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Transient-State Oxygen Diffusion Through Undisturbed Soil Columns

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Transient-State Oxygen Diffusion Through Undisturbed Soil Columns

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ABSTRACT

The transport of oxygen from the atmosphere to the soil as a function of soil depth and time has been analyzed theoretically. Laboratory experiments were conducted to collect data on relative oxygen concentrations as a function of tillage, time, and soil depth by using two undisturbed soil columns. Data collected from these experiments were used to verify mathematical models describing the nonsteady state diffusion of oxygen into the soil. The results of this study showed that the values of relative oxygen concentrations predicted by the mathematical model compared well with the experimental data.

INTRODUCTION

Much applied research has been conducted to determine the response of plants to excessive soil-water conditions (Kanwar et al., 1988b), but less work has been done to gain a better understanding of some of the basic problems of excessive soil water as they affect plant growth. Most of the available research data indicate that excessive soil water reduces the exchange of air between the soil and atmosphere and causes oxygen deficiency. Oxygen is required by plant roots for respiration and by microorganisms for metabolic activities. Taylor (1949) found that, under certain conditions, plant roots will quickly extract the existing supply of soil oxygen; subsequently, the rate at which oxygen is supplied to plant roots depends upon the rates of transport of oxygen from the atmosphere to the soil surrounding the roots.

Movement of oxygen from the atmosphere to plant roots takes place by diffusion through air-filled soil pores and subsequently through water films separating the root surfaces from the gas phase. Buckingham (1904) reported that oxygen transport to the soil by mass flow was insignificant compared with diffusion. In a recent review, Patwardhan et al. (1988) have indicated that the convection process may significantly contribute to the aeration status of soils; whereas, Troeh et al. (1982) considered diffusion to be the most important process causing gaseous interchange between the soil and the atmosphere.

One popular method of measuring the aeration status of a soil is the oxygen diffusion rate (ODR). This is the rate at which oxygen is replenished if it is used by respiring plants or replaced by subsoil water. Buckingham (1904) was the first to apply the kinetic theory of the diffusion of gases to soil aeration. The oxygen diffusion rate of soils has been proposed by several investigators as a good index of soil aeration (Erickson, 1982; Letey et al., 1962; Stolzy and Letey, 1964). Taylor (1949) concluded that the ODR may have a more meaningful relationship to soil-water tension than to soil-water content. A number of other researchers (Currie, 1984; Kristensen and Enoch, 1964; Taylor, 1949; Van Bavel, 1952) have investigated the diffusion coefficient in soils under steady-state conditions. Stolzy and Letey (1964) collected experimental data showing a relationship between ODR and the condition of different plants as a function of soil type. They concluded that plants are more affected by low ODR than by soil type.

Though the aeration status of soils is important to plant growth, no fast, reliable method accurately measures the oxygen content of soil air in the unsaturated zone. Some methods have been developed to measure oxygen concentrations at various depths in the soil profile (Patrick, 1977; Staley, 1980). However, there is some degree of uncertainty in these methods in how well the soil-air samples really represent what plant roots encounter. Cary and Holder (1982) have developed a simple rubber membrane for measuring oxygen in soil. This paper also briefly describes a method for making oxygen measurements in saturated and unsaturated soils (Kanwar et al., 1988a).

Other factors to be considered in the measurements of the aeration status of soils are the oxygen consumption by plants and chemical and biological processes within the soil mass as a function of temperature and tillage. This rate of consumption is termed "activity." Van Bavel (1951) developed a theory of soil aeration in which he has taken into consideration, not only the partial pressure of gases and the rate of diffusion, but also the rate at which gases are consumed or liberated by the dynamic processes occurring in soils. Van Bavel (1951) and Wesseling (1962) considered a constant activity factor in the development of steady-state analytical models to express the diffusion of gases in soils.

Because steady-state conditions often are nonexistent in field soils, other workers have considered transient-state analytical models (Papendick and Runkles, 1965; Kanwar, 1986; Kowalik et al., 1979) to describe the oxygen concentration in soils from a practical point of view. None of these mathematical models has yet been verified by actual field data. Therefore, the purpose of this research was to develop and experimentally validate analytical solutions for transient-state oxygen diffusion in soils using oxygen concentration data from undisturbed soil columns.
THEORY

The partial differential equation describing the transient-state diffusion of oxygen in a soil porous media can be written as:

\[ \frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - a \] \[ \text{[1]} \]

where

- \( c \) = the concentration of oxygen in the soil air at depth \( x \)
- \( t \) = time
- \( D \) = the diffusivity of oxygen in the soil
- \( a \) = the rate of oxygen consumption by biological and chemical processes within the soil mass.

Papendick and Runkles (1965) solved equation [1] for a finite column of length \( L \) and for the initial and boundary conditions:

\[ c(x,0) = c_0 \] \[ \text{[2]} \]
\[ c(0,t) = c_0 \] \[ \text{[3]} \]
\[ \frac{\partial c(L,t)}{\partial x} = 0 \] \[ \text{[4]} \]

where

- \( c_0 \) = the oxygen concentration in the atmosphere.

Equation [2] states that at the beginning of the experiment oxygen concentration is constant throughout the soil column and is equal to the oxygen concentration in the air atmosphere. But under field situations, this kind of condition is seldom valid. Therefore, the model given by Papendick and Runkles (1965) may be modified by incorporating a more meaningful initial condition, so that initially the oxygen concentration in the soil profile is different from the oxygen concentration in the atmosphere. Kanwar (1986) used the following two conditions:

\[ c(x,0) = c_t \] \[ \text{[5]} \]
\[ c(x,0) = c_0 - ax \] \[ \text{[6]} \]

where

- \( c_t \) = the uniform initial oxygen concentration in the homogeneous soil profile, which is less than \( c_0 \)
- \( a \) = a constant.

Equation [6] states that initially the oxygen concentration in the soil profile is a function of depth, and that it decreases as the depth of soil profile increases. This initial condition can be derived from the exponential distribution given below.

\[ c = c_0 \exp(-ax) = c_0 \left( 1 - \frac{ax}{1!} + \frac{a^2x^2}{2!} - + \right) \]

If only the first two terms of the series are taken as a first approximation (the value of \( a \) will be generally small, and the values of \( a^{-2}, a^{-3}, \text{etc.} \), will be much smaller), \( c = c_0 c_0 a^{-1} x = c_0 ax \). The parameter \( a \) will be a function of physical and chemical properties of the soil (\( a = a' c_0 \)). Also, a more general solution for a semi-infinite homogeneous soil profile can be obtained by using the boundary condition.

\[ \frac{\partial c}{\partial x} = 0 \text{ as } x \to \infty, t > 0 \] \[ \text{[7]} \]

In equation [1], the assumption of constant and uniform activity \( a \) has only the merit of simplicity. If oxygen in a given soil is absorbed by biological action, then the absorption presumably will vary with time and depth. It would be unrealistic to assume that the absorption will be uniform in an extremely deep homogeneous soil (if such exists). Therefore, in such a situation, the activity \( a \) could be assumed to vary with time and can be represented as \( a(t) = m + ne^{-t} \) where \( m, n, \text{ and } k \) are constants. In this case, equation [1] becomes

\[ \frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - (m + ne^{-t}) \] \[ \text{[8]} \]

Kanwar (1986) has solved various sets of equations to simulate typical field situations. These solutions are much simpler than the lengthy Fourier transform of the earlier solutions given by Papendick and Runkles (1965, 1966). For Case 1, Kanwar (1986) assumed activity \( a \) to be uniform and constant throughout the soil profile and solved the boundary value problem governed by equations [1], [3], [5], and [7] by using the Laplace transform method (Carslaw and Jaeger, 1959) for which the following solution was obtained.

\[ c(x,t) = c_t - \alpha t + (c_0 - c_t) \text{erfc} \frac{x}{2\sqrt{Dt}} \]
\[ + \alpha \left[ \left( \frac{x^2}{2D} \right) \text{erfc} \frac{x}{2\sqrt{Dt}} - x \left( \frac{t}{nD} \right)^{1/2} e^{-x^2/4Dt} \right] \]
\[ \text{[9]} \]

For Case 2, the initial condition described by equation [6] was used. The solution was then obtained for the boundary value problem governed by equations [1], [3], [6], and [7] as:

\[ c(x,t) = c_0 - ax - \alpha t + \alpha \left[ \left( \frac{t + x^2}{2D} \right) \text{erfc} \frac{x}{2\sqrt{Dt}} - x \left( \frac{t}{nD} \right)^{1/2} e^{-x^2/4Dt} \right] \]
\[ \text{[10]} \]

For Case 3, Kanwar (1986) assumed that activity \( a \) is not constant but varies with time. Then the solution of another boundary-value problem governed by equations [3], [5], [7], and [8] was obtained as:
ho.

these PVC pipes were beveled around the outer edges to avoid any clearance between the soil and the wall of the pipe having a wall thickness of 7.5 mm. The bottoms of the laboratory for further instrumentation.

ground to a total depth of 1.05 m. At this point, a steel PVC. To obtain the undisturbed soil columns, a Procedure for Obtaining the Undisturbed Soil Column

no-till plot. Because of high soil-moisture conditions at a loss of any soil moisture and was then brought back to the atmosphere into the soil profile. The procedure for data collection (including undisturbed soil column construction and the soil-air sampling technique) is described next.

Procedure for Obtaining the Undisturbed Soil Column

Two undisturbed soil columns (254-mm diameter) were obtained from plots with different long-term tillage histories. The plots were located on a Nicollet silt-loam soil. The containers of soil columns were made of PVC pipe having a wall thickness of 7.5 mm. The bottoms of these PVC pipes were beveled around the outer edges to decrease entry resistance into the soil. The pipes were lubricated on the inside with a general purpose grease to avoid any clearance between the soil and the wall of the PVC. To obtain the undisturbed soil columns, a 1.2-m-wide ditch was dug to a depth of 1.1 m with a back hoe.

The PVC pipe was placed vertically on top of the side wall of the ditch in such a way that about 50 mm of soil thickness was left between the outer edge of the pipe and the ditch. Then a wooden plank was placed on top of the pipe. The plank was hammered with a 3.6-kg sledge-hammer slowly to press about 50 mm of pipe into the soil at a time. Then, the soil around the outer circumference of the pipe was sloughed off, and the pipe was hammered in further to a depth of 100 mm through steady hammering of the wooden plank. This procedure was continued until the PVC pipe was pressed into the ground to a total depth of 1.05 m. At this point, a steel plate was pushed across the bottom of the pipe to separate the soil column from rest of the soil mass, and the soil column was recovered. The PVC pipe containing the soil column was capped on both ends to prevent the loss of any soil moisture and was then brought back to the laboratory for further instrumentation.

Two undisturbed soil columns were collected, one from the conventionally tilled plot and another from the no-till plot. Because of high soil-moisture conditions at a depth of 0.8 m in the no-till plot, full-length soil column could not be obtained. The approximate length of the soil column from the no-tillage field was about 0.85 m. No appreciable compaction or artificial cracking or structural damage of the soil in the columns was observed during or following the collection procedure.

Column Bottom Construction

A 250-mm diameter acrylic plate of 6.35 mm thickness was used for covering the column bottom and 1-mm diameter holes were drilled in the plate at 5 mm apart over the entire area of the plate. The total area of the perforations was nearly 4% of the total cross-sectional area of this circular plate. The purpose of this perforated circular plate was to prevent collapse of the soil when the soil column was set vertically on a pedestal and to allow even distribution of the injected N₂ gas from the bottom. A fiberglass matting (a very fine, filter-like material) was placed at the bottom of the soil column; then, the perforated circular plate was placed on top of the fiberglass matting. The perforated plate was then glued along its circumference to the PVC pipe using an epoxy adhesive. The bottom of the soil column was then capped with a specially made PVC cap of 267-mm diameter and 8-mm wall thickness. This cap was sealed along its circumference with a silicone rubber caulking.

The bottom cap of the soil container included an inlet manifold for either gas or water injection. This inlet manifold was constructed using two PVC pipes (12.7 mm inside diameter and 3.2-mm wall thickness having lengths of 230 mm and 330 mm, respectively) which were connected to each other at a right angle by using a four-way tee in the center. Each pipe had four equally spaced rows of 2-mm holes along the circumference. The short pipe (230 mm long) was plugged at the ends with solid rubber-stoppers and stayed inside the cap, and the long pipe protruded from the bottom cap through the holes drilled on the opposite sides of the cap. One end of this long pipe was used to inject either N₂ gas or water, and the other end was used to extract a gas or water sample to determine oxygen concentrations at the bottom of the soil column (see Fig. 1 for details).

Cap Construction for Column Top

The top part of the soil column was capped with a PVC cap of the same dimensions as those of the bottom cap. A rubber stopper with a 4-mm diameter tube was installed in the center of the cap for the gas outlet. A floating ball flow meter was connected to the 4-mm diameter outlet tube at the top of the cap to monitor the flow rate of N₂ passing through the soil column. Figure 1 gives details of the soil column.

Soil-Air Access Chamber Installation in the Soil Column

Details of the soil-air or oxygen access chambers are illustrated in Fig. 2. These chambers were made from stainless-steel cylindrical filter screen having 1.6 slots per linear mm (i.e., 40-mesh size). The oxygen chambers were 93 mm long and 40 mm in diameter. One side of the oxygen chamber was capped with a solid No. 8 rubber stopper, and the other side was capped with a double-hole, No. 8 rubber stopper. Two flexible tubings—one of 3.13 mm diameter (and 2.38-mm wall thickness) polyethylene tubing, and the second of 1.57 mm diameter (and 0.66-mm wall thickness) polyethylene
tubing—were inserted through the two-hole stopper so as to reach to the center of the chamber. Inside the chamber, a rubber balloon (90 mm long and 34 mm in circumference) was attached to the 3.13-mm-diameter polyethylene tubing. Both rubber stoppers were then pushed tightly to close both ends of the chamber. Also, a piece of fiberglass matting was wrapped around the soil-air access chamber to prevent any movement of the soil particles into the chamber.

A hole saw was used to drill 41.33-mm diameter holes through the wall of the PVC pipe of the soil columns. For the column from the conventionally tilled field, holes were drilled at depths of 150, 300, 450, and 600 mm; whereas, for the column from the no-till plot, holes were drilled at depths of 150, 300, and 450 mm. Each soil column was placed horizontally on a wooden structure designed to keep the column stationary during the drilling. Using a soil sampling auger, we extended these holes horizontally to a length of about 150 mm. Part of the soil removed from these holes was used for soil moisture analyses.

After the holes were drilled and augered, a soil-air access chamber was inserted into each hole. The remaining length of the holes was then plugged carefully by repacking the soil. Every attempt was made to minimize disturbances of the surrounding soil when repacking. The holes in the wall of the PVC pipe were patched with a two-hole 80 x 80 mm piece of 254-mm diameter PVC pipe. These patches were glued on the wall of the column with a PVC solvent cement. Two holes in the patch were used for passing the two flexible tubes (3.13-mm polyurethane and 1.57-mm polyethylene tubing) through to the soil access chamber. A general-purpose, silicone-rubber caulking was used to seal the outer edges of the patches as well as the clearance around the two flexible tubings connected to the soil-air chamber. The balloons were then filled with water just enough to keep them from completely deflating. The end of the 1.57-mm-diameter tube, outside the chamber, was inserted into a 10-mm-long piece of polyurethane tubing, and a septum stopper was mounted on it.

Soil-Air Sampling Procedure

Soil-air sampling from various depths of the soil column to determine oxygen concentrations involved the construction of soil-air access chambers, a dual action syringe assembly, and a sample analyzing chamber. The description of the soil-air access chamber was given in the previous section of this paper.

The Syringe Assembly

The dual-action syringe assembly consisted of two, 50-ml plastic, disposable syringes. These syringes were mounted on a metal brace with needle ends opposite each other in such a way that, when the plunger of one syringe was pulled to draw air or water, the plunger of the other was pushed automatically to release an equal volume of water from the second syringe filled with water.

Soil Air Sampling

To samples soil air at the desired depth, the dual-action syringe assembly was used. One syringe was filled with water; whereas, the second one was used for taking air samples. One of the syringes was connected to the polyurethane tubing (connecting to the balloon), and the needle of the other syringe was inserted through the septum stopper of the polyethylene tubing. A 10-ml soil-air sample was withdrawn from the oxygen access chamber very slowly. As the soil-air sample was withdrawn, water from the other syringe was being injected into the balloon simultaneously. This mechanism resulted in collecting an undisturbed air sample. The 10-ml soil-air sample collected from a particular depth was the result of the equivalent volume
of air displaced due to the simultaneous inflation of the balloon.

**Analyzing Chamber**

This chamber consisted of a centrifuge tube of 27-mm inside diameter, 50 mm long, and a wall thickness of 1 mm with both ends open. The bottom of this tube was capped with No. 3 rubber stopper. A 6-mm-diameter tygon tube was inserted into the rubber stopper to release water from the centrifuge tube, and the top end of the centrifuge tube was used to insert an O₂ probe. A 10-mm-diameter hole was drilled into the centrifuge tube 20 mm from its top. A polyethylene connector (male end) was inserted into the centrifuge tube through this hole and was sealed by using an epoxy adhesive. A septum stopper (white rubber, 8-mm standard glass tubing) was mounted on the end of the connector outside the centrifuge tube.

**Soil-Air Analyses for Oxygen Concentration**

A battery-operated portable oxygen meter (Model 7932, Leeds and Northrup, North Wales, Pa.) with an oxygen probe was used to measure oxygen concentrations in the soil-air and dissolved oxygen in the water. Before and at the end of each set of measurements, the oxygen probe was calibrated against the natural atmospheric oxygen content of the air at 20.2%.

For soil-air samples samples, the centrifuge tube of the analyzing chamber was totally filled with water through the open top end. The 6-mm-diameter tygon tube, connected to the bottom of the centrifuge tube, was raised in such a way that the water elevations in the tygon tube and the centrifuge tube (filled to the top) are at the same levels. At this point, the centrifuge tube and the tygon tube were clamped to a stationary stand. The oxygen probe was inserted into the water-filled centrifuge tube from the top and pushed down firmly to establish a complete seal between the probe and the centrifuge tube; thus, no air could penetrate into the centrifuge tube. During this procedure the amount of water displaced from the centrifuge tube (which was spilled over through the 6-mm-diameter tygon tubing) was equivalent to the volume of the probe staying inside the water-filled centrifuge tube. The 10-ml air sample collected from the soil column was then injected into the centrifuge tube through the septum stopper, while the other syringe (still connected to the polyurethane tubing of the oxygen access chamber) will withdraw simultaneously an equal volume of water out of the balloon. When 10 ml of soil-air sample is injected into the centrifuge tube, an equal volume of water is displaced from the centrifuge tube (through the tygon tubing) leaving the analyzer cell of the oxygen probe exposed to soil-air. The reading on oxygen concentration was taken when the meter reading became steady. After the reading was taken, 5 ml of soil-air sample was withdrawn from the analyzing chamber and was re-injected into the soil column at the sampling depth. This procedure was repeated for each set of sampling analysis to avoid an appreciable amount of vacuum in the soil column, which could enhance the diffusion of oxygen from the column surface. The room temperature around the soil column was maintained at 20° Celsius (plus or minus one degree). All soil-air measurements were made at 20° Celsius.

**Initializing Oxygen Concentration in the Soil Column**

Nitrogen (N₂) gas, supplied from a large portable cylinder fitted with a pressure regulator and needle valve, was passed through the soil column. The N₂ gas cylinder was connected to the inlet manifold of the soil column (connected to the bottom cap of the column). Nitrogen gas was supplied at a flow rate of about 50 ml/min and was allowed to diffuse from the bottom of the soil column and pass upward through the soil. But, before the injection of nitrogen gas, a cap fitted with a floating-ball flow meter was placed at the top of the soil column to regulate the flow of N₂ gas during the establishment of the initial condition only. As nitrogen gas was moving through the column, soil air containing oxygen was being pushed out through the top outlet. On the average, the process required 24 h to replace 99% of the soil air and to bring the concentration of oxygen in the soil air to less than 1%.

To verify the mathematical solutions given by equations [9] to [11], it was essential to bring the soil column close to the initial and boundary conditions of known levels. Once steady-state conditions were established, nitrogen supply was stopped and the top column cap was removed simultaneously. The soil column was exposed immediately to the atmospheric air, and the oxygen concentrations in the soil-air, at various depths of the column, were measured over a period of 24 to 72 h. This procedure resulted in establishing known initial and fixed boundary conditions. At time t = 0 (i.e., right before stopping the nitrogen supply), oxygen concentrations in the soil column were measured at different depths to make sure that oxygen concentrations were about constant throughout the soil column. At x=0 (i.e., at the soil surface), oxygen concentration was equal to the oxygen concentration in the air atmosphere. At x = L (i.e., at the bottom of the column), \( \partial c / \partial x = 0 \) was maintained. The bottom cap (installed at the bottom of the column) was kept filled with water from a marriotte bottle so that no change in oxygen concentration took place at x = L.

The experiments were conducted by using one soil column at a time. First, the conventionally filled soil column was used to run the oxygen diffusion experiments and then the no-tillage soil column was used to run the similar experiments. Each experiment was replicated three times.

**RESULTS AND DISCUSSION**

The experimental data on oxygen concentrations in soil air as a function of time, depth, and tillage were used to verify the mathematical model proposed in this paper. To use the experimental data collected in this study, the mathematical model must use the same initial and boundary conditions as were imposed on the soil columns. Therefore, an analytical solution proposed by equation [9] was used as a mathematical model for verification inasmuch as this model uses about the same initial and boundary conditions as were imposed on the soil columns during the period of data collection. The verification of this model requires the values of a, cᵢ, cₒ, and D. The oxygen concentration in the air atmosphere c₀ is known. The values of cᵢ (initial oxygen concentrations in the soil column) were measured and are given in Table 1. For simplicity, the activity factor α
TABLE 1. Oxygen diffusion coefficients and other experimental data

<table>
<thead>
<tr>
<th>Depth of Soil Profile, mm</th>
<th>Conventional Tillage Soil Column</th>
<th>No-till Soil Column</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vol. B.D.* M.C.* D(R²)* SE* cₜ*</td>
<td>Vol. B.D.* M.C.* D(R²)* SE* cₜ*</td>
</tr>
<tr>
<td>0-150</td>
<td>1.46 26.3 248.99 0.027 0.8 1.43 3.86 125.99 0.026 1.0</td>
<td></td>
</tr>
<tr>
<td>150-300</td>
<td>1.36 19.0 166.98 0.021 0.9 1.36 27.4 94.98 0.033 1.0</td>
<td></td>
</tr>
<tr>
<td>300-450</td>
<td>1.30 19.4 166.97 0.029 0.9 1.30 23.6 109.98 0.028 1.0</td>
<td></td>
</tr>
<tr>
<td>450-600</td>
<td>1.37 22.9 216.96 0.034 0.8 1.37 26.0 — —</td>
<td></td>
</tr>
</tbody>
</table>

*B.D. = Bulk density, Vol. M.C. = volumetric soil moisture content, D(R²) = oxygen diffusion coefficient with R² values in the parentheses, SE = standard error, cₜ = initial concentration of oxygen in the soil profile.

†Average of three replications and D values are for 0-150, 0-300, 0-450, and 0-600 mm deep soil profiles, respectively.

was assumed to be zero for all experimental runs during the study period. The reason for making this assumption was that in a short period of 24 to 48 h, the overall effect of α on the transport of oxygen from the atmosphere to the soil column will be almost insignificant. The diffusion coefficient D was determined by using the data collected at the conclusion of the oxygen diffusion run. A computer program was written to calculate the value of D at which the deviation between the observed values of relative concentration (c/c₀) from the experiment and the computed value of c/c₀ by equation [9] was minimal. This program was used to calculate the values of D for each depth profile (i.e., 0-150, 0-300, 0-450, 0-600 mm). The calculated values of D for various depth profiles are given in Table 1.

The data on oxygen diffusion coefficients (D) as a function of soil-moisture content, soil depth, and tillage are presented in Table 1. Higher values of D were observed under conventional tillage at all depths when compared with the no-tillage D values. Also, D values change with depth. The largest value of D was observed in the surface layer (0 to 150 mm). The D values decrease with depth until 300 mm and increase again after 300 mm depth. The significant decrease in the D values for the 0-150 and 0-300-mm soil profiles could be due to the presence of a plow layer or compaction. Much lower values of D at all depths under no-tillage conditions are affected because of higher soil-moisture conditions.

Figure 3 shows the experimental data for c/c₀ in the soil column (collected from the conventionally tilled field) at various depths as a function of time. The continuous lines in this figure show the data for c/c₀ as predicted by the mathematical model (equation [9]). This figure shows that the values predicted by the mathematical model are in good agreement with the measured data. The best agreement is seen at the depth of 150 mm. The deviation between the measured and predicted c/c₀ becomes progressively greater with increasing depth. This deviation could be due to some of the assumptions made in the formulation of the boundary-value problem. The apparent diffusivity of oxygen D in the soil-air was calculated by assuming that activity α was equal to zero. In spite of some of these assumptions, the values of coefficient of determination (R²), were 0.99, 0.98, 0.97, and 0.96 for depths of 150, 300, 450, and 600 mm, respectively. The values of standard error were 0.027, 0.021, 0.029, and 0.034 for depths of 150, 300, 450, and 600 mm, respectively.

Figure 4 shows the comparison between the measured and predicted data for c/c₀ at three depths of the soil column under no-tillage conditions. Again, the best agreement between the measured and computed values

Observed Vs Predicted Rel.Oxygen Conc.

![Graph showing the relationship between the theoretical and measured values of relative oxygen concentration as a function of time and depth (under conventional tillage at 20°C).](image)

Fig. 3—Relationship between the theoretical and measured values of relative oxygen concentration as a function of time and depth (under conventional tillage and at 20°C).
of $c/c_0$ was obtained at the 150-mm depth with $R^2$ value of 0.99. The $R^2$ values for the 300- and 450-mm depths were 0.98 and 0.98, respectively. However, on the average, the results of this study showed that the mathematical analysis of the oxygen diffusion process compared well with the experimental data and that the model presented in this paper could be used satisfactorily to predict the relative oxygen concentrations in the soil profile above the water table if data on oxygen diffusion coefficients were available.

CONCLUSIONS

This study resulted in the following conclusions.

1. The mathematical model presented in this paper can be used to determine the relative oxygen concentrations in the soil profile for any time, if the values of the oxygen diffusion coefficients are known. The verification of the model has been supported by comparing the results with the experimental data.

2. The apparent diffusivity of oxygen in soils seems to have a major effect on the transport of oxygen through the soil profile. The diffusivity of oxygen needs to be determined for each soil depth as a function of temperature and soil water content.

3. The soil moisture can have a major effect on the oxygen status of soils under certain field conditions.

References