Effect of Water-Filled Pore Space on Carbon Dioxide and Nitrous Oxide Production in Tilled and Nontilled Soils[1]

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ABSTRACT

The percentage of soil pore space filled with water (percent water-filled pores, % WFP), as determined by water content and total porosity, appears to be closely related to soil microbial activity under different tillage regimes. Soil incubated in the laboratory at 60% WFP supported maximum aerobic microbial activity as determined by CO_2 production and O_2 uptake. In the field, % WFP of surface no-tillage soils (0–75 mm) at four U.S. locations averaged 62% at time of sampling, whereas that for plowed soils was 44%. This difference in % WFP was reflected in 3.4 and 9.4 times greater CO_2 and N_2O production, respectively, from surface no-tillage soils over a 24-h period as compared to plowed soils. At a depth of 75 to 150 mm, % WFP values increased in both no-tillage and plowed soils, averaging approximately 70% for no tillage compared with 50 to 60% for plowed soils. Production of CO_2 in the plowed soils was enhanced by the increased % WFP, resulting in little or no difference in CO_2 production between tillage treatments. Nitrous oxide production, however, remained greater under no-tillage conditions. Substantially greater amounts of N_2O were produced from the N-fertilized soils, regardless of tillage practice. Production of CO_2 and N_2O was primarily related to the % WFP of tillage treatments although, in several instances, soil-water-soluble C and NO_3^- levels were important as well. Calculations of relative aerobic microbial activity between no-tillage and plowed soils, based on differences in % WFP relative to maximum activity at 60%, indicated linear relationships for CO_2 and N_2O production between WFP values of 30 to 70%. Below 60% WFP, water limits microbial activity, but above 60%, aerobic microbial activity decreases—apparently the result of reduced aeration.

Additional Index Words: **aerobic microbial activity, conservation tillage, respiration, soil aeration, nitrification, denitrification.**

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THE no-tillage management system, often characterized by an accumulation of crop residues on the soil surface, results in greater C, N, and water contents of the surface 50 to 100 mm of soil compared to conventionally tilled (plowed) soils (Blevins et al., 1977; Campbell et al., 1976; Doran, 1980; Fleige and Baeumer, 1974). The greater numbers of microorganisms and microbial activities in the surface 75 mm of no-tillage soils are largely a reflection of these higher C, N, and water contents (Doran, 1980). Facultative anaerobes and denitrifying bacteria also are more numerous in the surface 150 mm of no-tillage soils and constitute a larger proportion of the total microbial population than in plowed soils. Thus, the greater number of organisms capable of anaerobic activity and the greater potential for denitrification (Doran, 1980; Rice and Smith, 1982) indicate the biological environment of no-tillage soils to be less aerobic than that of plowed soils. Major factors responsible for the less-aerobic conditions in no-tillage soils are higher soil water contents and/or bulk densities which result in lower total soil porosity and greater water-filled pore space (WFP) in comparison with plowed soils (Doran and Power, 1983).

Previous soil aeration research has demonstrated the importance of the soil air/water balance upon aerobic and anaerobic microbial activities. Aerobic microbial activity increases with soil water content until a point is reached where water displaces air and restricts the diffusion and availability of oxygen. Maximum rates of microbial respiration, nitrification, and mineralization occur at the highest water content (lowest tension) at which soil aeration remains nonlimiting (Bhaumik and Clark, 1948; Miller and Johnson, 1964; Parker and Larson, 1962). When soil water contents approach or exceed field capacity, the percentage of soil pore space filled with air or water are better indicators of aerobic vs. anaerobic microbial activity than either water content or water potential (Miller and Johnson, 1964; Sommers et al., 1981).

The results of many studies, involving a wide range of soil types, indicate that a soil water content equivalent to 60% of a soil's water-holding capacity (WHC) delineates the point of maximum aerobic microbial activity (Table 1). The majority of studies examining interrelationships between soil water status and aero-

Table 1—The relationship between percent water-holding capacity (% WHC) or percent water-filled pore space (% WFP) and microbial activities and numbers.

Process (Parameter)	WHC (WFP†) For maximum activity	WHC (WFP†) Range tested	Number of soils evaluated	References
	%	%		
		Aerobic		
Ammonification	60	30–150	2	Pal and Broadbent, 1975
Ammonification	60	0–100	22	Greaves and Carter, 1920
Nitrification	60	0–100	22	Greaves and Carter, 1920
Bacterial numbers	50–60	20– 80	3	Seifert, 1960
	60–70	0–100	20	Seifert, 1961
Respiratory quotient	70†	30–100	3	Rixon and Bridge, 1968
	60	5–100	1	Rovira, 1953
Organic matter	60	15– 60	1	Gilmour et al., 1977
Decomposition	60–80	--	--	Kononova, 1961‡
(CO_2 production)	60	30–150	2	Pal and Broadbent, 1975
		Anaerobic		
Denitrification	>70	60–100	1	Nommik, 1956
Denitrification	>60	40–550	3	Bremner and Shaw, 1958
Denitrification	>60†	50– 80	3	Aulakh et al., 1982
		Aerobic/Anaerobic		
Nirogen fixation	70	0–100	22	Greaves and Carter, 1920

† Data originally expressed as percent air-filled porosity.
‡ The information presented by Kononova (1961) was from the late 1800's literature; neither the range of water-holding capacities used nor the number of soils evaluated in these studies was given

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bic/anaerobic microbial activities have used the degree of water-holding capacity (% WHC) as an index of aeration. The use of % WHC is somewhat ambiguous because this parameter depends on soil type, and the methods for its determination vary and are often poorly defined. Most researchers take WHC as the water content at saturation; however, some use WHC to designate water contents ranging from field capacity to saturation. We felt that % WFP would be a more practical index of soil aeration because it required only a knowledge of gravimetric soil water content and soil bulk density (assuming the particle density of mineral soils = 2.65 Mg/m^3). Technology for measurement of both these parameters should be readily available to anyone conducting aeration or soil management research.

The objectives of this study were two-fold: (i) to examine under laboratory conditions the hypothesis that, regardless of soil bulk density, % WFP is an accurate index of aerobic microbial activity; and (ii) to evaluate this hypothesis under field conditions by comparing CO_2 and N_2O evolution with % WFP values from surface soils subject to different tillage management regimes.

MATERIALS AND METHODS

The soil used in the laboratory studies was a Crete-Butler silty clay loam (Pachic Argiustolls–Abruptic Argiaquolls) from the Agronomy Farm of the Univ. of Nebraska-Lincoln, near Lincoln. A bulk sample from the surface 150 mm of this soil was sieved (2-mm mesh), air-dried, and stored at room temperature until needed. Textural analysis of this soil was 12% sand, 54% silt, and 34% clay. Total organic C content by wet combustion (Smith and Weldon, 1941) was 2.06%, and total Kjeldahl N content (Schuman et al., 1973) was 0.158%. Initial soil pH, determined in a 2:1 ratio of 0.01*M* $CaCl_2$-to-soil mixture after a 1-h equilibration period, was 5.8 (Peech, 1965).

An incubation study was conducted to examine the effect of a range of WFP values on soil microbial activity. The soil received 1% (wt/wt), steam-sterilized, finely ground (60 mesh) corn stover residue with total C and Kjeldahl N contents of 42.1% and 1.27%, respectively. The bulk soil was brought to a water content of 10% (wt/wt) by the addition of small amounts of sterile distilled water while constantly mixing with the soil. The bulk soil was then divided into 100-g (oven-dried basis) subsamples, placed in 100-mL Pyrex[3] beakers, and mechanically compressed with a hydraulic press to a bulk density of either 1.14 or 1.40 Mg/m^3. These bulk densities were chosen to simulate soil bulk densities commonly encountered with conventional and no-tillage management systems.

Assuming a soil particle density of 2.65 Mg/m^3, soil water contents were then adjusted, by adding water to the soil surface, to a range of WFP values of 20 to 97%. Triplicate samples were incubated at 28°C in 1.9-L glass jars sealed with screw-cap lids in which a serum stopper had been fitted for gas sampling.

A 1-cm^3 sample of the headspace atmosphere of each jar was analyzed for CO_2 and O_2 using gas chromatographic techniques after 3-, 6-, 10-, 13-, and 18-d incubation. Carbon dioxide and O_2 concentrations were determined using a thermal conductivity detector at an operating temperature of 110°C, a column oven temperature of 60°C, and helium as a carrier gas. The column packing material used for CO_2 detection was Porapak Q (50/80 mesh) with a precolumn containing $CaCl_2$ (8 mesh) for trapping water vapor. The column packing material used for O_2 detection was Molecular Sieve 5A.

To further evaluate the relationship between WFP and soil microbial activity, determinations were made of CO_2, N_2O, soil water content, bulk density, NO_3^--N, water-soluble C, and temperature from surface soils of long-term tillage comparison experiments at four locations across the U.S. At all locations, soils subject to no-tillage methods were compared to those with plowing. Climatic, soil, and cropping management characteristics for each site are given in Table 2. Tillage treatments at all locations were replicated four times in randomized, complete block design, and the crop was continuous corn (*Zea mays* L.) receiving NH_4NO_3 fertilizer at rates recommended for optimum crop production.

Carbon dioxide and N_2O production were measured at two sampling depths, 0 to 75 mm, and 75 to 150 mm. Gas sampling cans, 65 mm diam, with bottoms removed, were pushed 75 mm into the soil and stoppered with a rubber serum stopper. Cans were installed at the 75- to 150-mm depth by removing the 0- to 75-mm layer of soil, sealing the cans with a rubber stopper, and recovering them with surface soil. Initiation of the incubation period for gas sampling was begun, approximately 24 h later, by flushing the headspace of cans at the second depth with air and then sealing cans for both depths with rubber stoppers. Headspace atmosphere was sampled after 24-h incubation and immediately analyzed for CO_2 and N_2O content. Nitrous oxide content was determined with a ^{63}Ni electron capture detector at an operating temperature of 350°C with argon/methane (95:5 ratio) as the carrier gas. Three gas sampling cans were placed in each plot at the 0- to 75- mm depth and two at the 75- to 150-mm sampling depth at each location. At every location, the gas sampling cans were placed midway between corn rows and in a portion of the plot which appeared representative of the whole plot.

Soil temperatures at midpoint for each sampling depth during the 24-h period were determined using min/max thermometers placed into the soil near the gas sampling cans. At the Minnesota location, however, soil temperatures were

Table 2—Climatic, soil, and cropping/management characteristics of the experimental field sites comparing no tillage with moldboard plowing.

Location	Soil series (classification)	Conventional tillage method (depth)†	Years comparison in corn, previous cropping	Nitrogen fertilizer (kg N/ha)
Waseca, MN	Webster clay loam (Typic Haplaquolls)	Fall plow (200–250 mm) Spr. cult. with mulch harrow	7 yr, Continuous corn	190
Elwood, IL	Blount silt loam (Aeric Ochraqualfs)	Fall disk (150 mm) Spr. plow (200 mm) Spr. disk (75–100 mm)	9 yr, Continuous corn	0 & 179
Lexington, KY	Maury silt loam (Typic Paleudalfs)	Spr. plow (200 mm) disked twice prior to planting	11 yr, 50–60 yr, Bluegrass sod	0 & 168
Lincoln, NE	Crete-Butler silty clay loam (Pachic Argiustolls-Abruptic Argiaquolls)	Spr. plow (200 mm) disked twice prior to planting	5 yr, Soybeans	0 & 140

† Spr. cult. = spring cultivation, Spr. plow = spring moldboard plow, Spr. disk = spring disk. Values in parentheses represent depth of tillage in mm.

[3] Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the USDA and does not imply its approval to the exclusion of other products or vendors that may be suitable.

obtained for the 100-mm soil depth only. Gravimetric water content (θ_m), water-soluble C, and NO_3^--N levels in soil were determined on samples taken at the time of soil gas analyses as described by Linn and Doran (1984).

Soil bulk density (P_B) determinations were made on the undisturbed soil contained in each gas sampling can. After CO_2 and N_2O sampling was completed, cans were carefully removed from the plots, weighed, and the volume of each soil core determined. Soil was then removed from each can, mixed thoroughly, and a subsample removed for θ_m determination. Individual bulk density and replicate tillage treatment θ_m values were used to determine WFP for each soil core at the time of CO_2 sampling, using the equation:

$$\% \text{ WFP} = (\theta_v/\text{TP})(100)$$

where θ_v = percent volumetric water content = ($\% \theta_m$) (P_B), and TP = percent total soil porosity = $(1 - P_B/P_P)$ (100), where P_P = soil particle density—assumed to be 2.65 Mg/m^3, P_B = soil bulk density (Mg/m^3), and θ_m = gravimetric water content (g/g).

RESULTS

Under laboratory conditions, microbial respiration, as estimated by CO_2 production and O_2 uptake, from residue-amended Crete-Butler soil was maximum at soil water contents equivalent to 60% WFP (Table 3). Trends in CO_2 production and O_2 consumption with increasing % WFP were similar between soils compacted to bulk densities of either 1.14 Mg/m^3 or 1.40 Mg/m^3, although total respiration was slightly greater at 1.14 Mg/m^3. The respiratory quotients for soils incubated at 65% WFP or below ranged from 0.9 to 1.1 and are characteristic of aerobic microbial respiration. The increase in respiratory quotients to values of 1.3 to 1.7 at water contents above 78 to 90% WFP indicates a shift towards anaerobic metabolism. These results agree with those of Bridge and Rixon (1976), who reported maximum aerobic respiration in three Australian soils at air porosities of 8 to 16% (equivalent to 62 to 78% WFP). At higher water contents, reduced oxygen diffusion resulted in increased anaerobic respiration as indicated by an increase in respiratory quotients to values considerably greater than one.

In the field evaluations, % WFP of no-tillage soils at the 0- to 75-mm sampling depth averaged 62%, whereas that for plowed soils averaged 44% (Tables 4 and 5). The % WFP values at the 75- to 150-mm sampling depth, while not significantly different at every location, did follow the same trends noted for the surface soil. There was no significant effect from N fertilization at either sampling depth. Average % WFP for all locations at the 75- to 150-mm sampling depth was 69% and 57% for no-tillage and plow treatments, respectively.

The greater WFP of the no-tillage soils is a reflection of their higher soil water contents and/or bulk densities in comparison to the plowed soils (Tables and 4 and 5). Furthermore, the importance of soil water content and bulk density as independent variables influencing % WFP should be stressed. For example, at both the Minnesota and Nebraska locations, water contents of soil from the two tillage treatments at the 0- to 75-mm sampling depth were not significantly different. This resulted from rainfall events and cool weather prior to sampling (22.4 mm of rain 48 h before sampling and 26.4 mm of rain 72 h before sampling at the Minnesota and Nebraska locations, respectively); however, as a result of significant differences in soil bulk densities between tillage treatments at these locations, the differences in % WFP between no-tillage and plowed soils were significant. The reverse case, in which bulk density values for no tillage were the same or lower, while soil water contents were higher than those for plowed soils, can be noted from data for the 0- to 75-mm sampling depth at the Kentucky location. Here also, the % WFP for the no-tillage treatment was significantly higher than that for plowing.

Table 3—Oxygen uptake, CO_2 production, and respiratory quotients (RQ) of a residue-amended silty clay loam as related to % WFP and soil bulk density.

Bulk density, % WFP	Gas concentrations on days† O_2 3	O_2 13	CO_2 3	CO_2 13	RQ‡ on day 3	RQ‡ on day 13
			1.40 Mg/m^3			
30	19.8	18.9	1.2	2.4	1.0	1.1
53	15.6	10.6	5.8	10.2	1.1	1.0
60	14.7	7.6	7.0	13.2	1.1	1.0
64	15.8	10.3	5.5	10.5	1.1	1.0
78	19.7	16.7	1.3	5.4	1.0	1.3
89	19.7	17.7	1.3	5.4	1.0	1.6
97	20.3	18.0	0.9	4.8	1.3	1.6
			1.14 Mg/m^3			
20	19.3	18.0	1.6	3.3	0.9	1.1
40	14.5	8.0	6.9	12.5	1.1	1.0
53	16.0	9.7	5.4	10.8	1.1	1.0
60	13.3	4.0	7.4	15.4	1.0	0.9
65	17.3	10.7	3.9	10.0	1.1	1.0
80	19.4	15.7	2.3	7.4	1.4	1.4
97	20.3	17.4	0.9	6.1	1.3	1.7

† Initial CO_2 and O_2 concentrations in the incubation chamber headspace at time 0 were 0.025% and 21.0%, respectively.
‡ RQ values represent the quotient of CO_2 produced divided by O_2 consumed.

Carbon dioxide production from soil for the 0- to 75-mm sampling depth, for both fertilized and nonfertilized soils, was highly correlated with % WFP (r = 0.892, $p < 0.001$), and the amount of CO_2 produced from no-tillage soils at all locations except Kentucky averaged 3.7 times greater than that from plowed soils (Tables 4 and 5). There was no significant ($p <$ 0.1) correlation between water-soluble C levels and CO_2 production at the 0- to 75-mm depth, although soluble C levels with no tillage tended to be higher than those with plowing. At the Kentucky location, the WFP values for both the plowed and no-tillage soils were close to the water content for maximum aerobic activity (60% WFP), and this was the only location for which CO_2 production from no-tillage soils (0–75 mm) was not significantly greater than that from plowed soils.

Although there was little or no difference in CO_2 production between tillage treatments at the 75- to 150-mm sampling depth, there was a trend for greater CO_2 production and water-soluble C levels in plowed soils. Values of % WFP for no-tillage soils were generally close to 70%, whereas plowed soils ranged from 50 to 60%. Based on results from the laboratory study, production of CO_2 at this depth would be greater for plowed soils, which had water contents closer to 60% WFP.

Table 4—Soil physical and chemical characteristics and CO_2 and N_2O production from no-tillage and plowed soils at four U.S. locations. Results from 1981, N fertilizer added.

Sampling depth, location	Tillage treatment	Median soil temperature	Bulk density	Soil water content (g/g)	WFP	CO_2†	N_2O†	Water-soluble C	NO_3^--N
		°C	Mg/m³	%		mg/L	μg/L	g/m³	
0 to 75 mm									
Illinois	No till	26.6	1.46‡	20.2	65.4*	33.2*	35.0‡	104‡	81
	Plow	31.6	1.35	12.3	36.5	6.9	1.1	76	82
Kentucky	No till	23.8	1.26	27.3*	66.4‡	27.3	27.3	191	31*
	Plow	24.8	1.36	19.4	54.6	21.4	61.4	150	68
Nebraska	No till	21.4	1.26**	23.5	57.1**	14.5**	79.6§	244	27
	Plow	21.6	1.04	24.2	40.9	3.7	7.1	154	33
Minnesota	No till	18.2	1.00**	34.9	56.6‡	15.3*	72.7**	167	72
	Plow	18.6	0.89	36.3	49.2	8.3	14.9	154	71
75 to 150 mm									
Illinois	No till	24.0	1.50*	19.6‡	69.2*	15.7	9.0	121	23
	Plow	25.6	1.39	17.3	50.6	18.5	12.1	113	22
Kentucky	No till	23.6	1.42**	22.4*	68.2*	20.2	41.1§	93	41*
	Plow	23.7	1.33	19.1	51.2	23.4	5.4	129	56
Nebraska	No till	21.0	1.31‡	23.2**	60.3	5.1	73.4*	143	48
	Plow	20.6	1.18	25.2	53.6	5.3	39.3	213	62
Minnesota	No till	18.2	1.19	32.5**	70.7	8.3	70.0§	175	54
	Plow	18.6	0.99	38.2	60.3	12.2	49.8	195	52

* $p < 0.05$, ** $p < 0.01$.
† Gaseous concentrations in reservoir headspace (0.124 L) after 24 h under ambient field conditions.
‡ $p < 0.10$; § $p < 0.20$: Levels of significance pertain to comparisons of no tillage with plow within locations and sampling depths.

Nitrous oxide production from the 0- to 75-mm sampling depth was related to changes in % WFP in a manner similar to that for CO_2 production. At all locations, except Kentucky, N_2O production from N-fertilized, no-tillage soils was 9.4 times greater than with conventional tillage (Table 4). Nitrous oxide production from nonfertilized soil was slightly greater for no tillage and highly correlated ($p < 0.01$, $r = 0.983$) with water-soluble C, but amounts produced over 24 h were much lower than those from fertilized soil (Table 5). There was no correlation between N_2O production and soil NO_3^- levels, although NO_3^- levels in plowed soils were often higher than those with no tillage.

The production of N_2O from the N-fertilized Maury soil in Kentucky was significantly affected by differences in % WFP between replicates with conventional tillage. The average value of 61.4 μg/L listed in Table 4 was mainly due to the amount of N_2O produced from only one replicate which had a WFP of 65.6% (234.5 μg/L N_2O was produced from this replicate vs. an average of 3.7 μg/L from the remaining three replicates at 50.9% WFP). Removing this replicate from consideration for both tillage treatments at the Kentucky location results in a difference of 33.0 vs. 3.7 μg/L N_2O at % WFP values of 65.4% and 50.9% for the no-tillage and plow treatments, respectively. These values are more in line with the observations at the other locations and illustrate the importance of % WFP as a factor regulating N_2O production from soil.

Nitrous oxide production at 75 to 150 mm, for both fertilized and nonfertilized soils, was generally greater for no-tillage than for plowed soils. Exceptions to this trend, noted at the Illinois (fertilized) and Nebraska (nonfertilized) sites, could not be explained by differences in water-soluble C or NO_3^- levels between tillage

Table 5—Soil physical and chemical characteristics and CO_2 and N_2O production from no-tillage and plowed soils at three U.S. locations. Results from 1981, no N fertilizer added.

Sampling depth, location	Tillage treatment	Median soil temperature	Bulk density	Soil water content (g/g)	WFP	CO_2†	N_2O†	Water-soluble C	NO_3^--N
		°C	Mg/m³	%		mg/L	μg/L	g/m³	
0 to 75 mm									
Illinois	No till	28.2	1.45*	18.2*	58.0*	27.1**	5.8	244‡	18.1
	Plow	31.8	1.32	12.8	33.8	6.9	0.7	92	27.1
Kentucky	No till	24.7	1.31**	27.4*	71.5*	34.4	4.8§	189	7.6
	Plow	25.4	1.37	19.7	56.2	20.6	1.8	106	7.3
Nebraska	No till	22.3	1.25*	25.1	59.6*	14.1*	6.4	253	5.5*
	Plow	22.4	0.98	24.5	38.2	3.5	2.5	151	8.7
75 to 150 mm									
Illinois	No till	24.4	1.54‡	18.8‡	69.1**	15.3	6.3§	94	9.4*
	Plow	26.5	1.44	17.4	55.4	17.5	1.9	119	12.0
Kentucky	No till	24.2	1.44§	23.8*	75.4*	24.6	3.9	128‡	5.4
	Plow	24.4	1.38	20.4	58.9	27.7	2.1	157	4.8
Nebraska	No till	21.3	1.36	24.2	67.5	4.5	5.2§	240	4.3*
	Plow	20.8	1.29	25.6	64.6	5.1	34.0	154	9.4

* $p < 0.05$, ** $p < 0.01$.
† Gaseous concentrations in reservoir headspace (0.124 L) after 24 h under ambient field conditions.
‡ $p < 0.10$; § $p < 0.20$: Levels of significance pertain to comparisons of no tillage with plow within locations and sampling depths.

practices. At the Kentucky location, NO_3^- levels were significantly lower in no-tillage soil, yet substantially more N_2O was produced than from the plowed soil. In contrast, at the Nebraska location, both soil NO_3^--N and N_2O production levels with no tillage were significantly lower than those with plowing (Table 5).

Soil temperature apparently had little influence on observed differences in CO_2 and N_2O production between tillage treatments. Production and release of N_2O and CO_2 generally increase with soil temperature because of increased biological activity and decreased gas solubility in the soil solution. Although slight differences at the 0- to 75- mm soil depth were evident between no-tillage and plow treatments (Tables 4 and 5), differences in soil temperatures were neither in the range nor of the magnitude necessary to explain observed differences in CO_2 or N_2O production from these soils. Moreover, if temperature were a critical factor, it would seem that plowed soils would have higher CO_2 and N_2O levels because of their warmer temperature, and this was not the case.

DISCUSSION

Among tillage-related differences in soil, the percentage of the soil pore space filled with water appears well correlated with aerobic microbial activity as estimated by CO_2 or N_2O production. In our study we did not determine if N_2O production resulted from microbial nitrification (Blackmer et al., 1980) or denitrification. Both of these processes can occur simultaneously in the range of soil water contents normally encountered in agricultural soils, but the relative importance of each process to gaseous N losses depends largely on soil water content and aeration status. Freney et al. (1979) found nitrification an important source of N_2O released from soil at low soil water contents (< 62% WFP). Aulakh et al. (1982) found N_2O production from cropped and fallowed Canadian soils resulted from both nitrification and denitrification. Total losses of gaseous N during the growing season, however, were twice as high for no tillage as compared with conventional tillage, and maximum losses from denitrification occurred shortly after rainfall when the soil air-filled porosity fell below 40% (or WFP > 60%). Other work suggests that significant denitrification losses from soil only occur when WFP exceeds 80% (Nommik, 1956). Since the soil water contents of the soils we studied were generally less than 70% WFP, we assume the majority of N_2O measured was produced from aerobic nitrification.

The % WFP in soil may be a useful indicator of the relative potential for aerobic and anaerobic microbial activity in soil. This is illustrated by the findings of several research studies as illustrated in Fig. 1. The relative rates of respiration (O_2 uptake and CO_2 production) and nitrification increase linearly with increasing soil water content to a maximum at 60% WFP and decrease thereafter. The relative activity of anaerobic denitrification, however, is negligible at 60% WFP, but increases with increasing water and reaches a maximum at saturation. Thus, soil aeration appears a major factor limiting microbial activity above 60% WFP with obligate aerobic processes declining most rapidly with increasing water. Between 30 and 60% WFP, and also between 60 and 70% WFP, the relationships between aerobic microbial processes and WFP appeared linear. To test these relationships with differences observed between tillage treatments in the field, we used the following functions to relate % WFP to relative aerobic activity:

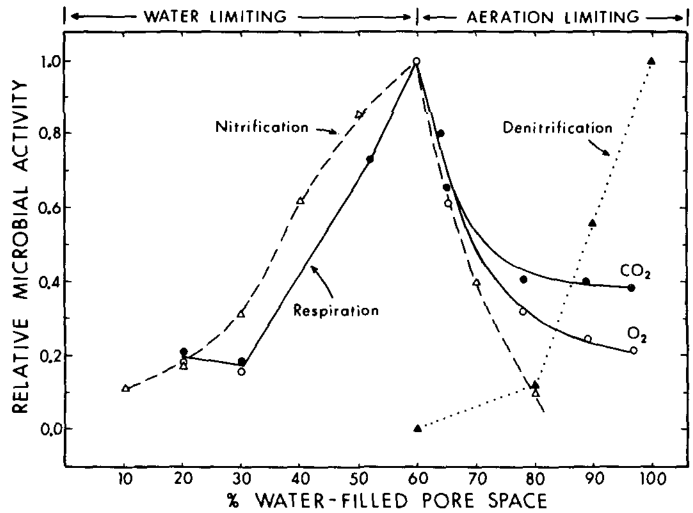

Fig. 1—The relationship between water-filled pore space and relative amount of microbial nitrification (after Greaves and Carter, 1920), denitrification (after Nommik, 1956), and respiration [O_2 uptake (O-O) and CO_2 production (●-●) as determined in this study]. Data for nitrification originally expressed as percentage water-holding capacity.

$$\text{Relative aerobic activity} = \%\ \text{WFP}/60\%\,,\quad \text{for WFP} < 60\%$$

and

$$= 60\%/\%\ \text{WFP}\,,\ \text{for } 60\% < \text{WFP} < 70\%\,.$$

If % WFP is a major factor influencing differences in aerobic microbial activity, regardless of tillage practice, then a graphical plot of the ratios of relative aerobic activities between tillage treatments vs. the ratios of CO_2 or N_2O produced (no tillage/plow) across locations should be linear.

As shown in Fig. 2, a significant linear response is observed for ratios of CO_2 and N_2O production when compared to ratios of relative aerobic activity between no tillage and conventional tillage across locations and sampling depths. Moreover, for CO_2 production, these data indicate that 90% of the variation between no-tillage and plowed soils was accounted for by differences in WFP, regardless of the application of N fertilizer. The correlations for N_2O production between N treatments, while not as high as for CO_2 production, also were statistically significant. Not unexpectedly, however, the presence or absence of additional fertilizer N is also a major factor, along with differences in WFP, in regulating N_2O production between tillage treatments. Thus, in the absence of N fertilizer, availability of soil N plays a greater part in regulating N_2O production, helping to explain the lower correlations for N_2O production in comparison to those for CO_2 production.

Percent WFP of a soil appears to be a reliable, and relatively simple, measurement for evaluating soil mi-

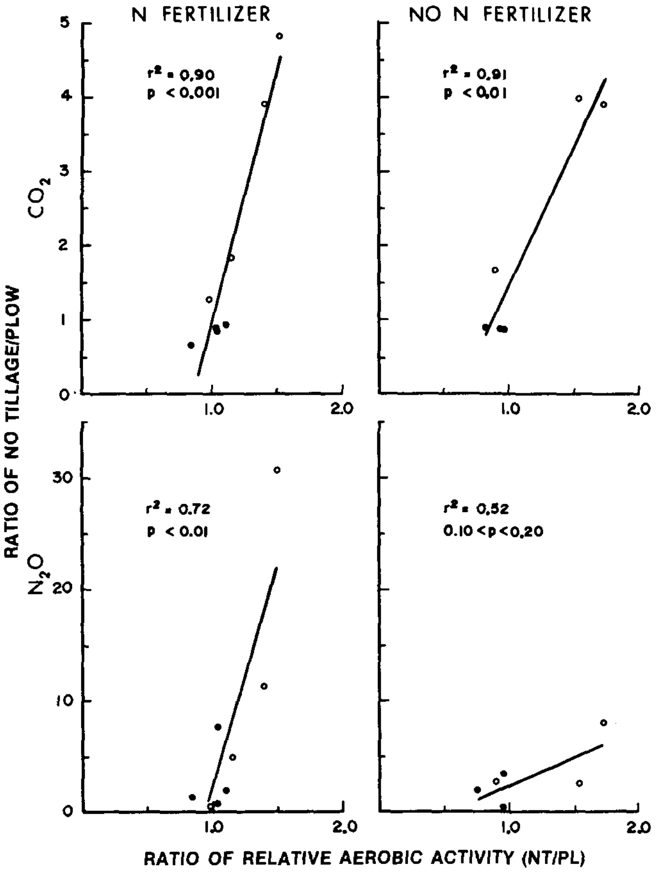

Fig. 2—Relationship between the ratios of no tillage over plow (NT/PL) for CO_2 and N_2O production vs. relative aerobic activity (NT/PL) from four U.S. locations (three locations for no N fertilizer). (○) 0- to 75-mm sampling depth values; (·) 75- to 150-mm sampling depth values.

crobial activity with respect to simultaneous effects of water content and aeration status. Thus, the percentage of soil pore space filled with water could be useful in determining the relative contributions of nitrification and denitrification to N_2O production and gaseous N losses from soil. Furthermore, the use of % WFP allows direct comparison of microbial activities between soils differing significantly in either bulk density or water content. Additional research is needed, however, to determine the full extent to which % WFP, over a range of soil textures and clay types, influences aerobic and anaerobic microbial activities. Similar studies evaluating the influence of WFP on crop growth and productivity are also needed to fully determine the extent to which this parameter can serve as a general index of soil productivity in varying climates.

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