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A METHOD FOR MEASURING OXYGEN AND CARBON DIOXIDE IN SOIL[1]

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Abstract

A simple rubber membrane gas sampling device is described for measuring soil oxygen and carbon dioxide levels. The O_2 measurements are compared to results from the Pt electrode method and found to show similar trends when soil respiration was low. The membrane sensor samples a larger volume of soil and so its results have lesser coefficients of variation than do oxygen diffusion rate (ODR) measurements with Pt electrodes.

Additional Index Words: **aeration, soil structure, roots.**

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Composition of the soil's gas phase has significant effects on plant growth. Small samples of soil gas may be drawn out through a buried port and then analyzed (Van Bavel, 1965; Staley, 1980). When this method is used, there is some uncertainty in how well the samples represent what plant roots encounter. Consequently, soil oxygen levels are more often measured with the Pt electrode. It has been shown that some plant growth responses do correlate with oxygen diffusion rates (ODR) as measured with Pt electrodes (Stolzy and Letey, 1964). This method is not without problems, however, particularly as the soil gas phase

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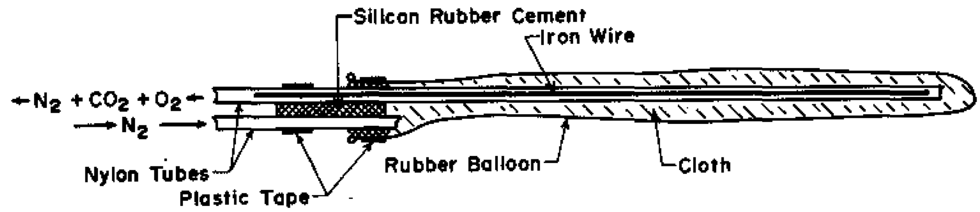

Fig. 1—A cross-section diagram of a rubber membrane gas sampler for measuring levels of soil oxygen and carbon dioxide.

increases (McIntyre, 1970). Our purpose is to describe an alternative method for characterizing the soil oxygen status and to further point out its use for measuring CO_2 levels.

Methods

Nitrogen gas is passed through the sampling device shown in Fig. 1. Both O_2 and CO_2 diffuse into the rubber balloon from the outside and are carried away in the nitrogen stream to O_2 and CO_2 analyzers. Given steady-state conditions, the concentration of O_2 and CO_2 around the outside of the balloon is (for practical purposes) directly proportional to the amount of O_2 or CO_2 that is measured in the nitrogen stream leaving the balloon. The proportionality constants, i.e., the gas diffusion coefficients for balloons, may be found by knowing the ambient O_2 or CO_2 concentrations outside the balloon and measuring the amount of O_2 and CO_2 in the nitrogen stream at a convenient steady-state flow rate. Specifically in our case, the proportionality constant for O_2 was found in ambient air with a nitrogen flow rate of 40 mL · min^{-1} and a portable oxygen meter that measures gas concentration in the range of 0 to 200 ppm.[3] The CO_2 diffusion coefficient was measured with the sampler in a container of pure CO_2 and a flow rate of 90 mL · min^{-1}. The outflow gas was passed through the type of infrared CO_2 analyzer commonly used in photosynthesis studies.[3] Nitrogen gas was supplied from a small portable cylinder filled with a pressure regulator, needle valve, and floating ball flow meter. Four or five minutes were required to obtain steady state as illustrated by the response curve (Fig. 2).

Balloons may be purchased at local toy outlets. The ones we used were about 2 cm in circumference and 25 cm in length. Care was taken to keep the pressure of the nitrogen stream <5 kPa so that the rubber was not stretched. The cotton cloth filler keeps the balloon from being completely flattened in the soil so that all of its surface remains effective for gas exchange. The soft iron wire in the nylon tube allows it to be bent into any shape.

In the first of three preliminary experiments, a silt loam soil was crushed and poured into plastic rings 25 cm in diameter and 7 cm in height. Three balloons were placed in each ring as the soil was added. The soil in two rings was mixed with wheat flour, 2.5% by weight. The rings with soil in place were shaken to settle the soil before it was saturated and brought to various water contents using the standard pressure plate method. Oxygen levels were then measured in each container of soil using the rubber membrane samplers and Pt electrodes so that their results could be compared. The second experiment used about 2 kg of silt loam soil in a pot with one balloon sampler buried at the 6-cm depth. The O_2 and CO_2 levels were measured from day to day as the soil passed through a number of wetting and drying cycles. In two trials the soil was wet with sucrose dissolved in water (about 1.5% sucrose on a soil dry-weight basis). The third preliminary test was done in a potato field with loam soil under sprinkler irrigation. Six balloons were installed horizontally in three potato rows. This was accomplished by digging narrow trenches 15 cm deep and 30 cm long followed by careful backfilling and repacking. Then soil oxygen measurements were compared to simultaneous platinum electrode ODR measurements on several occasions over a period of 66 d.

Results and Discussion

The concentration of O_2 and CO_2 in the nitrogen stream is much less than the concentration outside the balloon. Consequently, from Fick's law, the data were reduced by the relation

$$J = kC, \qquad [1]$$

where J is the concentration in ppm of the O_2 or CO_2 in the nitrogen stream corrected to a flow rate of 40 mL · min^{-1}. The concentration, C, expressed as a percent, is the amount of O_2 or CO_2 outside the sampler, and k is a proportionality constant. The sampler may be used equally well in water or in air. When used in moist soil the value of C represents an integrated measure of the O_2 or CO_2 concentrations over the exterior of the balloon. Thus its value will be intermediate to that in the individual soil air and water phases.

The constant, k, is affected by the surface area, thickness, and permeability of the rubber. Its value

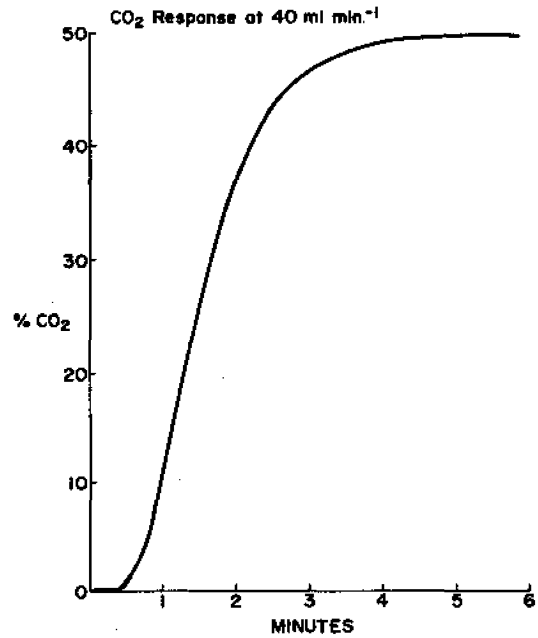

Fig. 2—A CO_2 response curve due to an abrupt change in external CO_2 concentration from 0 to 50%.

[3] Model 64800 Oxygen Monitor, Research Inc., Minneapolis, Minn., and Model 865 Infrared CO_2 Analyzer, Beckman Instruments, Inc., Fullerton, Calif. Field portable CO_2 analyzers are available from other manufacturers.

Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the USDA.

Table 1—Standard deviations (SD) for average oxygen diffusion rates (ODR) and apparent soil oxygen contents (percent O_2) as measured with Pt electrodes and the membrane sensors respectively.

Entry†	Volume fractions: Water	Volume fractions: Gas	ODR, µg cm⁻²·min⁻¹	SD	% O_2	SD
1	0.398	0.149	0.08	0.02	2.1	0.6
2	0.367	0.180	0.07	0.03	4.8	2.3
3	0.336	0.211	0.26	0.26	1.0	0.2
4	0.336	0.211	0.26	0.05	0.3	0.3
5	0.331	0.216	0.24	0.17	11.9	0.8
6	0.325	0.225	0.37	0.18	10.9	0.5
7‡	0.201	0.300	1.98	0.33	18.1	-
8	60 kPa§	-	0.89	0.23	11.9	0.8
	Average coef. of variation			30%		13%

† Entries 1-7 are laboratory measurements on a silt loam soil, bulk density 1.2. Entries 3 and 4 represent soil that was mixed with 2.5% flour before wetting. Entry 8 is an average from measurements made in a potato field plot with loam soil under sprinkler irrigations.
‡ A smaller sample, bulk density 1.3.
§ Average soil water matric potential.

for balloons from several different lots was found to be 7.5 + 1.5 for O_2. The balloons were more permeable to CO_2, having k values around 50. There was a tendency for k to decrease by as much as 10% after the sensors had been in moist soil for several days, but they returned to original values after drying in air at room temperatures for a few hours. This may have been due to adsorption of water by the rubber or to the growth of organisms on the outer surface. The balloons were stained after several weeks in the soil.

Results from the two studies comparing simultaneous soil oxygen analysis with the membrane samplers and the Pt electrodes are summarized in Table 1. The first seven entries show the percent soil oxygen expressed as the average from three balloons in each soil sample, and as the average ODR from 10 Pt electrodes in each sample. Trends in the data from the two methods are similar except when flour was mixed with the soil which no doubt increased the soil oxygen demand (Table 1, entries 3 and 4). The membrane samplers appear to be more sensitive to this increased demand than the Pt electrodes indicating the two methods are not necessarily interchangeable.

Entry 8 shows the average of six tensiometer readings, six membrane samplers, and 30 Pt electrode measurements made in a potato field over a 2-m distance during a 1-h time period. Neither method indicated any soil aeration problems before or after irrigation during the course of the field observations. The average coefficients of variation show there are smaller differences between the duplicate measurements made with the membrane samplers than with the Pt electrodes. This is to be expected as the Pt electrode samples a much smaller soil volume.

Figure 3 shows the O_2 and CO_2 measurements made during three drying cycles of 2 kg of soil in a pot on the laboratory bench. As expected, dilute sucrose solutions produced large bursts of CO_2 which were measured with the membrane sampler. Soil oxygen levels changed inversely to CO_2 contents, but were also affected by the soil water as reflected in the matric potential changes. The membrane sampler used in this pot of soil was removed after 82 d. The balloon surface

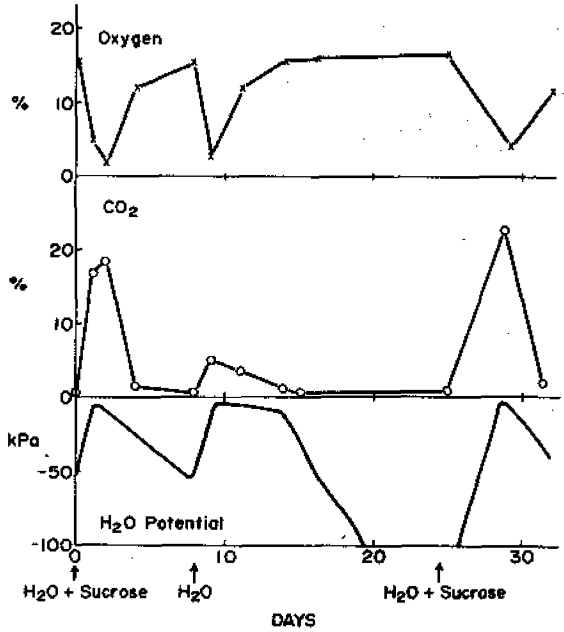

Fig. 3—Changes in soil concentrations of O_2 and CO_2 as affected by matric potential and the addition of sucrose.

was discolored, but the rubber itself gave no indication of deterioration. On the other hand, of the six sensors removed from the potato field after 66 d in place, one had a small leak due to deterioration of the balloon where it was stretched over the shoulder of an end plug that held the nylon tubes. Uneven and excessive stretching of the balloon over the shoulder of the seal should be avoided during assembly as it leads to accelerated deterioration. Making the seal with a noncorrosive silicon rubber as shown in Fig. 1 seems to be a good method.[4]

Root surfaces are in contact with both the soil liquid and gas phases. The diffusion coefficient for oxygen through water is much smaller than the diffusion coefficient through air, so most oxygen uptake by roots should occur through that portion of root surface in contact with the soil gas phase. Consequently absorption of oxygen by the long slender balloons may better mimic the roots over a wider range of water contents than do the surfaces of Pt electrodes which must be covered with a film of soil water to be sensitive to the O_2 content. On the other hand, the low oxygen permeabilities of the balloons cause them to be less intensive oxygen sinks than both the Pt electrodes and the more active root surface sites. Because the concentrations of both O_2 and CO_2 are heterogeneous in any biologically active soil, it seems likely the sampling method described here gives an integrated measure of gas levels that will be useful in both plant response and soil chemistry studies.

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[4] Dow Corning 738 RTV (noncorrosive electronics grade).