Effect of Short-term Flooding and Drainage on Soil Oxygenation

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Abstract
Three aeration indicators, namely oxygen (O2) concentration, redox potential (Eh), and oxygen diffusion rate (ODR), were measured to determine the aeration status of soil under short-term flooding and unflooded conditions. Relationships between these indicators were developed and results of some measurements made over short time intervals during flooding and drainage of soil are presented.

Keywords
Aeration, Flooding, Oxygen, Soil air, Water table

Disciplines
Agriculture | Bioresource and Agricultural Engineering | Soil Science | Water Resource Management

Comments
EFFECT OF SHORT-TERM FLOODING AND DRAINAGE ON SOIL OXYGENATION

S. Mukhtar, J. L. Baker, R. S. Kanwar

ABSTRACT. Three aeration indicators, namely oxygen \((O_2)\) concentration, redox potential \((Eh)\), and oxygen diffusion rate \((ODR)\), were measured to determine the aeration status of soil under short-term flooding and unflooded conditions. Relationships between these indicators were developed and results of some measurements made over short time intervals during flooding and drainage of soil are presented.

In general, \(O_2\) concentration of above 80% (saturated) was needed for ODR and Eh values to be above critical values of \(20 \times 10^{-8}\) g cm\(^{-2}\) min\(^{-1}\) and 600 mV, respectively, indicating a well oxidized soil system. Within hours of inundation, \(O_2\) concentration and ODR values reduced below their critical levels at all the sampling depths. The ODR at all the sampling depths remained depressed for several hours after lowering the water table, indicating partial blocking of the air-filled pores by water films. Keywords: Aeration, Flooding, Oxygen, Soil air, Water table.

Soil oxygenation as defined by Glinski and Stepniewski (1985) is the part of soil aeration connected with oxygen \((O_2)\) distribution in soil and its availability for microorganisms and plant roots.

Exchange of gases between the soil and the atmosphere is primarily due to the mechanism of diffusion (Buckingham, 1904; Penman, 1940). Under excessive soil moisture conditions, a large percentage of the soil pores are filled with water. As a result, the diffusion of \(O_2\) into the soil from the atmosphere above it is reduced because diffusive movement of \(O_2\) is nearly 10,000 times slower in water than in the air (Grable, 1966). It is possible that under these conditions low concentrations of \(O_2\) may occur in soil as a result of a temporary increase in the rate of \(O_2\) consumption by the soil (plant roots and microorganisms, etc.), and/or a reduced supply of \(O_2\).

An adequate soil-water-air environment is essential for good plant growth (Patwardhan et al., 1988). Excessive soil water conditions may occur at any time during the growing season, and, therefore, an assessment of soil oxygenation under flooded and unflooded conditions during the cropping season may help us understand in what ways poor soil aeration can inhibit crop growth.

Over the years, several methods of sampling soil \(O_2\) have been used. These include diffusion chambers or reservoirs buried in the soil and designed to be left in place for several samplings (Boynton and Reuther, 1938; Patrick, 1977; Carter et al., 1984), point source sampling using buried ports (Staley, 1980), portable field probes (Robertson and Bracewell, 1979), and diffusion-chamber techniques (Dasberg and Bakker, 1970) to withdraw samples of soil air. While sampling, it is important to avoid soil air drawn into the sampling chamber or reservoir from a layer other than the intended soil sampling depth. Among the aforementioned soil sampling methods, where a syringe and hypodermic needle are used to withdraw samples from chambers, reservoirs, or ports, it is possible to obtain samples from the zone of a least-resistant flow, such as a continuous macropore. In this study, soil \(O_2\) concentrations were measured using a new sampling technique (Mukhtar et al., 1990a) that permitted rapid and nondisruptive measurements of soil atmospheres at various depths. Laboratory and field testing (Mukhtar et al., 1990a) of this new technique suggested that the samples withdrawn should represent point sampling at a desired depth.

During the 1987 growing season, specially constructed "isolated field plots" (Mukhtar et al., 1990b) were used to create temporary flooding conditions at various physiological growth stages of corn. Three well known aeration indices, namely \(O_2\) concentration, oxygen diffusion rate \((ODR)\), and redox potential \((Eh)\) were used to evaluate the soil aeration status.

This article describes relationships between these aeration indicators measured during flooded and unflooded conditions. Results of some measurements made over short time intervals to assess the rate of \(O_2\) depletion with flooding and resupply with drainage also are presented.

MATERIALS AND METHODS

Twelve experimental plots \((3 \times 6\) m\) were established in 1986 near Ames, Iowa, to conduct flooding experiments in 1987. These plots were used to make \(O_2\) concentration, Eh, and ODR measurements during the 1987 growing season.
The major soil type at this site was a Nicollet loam (Aquic Hapludoll). Selected physical properties of this soil are presented in Table 1.

Ten of the 12 plots were specially constructed to permit control of the water-table elevations and creation of flooding through drainage and subirrigation. Each isolated plot was completely surrounded by a plastic barrier extending from the soil surface to a depth of 1.2 m. On the inside of this barrier, a corrugated and perforated plastic tube (100-mm OD) was installed at 1.2 m depth to raise and lower the water table through subirrigation and drainage, respectively. A hole was dug inside the plastic barrier to a depth of 1.35 m to install a 1.5-m-tall corrugated plastic pipe (0.46-m OD) at one corner of each plot. The 1.2-m-deep drain tube was connected to this vertical sump. A pump assembly was used to control water table elevations in each plot. The construction of these “isolated field plots” has been described earlier (Mukhtar et al., 1990b).

Plots were flooded for a 10-day period during early vegetative (36 days after planting), late vegetative (56 days after planting), flowering (76 days after planting), and yield formation (100 days after planting) stages of corn growth. Two of the 10 isolated field plots were assigned to a control treatment in which the water table was constantly maintained at a depth of about 90 cm below the soil surface. The water tables on the flooding treatment plots also were maintained at the 90 cm depth when not being flooded. The other 2 of the 12 plots were not assigned to any water-table treatments and no artificial flooding or drainage was introduced.

The O2 concentration, Eh, and ODR at 15, 30, and 60 cm below the soil surface were determined in each plot. An undisturbed area between the middle two of four planted rows within each plot was allocated for such measurements. To measure soil O2 concentrations, specially constructed soil atmosphere access chambers were installed at 15, 30, and 60 cm depths. A dual-action syringe sampling assembly and a sample-analysis reservoir were used to withdraw air or water samples from each access chamber and to analyze those samples for O2 concentration. Several researchers have suggested critical values for the three aeration indicators after which little or no O2 is present in the soil and O2 supply to the plant roots may be restricted. An O2 concentration of more than 10% by volume is considered adequate for good root growth (Kohnke, 1968; Kramer, 1969). Erickson (1965) and Stolzy (1974) noted that plant roots may cease to grow at an ODR value of 20 X 10^-8 g cm^-2 min^-1 whereas ODR values above 40 X 10^-8 g cm^-2 min^-1 provide favorable aeration conditions. Carter (1986) suggested that little or no O2 is present in the soil at an Eh value of 350 mV, and that a redox value of 700 mV or above indicates a well-oxidized soil.

### Table 1. Selected physical properties of the Nicollet loam soil

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>pH*</th>
<th>Bulk Density (Mg m^-3)</th>
<th>Organic Matter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>31.3</td>
<td>43.6</td>
<td>25.1</td>
<td>7.3</td>
<td>1.20</td>
<td>4.3</td>
</tr>
<tr>
<td>30</td>
<td>31.2</td>
<td>42.8</td>
<td>26.0</td>
<td>6.7</td>
<td>1.30</td>
<td>4.0</td>
</tr>
<tr>
<td>60</td>
<td>27.7</td>
<td>42.2</td>
<td>30.1</td>
<td>6.9</td>
<td>1.35</td>
<td>2.9</td>
</tr>
</tbody>
</table>

* Mean value determined from soil samples (n = 6 per depth) obtained from the experimental site.
† Soil survey of Story County, Iowa (USDA, 1984).
‡ Kanwar et al. (1987).

Ten microelectrodes were used at 15 and 30 cm; for the 60 cm depth, only five microelectrodes were used. Soil Eh values (mV) were obtained with a digital multivoltmeter (Oxygen/ORP meter, model P5E, Jensen Inst., Tacoma, Wash.), a Ag/AgCl reference electrode, and the microelectrodes. The Eh value with respect to a standard hydrogen electrode was calculated for each electrode by adding 222 mV (the potential of the Ag/AgCl reference electrode) to the measured reading. No adjustments for soil pH were made because of the small variation in soil pH values with depth (Table 1).

To measure ODR, electrode current readings were made using the microelectrodes, a model D Jensen oxygen diffusion ratemeter (Jensen Inst., Tacoma, Wash.), and a Ag/AgCl reference electrode which was placed at 4 cm depth below the soil surface. The ratemeter was set to apply 0.65 V to a complete set of microelectrodes at a given depth. Current readings were recorded at each depth after waiting 4 min. The ODR for each microelectrode at each depth was calculated by:

$$ ODR = 5.95 \times 10^{-5} C $$

where C was the current reading in microamperes and ODR was the oxygen diffusion rate (10^-8 g cm^-2 min^-1) for a given soil depth. For both Eh and ODR, an average value for each depth was obtained by averaging over the number of microelectrodes used.

In each plot, simultaneous Eh and ODR measurements and soil air or water sampling for O2 concentration were performed three times a week at all depths, except at 60 cm, where Eh and ODR were measured only once a week. For the plots assigned to flooding treatments, Eh and ODR measurements and O2 concentrations were determined at least five times per depth within the first 48 h of a water-table raising or lowering event.

### RESULTS AND DISCUSSION

Several researchers have suggested critical values for the three aeration indicators after which little or no O2 is present in the soil and O2 supply to the plant roots may be restricted. An O2 concentration of more than 10% by volume is considered adequate for good root growth (Kohnke, 1968; Kramer, 1969). Erickson (1965) and Stolzy (1974) noted that plant roots may cease to grow at an ODR value of 20 X 10^-8 g cm^-2 min^-1 whereas, ODR values above 40 X 10^-8 g cm^-2 min^-1 provide favorable aeration conditions. Carter (1986) suggested that little or no O2 is present in the soil at an Eh value of 350 mV, and that a redox value of 700 mV or above indicates a well-oxidized soil.

### RELATIONSHIPS BETWEEN O2 CONCENTRATION, Eh, AND ODR

The data describing these relationships were pooled from all the experimental plots from both flooded and unflooded conditions.

### O2 CONCENTRATION VERSUS Eh

The relationship between O2 concentrations and the corresponding Eh values at the 15, 30, and 60 cm depths are presented in Figure 1. A considerable amount of
variation \( (R^2 = 0.65, 0.42, \text{ and } 0.25 \text{ for data at the 15, 30, and } 60 \text{ cm depths, respectively}) \) exists in the Eh plot versus measured \( O_2 \) concentration for all the sampling depths. The variation is greatest up to an \( O_2 \) concentration of about 80%; above that, Eh values fluctuate around 600 mV, indicating a well-oxidized soil system. These Eh values for 80 to 100% \( O_2 \) concentrations are similar to those measured by Carter (1986) at 25 and 75 cm depths below the surface of a silt loam soil that was continuously drained to a depth of 135 cm throughout the wheat growing season in Louisiana.

**\( O_2 \) Concentration versus ODR**

Figure 2 shows the relationships between \( O_2 \) concentrations and corresponding ODR values measured at the 15, 30, and 60 cm depths. Although considerable amounts of variation exist \( (R^2 = 0.26, 0.26, \text{ and } 0.23 \text{, for data at the 15, 30, and } 60 \text{ cm depths, respectively)}) \), this plot can be separated into three different soil moisture regimes—flooded or nearly saturated with water (0 to 30% saturated oxygen), draining or transition state from flooded to unflooded conditions (40 to 80% saturated oxygen), and unflooded conditions (80 to 100% saturated oxygen). In general, it can be observed that \( O_2 \) concentrations of nearly 80% is required before an adequate supply of oxygen (ODR above \( 20 \times 10^{-8} \text{ g cm}^{-2} \text{ min}^{-1} \)) is available to the plant roots.

**ODR versus Eh**

The relationships between Eh and ODR are illustrated in figure 3 for the 15, 30, and 60 cm depths. Again, much variation in the Eh values exists \( (R^2 = 0.27, 0.10, \text{ and } 0.06 \text{ for data at the 15, 30, and } 60 \text{ cm depths, respectively}) \).
relative to the ODR values determined at these sampling depths. Up to an ODR of about $10 \times 10^{-8} \text{ g cm}^{-2} \text{ min}^{-1}$, it is difficult to establish accurately the oxidation status of the soil. But beyond this value of ODR, Eh at all depths varied mostly between 600 to 700 mV, suggesting well-oxidized soil conditions. Field measurements by Armstrong (1967) on a waterlogged organic soil (Scottish blanket-bog peat) indicated a similar pattern for Eh in relation to ODR, with the exception that in Armstrong’s study, maximum ODR and Eh values were less than $10 \times 10^{-8} \text{ g cm}^{-2} \text{ min}^{-1}$ and 400 mV, respectively, and large variation in Eh occurred only up to an ODR of $1 \times 10^{-5} \text{ g cm}^{-2} \text{ min}^{-1}$.

**Figure 3**—Relationship between ODR and corresponding Eh at the 15, 30, and 60 cm depths (pooled data from all the experimental plots).

**Figure 4**—Soil aeration status ($O_2$ concentration, Eh, and ODR) monitored at the 15, 30, and 60 cm depths during the short-term flooding period.

**EFFECT OF WATER TABLE RAISING AND LOWERING ON SOIL OXYGENATION**

Figures 4 and 5 show the short-term effects of soil flooding (raising water table) and drainage (lowering water table), respectively, on $O_2$ concentration, Eh, and ODR measured at 15, 30, and 60 cm depths below the soil.
surface in one of the plots assigned to flooding treatments. Figure 5 begins where figure 4 leaves off; the choice of the specific plot for which to illustrate this data was based on the most complete set with the least influence from natural rainfall (e.g., the depression for all the parameters at 20 h into drainage were due to 6.4 cm of rain).

It took about 19 h to totally flood the plot through subirrigation; the water table level rose above the 15-cm depth (fig. 4) between 11 and 19 h after beginning subirrigation. Within that time period, O$_2$ concentration and ODR values at the 15-cm depth were reduced from 97 to 30% of saturation and from $45 \times 10^{-8}$ to $9 \times 10^{-8}$ g cm$^{-2}$ min$^{-1}$, respectively, indicating an inadequate supply of oxygen to plant roots. The average time for O$_2$ concentration to fall below the critical level (less than 50% saturated) at 15-cm depth was 36 h (range = 19 to 55 h, n = 8) after beginning subirrigation. The average time it took for ODR to be less than the critical value ($20 \times 10^{-8}$ to $9 \times 10^{-8}$ g cm$^{-2}$ min$^{-1}$) at the 15 cm depth was 19 h (range = 0 to 43 h, n = 8) after beginning subirrigation.

On the other hand, soil Eh at the 15 cm depth (fig. 4) did not decrease below 350 mV (a value indicating little or no O$_2$ present at that depth in the soil) until 42 h (23 h of inundation) after beginning subirrigation. At this depth, the average time for Eh to decrease below 350 mV was 46 h (range = 11 to 74 h, n = 8) after subirrigation began. Both O$_2$ concentration and ODR values obtained at the 30 and 60 cm depths also were less than the critical levels in about 11 h after subirrigation. At the 30 cm depth, average time for O$_2$ concentration and ODR values to fall below critical levels was 16 h (range = 4 to 29 h, n = 8), and 9 h (range = 0 to 19 h, n = 7) after beginning subirrigation, respectively. At the 60-cm depth these averages were 12 h (range = 4 to 38 h, n = 8), and 0 h (n = 7) after beginning subirrigation for O$_2$ concentration and ODR, respectively. Regardless of short-term flooding, ODR values at the 60 cm depth were seldom above the critical levels. At the 30 and 60 cm depths it took even longer, 114 h after beginning subirrigation (95 h of inundation), for soil Eh to fall below the critical level of 350 mV. After beginning subirrigation, the average time for Eh to fall below its critical value was 89 h (range = 36 to 170 h, n = 8) for 30 cm depth, and 166 h (range = 67 to 240 h, n = 8) for 60 cm depth, respectively.

After the 10-day flooding period, the soil was allowed to drain. Within 12 h after beginning drainage, the water levels reached a depth of 80 cm and soil O$_2$ concentration and Eh values, measured at the 15 cm depth (fig. 5), increased substantially. These parameters reached nearly 100% saturation and 530 mV, respectively, 147 h after drainage began; and the ODR remained near the critical level of $20 \times 10^{-8}$ g cm$^{-2}$ min$^{-1}$ (fig. 5). At this depth the average time it took for O$_2$ concentration, Eh, and ODR to reach above their critical levels was 6 h (range = 2 to 12 h, n = 6), 14 h (range = 2 to 46 h, n = 6), and 138 h (range = 21 to 291 h, n = 6), after beginning drainage, respectively. The O$_2$ concentration for the 30 and 60 cm depths reached 50% within 6 h after beginning drainage. The average time it took after beginning drainage for O$_2$ concentration to reach above critical levels at 30 and 60 cm depths was 18 h (range = 2.5 to 79 h, n = 6) and 28 h (range = 6 to 79 h, n = 6), respectively. The ODR values at these depths remained less than the critical levels even after 214 h of drainage, suggesting that plant roots were under some O$_2$ stress even 202 h (214 - 12 h) after the water table was lowered to 90 cm below the soil surface.

Even though the soil continued to drain with time and substantial increases in O$_2$ concentrations and Eh values were observed at all depths, the small corresponding...
increases in the ODR values suggest that many air-filled pores were discontinuous or blocked by water films. These ODR measurements agree with those of Wilson et al. (1985) who, after allowing a nearly saturated silt loam soil to dry by drainage and evaporation for nearly 10 days, observed that at depths below 10 cm, the ODR failed to increase above $10 \times 10^{-8}$ g cm$^{-2}$ min$^{-1}$.

**CONCLUSIONS**

- Generally, an O$_2$ concentration of above 80% (saturated) was needed to achieve ODR values greater than $20 \times 10^{-8}$ g cm$^{-2}$ min$^{-1}$ and Eh values above 600 mV.
- Within hours of inundation through subirrigation, O$_2$ concentration and ODR values were reduced from well above critical to well below critical levels at all the sampling depths, indicating restricted supply of oxygen to plant roots.
- High O$_2$ concentration and redox potential (Eh) in the soil profile sampled after lowering the water table were not always accompanied by high ODR, indicating discontinuities or blocking of the corresponding air-filled pore spaces by water films.

**REFERENCES**


