were blocked by the intravenous injection of barbiturates but not by electronarcosis sufficient to permit stimulation of peripheral nerves. However, preliminary experimental results indicate that larger values of current may be capable of reducing the evoked responses at the cortex (*3*).

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3 May 1963

Labeled Oxygen: Increased Diffusion Rate through Soil Containing Growing Corn Roots

Abstract. *The diffusion of oxygen labeled with oxygen-18 through cores of wet soil increased significantly when roots of growing corn seedlings penetrated the cores. The increase was small or absent when roots grew through a layer of soft wax or a layer of water-saturated 0.5-mm glass beads, indicating that the diffusion increase was a joint effect of the roots and air-filled pores in the soil. A possible mechanism is suggested.*

This report describes an unexpected effect observed while developing techniques for studying soil aeration, which entailed the use of oxygen-18. Moist Webster silty clay loam was packed into vertical Plexiglas cylinders which were then closed at both ends, leaving an air space above and below the soil (Fig. 1). Soil cores thus formed were 8.0 cm high, 7.6 cm in diameter, and had a bulk density of about 1.3 g/cm^3. A 4-cm layer of 5-mm glass beads was placed on top of the core to provide a medium in which 18 pregerminated corn seedlings (*Zea mays* var. Iowa 4570) were planted without disturbing the soil. Openings in the Plexiglas cylinder permitted the passage of equal streams of air above and below the soil core at a slow rate (3.7 ml/min). The oxygen of the upper air stream was enriched so that for every 100 atoms of O^{16} it contained about 1.2 atoms of O^{18}. The lower air stream contained O^{18} in its natural abundance—that is, 0.2 atom percent. Both air streams were produced by a special train described elsewhere (*1*). Samples were taken daily from the air streams and from the air spaces just above and below the soil for several days, during which the primary roots of the seedlings grew through the soil and emerged from the bottom of the core. The ratio of O^{18} to O^{16} in these samples was measured with a mass spectrometer.

Compartmental analysis (*2*) may be used to derive an expression for the downward rate of oxygen diffusion through the soil core. For the air space below the core,

$$a_0\rho_{10} + a_2(\rho_{12} - \rho_{r2}) - a_1(\rho_{21} + \rho_{r1} + \rho_{31}) = 0$$
$$\rho_{10} + (\rho_{12} - \rho_{r2}) - (\rho_{21} + \rho_{r1} + \rho_{31}) = 0 \qquad (1)$$

where the symbols are those defined in the legend of Fig. 1. The solution of Eq. 1 is

$$\rho_{12} - \rho_{r2} = \frac{a_1 - a_0}{a_2 - a_1}\rho_{10} \qquad (2)$$

and hereafter $\rho_{12} - \rho_{r2}$ will be referred to as ρ. Table 1 shows the values of ρ for three soil cores, together with the number of roots, R, transfixing the core, and the air-filled pores of the soil, A, at the time of sampling. Porosity was maintained at low levels by daily additions of distilled water. The value of A was determined from the weight (corrected for seedling weight) and dimensions of the core, the soil particle density (2.575 g/cm^3), and the initial moisture content (measured by oven-drying two subsamples).

Equation 3 shows the regression of ρ on the number of roots, R, and the air-filled porosity, A, as deduced by multiple-regression analysis (*3*) of the results in Table 1.

$$\hat{\rho} = -3.8 + 0.096R + 0.62A \qquad (3)$$

The regression coefficient of R is significant with a probability less than 0.025 that it is zero [$P(0) < 0.025$]. For the coefficient of A, $P(0) < 0.10$. Evidently, the presence of corn roots increased significantly the diffusion of oxygen through the soil core.

Analysis of variance showed that variation between cores was significant at the 1 percent level. Part of this variation results from different ranges of R and A for the three cores; however, part of it may result from differences in such factors as packing and soil respiration. Hence, a result of greater significance might be obtained for the regression coefficients by adjusting ρ for variation between cores. This adjustment was made by calculating $\hat{\rho}_{\bar{R},\bar{A}}$ from multiple regression analyses for each core separately, and by adjusting ρ so that $\hat{\rho}'_{\bar{R},\bar{A}} = \hat{\bar{\rho}}_{\bar{R},\bar{A}}$, where the prime indicates adjusted ρ values. Accordingly, each value of ρ for core No. 1 was adjusted by + 0.4, for core No. 2 by + 1.6, and for core No. 3 by − 2.0. The effect of this adjustment is to translate, without rotation, the separate regression planes for the cores parallel to the ρ-axis until they intersect at

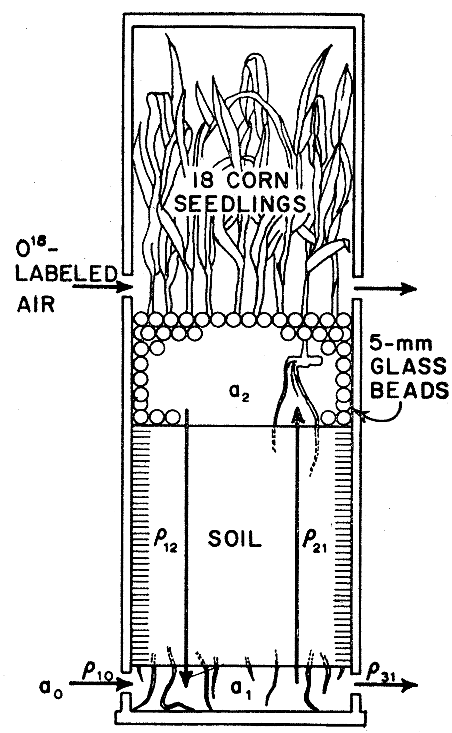

Fig. 1. Experimental container for the determination of oxygen diffusion through soil in which corn roots are growing. The symbols are defined as follows: a_0 is the ratio of O^{18} to O^{16} in the unenriched air stream; a_1 is the ratio of O^{18} to O^{16} in the air below the soil core; a_2 is the ratio of O^{18} to O^{16} in the air above the soil core; ρ_{10} is the rate of oxygen entry into space below soil; ρ_{21} is the rate of oxygen diffusion upward through the soil core; ρ_{12} is the rate of oxygen diffusion downward through the soil core; and ρ_{31} is the rate of oxygen exhaust from the space below soil. Other symbols not shown in the figure are ρ_{r1}, which is the respiratory loss of oxygen from the space below the soil caused by roots extending into this space, and ρ_{r2}, which is the respiratory loss of oxygen from ρ_{12}.

Table 1. Oxygen diffusion through three soil cores containing growing corn roots. Calculated as values of ρ (see Eq. 2).

R (No.)	A (%)	Diffusion rate (10^{-4} ml/sec) ρ	ρ'	$\hat{\rho}'$
		Core No. 1		
0	12.2	0.5	0.9	3.5
3	12.7	1.5	1.9	4.0
23	11.7	4.9	5.3	5.4
		Core No. 2		
0	10.5	2.2	3.8	2.8
0	6.5	0.2	1.8	1.1
3	7.7	0.9	2.5	1.9
6	8.0	1.6	3.2	2.3
18	9.8	4.1	5.7	4.1
35	10.1	4.4	6.0	5.8
47	8.2	2.4	4.0	6.0
58	6.6	2.8	4.4	6.3
		Core No. 3		
0	7.3	1.4	−0.6	1.5
12	9.1	5.1	3.1	3.3
21	9.9	7.7	5.7	4.4
28	10.1	9.2	7.2	5.1
31	10.7	9.0	7.0	5.6
38	10.4	9.4	7.4	6.1
		Means		
19	9.52	3.96	4.08	4.07

($\bar{\rho}_{\bar{R},\bar{A}}$, $\bar{R}$, $\bar{A}$). A new regression equation was then calculated from the ρ'.

$$\hat{\rho}' = -1.6 + 0.089R + 0.42A \qquad (4)$$

The regression coefficient of R is now significant at $P(0) < 0.005$, while the coefficient of A is still at $P(0) < 0.10$. Figure 2 shows the regression plane and deviations, $\rho' - \hat{\rho}'$. Values of ρ' and $\hat{\rho}'$ are given in Table 1.

To test the importance of the air-filled pores of the root medium for the increased diffusion of oxygen, measurements were made on two additional cores. A layer of water-saturated 0.5-mm glass beads, 1.7 cm thick, was placed below one core with an air space, from which the air could be sampled, above and below the layer. The glass beads were supported by a single sheet of tissue paper on top of a plastic screen. A 0.6-cm layer of soft paraffin wax (rosebush wax) was placed below the other soil core. The measurements of the rates of oxygen diffusion which were made as roots grew through these layers are given in Table 2. The results are not directly comparable to those in Table 1 because of differences in thickness of the soil core and the bead and wax layers; however, it is apparent that the diffusion rates are greatly reduced through the nonporous bead and wax layers. Evidently, the observed increase in the rate of oxygen diffusion through the soil cores containing roots is a joint effect of the roots and the air-filled pores in the soil.

Table 2. Oxygen diffusion through two nonporous media transfixed by corn roots. Calculated in terms of ρ (see Eq. 2).

ρ (10^{-4} ml/sec)	R (No.)
Water-saturated 0.5-mm glass beads	
0.0	0
1.2	17
0.0	48
0.0	56
0.7	65
Soft paraffin wax	
0.0	0
0.5	23
0.4	33
0.8	46
1.2	62

These data suggest that the effect of the roots on ρ occurs solely because of changes in porosity produced by removal of soil moisture during transpiration. Although not measured, transpiration was probably small because the air around the seedlings was saturated with water vapor. Nevertheless, if it is assumed that the roots were effective only because they changed the soil porosity, then the relations shown in Eq. 5 should hold approximately,

$$\hat{\rho}' = b_1A, \quad A = b_2R, \quad \hat{\rho}' = b_1b_2R \qquad (5)$$

where b_1 and b_2 are constants. From Eq. 4, $b_1 = 0.42$ and $b_1b_2 = 0.089$, from which $b_2 = 0.089/0.42 = 0.21$. The regression coefficient of A on R is b_2 and thus may also be calculated from the data in Table 1. The result is $b_2 = -0.013$ which differs in sign and magnitude from 0.21 calculated from Eq. 4. In addition, $b_2 = -0.013$ is nonsignificant with $P(0) > 0.50$. Hence Eq. 5 is not supported by the data and the effect of the roots on ρ cannot be regarded as taking place simply through changes induced in the air-filled pores of the soil.

A more probable explanation for the root effect is as follows. At the low soil porosities maintained in these experiments, most of the air-filled pores are discontinuous and nearly ineffective for oxygen diffusion. When penetrated by roots, these pores are linked up by the continuous system of air space within the root, resulting in an overall increase in oxygen diffusion. In the complete absence of air-filled pores, as in the bead and wax layers, the roots would be much less effective. Evidence for the rapid diffusion of oxygen through roots was obtained by tracer studies with O^{15} (*4*), which have shown that oxygen within the roots of broad bean, rice, and barley is near exchange equilibrium with the air around the foliage.

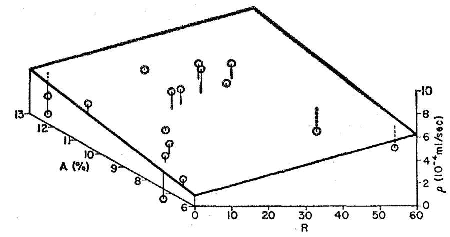

Fig. 2. The regression of ρ' on air-filled pores of the soil A and the number of primary roots R. The regression plane is $\hat{\rho}' = -1.6 + 0.089R + 0.42A$. The deviations, $\rho' - \hat{\rho}'$, are indicated by vertical lines.

Our results together with those of others (*4*) are of importance because they suggest that roots of terrestrial plants can increase the diffusion of oxygen through the soil without causing changes in the air-filled pores, and that they are not entirely dependent upon the soil for their oxygen supply (*5*).

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A Speculation on New Molecules

The remarkable discovery (*1*) of molecules containing atoms of rare gases leads naturally to the following speculation: it should, in general, be possible to create new molecules from already existing, stable molecules merely by the addition of atoms or "functional groups" by means of appropriate synthetic procedures. This concept is based on the simple observation that the usual, diamagnetic molecule, just as a rare-gas atom, has its electrons in what can be called the "perfect octets" of classical chemistry. In molecular-orbital language the molecule is said to have its electrons filling the lowest avail-