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AERATION MEASUREMENT

R.E. Sojka
Soil Scientist, Kimberly, Idaho, U.S.A.

H.D. Scott
University of Arkansas, Fayetteville, Arkansas, U.S.A.

INTRODUCTION

Soil oxygen enables aerobic respiration of plant roots and soil micro- and meso-flora and fauna. Its availability can be limited by soil wetness, compaction, discontinuous pores, or high respiration in moist soil due to elevated soil temperature or incorporation of fresh organic substrate. With oxygen depletion, soil redox potential shifts from oxidative to reducing conditions, hampering plant growth because of less efficient metabolic pathways and release into soil of toxic by-products of reduction chemistry or anaerobic respiration. Several texts are excellent sources for fundamental soil aeration concepts (1–3).

Measurements of soil aeration fall into three categories: "capacity," volume of gas-filled void space; "Intensity," partial pressure or concentration of oxygen (or other gases) in the voids; and "transport rate," the rapidity at which oxygen can be supplied to a point in the soil. Measurement difficulty increases in the order capacity $<$ intensity $<$ rate, as do the value and insight of the measurements.

CAPACITY MEASUREMENT

Capacity describes the ability of soil to contain air. Soil capacity parameters include total porosity, void ratio, relative saturation and air-filled porosity. These parameters are calculated from simple measurements of soil volume, particle density, bulk density and water content. Capacity has been used to understand plant growth and yield for over a century. A "rule of thumb" associates impaired plant growth with $<10\%$ soil air volume. Soil attributes affecting capacity include texture, structure, water content, clay mineralogy and sodium adsorption ratio (SAR). Sandy soils have less total porosity than clays, but in sands the pores are large and well-connected. Percent void space tends to increase in finer-textured (more clay), less-compact soils. Because clays have many small unconnected pores, and retain water more readily than coarser textured soils (sands), plants tend to suffer oxygen limitation more commonly in clays, despite their greater porosity. High soil sodium content or smectitic clay mineralogy (swelling clays) can exacerbate this tendency. Well-aggregated clays often avoid poor aeration because structure enhances macro-porosity. Inter-aggregate pores are larger, better connected and better drained than smaller intra-aggregate pores which usually contain more water.

INTENSITY MEASUREMENT

Intensity (partial pressure or concentration) measurements have been facilitated by instrumentation allowing rapid measurement of oxygen and other gas concentrations. The ambient atmosphere is 78% N and 21% O_2. The remaining gases total 1%. Ambient CO_2 is about 0.03%. In soil air, the O_2 concentration is $<21\%$. The drop in O_2 below 21% generally corresponds to the CO_2 concentration increase, due to respiration of roots and soil organisms. In soil air, CO_2 is commonly 0.3–1%, but can be much higher. In warm wet soil with freshly incorporated organic matter, or where carbonates are abundant, CO_2 can rise above 10%, and, where drainage is restricted, can reach 20%. When water logging occurs and reducing conditions prevail, a few percent by volume of gaseous products of reducing chemistry or non-oxidative metabolism, e.g. methane or nitrous oxide, can be present.

Soil air oxygen concentration can be measured using various analytical techniques, depending mostly on whether air is withdrawn from the soil or analyzed in-situ (2, 4, 5). Withdrawn soil air samples have an interpretation problem stemming from over-representation of macro-pore composition and/or mixing during convective extraction from the heterogenous pore sites within the soil matrix. Buried diffusion cavities (artificial porous voids) are sometimes used for sampling points, but questions remain as to representativeness of cavity-equilibrated air. Once withdrawn, soil air samples can be analyzed by wet

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chemistry, paramagnetic or polarographic methods, or using gas chromatography (6, 7). Paramagnetic and polarographic instruments can be used in situ, but they still have limitations. Paramagnetic analyzers require gas flows of tens of cubic centimeters over the sensors. Polarographic soil oxygen sensors are usually membrane-covered. Double membrane probes are used in situ, to overcome calibration shifts caused by condensation on sensors. Sensors can be small enough to measure oxygen between small aggregates or within large aggregates (8). Samples withdrawn from soil allow for analysis of gases besides oxygen. Knowing the soil O_2 concentration, does not indicate if the O_2 consumption rate can be satisfied by the rate of O_2 convection and diffusion through soil.

Soil O_2 concentration $<10\%$ by volume indicates poor aeration. However, O_2 concentration per se is an imperfect predictor of plant response. The composition of other soil gases, such as carbon dioxide, ethylene, methane, etc., can affect response to a given oxygen concentration. Furthermore, O_2 concentration gives little information about the amount (mass) of O_2 (volume × concentration) in soil, or the rate at which it can move through tortuous soil pores or across water films and root membranes to reach metabolic sites where it is reduced (9). Specific composition of soil atmospheres vary with organic matter and mineral content, soil redox potential and pH, making it hard to make generalizations about soil air trace gas composition as soils become wetter and O_2 concentration decreases (1, 2).

TRANSPORT RATE MEASUREMENT

Measurements of the rate of gaseous transport in soil are of two types: diffusion and convection. To characterize diffusion, Lemon and Erickson (10) proposed placing a small platinum (Pt) wire micro-electrode in soil to electrically reduce oxygen. The Pt electrode simulates a respiring root to which oxygen diffuses through air- and water-filled pores and then through a water film surrounding the root. The micro-electrode measures the effect of restrictions along this pathway on the O_2 supply to the electrode surface. The current measured through an electrode tip of known geometry, supplied at steady potential, is related to the steady state reduction of oxygen supplied by diffusion to root surfaces of similar geometry. The technique became known as the soil ODR measurement (from "oxygen diffusion rate"). Lemon and Erickson's seminal concept, was perfected and field-adapted by others (11–13), providing a standardized approach to the technology and a unified interpretive framework. Eventually commercialization provided mass production of uniform reliable Pt electrodes and compact portable semi-automated multi-probe instrumentation.

ODR is probably the most common characterization of in situ soil oxygen status now conducted, and it is well correlated with plant physiological, nutritional and growth responses. ODR is the only soil oxygen status measurement suited to prolonged remote and nearly continuous measurement of dynamic soil oxygen status (14). Factors affecting ODR include water content, electrode contact with soil, presence of reducible compounds, salinity, temperature and oxygen concentration (5, 6). Numerous studies (1, 2) have identified an ODR value of $20\,\mu\mathrm{g\,m^{-2}s^{-1}}$ as a threshold for a variety of plant physiological, nutritional, and growth responses to limited soil oxygen.

Subsequent ODR advances have been achieved. Electrode miniaturization allows oxygen flux measurements within roots and root microstructures, and within intact aggregates (15, 16). Also, due to potential poisoning of the Pt micro-electrodes during long term exposure to soil by oxides, alternatives to Pt have been developed. Wax-impregnated graphite electrodes (WIGEs) have greater current efficiencies and a wider current plateau than Pt electrodes (17). In moist soil, the current plateau region was a function of soil water content and the response was linear in atmospheres containing as much as 60% O_2. The WIGEs are less susceptible to oxide poisoning, can be fabricated easily and are less expensive.

Measurements of soil aeration based on convection of gas use simple flow permeameters to accurately measure mass flow through soil directly (18), or to measure the total air pressure or the difference in air pressure between the atmosphere and soil (19). Convection of soil air arises from spatial differences in total air pressures due to abrupt changes in air pressure of the atmosphere, the effects of temperature differences on gas properties, infiltration and redistribution of water in the soil profile, and microbial production of gases such as CO_2, NO, N_2O, and CH_4 (3). Flühler and Laser (8) developed a hydrophobic membrane probe (HMP) to measure total pressure and partial pressure in soil atmospheres. The HMP consisted of a membrane-covered chamber having a small volume and two teflon capillaries connected to a differential pressure transducer or to an oxygen electrode. A water-repellent non-rigid teflon membrane excluded wet soil from the continuous gas phase of the HMP. The total air pressure in the HMP is compared with the soil surface air pressure to determine pressure difference between the two locations. Renault et al. (20) developed an absolute pressure probe to measure in situ air pressure fluctuations at the soil surface and at varying depths within the profile. Their probe had negligible signal drift and an accuracy to 10 Pa. The sensitive component of the probe is a differential pressure sensor that functions from −14,000 to 14,000 Pa and senses a pressure differential of 2500 Pa. The signal results from resistance changes in an Arsenic-doped silicone membrane that functions as a Wheatstone bridge. The sensor requires a 1.5 mA direct current and its output is a −40 to 40 mV voltage. Circuitry converts the input voltage (24 V) into the stabilized current output (4–20 mA), providing a linear relationship between the differential air pressure and the output signal at a given temperature. The characteristics of the air pressure probe allow for in situ calibrations.

SUMMARY

Soil aeration is important to soil processes and plant growth. It can be characterized at various levels of complexity in terms of capacity, intensity or transport rate. Quantification of O_2 transport rates and measurement of concentrations of other important gases besides O_2 provide the best overall characterization of soil aeration for modern investigations, but simpler measurements can be valuable as rapid diagnostics for land managers. Modern instrumentation has made sophisticated characterization of soil aeration attainable at reasonable cost.

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