from below with a 0.005 M CaSO₄ solution, followed by 48 h of drainage, after which it was placed under the rainfall simulator developed by Andreini and Steenhuis (1990), capable of applying water uniformly at a very low rate. A 0.005 M CaSO₄ solution was applied at a rate of 3 cm d⁻¹. The

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Abbreviations: PVC, polyvinyl chloride; SAC, soil air chamber; SAMS, soil air measurements sampler; TDR, time domain reflectometry.

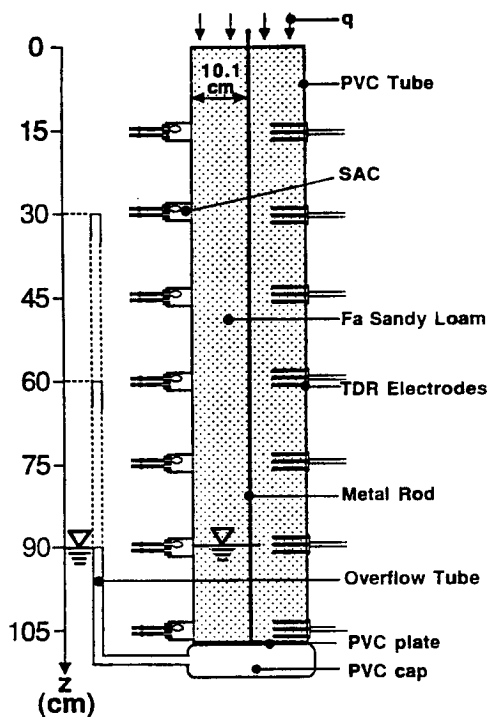


Fig. 1. Soil column with soil air chamber (SAC) and time domain reflectometry (TDR) electrodes.

intensity was checked before and after each experiment. All experiments were performed in a temperature-controlled room at 20°C.

Oxygen concentrations were measured at 15-cm intervals near the wall with seven soil air chambers (SAC), similar to those of Kanwar et al. (1989) (Fig. 1). Each SAC was made of PVC pipe, 5.5 cm long and 3.2 cm i.d. (Fig. 2a). Oxygen concentrations were measured by taking 7 to 10 mL of air out of the SAC into the soil air measurements sampler (SAMS, depicted in Fig. 2b) and replacing this volume by inflating a balloon within the SAC in order to minimize air movement in the soil. The SAMS (Fig. 2b) consisted of a digital O₂ analyzer (Sensitron Associates, Inc., Reading, PA), soil air sampling cell, "push-pull" two-syringe (60 mL) system, and the water-level vessel made from a 60-mL syringe. The three glass stopcocks (A, B, and C) were used for (i) calibration of

the SAMS against the atmospheric air, (ii) equalization of gas pressure inside the sampling cell to atmospheric pressure, and (iii) sampling soil air from the SAC. Readings of O₂ concentration (stopcock A closed, B and C open) were taken after equalization of the water level inside the sampling cell and in the water leveling vessel. For measurement of the O₂ concentration in the macropore, the SAMS were also used. Polyethylene tubing (0.86 mm i.d.) fastened to a 15-cm-long thin (0.5 mm i.d.) metal rod, was attached to stopcock B and lowered into the macropore. The end of the second tubing (previously connected to the balloon of the SAC) was kept in a vessel with water. The volume of air sampled was 7 to 9 mL.

Time domain reflectometry (TDR) with a three-electrode system was used to measure moisture content at the same depth as the SAC (Fig. 1). The wave guide electrodes, spaced 2.5 cm apart, were 19.3 cm long and 0.32 cm in diam. The TDR and electrodes were calibrated in half cylinders with a diameter of 20 cm and a height of 9.7 cm and filled with Fallsington sandy loam with a bulk density of 1.35 g cm⁻³. Different amounts of a 0.005 M CaSO₄ solution were added to the half cylinders and left to calibrate for 2 wk to reach steady state, after which TDR and gravimetric moisture content readings were taken. Evaporation was prevented by placing each vessel in a plastic bag. The calibration procedure was repeated twice.

Two series of experiments were carried out with the same three columns. In the first series, the vertical metal rod was retained in the soil (from now on called *homogeneous columns*), and in the second series, the metal rod was removed to create a 0.95-cm cylindrical pore (called the *macropore column*). For each experimental series, the soil in the column was saturated first and then drained to field capacity with the groundwater level at 105 cm. The steady rainfall intensity was applied at the soil surface during the experiments. Steady-state water content and O₂ concentration were determined when the O₂ concentration did not change during a 24-h period. The groundwater level was then increased in three increments of 30 cm each to depths of 90, 60, and 30 cm, and measurements of O₂ flux were conducted at each groundwater level until the concentrations did not change anymore. In this paper we only report on the steady-state values.

Results and Discussion

It is generally known that moisture content affects the O₂ concentration in the soil and we present, therefore, both the moisture content (and air-filled porosity) and O₂ concentration for the homogeneous and macropore columns. Figure 3a shows the moisture content in the homogeneous column for water table depths of 30, 60, 90, and 105 cm. As expected for the 30-, 60-, and 90-cm water table depth, the height of the capillary fringe is the same (and almost negligible). These water table depths were established by increasing the water level, and the capillary fringe is, thus, roughly equal to the "water-entry value" of the Fallsington sandy loam soil. The capillary fringe for the water table at 105 cm was established after lowering the water level and the height of the capillary fringe is equal to approximately 7.5 cm, which is the "air-entry value". Above the capillary fringe, the moisture content decreased rapidly within 20 cm to a nearly constant value of 20%.

The moisture contents in the macropore column were similar to that in the homogeneous column for the water table depth at 105 cm (Fig. 3b). The largest difference occurred near the top of the capillary fringe, at 75 cm,

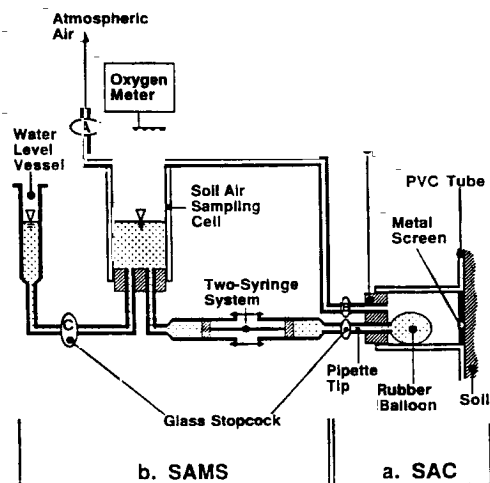


Fig. 2. Schematic diagram of soil air chamber (SAC) and soil air measurements sampler (SAMS).

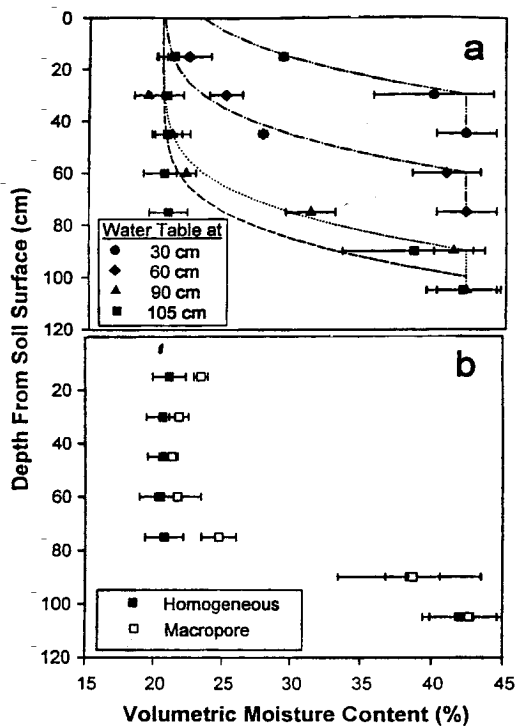


Fig. 3. Average observed (symbols) together with standard deviations for the three columns (horizontal bars) and fitted (lines) moisture contents: (a) observed and fitted moisture content measurements for the homogeneous column for water table depths at 30, 60, 90, and 120 cm; (b) comparison of moisture content for the homogeneous and macropore columns with water table at 105-cm depth.

where the macropore column was wetter. Slight differences in rainfall intensity changed the capillary fringe slightly, causing the moisture content difference. Since the macropore took up <0.3% of the pore space, and flow through the columns was unsaturated so that the largest pores did not take part in water transport, the similarity of the moisture profile was expected.

The O₂ concentration for the homogeneous column as a function of the depth from the soil surface is shown for the four water table depths in Fig. 4. The O₂ concentration at the water table in all cases is zero (not shown) because the high moisture content in the soil prevents O₂ diffusion. Surprisingly, the remaining O₂ measurements (i.e., for 15 cm and up from the water table) all fall on the same line. As expected, near the surface the O₂ concentration is the same as in the air and initially decreases linearly. For the water tables at 90 and 105 cm, the O₂ concentration became zero and the soil became anoxic at 75-cm depth.

The O₂ concentration for the water table depths of 90 and 105 cm were fitted against the one-dimensional steady-state O₂ diffusion equation with constant uptake (Kanwar, 1986; Jury et al., 1991):

$$C = C_a - \frac{\Gamma(z^2 - Lz)}{\theta \left(\frac{z}{2} - Lz\right)} \quad [1]$$

$$\Gamma = \frac{a\lambda}{D}$$

where a = rate of O₂ consumption (cm³ cm⁻³ d⁻¹), which is constant to a depth L whereafter the O₂ concentration

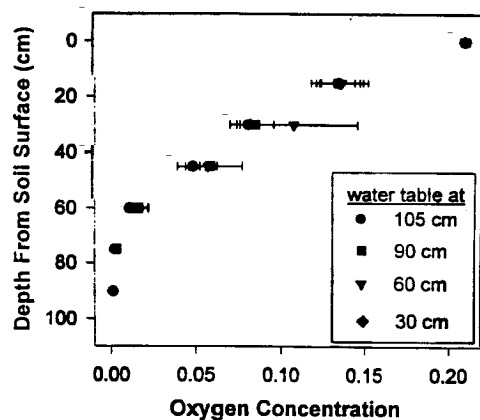


Fig. 4. Oxygen concentration (symbols) in homogeneous columns with groundwater table at depths of 105, 90, 60, and 30 cm.

and consumption is zero, $D = O_2$ diffusion in air (cm² d⁻¹), $\lambda =$ tortuosity, $\theta =$ moisture content, $C = O_2$ concentration in the soil at depth z (cm³ cm⁻³), $C_a = O_2$ concentration in the air (cm³ cm⁻³), and $z =$ vertical coordinate taken positive downward. By substituting in Eq. [1] $C = 0$, when $z = L$, we can determine Γ (a , λ , and D cannot be evaluated separately) simply as

$$\Gamma = \frac{2\theta C_a}{L^2} \quad [2]$$

By taking $\theta = 0.20$, $C_a = 0.21$, and $L = 75$ cm, we find that $\Gamma = 1.5 \times 10^{-5}$ cm⁻². In Fig. 5 the theoretical O₂ concentration is compared with the measured data points. A good fit was obtained with a R^2 of 99.6% between observed and predicted values.

In Fig. 5, the O₂ concentrations in the macropore and homogeneous columns are compared. The bar indicates the range of observed O₂ concentration at that depth for all groundwater table depths. The zero concentrations at and below the groundwater are not included. Compared with the homogeneous column, the O₂ concentrations are higher, from 30 to 90 cm at the macropore and at 10-cm radial distance from the macropore, even though the macropore was slightly wetter. From the surface

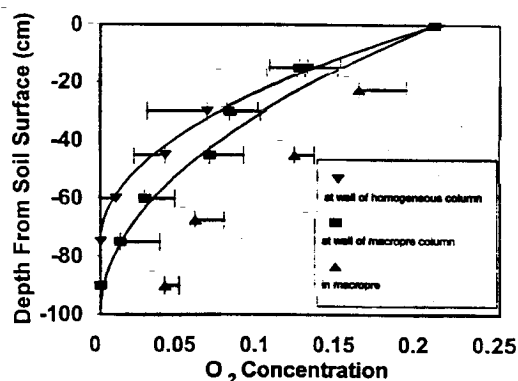


Fig. 5. Comparison of O₂ concentration as a function of the depth to the surface for all groundwater levels (symbols) near the column wall for the homogeneous and macropore columns and in the macropore for the macropore column. The symbols are the observed values. The upper line is the predicted one-dimensional O₂ profile near the wall of the homogeneous column. The lower line is the predicted profile for the macropore column.

to the 30-cm depth, the O₂ concentration between the homogeneous and macropore columns at 10 cm from the macropore were almost the same. Thus, near the surface O₂ transport through the soil surface is the most significant, while at lower depths macropores play a role in the O₂ transport process.

To confirm the different behavior of the macropore column, we again fitted the one-dimensional O₂ diffusion equation to the O₂ profile data with the water table at 90- and 120-cm depths. We found a value for $L = 100$ cm and $\Gamma = 8.4 \times 10^{-6}$ cm⁻² (which is almost two times as large compared with the homogeneous column). Also, the fit ($R^2 = 97.6\%$) is not as good as for the homogeneous column, indicating that the one-dimensional assumption is less valid for the macropore column. At the same time, it indicates more O₂ deeper in the soil profile.

This greater O₂ concentration at lower depths cannot be explained by the diffusion process only. Unlike the convective flux, which greatly depends on the portion of large pores in the soil, diffuse O₂ flow depends mainly on the air-filled porosity. Since both the moisture content for the macropore was the same (and slightly higher) and the macropore increased the porosity by only 0.3%, we did not expect to see the increase in O₂ concentration for the macropore column if diffusion was the only transport mechanism. Thus, the question of the existence of preferential flow of O₂ in soil can be answered positively. Diffuse transport is probably not the only transport mode for O₂ in the macropore column.

The results of these studies should be interpreted carefully since they were done in the laboratory and with an artificial macropore. Despite this, the study demonstrates the importance of the large pores on the depth of penetration of O₂ in the soil profile. Since the earthworm population is dependent on the type of tillage, and is much higher in no-till than under conventional tillage, no-tillage might help improve the O₂ in the soil significantly. Modeling and experimental studies should be carried out to examine this further. This study hopefully gives the impetus.

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