MICROBIAL ACTIVITY AS REGULATED BY SOIL WATER-FILLED PORE SPACE

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Agricultural tillage and crop residue management have a profound influence on the soil physical environment and associated microbial activities. Recent trends towards reduced soil tillage and increased maintenance of crop residues on the soil surface have resulted in soils which are often cooler, wetter, and more compact than conventionally tilled soils (Mielke et al. 1986). These differences in soil physical environment in reduced-tillage soils are sometimes associated with a less aerobic microbial environment, lower net mineralization of N, and greater gaseous N losses through denitrification as compared with cultivated soils (Linn and Doran 1984a, Fox and Bandel 1986). Doran and Linn (1984b) identified the proportion of soil pore space filled with water as a major factor controlling aerobic and anaerobic soil microbial activity and denitrification in tillage management comparisons at several USA locations.

The present study was initiated to evaluate the utility of soil water-filled pore space as a practical index of aerobic and anaerobic microbial processes and N transformations across a range of soils varying in texture, organic matter status, and previous management. Water-filled pore space was chosen as a practical index of soil aeration status since it integrates soil management effects on both soil porosity and water content, requires relatively simple and inexpensive measurements of soil bulk density and water content, and thus can be utilized by a greater number of researchers and agricultural producers.

METHODS

Eighteen soils for experimentation were collected from surface soil A horizons of benchmark sites in Major Land Resource Areas in the USA. Nine of 10 taxonomic soil orders were represented. The soils varied in texture, organic matter, and management history with respect to cropping, native vegetation, and soil cultivation. To reestablish soil biological activity after collection and storage, soils were pre-conditioned in the glasshouse before experimentation by cropping to oats (Avena sativa L.). Where necessary, soils were limed to achieve a pH of 6.5 to 7.0 and amended with N or P to narrow the factors limiting plant and microbial growth to those of primary interest—namely soil aeration and water content.

Soils were hand compacted to bulk densities representative of reconsolidation values characteristic of several wetting and drying cycles without loading and also of those after a normal equipment load in the field (47.9 kPa) at a soil water tension of 10 kPa. Experimental treatments for each of the 18 soils consisted of five soil water contents approximating water-filled pore spaces of 30, 45, 60, 75, and 90%. Soil water-filled pore space, synonymous with relative saturation, was calculated from the quotient of soil volumetric water content divided by total soil porosity. Soil porosity was calculated from soil bulk density assuming a soil particle density of 2.65 g cm⁻³.

Soil respiration, a measure of aerobic microbial activity, was estimated from repacked soil cores by measuring carbon dioxide produced over a four week period. Anaerobic microbial activity was estimated by measuring nitrous oxide produced (denitrification) during the second week of incubation using the acetylene blockage technique. Net mineralization of N was determined through comparison of initial and final ammonium and nitrate levels in 2M KCl soil extracts. Further analytical details are given by Doran et al. (1988).
RESULTS

Soil respiration in repacked cores for 16 of the 18 soils tested responded similarly to variations in the proportion of soil pore space filled with water (Fig. 1). Above 30% WFPS relative soil respiration increased 20 to 60% with increasing water content attaining maximum values between 55 and 61% WFPS. Further increasing water content to between 80 and 90% WFPS decreased respiration by 20 to 60%. Respiration data were expressed relative to maximum carbon dioxide produced from each soil to normalize large differences in soil organic C and other chemical characteristics between soils and to permit better evaluation of the direct effects of soil WFPS among soils. A quadratic model of WFPS with relative soil respiration within three soil groupings provided a good fit for the experimental data (R²=0.58 to 0.87, p<0.0001). Response of coarse textured soils (Fig. 1a), having a sand content > 50%, varied somewhat from that of medium to fine textured soils (Fig. 1a). The WFPS for maximum respiration, as determined from the first derivative of the quadratic relationship, was somewhat lower for coarse than for finer textured soils (54.1% versus 60.7%). Increases in relative respiration for coarse textured soils with increasing water content were somewhat smaller at WFPS below the optimum for maximum respiration; decreases with increased water above the optimum were somewhat greater than those in medium to fine textured soils. The other two soils, both highly weathered Hawaiian soils with very fine granular structure, exhibited increasing respiration until soil WFPS exceeded approximately 78% (Fig. 1c).

Changes in soil nitrate-N over the four week incubation period were related to soil WFPS in a manner similar to those for soil respiration (Table 1). Maximum accumulation of nitrate-N over the four week incubation occurred at WFPS of 56 to 72% for 16 soils and at 74 and 83% for the two Hawaiian soils. Major losses of nitrate-N (7 to 90 mg N kg⁻¹ soil) usually occurred when WFPS exceeded 75%. These losses of nitrate-N, equivalent to 8 to 63% of the amounts accumulated under presumably more aerobic conditions at lower WFPS values, coincided with anaerobic microbial denitrification which increased exponentially when WFPS exceeded 70 to 75% (Fig. 2). These findings agree with those of Stanford and Epstein (1974) who found relative mineral N accumulation in 9 texturally different soils increased with increasing soil water content to 80 to 90% WFPS and then declined, presumably from increased denitrification. Grundmann and Rolston (1987), working with one of the soils used in our study (Yolo silt loam), found denitrification exponentially increased with soil WFPS between 62% WFPS (no denitrification) and 100% WFPS (maximum denitrification).

In our study, nitrate accumulation in the highly weathered Hawaiian soils increased with WFPS up to 74% for the Kole Kole loam and 83% for the Wahiawa clay. No significant denitrification losses were recorded from either soil at average WFPS values of 84 and 82%, respectively.

DISCUSSION

For a wide range of soils the percentage of soil pore space filled with water appears well correlated with aerobic and anaerobic microbial activity and associated processes of respiration, mineralization, and denitrification. Results of this study agree with earlier findings (Linn and Dorn 1984a & b) with fewer soils that aerobic microbial activity increased in a linear manner with increased water content between 30 and 60% WFPS. It was also observed that aerobic microbial activity declines above 60 to 70% WFPS, presumably as a result of additional water presenting a barrier for diffusion of oxygen to and waste products away from soil microorganisms.
Fig. 1 - Relationship between soil water-filled pore space and relative soil respiration for repacked cores of 18 surface benchmark soils by soil texture or structure.
FIG. 2 - WFPS versus denitrification over 7 days, all soils

\[ \log (N_2O + 1) = 3.3(WFPS) - 2.08 \]
No \( N_2O \) at WFPS \( \leq 0.03 \)

FIG. 3 - Denitrification from Clarion surface soil in field as related to tillage and soil WFPS.
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<th>Net Loss in Nitrate</th>
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<td>0.5</td>
<td>1.3</td>
<td>3.46</td>
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<tr>
<th>Soil Series</th>
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<th>WFPS mg/kg</th>
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Table 1. Soil characteristics, soil bulk density, and soil nitrate change in 4 weeks.
In earlier research 80% WFPS was proposed as the point at which significant denitrification would occur in most soils, given adequate supply of available C and nitrate-N, and that at 60% WFPS little or no denitrification would occur. This postulation was confirmed in the present study for a wide range of soils in which denitrification was absent below 53% WFPS but increased exponentially at WFPS exceeding 70 to 75%. Exceptions were two Hawaiian soils which differed considerably in soil physical properties and presumably pore-size distributions. This relationship between soil WFPS and denitrification also holds very well in the field environment where WFPS is readily altered by tillage management, surface residue concentrations, and wheel traffic patterns (Fig. 3).

CONCLUSIONS

The proportion of soil pore space filled with water appears useful for simultaneously evaluating the effects of soil bulk density and water content on aeration-dependent microbial processes as related to management-induced changes in the soil physical environment. The consistency of relationship between soil WFPS and microbial activity for a wide range of soils enhances predictions of soil management effects on aeration-dependent microbial processes over a range of climatic and soil drainage conditions. Of particular importance is the utility of WFPS to predict potential losses of soil and fertilizer nitrate-N through microbial denitrification.

REFERENCES


