

## Oxygen Diffusion Rate

Air and water comprise a large part of the soil. For an average soil, air and water take up 50% of the space (Figure 12.1). Organic matter and mineral matter take up the other 50%. At optimum moisture content for plant growth, the air and water spaces are about equal, each about 25% of the soil volume (Kirkham and Powers, 1972, p. 1). With so much of the soil volume taken up by air and water, it is obvious that air and water play a major part in soil and plant–water relations.

We have looked at methods to measure the soil-water matric potential (tensiometers and pressure plates; see Chapter 5) and to measure mechanical impedance (penetrometers; see Chapter 11). In this chapter, we look at the most widely used method to monitor aeration status of the soil, the oxygen diffusion rate (ODR) method.

### 12.1 THE OXYGEN DIFFUSION RATE METHOD

Respiration by plant roots depends on soil oxygen. Roots, like animals, do not photosynthesize, and they give off carbon dioxide and take in

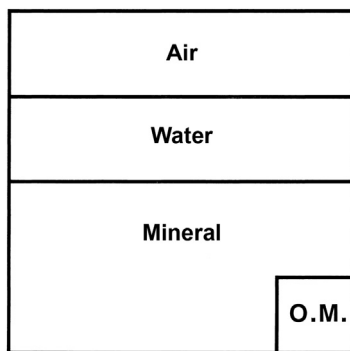


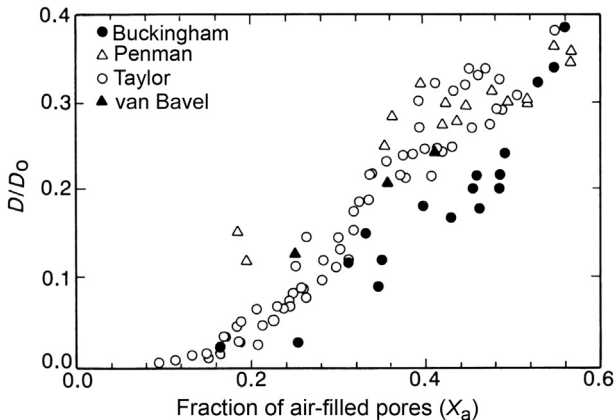
FIGURE 12.1 Space in a soil. O.M. stands for organic matter. From *Kirkham and Powers (1972)*. This material is used by permission of John Wiley & Sons, Inc. and William L. Powers.

oxygen during respiration. Diffusion of gases in the soil practically stops when the fraction of air-filled pores is less than 10% (Wesseling and van Wijk, 1957, p. 468) (Figure 12.2). Therefore, roots need at least 10% by volume air space in the soil to survive (Kirkham, 1994).

Evaluation of the aeration conditions at the interface between the root and the soil systems presents the greatest possibility of defining the influence of aeration on plant growth (Phene, 1986). In the process of respiration, plants quickly take up the oxygen surrounding the roots in the rhizosphere, and an increasing oxygen concentration gradient develops between the soil atmosphere and the atmosphere next to the root surrounded by the water film. Movement of oxygen from the atmosphere to a respiring root involves diffusion through the following three phases (Lemon and Erickson, 1952):

1. The gaseous phase of the soil;
2. The gas–liquid phase boundary; and
3. The liquid phase of the water film around the root.

Because the diffusion coefficient of oxygen in water is about  $2.4 \times 10^{-5} \text{ cm}^2/\text{s}$  and the diffusion coefficient of oxygen in air is about  $1.8 \times 10^{-1} \text{ cm}^2/\text{s}$ , the limiting factor for this transport of oxygen is usually the diffusion rate through the water film rather than through the gas-filled pore space (Phene, 1986). (We can check out how fast one gas diffuses through another by spilling ammonia, for example, in a back corner of a



**FIGURE 12.2** Scatter diagram of the relation between the ratio  $D/D_o$  and the fraction of air-filled pores  $x_a$  calculated from data of Buckingham (1904) (closed circles), Penman (1940) (open triangles), Taylor (1949) (open circles), and van Bavel (1952) (closed triangles).  $D_o$  is the coefficient of diffusion of  $\text{CO}_2$  in still air.  $D$  is the coefficient of diffusion of  $\text{CO}_2$  in the soil. If  $x_a$  decreases to 0.1 to 0.2,  $D$  appears to become zero. From Wesseling and van Wijk (1957). Reprinted by permission of the American Society of Agronomy.

large lecture hall. The speaker would smell the ammonia within a matter of seconds.)

When we are considering oxygen diffusion through air, we need to know the components of air, which are given in [Table 12.1](#) ([Weast, 1964](#), p. F-88). Air contains 20.946% oxygen.

In view of these concepts, a method to measure the ODR through the liquid phase to a reducing surface approximating that of the plant root should be useful for assessment of soil aeration ([Phene, 1986](#)). And, indeed, the ODR method is the best index of oxygen availability for plant roots in soil ([Gliński and Stepniewski, 1985](#), p. 189). Direct measurement of the concentration of oxygen in the soil is insufficient to describe plant reactions, as its availability to plants is dependent on other factors ([Stepniewski et al., 2005](#), p. 52), such as the thickness of the liquid layer surrounding the root. The ODR method is advantageous because it simulates a root in the soil. Also, it is easier to measure ODR than the oxygen

TABLE 12.1 Components of Atmospheric Air (Exclusive of Water Vapor)

Constituents	Percentage	Parts per Million <sup>1</sup>
N <sub>2</sub> (nitrogen)	78.084	
O <sub>2</sub> (oxygen)	20.946	
CO <sub>2</sub> (carbon dioxide) <sup>2</sup>	0.033	
Ar (argon) <sup>3</sup>	0.934	
Ne (neon)		18.18
He (helium)		5.24
Kr (krypton)		1.14
Xe (xenon)		0.087
H <sub>2</sub> (hydrogen)		0.5
CH <sub>4</sub> (methane)		2
N <sub>2</sub> O (nitrous oxide)		0.5

<sup>1</sup>1% = 10,000 ppm.

<sup>2</sup>The concentration of carbon dioxide is increasing in the atmosphere at a rate of 1–2 ppm/year and has been doing this since the 1980s. This increase is not noted in the 2013–2014 Handbook of Chemistry and Physics ([Haynes, 2013](#)), which lists the components of air as above, except the concentration of oxygen is given as 20.9476% and that of CO<sub>2</sub> as 314 ppm or 0.0314%, a value even lower than that in the 1964 handbook (see above; 330 ppm or 0.033%). The concentration of CO<sub>2</sub> in the air in 2012 was 392.6 ppm ([Hall et al., 2013](#)).

<sup>3</sup>Argon, neon, helium, krypton, and xenon are inert gases in Group VIIIA of the periodic table. The sixth element in this group is radon, which is of environmental concern because it is toxic. It is a radioactive gaseous chemical element formed, together with alpha rays, as a first product in the atomic disintegration of radium and used in the treatment of cancer. It is produced naturally in the ground in some regions of the United States and can build up in basements. Homes need to be checked to make sure that they do not have radon.

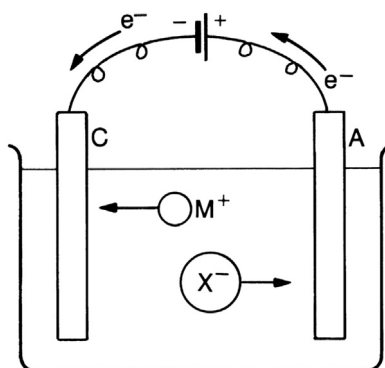
Numbers come from [Weast \(1964\)](#), p. F-88.

concentration in the soil. [Feng et al. \(2002\)](#) evaluated soil aeration criteria by examining the relationships between ODR and soil–water potential, soil–water content, air-filled porosity, and gas diffusion rate. They concluded that ODR, which mimics the oxygen supply to the root surface, should be used instead of the other measures to evaluate soil aeration status. In the ODR method, developed by [Lemon and Erickson \(1952\)](#), we use a platinum (Pt) microelectrode to simulate the root in an electrolytic solution (the soil water with its dissolved solutes).

## 12.2 ELECTROLYSIS

Because we are dealing with an electrolytic solution, we need to understand electrolysis ([Figure 12.3](#)). Electrolysis is defined as the decomposition into ions of a chemical compound in solution by the action of an electric current passing through the solution. In electrolysis, we have the electrolytic solution, an anode, a cathode, and a battery. Electrons flow from the positive terminal, the anode, to the negative terminal, the cathode. The anode is defined as a positive electrode or positive terminal of an electric source. The cathode is defined as the negative pole or electrode of an electrolytic cell. (*Anode* comes from the Greek *anodos*, meaning “a way up”, which comes from *ana*, which means “up”, and *hodos*, which means “way”. *Cathode* comes from the Greek *kathodos*, going down, which comes from *kata-*, which means “down”, and *hodos*, which means “way”.)

Anions, which are negatively charged, are attracted to the anode, and cations, which are positively charged, are attracted to the cathode. The



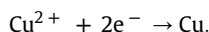
**FIGURE 12.3** Electrolysis. A = anode; C = cathode; battery at top;  $X^-$  = anion;  $M^+$  = cation. Reduction occurs at cathode. From [Sienko and Plane \(1957\)](#). This material is reproduced with permission of The McGraw-Hill Companies.

chemical in a solution, therefore, can be separated into its components (anions going to the anode; cations going to the cathode), if an electrical current passes through the solution. In the ODR method, the root is going to be simulated by a Pt microelectrode, which is the cathode. The root (Pt microelectrode) is a reducing surface. At the cathode, reduction takes place. At the anode, oxidation takes place. Reduction is the gain of electrons, and “to reduce” means to remove  $O_2$  from. In oxidation, there is a loss of electrons.

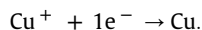
We now need to review the laws of electrolysis. Michael Faraday (1791–1867) (see Appendix for his biography), an English chemist and physicist, who is best known for discovering electromagnetic induction, formulated the laws of electrolysis, which are as follows (Schaum, 1961, p. 169).

### 12.2.1 Faraday's Laws of Electrolysis

1. The mass of a substance liberated or deposited at an electrode is proportional to the quantity of electricity (i.e., to the number of coulombs) that has passed through the electrolyte. The coulomb is named after Charles Augustin de Coulomb (1736–1806), a French physicist. A coulomb is a unit for measuring the quantity of an electric current. It is the amount of electricity provided by a current of one ampere flowing for one second; one ampere = one coulomb per second; in symbols,  $I$  (ampere) =  $q$  (coulomb)/ $t$  (second).
2. The masses of different substances liberated or deposited by the same quantity of electricity are proportional to their equivalent weights. The equivalent weight of an element is its atomic weight divided by its valence. Thus, the equivalent weight of copper is half of its atomic weight for the electrolysis of solutions containing  $Cu^{2+}$ , because the reaction at the cathode is



If a solution of  $Cu^{+}$  were electrolyzed, the equivalent weight of copper would be the same as the atomic weight, because only one electron would be involved in the electrode reaction:



When the equivalent weight of a substance is expressed in grams, it is called the *gram-equivalent weight*.

One *faraday*, or 96,500 coulombs, is the quantity of electricity that will deposit one gram-equivalent weight of any substance. Thus, the mass  $m$  in grams of any substance liberated in electrolysis is

$$m = \text{gram} - \text{equivalent weight} \times \text{number of faradays transferred.}$$

### 12.3 MODEL AND PRINCIPLES OF THE ODR METHOD

Let us now consider the model that is assumed in the ODR method (Figure 12.4) (Phene, 1986, p. 1139). As noted, a cylindrical Pt microelectrode simulates the root. Around it are soil particles and the water film, which is right up against the root. The radius of the root (Pt microelectrode) is  $a$  and the radius of the root plus the water film is  $b$ , so the thickness of the water film is the length  $(b - a)$ .

The governing equations are as follows (Phene, 1986, his Eqn 5):

$$Q/(At) = (D_e c_2)/[a(\ln b - \ln a)] \quad (12.1)$$

where

$Q$  = amount of oxygen flowing to root (g)

$A$  = surface area of electrode ( $\text{cm}^2$ )

$t$  = time (s)

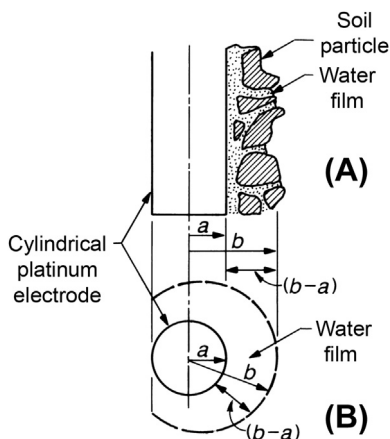
$D_e$  = effective diffusion coefficient of oxygen through the medium surrounding the electrode ( $\text{cm}^2/\text{s}$ )

$a$  = radius of root (or of the microelectrode) (cm)

$b$  = radius of root (or of the microelectrode) + water film (cm)

$c_2$  = concentration of oxygen at the liquid–gas interface (radius =  $b$ ) ( $\text{g}/\text{cm}^3$ )

We note that there is no  $c_1$  in the equation, and this is because  $c_1$ , the concentration of oxygen at the root surface or at the Pt microelectrode, is considered to be zero, which we shall see later.



**FIGURE 12.4** The model that is assumed in order to explain microelectrode behavior. (A) Particles and solution separating the electrode from gas-filled pores. (B) Coaxial cylindrical model with water film of mean thickness  $(b-a)$ . From Phene (1986). Reprinted by permission of the American Society of Agronomy.

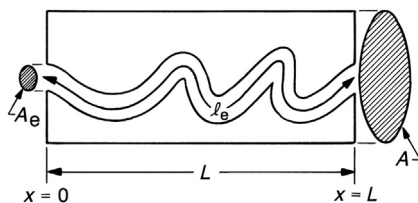


FIGURE 12.5 Diffusion model relating the actual path length ( $l_e$ ) and area ( $A_e$ ) to the block length ( $L$ ) and cross-section ( $A$ ). From Troeh et al. (1982). Reprinted by permission of Elsevier, Amsterdam.

$D_e$  is dependent on the properties of the soil medium surrounding the microelectrode.

$$D_e = D_o \theta (L/L_e)^2 \quad (12.2)$$

where

$D_o$  = the diffusion coefficient of oxygen through pure water

$\theta$  = fraction of the surface area of the microelectrode covered with water as opposed to solid

$L/L_e$  = tortuosity factor of the diffusion path

Troeh et al. (1982) illustrate the effect of tortuosity on diffusion (Figure 12.5). An oxygen molecule must move through the tortuous (twisted) paths of pores in the soil, which is the length  $L_e$  (or  $l_e$ , as shown by Troeh et al., 1982). The length of the way that the crow flies is  $L$ . The tortuosity factor, therefore, is  $L/L_e$  (a ratio and dimensionless).

If the electrical potential of the Pt microelectrode is lowered with respect to a reference electrode (the potential at the reference electrode is known), the oxygen at the microelectrode surface is reduced electrolytically until the oxygen concentration at the surface is zero. The reduction rate and the diffusion rate of oxygen are equal. They must be independent of the voltage. Experimentation shows that the current is independent of the voltage when the applied electrical potential (volts) is between 0.3 and 0.7 V (Figure 12.6). In this range, the current is independent of the voltage and a function only of the diffusion rate of oxygen to the microelectrode surface.

The resulting electrical current is expressed as follows:

$$i = nFAf_{a,t} \quad (12.3)$$

where

$i$  = current ( $\mu\text{A}$ )

$n$  = the number of electrons required to reduce one molecule of oxygen ( $n = 4$ )

$F$  = Faraday constant ( $F = 96,500 \text{ C/mol of oxygen}$ , where C = coulomb)

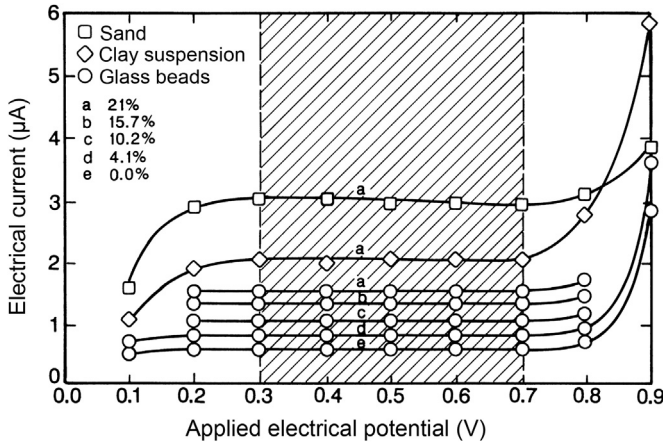


FIGURE 12.6 Electrical current–voltage relations for water-saturated media: open squares, sand; open diamonds, clay suspension; open circles, glass beads 18  $\mu\text{m}$  median diameter. Letters a–e refer to concentration of  $\text{O}_2$  in equilibrium with saturating solution. From *Phene* (1986). Reprinted by permission of the American Society of Agronomy.

$A$  = surface area of the microelectrode

$f_{a,t}$  = flux of oxygen at the surface of the microelectrode of radius  $a$  at time  $t$

The oxygen flux ( $f_{a,t}$ ) is calculated by measuring the steady state current ( $i$ ) after 4 or 5 min, assuming that the rate of oxygen reduction is limited by the rate of oxygen diffusion and equal to it. The transport is strictly a diffusion process.

$$\text{ODR} = f_{a,t} = (iM)/(nFA) = \left[ D_o \theta (L/L_e)^2 c_2 \right] / [a(\ln b - \ln a)] \quad (12.4)$$

where  $M$  = molecular weight of oxygen ( $M = 32 \text{ g/mol}$ ) and is inserted to convert the units from moles to grams.

Substitution of the values for  $M$ ,  $n$ , and  $F$  into Eqn (12.4) gives

$$\text{ODR} = C(i/A) \mu\text{g}/\text{cm}^2/\text{min} \quad (12.5)$$

where  $\text{ODR}$  = oxygen diffusion rate ( $\mu\text{g}/\text{cm}^2/\text{min}$ )

$$C = (M60)/(nF) = 0.00497 \mu\text{g}/\mu\text{A}/\text{min}, \quad (12.6)$$

where  $A$  is the SI symbol for ampere ( $A$  does not stand for area, as we defined it above).

The 60 is used to convert from seconds to minutes. Remember one coulomb per second is an ampere:

$$(q/t) = I \text{ where } q = \text{coulombs}; t = \text{seconds}; \text{ and } I = \text{amperes.}$$



Or we can write

$$\begin{aligned}\text{ODR}(\mu\text{g}/\text{cm}^2/\text{min}) &= (60Mi)/(nFA) = (60 \times 32 \times i)/(4 \times 96,500) \times A \\ &= 0.00497(i/A)\end{aligned}\tag{12.7}$$

where  $i$  is the current and  $A$  is the surface area of the microelectrode.

Equation (12.5) or (12.7) includes all physical factors that affect the ODR to a single root of constant dimensions similar to that of the Pt microelectrode.

## 12.4 METHOD

For many years (c.1980–2010) in the United States, ODR was determined by using a commercially available soil oxygen diffusion ratemeter available from Jensen Instruments (Tacoma, WA, USA). Jensen Instruments no longer sells the ratemeter as one of its supplies. However, one can construct the equipment based on instructions in the literature (Powers and Kirkham, 1965, pp. 72–73; Farrell et al., 2002). The equipment is easy to make (Witold Stępniewski, personal communication, August 30, 2006, builds the ODR equipment used in his laboratory). The Jensen Instruments Pt microelectrodes have a length of 4.0 mm and a diameter of 0.65 mm. The formula given in Eqn (12.7) then reduces to

$$\text{ODR} = 0.059i(\mu\text{g}/\text{cm}^2/\text{min}).\tag{12.8}$$

The ODR measurement system consists of the following components (Figure 12.7):

1. The platinum microelectrode (the cathode)
2. The Ag–AgCl half-cell (reference electrode)
3. The anode (Jensen Instruments has a brass anode)
4. The electrical circuit
5. A milliammeter to measure the output current.

Oxidation potentials are available from the literature (for example, see Sienko and Plane, 1957, pp. 600–601), so we know the potential of the reference Ag–AgCl half-cell.

Any spatial arrangement or maximum distance among the three electrodes (cathode, anode, and reference electrode) is permissible, as long as they all contact the same body of soil water. That is, there must be an electrically conductive pathway among electrodes in the soil (Jensen Instruments, 1987). For example, one could not do a split-root experiment, with a root system split between two boxes of soil, and put, say, two electrodes in one soil box and one electrode in the other box. The

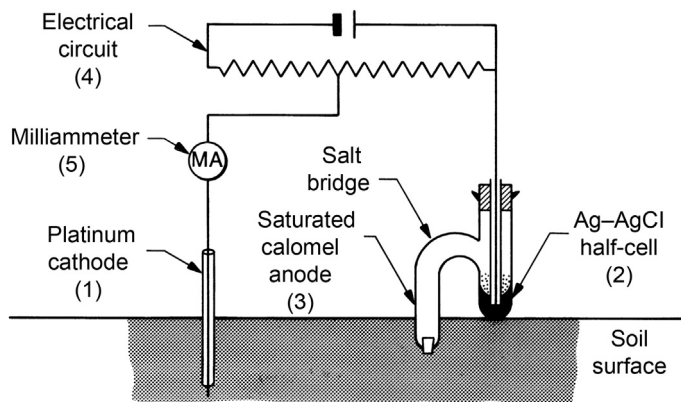


FIGURE 12.7 Diagram of apparatus used to make in situ soil measurement of  $O_2$  diffusion. From [Phene \(1986\)](#). Reprinted by permission of the American Society of Agronomy.

electrolytic solution (the soil water with its dissolved ions) must be in common contact with all three electrodes.

Measurements need to be made at the same voltage. A voltage of 0.65 V relative to a Ag–AgCl reference electrode has become a fairly standard voltage for ODR measurements ([Jensen Instruments, 1987](#)). The initial current following application of the selected voltage (0.65 V) will be high and will decrease rapidly as oxygen in the immediate vicinity of the microelectrode is depleted. As the current decreases, the rate of decrease will lessen, and the current will tend toward an equilibrium with the rate of oxygen diffusion to the electrodes. After 4 or 5 min, the rate of decrease of the current will be small enough that the current can be observed with sufficient accuracy. The current then is read out on the display. The measurements are simple, and a technician easily can be trained to take the readings. However, they are tedious to take because one needs to wait 4–5 min between each reading.

Let us assume that we measure a current of  $7.94 \mu\text{A}$  with the Jensen Instrument. What is the ODR? Using [Eqn \(12.8\)](#), we find

$$0.059(7.94) = 0.468 \mu\text{g}/\text{cm}^2/\text{min}.$$

We wish to compare this value with others in the literature. We look at values given by [Gliński and Stepniewski \(1985\)](#) in their Figure 20 on page 80 ([Figure 12.8](#)). The figure is reproduced by [Stepniewski et al. \(2005, p. 52\)](#). On their ordinate, they give units in  $\mu\text{g } O_2/\text{m}^2/\text{s}$ ;  $50 \mu\text{g } O_2/\text{m}^2/\text{s} = 0.3 \mu\text{g}/\text{cm}^2/\text{min}$ ;  $100 \mu\text{g } O_2/\text{m}^2/\text{s} = 0.6 \mu\text{g}/\text{cm}^2/\text{min}$ ; and  $150 \mu\text{g } O_2/\text{m}^2/\text{s} = 0.9 \mu\text{g}/\text{cm}^2/\text{min}$ . So our value of  $0.468 \mu\text{g}/\text{cm}^2/\text{min}$  falls within values they give, and, consequently, seems reasonable. [Stepniewski et al. \(2005, p. 52\)](#) say that ODR values in soils usually vary within the range from 0 to  $200 \mu\text{g}/\text{m}^2/\text{s}$ .

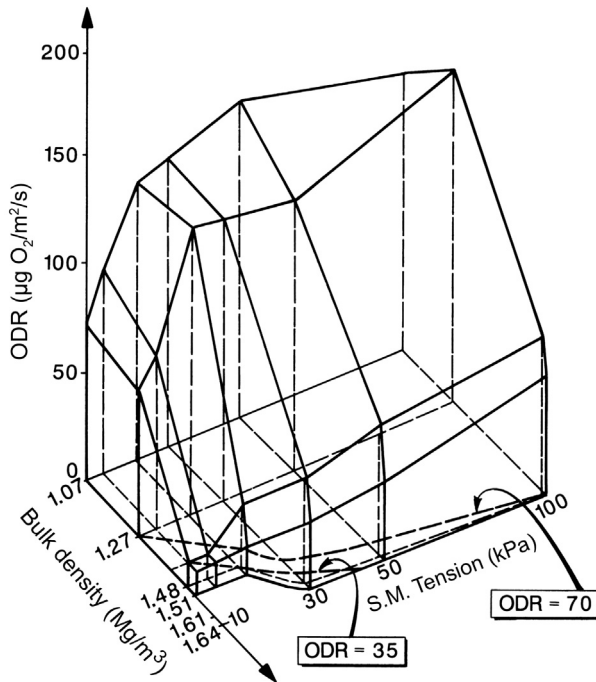


FIGURE 12.8 Oxygen diffusion rate versus bulk density and soil moisture tension in a loamy textured black earth. From Gliński and Stepniewski (1985). Reprinted by permission of CRC Press.

We can also compare our value with those presented by Huang et al. (1998), who studied the effect of temperature and aeration status on creeping bent grass (*Agrostis palustris* Huds.) grown in sand and fritted clay in polyvinyl tubes in a growth chamber. Plants were grown under two temperature regimes (22/15 °C day/night and 35/25 °C day/night) and two soil aeration treatments, a well-aerated one in which the soil oxygen status was maintained at a sufficient level ( $\text{ODR} = 1.5 \mu\text{g}/\text{cm}^2/\text{min}$ ) and an overwatered one in which ODR was maintained at a hypoxic level of about  $0.2 \mu\text{g}/\text{cm}^2/\text{min}$  (Figure 12.9). Our ODR value of  $0.468 \mu\text{g}/\text{cm}^2/\text{min}$  again falls within the range of values reported by Huang et al., so we can be reassured that our value is reasonable.

For the factors affecting ODR measurements, see Phene (1986, pp. 1145–1150). Only one factor will be mentioned here: electrode poisoning. This expression is used to indicate anything that can happen to the electrodes other than breakage. Most often, poisoning results from a chemical deposit that changes the characteristics of the Pt surface. Rickman et al. (1968) studied two of the phenomena that cause electrode poisoning: (1) oxide plating at the Pt tip; and (2) the magnitude and nature of the

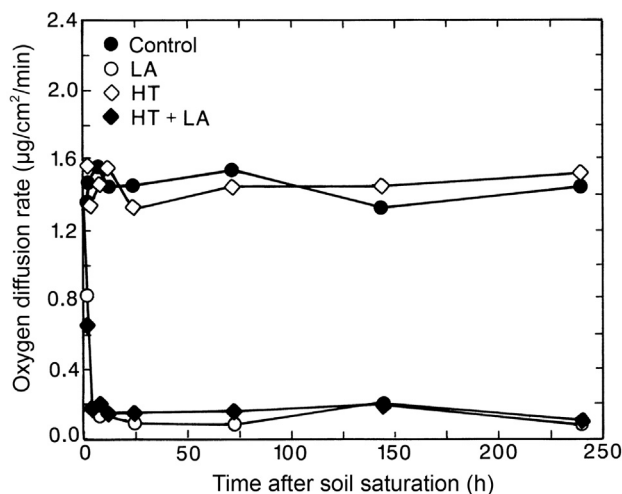


FIGURE 12.9 Soil aeration status for creeping bent grass expressed as oxygen diffusion rates during the experimental period in the well-aerated and optimum temperature treatment (control), low aeration (LA) treatment, high temperature (HT) treatment, and combination of high temperature and low aeration treatments (HT + LA). From [Huang et al. \(1998\)](#). Reprinted by permission of the Crop Science Society of America, Madison, Wisconsin.

poisoning affecting electrodes installed for periods of 4 weeks or more in different soils. They found that salts (principally calcium bicarbonate) and clay particles (principally biotite) were deposited on Pt microelectrodes left in place in a loamy sand for 2 months, and reduced the ODR by an average of 50% when compared to ODRs from periodically reinserted electrodes in the same soil. [Devitt et al. \(1989\)](#) show excellent pictures of electrodes that have been poisoned.

## 12.5 APPENDIX: BIOGRAPHY OF MICHAEL FARADAY

Michael Faraday (1791–1867), who according to [Cajori \(1929, p. 240–245\)](#) was the greatest experimentalist of the nineteenth century in the field of electricity and magnetism, was born on September 22, 1791, at Newington, Surrey, which later became part of the borough of Southwark in south London, but was then in the country. He was the son of a blacksmith. His family was often penniless, sometimes hungry, and his father died before he turned 19 ([Morrison, 1991](#)). He, himself, would have said that he was a “natural philosopher” instead of a physicist and chemist ([da Costa Andrade, 1971](#)). “My education”, he said, “was of the most ordinary description, consisting of little more than the rudiments of reading, writing, and arithmetic at a common day-school. My hours out of school were passed at home and in the streets” ([Cajori, 1929](#)).

In 1804, he served as errand boy at a bookstore and bookbindery near his home. The following year, when he was 14 years old, he became an apprentice to the bookbinder. At that time he liked to read scientific books, which happened to pass through his hands. "I made such simple experiments in chemistry," he said, "as could be defrayed in their expense by a few pence per week, and also constructed an electrical machine" (Cajori, 1929). At the age of 19 years he sometimes in the evening attended lectures given by a Mr Tatum on natural philosophy, his brother paying the admission fee for him. In 1812, he had the good fortune to hear four lectures delivered at the Royal Institution by Sir Humphry Davy, the great English chemist (1778–1829).

About this time, Faraday started to work as a journeyman bookbinder for a Frenchman in London. His new work was uncongenial. "My desire", he said, "to escape from trade, which I thought vicious and selfish, and to enter into the service of science, which I imagined made its pursuers amiable and liberal, induced me at last to make the bold and simple step of writing to Sir H. Davy, expressing my wishes, and a hope that if an opportunity came in his way he would favor my views; at the same time, I sent the notes I had taken of his lectures" (Cajori, 1929). Davy replied, "I am far from displeased with the proof you have given me of your confidence...." Faraday became Davy's assistant at the Royal Institution in 1813. In the autumn of that year, Davy and his wife started on a tour abroad, Faraday going with them as amanuensis. Even though Faraday had many menial duties to perform on this trip, he saw much of the active scientific research in Europe, and the trip expanded his view. "His University was Europe; his professors the master whom he served, and those illustrious men to whom the renown of Davy introduced the travellers" (da Costa Andrade, 1971).

After being with Davy in France, Italy, and Switzerland, he returned to the Royal Institution in 1815. Soon after his return he began original researches, and published his first paper in 1816. He also began to lecture before the City Philosophical Society. In a letter he wrote about "the glorious opportunity I enjoy of improving in the knowledge of chemistry and the sciences with Sir H. Davy". In 1821, in his 30th year, Faraday married and brought his wife to his rooms at the Royal Institution, where they lived together for 46 years. They had no children. In 1824, he was elected member of the Royal Society at a time when Davy was its president, in spite of Davy's jealous opposition to Faraday's election (Cajori, 1929). In 1823, Faraday had liquefied chlorine, which aroused the jealousy of Davy, who considered that he had initiated the work and was entitled to the credit (da Costa Andrade, 1971). Nevertheless, Faraday always spoke with respect and admiration for the talents of the man who had done so much to start him in his early scientific career (Cajori, 1929).

In 1825, Faraday made a chemical discovery of the first importance by isolating benzene from a liquid obtained in the production of oil gas (da Costa Andrade, 1971). In that same year Faraday's position at the Royal Institution was improved by his promotion to the post of director of the laboratory. The next year he began to give formal lectures for the members of the Institution on Friday evenings, and those Friday evening discourses have continued ever since (da Costa Andrade, 1971). He also initiated the Christmas lectures for young people, known formally as Christmas Courses of Lectures Adapted to a Juvenile Auditory, of which he himself gave 19 courses. As an inspiring lecturer and deviser of effective lecture experiments Faraday was supreme, and there are many contemporary accounts of the interest and enthusiasm that his discourses aroused.

Faraday's conceptions of electric and magnetic force and their interrelations, expressed in terms of his lines of force, were fundamental. It was from them that James Clerk Maxwell (Scottish physicist, 1831–1879) developed his equations and the concept of electromagnetic waves, which lie at the base of all modern theories of electromagnetic phenomena (da Costa Andrade, 1971).

Cajori (1929, pp. 244–245) says:

Faraday's first magnetoelectric apparatus, the forerunner of the dynamo, produced such insignificant results that Faraday after lecturing upon it, was asked what on earth was the use of it. A church dignitary had a conception of its dangerous possibilities in the hands of incendiaries, and deplored the discovery. Knowledge antedates understanding.... We live forward, but we understand backwards.... There is an aspect here of our physical research that is often lost sight of, namely, the small proportion of successful discoveries compared with the number of investigators. Certainly the number of unsuccessful attempts, even in the case of those fortunate individuals who make the great discoveries, is very much greater than the number of their successful attempts. Faraday's reputed satisfaction with 1/10 percent return comes to mind.

Faraday was a Sandemanian (Cantor, 1991), a Christian group prevalent in the Pennines (hills in northern England on the Scottish border) that has now died out. Tanford (1991) says: "There is no question about Faraday's faith and that it guided him when addressing moral issues, but Faraday himself never claimed a connection with his scientific work and indeed emphasized the need to separate religious and ordinary beliefs in an 1854 lecture."

It was shortly after his work on electromagnetic induction that Faraday, always in search of unity, showed that the five kinds of electricity then distinguished—frictional, galvanic, voltaic, magnetic (induced current), and thermal—were fundamentally the same. In this same period of his researches (c.1831–1844), he arrived at the basic laws of electrolysis that bear his name, and introduced the terms that are universally used: anode, cathode, anion, cation, and electrode.

In 1858, he retired to live near Hampton Court, Surrey, but retained a lively interest in science. His health gradually waned, and there he died on August 25, 1867. Faraday was possibly the greatest experimental genius the world has known (da Costa Andrade, 1971). He was incessantly prompted by the belief that certain fundamental relations were waiting to be found. He was not dismayed by dozens of fruitless experiments, and he persisted until basic discoveries were established. To all his other gifts he added the ability to describe his ideas in clear and simple language. Five books about Faraday were published in 1991 and 1992, and have been reviewed by Hunt (1992).

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