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Microbial activity in response to water-filled pore space of variably eroded southern Piedmont soils

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Abstract

Potential C and N mineralization and soil microbial biomass C (SMBC) are soil biological properties important in understanding nutrient and organic matter dynamics. Knowledge of soil water content at a matric potential near field capacity is needed to determine these biological properties. The objective of this study was to examine whether adjustment of soil water content to a common level of water-filled pore space (WFPS) may be an acceptable alternative that would require little prior analysis in comparison with adjustment based on matric potential. Potential C and N mineralization and SMBC were determined from 15 variably eroded soils of the Madison–Cecil–Pacolet association (clayey, kaolinitic, thermic Typic Kanhapludults) in response to WFPS. The levels of WFPS to achieve maximum activity and biomass under naturally settled conditions were unaffected by clay content and occurred at 0.42±0.03 $m^3\ m^{-3}$ for net N mineralization during 24 days of incubation, 0.51±0.22 $m^3\ m^{-3}$ for specific respiratory activity of SMBC, 0.60±0.07 $m^3\ m^{-3}$ for cumulative C mineralization during 24 d of incubation, and 0.76±0.27 $m^3\ m^{-3}$ for SMBC. Selecting a common WFPS level of 0.5 $m^3\ m^{-3}$ resulted in 96±2%, 97±5%, 97±4%, and 88±10% of the maximum for these four properties, respectively, and was a reasonable compromise when attempting to estimate these properties during simultaneous incubations. Adjusting soil water content based on WFPS was simpler and nearly as reliable as based on matric potential, in which soil water content at −33 kPa varied from 0.16 to 0.30 $g\ g^{-1}$. © 1999 Elsevier Science B.V.

Keywords: Carbon mineralization; Microbial biomass; Nitrogen mineralization; Soil texture; Soil water

1. Introduction

Potential soil C and N mineralization and SMBC are important biological characteristics in understanding management-induced changes in soil fertility, C sequestration, and soil quality (Doran and Parkin, 1994, 1996). Soil microbial activity is known to be strongly influenced by soil water content (Parr et al., 1981). Soil CO_2 evolution increases with water additions above −5000 kPa (Wilson and Griffin, 1975) up to a maximum near −15 kPa (Miller and Johnson, 1964) and subsequently declines near saturation due to O_2 limitations (Skopp et al., 1990). Net N mineralization has been shown to follow a similar response to soil matric potential, although a stronger decrease in net N mineralization occurs near saturation compared with C mineralization (Miller and Johnson, 1964). Nitrate serves as an alternative electron acceptor when

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O_2 becomes limiting, resulting in the conversion of NO_3 to N_2 or N_2O via denitrification (Linn and Doran, 1984).

Gravimetric soil water content to achieve maximum C and N mineralization varies among soils, depending mainly upon soil texture and organic matter content (Stanford and Epstein, 1974; Howard and Howard, 1993). Expressing soil water content as matric potential, however, results in a unifying concept based on thermodynamics for predicting the potential of C and N mineralization (Sommers et al., 1981). Despite the strong relationships between matric potential and C and N mineralization, 20–40% of the variation remained unexplained and the matric potential to achieve maximum microbial activity ranged from -10 to -400 kPa for individual soils (Sommers et al., 1981).

Matric potential is logarithmically related to gravimetric soil water content with the relationship depending mainly upon soil texture and organic matter content (Cassman and Munns, 1980; Kladivko and Keeney, 1987). The water retention curve of a soil can also be altered with changes in the bulk density (Box and Taylor, 1962), suggesting that handling of soil (i.e., undisturbed cores vs. sieving and repacking) could be an important consideration when determining the water content to achieve maximum C and N mineralization. Unfortunately, bulk density has rarely been reported in many previous investigations regarding the effect of water on microbial activity. Although the concept of WFPS, which uses bulk density to calculate available porosity, has been used to explain microbial activity (Stanford and Epstein, 1974; Linn and Doran, 1984; Doran et al., 1988, 1990), the effect of altering bulk density on the relationship between WFPS and C and N mineralization has not been adequately differentiated from the effect of water alone (Torbert and Wood, 1992; Liebig et al., 1995). Water-filled pore space would be a more easily obtained property than the determination of gravimetric soil water content at a desired matric potential (e.g., -10 to -33 kPa).

The effect of soil water content on SMBC has been both positive and negative and certainly not been adequately defined, especially with consideration to the concept of WFPS (Wardle, 1992).

Soils of the southern Piedmont USA that were once sandy have been subjected to accelerated erosion for many years due to excessive cultivation (Langdale et al., 1992). Surface horizons of these eroded soils now contain various quantities of subsurface, clayey material mixed with the sandy surface material. The primary objective of this study was to determine whether a common level of WFPS could be used instead of a common matric potential to estimate maximum C and N mineralization, SMBC, and specific respiratory activity of SMBC for soils that vary in clay content, bulk density, and organic matter content, such as typically found on eroded southern Piedmont landscapes. A secondary objective was to relate the level of WFPS to achieve maximum microbial activity and biomass to clay content, bulk density, and matric potential.

2. Materials and methods

A variably eroded, 15 ha upland landscape near Farmington, GA (33°20′N, 83°23′W) with slopes ranging from 0 to 10% had been continuously conventionally cultivated (wheat, soybean, cotton) for several decades prior to the establishment of coastal bermudagrass (*Cynodon dactylon* L.) in 1991. Bermudagrass received ≈200 kg N ha^{-1} $year^{-1}$ and was grazed by steers. Mean annual temperature is 16.5°C, rainfall is 1250 mm, and potential evaporation is 1560 mm.

Soil was collected on 30 May 1996 with a 41 mm diameter auger to a depth of 0–10 cm at 15 locations that were selected to obtain a range in management and soil texture (Table 1). Soil samples were oven-dried at 37°C for several days and gently crushed to pass a 4.75 mm screen. Triplicate subsamples were further ground to <0.05 mm for analysis of total organic C and N using dry combustion. Soil pH and electrical conductivity were determined in 1:1.5 (w:v, soil:distilled water) mixtures (Smith and Doran, 1996). Electrical conductivity was very low in all soils (i.e., 0.01–0.02 dS m^{-1}). Clay content was determined using the hydrometer method (Gee and Bauder, 1986).

For each of the 15 soil samples, sixteen 50 g subsamples were weighed into 60 ml bottles (47 mm diameter). Water was added to the surface of each subsample (either 2.3, 5.7, 9.1, 11.4, 13.7, 16.0, 19.4, or 22.8 ml to naturally settled soils and 1.4, 3.6, 5.8,

Table 1
Soil characteristics of the 15 soil samples

Soil	Series	Clay	Sand	Depth of		Soil organic		pH	Inorganic N	Bulk density	
				Ap	Bt	C	N			Natural	Compressed
		(mg g^{-1})		(cm)		(mg g^{-1})			(μg g^{-1})	(Mg m^{-3})	
Mineral N											
1	Cecil LS	90	820	24	104	13.6±0.9	0.96±0.07	5.8	12	1.27±0.09	1.43±0.08
2	Madison SL	120	760	30	139	15.1±0.5	1.04±0.03	6.1	4	1.19±0.04	1.38±0.08
3	Pacolet SL	175	660	19	50	20.2±0.1	1.51±0.02	5.8	12	1.08±0.04	1.28±0.07
4	Cecil SL	190	710	13	128	10.7±0.3	0.71±0.02	5.9	10	1.24±0.08	1.49±0.09
5	Madison SCL	260	570	13	29	13.1±0.5	0.94±0.04	6.0	6	1.08±0.03	1.30±0.06
Clover+mineral N											
6	Appling LS	100	775	29	99	13.6±0.4	0.88±0.02	6.5	2	1.19±0.05	1.38±0.08
7	Madison SL	160	670	24	109	21.2±0.8	1.32±0.06	6.6	4	1.10±0.05	1.27±0.07
8	Grover SL	215	510	30	98	29.4±0.8	1.74±0.03	6.3	5	0.98±0.04	1.14±0.05
9	Grover SCL	255	540	14	102	17.4±1.2	1.20±0.08	6.5	4	1.06±0.04	1.27±0.09
10	Pacolet SCL	245	610	10	50	11.8±0.6	0.83±0.04	6.5	4	1.13±0.05	1.38±0.12
Broiler litter											
11	Pacolet LS	110	780	17	72	13.8±0.3	0.96±0.03	6.0	4	1.17±0.05	1.34±0.07
12	Madison SL	150	725	25	81	15.2±0.7	1.07±0.05	6.0	5	1.12±0.03	1.31±0.07
13	Madison SL	210	615	11	80	16.1±0.8	1.09±0.07	6.1	6	1.08±0.03	1.25±0.07
14	Cecil L	245	535	19	107	18.9±0.4	1.25±0.02	6.2	8	1.02±0.04	1.20±0.06
15	Madison SCL	330	490	15	67	16.4±1.0	1.25±0.07	6.1	11	0.97±0.04	1.15±0.05

7.2, 8.7, 10.1, 12.3, or 14.5 ml to compressed soils) to achieve a range of WFPS from ≈0.1–0.9 m^3 water m^{-3} pore space. Each subsample was placed into a 1 l canning jar along with a vial containing 10 ml of 0.5 M NaOH to trap evolved CO_2 and a vial of water to maintain humidity. Canning jars were sealed and incubated in the dark at 25°C for 45 days. Alkali traps were replaced at 3 and 10 days and were removed at the end of 24 days. Carbon mineralization was determined by titrating alkali to a phenolphthalein endpoint with 0.5 M HCl (Anderson, 1982). Basal soil respiration (BSR) was calculated as the linear rate of C mineralization during 10–24 days of incubation (Franzluebbers and Arshad, 1996).

At the end of 3 days of incubation, half of the subsamples were pressed by the thumb to increase bulk density from ≈1.1 Mg m^{-3} in a naturally settled condition to ≈1.3 Mg m^{-3} in a compressed condition (Table 1). The level of the soil was marked prior to reincubation and the volume of the soil was determined following the removal of soil at the end of 45 days. Volume was determined from the weight of water added to the marked level. WFPS was calculated from the equation:

$$\mathrm{WFPS} = (\mathrm{SWC} \times \mathrm{BD})/(1 - (\mathrm{BD}/\mathrm{PD}))$$

where, SWC is the soil water content (g g^{-1}), BD is the bulk density (Mg m^{-3}), and PD is the particle density (2.65 Mg m^{-3}).

At the end of 10 days of incubation, three cores (7 mm diameter) from each sample were collected with tared sections of a plastic drinking straw. Cores were composited (dry weight of 2.2±0.4 g), shaken with 10 ml of 2 M KCl for 30 min, and filtered and the extract was frozen until analyzed for inorganic N $(NO_3^- + NO_2^- + NH_4^+)$ using Cd reduction and salicylate autoanalyzer techniques (Bundy and Meisinger, 1994).

At the end of 24 days of incubation, the procedure for inorganic N accumulation was repeated. Following removal of soil for inorganic N on day 24, remaining soil was fumigated under vacuum with $CHCl_3$, vapors were removed the following day, the procedure for inorganic N accumulation was repeated, and the bottle of the soil was placed back into a canning jar along with alkali and water to determine the CO_2 evolution during 10 days of incubation at 25°C. Soil microbial biomass C was calculated as the CO_2–C evolved from fumigated soil without subtraction of a control divided by an efficiency factor of 0.41 (Voroney and Paul, 1984). Specific respiratory activity of SMBC was calculated by dividing BSR by SMBC.

At the end of 35 days of incubation (10 days following fumigation), a Whatman-42 filter paper (42 mm diameter) was placed on the soil with a 37 mm diameter galvanized flat washer (68 g) on top of the filter paper to ensure good contact. Soil and filter paper were incubated for 10 days at 25°C, wet weight was recorded, dried at 55°C for 24 h, dry weight was recorded, and soil matric potential was calculated from the following equations reported by Deka et al. (1995):

$$\log_{10}(-\psi_m) = 5.144 - 6.699M,\ \psi_m < -51.6\,\text{kPa}$$

$$\log_{10}(-\psi_m) = 2.383 - 1.309M,\ \psi_m > -51.6\,\text{kPa}$$

where, M is water content of paper (g g^{-1}).

Dry-aggregate distribution was determined from the fraction of whole soil (≈100 g) that was retained on a nest of sieves (1, 0.25, and 0.06 mm) shaken for 1 min.

Statistical analyses of the levels of WFPS and matric potential to achieve maximum microbial activity and biomass were performed using each of the 15 soil samples as observations. For graphical presentation only, five soil textural classes were averaged across the three management types. Regression analyses of the effect of WFPS and clay content on microbial activity were performed using SAS (SAS Institute Inc., 1990). The level of WFPS to achieve maximum microbial activity and biomass was estimated by taking the first derivative of a second-order polynomial function. Regression of biological properties (i.e., potential C and N mineralization, SMBC, and specific respiratory activity of SMBC) on matric potential used the general equation:

$$\text{biological property} = a \times e^{(k\times\psi)} + (b/\psi)$$

where a, b, and k are derived constants and ψ is the matric potential (kPa). This equation tended to have a broader optimum range than a more traditional polynomial equation on log-transformed matric potential, but provided better fit to the data. A paired t-test was used to differentiate soil bulk density effects on soil properties. Duncan's multiple range test was used to separate differences in optimum WFPS among biological properties. All effects were considered significant at $p<0.1$ unless otherwise indicated.

3. Results and discussion

3.1. Soil physical and chemical characteristics

Soil organic C and N were not related to clay content (r=0.16, Table 1). Clay content explained 58% and SOC explained a further 30% of the variation in soil bulk density under naturally settled conditions. The decrease in soil bulk density with increasing clay content was primarily due to the greater number of large aggregates with higher clay content (Fig. 1) that resulted in greater pore volume. Under compressed conditions, SOC explained 56% and clay explained a further 23% of the variation in soil bulk density. Soil organic C appeared to offer more resistance to compression than clay content. Under compressed conditions, an increase in clay or SOC of 10% of the observed range (i.e., 2 mg SOC or 24 mg clay g^{-1} soil) resulted in a decrease in soil bulk density of 0.028 and 0.017 Mg m^{-3}, respectively.

Although bulk density was not determined under undisturbed field conditions, a pedotransfer function based on sand, silt, clay, and soil organic matter (Rawls, 1983), indicated that soil bulk density under compressed condition would have been similar to those under field conditions. Undisturbed bulk density in the field was predicted to be 0.07±0.05 Mg m^{-3}

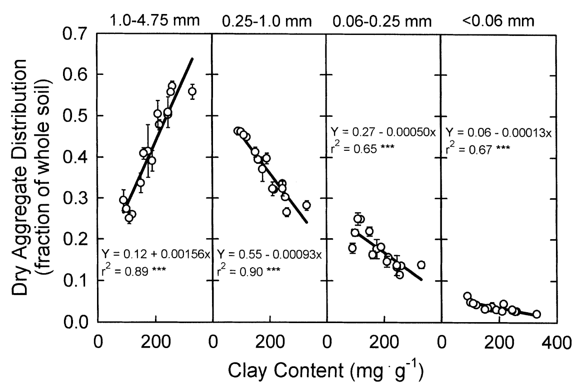

Fig. 1. Dry-aggregate distribution of soils as affected by clay content. Error bars are standard deviation of duplicate subsamples. *** indicates significance at $p \leq 0.001$.

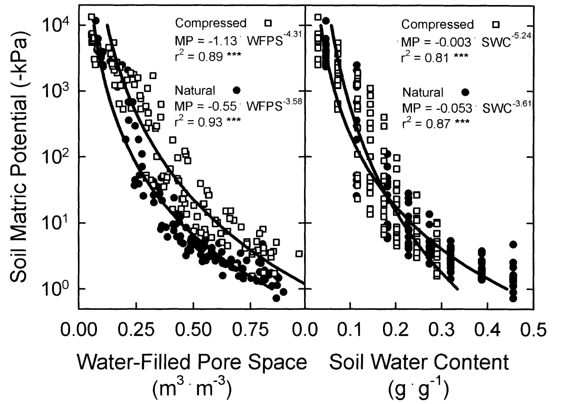

Fig. 2. Soil matric potential as affected by bulk density, WFPS, and soil water content. *** indicates significance at $p \leq 0.001$.

greater than the values under compressed condition. Rawls (1983) indicated that surface samples used to derive the equation were overpredicted by 0.05 Mg m^{-3}.

Soil matric potential was more negative under compressed than under naturally settled conditions at all levels of WFPS (Fig. 2), indicating that more of the available pores were filled with water at a given matric potential under compressed than under naturally settled conditions. The WFPS to achieve -10 kPa of matric potential was greater under compressed than under naturally settled conditions at all levels of clay content, although the difference increased with increasing clay content (Fig. 3). Gravimetric soil water content at -10 kPa was unaffected

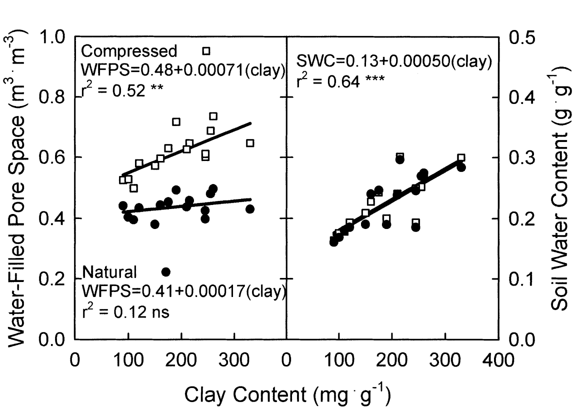

Fig. 3. WFPS and soil water content at a matric potential of -10 kPa as affected by bulk density and clay content. ** and *** indicate significance at $p \leq 0.01$ and $p \leq 0.001$, respectively.

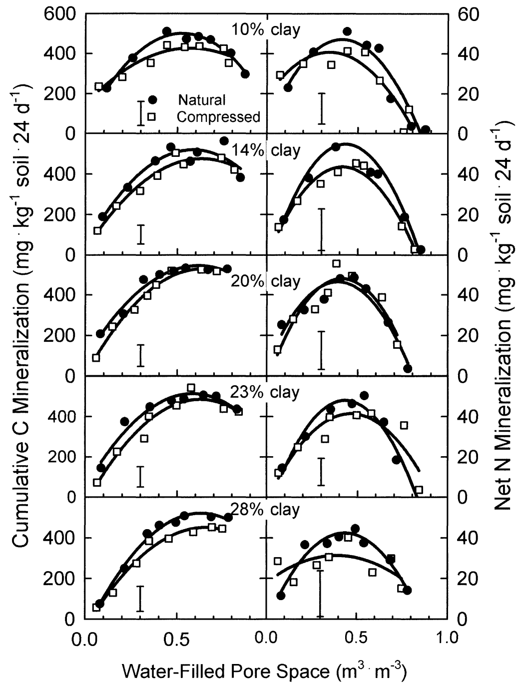

Fig. 4. Cumulative C mineralization and net N mineralization as affected by bulk density, clay content, and water-filled pore space. Observations are means of three soils. Error bars are LSD at $p \leq 0.05$.

by soil bulk density, but increased with increasing clay content. Using multiple regression, clay content explained 61% and SOC explained an additional 27% of the variation in gravimetric soil water content at -10 kPa, thereby confirming the importance of these two soil properties for water content–matric potential relationships (Gupta and Larson, 1979).

3.2. Potential carbon mineralization

Cumulative C mineralization during 24 days of incubation increased with increasing level of WFPS to a maximum between 0.53 and 0.66 m^3 m^{-3} for all soils (Fig. 4). Clay content had no effect on the level of WFPS to achieve maximum C mineralization under either bulk density regime, except during the period of 0–3 days, in which soils with higher clay content resulted in a higher optimum level of WFPS than soils lower in clay content (data not shown). However, soil matric potential to achieve maximum C mineralization during the periods of 0–3, 3–10, and 0–24 days

Table 2
Effect of soil bulk density (BD) on the level of WFPS and matric potential (ψ) for maximum microbial activity and biomass (n=15 for each property and BD)

	Naturally settled (BD=1.1±0.1 Mg m^{-3})			*T*-test	Compressed (BD=1.3±0.1 Mg m^{-3})		
	WFPS (m^3 m^{-3})		S.D.		WFPS (m^3 m^{-3})		S.D.
CMIN (0–3 days)	0.53	bc	0.06		N.D.		N.D.
CMIN (3–10 days)	0.62	b	0.06	***	0.51	cd	0.05
CMIN (10–24 days)	0.73	a	0.16	NS	0.78	a	0.18
CMIN (0–24 days)	0.60	bc	0.07	*	0.64	b	0.10
NMIN (0–10 days)	0.42	de	0.04	NS	0.44	d	0.05
NMIN (10–24 days)	0.38	e	0.13	NS	0.41	d	0.28
NMIN (0–24 days)	0.42	de	0.03	NS	0.42	d	0.21
SMBC	0.76	a	0.27	NS	0.87	a	0.15
SRAC	0.51	cd	0.22	NS	0.60	bc	0.28
	ψ (kPa)		S.D.		ψ (kPa)		S.D.
CMIN (0–3 days)	−8		6		N.D.		N.D.
CMIN (3–10 days)	−4		5	*	−2		3
CMIN (10–24 days)	−2		3	NS	−2		3
CMIN (0–24 days)	−5		5	NS	−4		5
NMIN (0–10 days)	−53		1	***	−102		1
NMIN (10–24 days)	−108		11	NS	−130		9
NMIN (0–24 days)	−51		2	*	−156		6
SMBC	−4		7	*	−1		4
SRAC	−9		13	NS	−22		14

CMIN is carbon mineralization, NMIN is nitrogen mineralization, SMBC is soil microbial biomass carbon, and SRAC is specific respiratory activity of SMBC.
Means within a column followed by the same letter are not significantly different at $p\leq0.05$. *, ** and *** indicate significance between bulk density regimes at $p\leq0.1$, $p\leq0.01$, and $p\leq0.001$, respectively.

increased with increasing clay content under naturally-settled conditions, but was unaffected by clay content under compressed conditions (data not shown).

The effect of bulk density regime on the level of WFPS or matric potential to achieve maximum C mineralization varied depending upon the time of incubation. Soils that were compressed achieved maximum C mineralization during the period of 3–10 days at a lower level of WFPS than under naturally settled conditions, but at a higher level of WFPS during the period of 0 to 24 days (Table 2). Bulk density regime had only a minor, but significant effect on the level of matric potential to achieve maximum C mineralization during the period of 3–10 days.

The level of WFPS to achieve maximum C mineralization increased during the course of incubation under both bulk density regimes (Table 2). This may have resulted from (1) C substrate limitations later in the incubation that may have resulted in the need for more water to move substrates to where they could be effectively utilized by microorganisms and/or (2) high C availability early in the incubation that may have reduced O_2 supply through high microbial consumption rather than through slow diffusion of O_2 through water.

When calculated as a fraction of maximum C mineralization for each of the 15 soil samples, relative C mineralization at WFPS levels of 0.3, 0.6, and 0.9 m^3 m^{-3} was 75±8%, 98±2%, and 76±17% of maximum, respectively, in this study. Doran et al. (1988, 1990) observed maximum C mineralization at these same WFPS levels of 53–69%, 96%, and 33–56% of maximum, respectively. The discrepancies in relative C mineralization at sub- and supra-optimal conditions between this study and Doran et al. (1988, 1990) may have been due to the method of determining CO_2 evolution. I used alkali absorption to keep head-space atmosphere at a low concentration, while they used head-space increase in CO_2 measured with a gas chromatograph. Also, this study extended the lower range of WFPS to $\approx 0.05\ m^3\ m^{-3}$ compared to $0.3\ m^3\ m^{-3}$ in the study of Doran et al. (1988, 1990). Averaged across clay contents and bulk density regimes, relative cumulative C mineralization during 24 days in this study approached zero at zero WFPS:

$$CMIN = 0.06 + 3.025(WFPS) - 2.4857(WFPS)^2, \quad r^2 = 0.80.$$

The increase in cumulative C mineralization from low to optimum WFPS was greater for soils with higher than with lower clay content (Fig. 4). Preferential adsorption of limited water to clay particles probably restricted microbial activity at very low levels of WFPS in soils with high clay content. However, cumulative C mineralization in soils with low clay content responded more negatively to increasing WFPS beyond the optimum WFPS level than in soils with high clay content. The greater response in cumulative C mineralization to WFPS in soils with increasing kaolinitic clay content in this study was similar to that observed for several predominantly montmorillonitic soils by Doran et al. (1988, 1990).

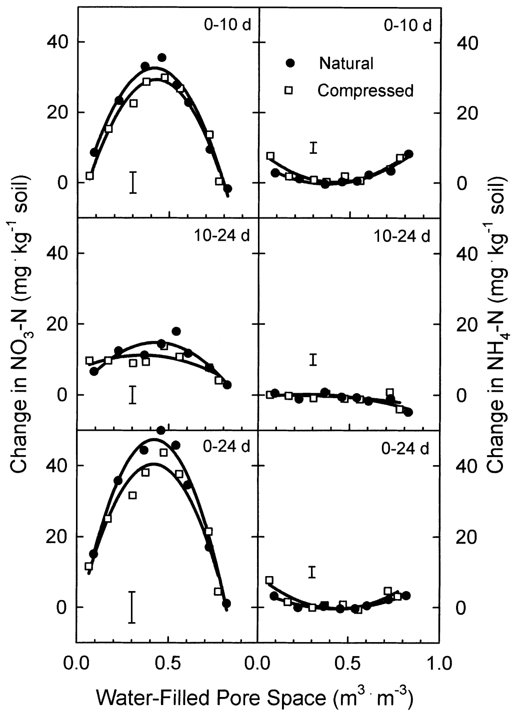

Fig. 5. Change in soil nitrate and ammonium concentrations as affected by bulk density, time of incubation, and WFPS. Observations are means of 15 soils. Error bars are LSD at $p \leq 0.05$.

3.3. Potential nitrogen mineralization

Unlike C mineralization, net N mineralization decreased sharply when exceeding the optimum WFPS level and approached zero at values near $0.8–0.9\ m^3\ m^{-3}$ (Fig. 4). At high WFPS levels, NO_3–N decreased dramatically (Fig. 5), likely due to denitrification that occurs at WFPS $>0.7\ m^3\ m^{-3}$ (Doran et al., 1988, 1990). Accumulation of a small quantity of NH_4–N occurred at WFPS levels $>0.7\ m^3\ m^{-3}$, which was also observed in two of ten soils investigated by Stanford and Epstein (1974), indicating restricted O_2 diffusion through water that inhibited nitrification (Linn and Doran, 1984).

Like cumulative C mineralization, net N mineralization at very low WFPS levels was lower in soils with high clay content than those with low clay content. Net N mineralization during 24 days increased sharply up to a WFPS level of $0.42\ m^3\ m^{-3}$, independent of clay content. However, for the 0–10 and 10–24 day periods the level of WFPS to achieve maximum net N mineralization increased slightly with increasing clay content (data not shown). Clay content had no effect on the matric potential to achieve maximum net N mineralization during any time period (data not shown). Only for the 0–24 days period of incubation was the level of WFPS or matric potential to achieve maximize net N mineralization independent of clay content.

The level of WFPS to achieve maximum net N mineralization during 24 days was lower than that to achieve maximum C mineralization and ranged from 0.34 to $0.46\ m^3\ m^{-3}$ (Fig. 4). These optimum WFPS values are much lower than those calculated from the data of Stanford and Epstein (1974), where maximum net N mineralization during 14 days at 35°C was achieved at WFPS levels of $0.79 \pm 0.18\ m^3\ m^{-3}$. Soils in the study of Stanford and Epstein (1974) had higher bulk densities (1.5 ± 0.2 mg m^{-3}) than in this study, despite similar to higher clay and organic matter contents. In this study, aggregation was preserved (Fig. 1) by gently crushing soil to pass a 4.75 mm screen. In the study of Stanford and Epstein (1974) soil was ground finely and water was stirred into soil for more complete homogenization. From 18 benchmark soils, the level of WFPS to achieve maximum net N mineralization was 0.6±0.1 $m^3\ m^{-3}$, similar to that needed to maximize C mineralization, when soils were packed to native densities of 1.1±0.1 Mg m^{-3} (Doran et al., 1988, 1990).

Similar to that of WFPS, the matric potential to achieve maximum net N mineralization (−51 kPa) was lower than that to achieve maximum C mineralization (−5 kPa) (Table 2). When data were characterized using the same non-linear equation as in this study, the matric potential to achieve maximum net N mineralization during 14 days at 30°C was −85± 2 kPa and to achieve maximum C mineralization was −2±4 kPa in four different soils (Miller and Johnson, 1964). Many other studies have investigated the optimum matric potential to achieve either maximum N or C mineralization, but few have determined both simultaneously.

Maximum net N mineralization for soil under naturally settled condition was an average 11% greater than under compressed condition. Reduced N and C mineralization when soil was compressed could not be easily explained, but deserves further investigation. Compression of soil had no effect on the level of WFPS to achieve maximum net N mineralization in comparison with the naturally settled condition, but decreased the matric potential to achieve maximum net N mineralization during the periods of 0–10 and 0–24 days (Table 2).

3.4. Soil microbial biomass carbon (SMBC)

Soil microbial biomass C responded nearly linearly to increasing WFPS with optimum WFPS levels ranging from 0.65 to 1.0 $m^3\ m^{-3}$ (Fig. 6). There was no evidence of reduced SMBC near saturation as was observed for cumulative C and net N mineralization. Soil microbial biomass C under naturally settled conditions was greater at low levels of WFPS than when soil was compressed, but similar at high levels of WFPS, irrespective of clay content. This effect was also observed for cumulative C and net N mineralization, but not consistently across clay contents.

The level of WFPS to achieve maximum SMBC was greater than that to achieve maximum C or N mineralization (Table 2). However, the matric potential to achieve maximum SMBC was similar to the

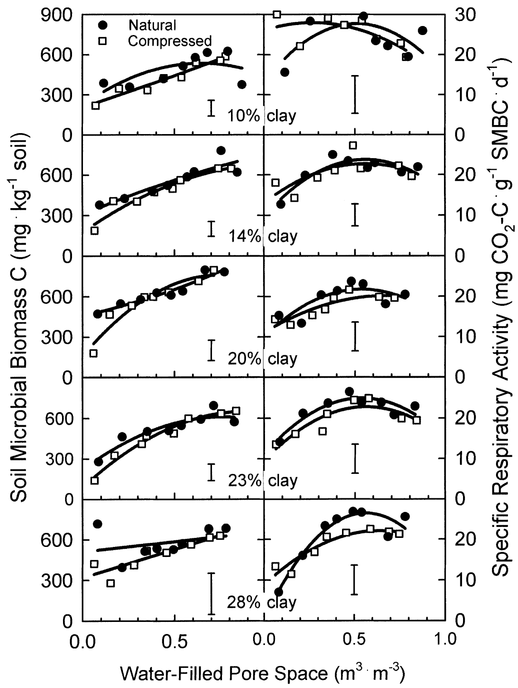

Fig. 6. Soil microbial biomass C and specific respiratory activity of SMBC as affected by bulk density, clay content, and WFPS. Observations are means of three soils. Error bas are LSD at $p \leq 0.05$.

matric potential to achieve maximum C mineralization, but higher than the matric potential to achieve maximum net N mineralization. Little information is available in the literature regarding the effect of WFPS and matric potential on SMBC.

Maximum specific respiratory activity of SMBC was achieved at WFPS levels ranging between 0.27 and 0.68 $m^3\ m^{-3}$ (Fig. 6). Specific respiratory activity of SMBC generally reflected the differences in cumulative C mineralization as affected by soil bulk density and clay content. In particular, specific respiratory activity of SMBC was higher at low levels of WFPS in soils low in kaolinitic clay content than in soils high in clay content, similar to that reported for montmorillonitic soils in Texas (Franzluebbers et al., 1996), but more similar among soils at high levels of WFPS (Fig. 6). Differences in substrate utilization, efficiency, and competition among fungi, bacteria, actinomycets, protozoa, etc. under different water regimes may also have contributed to different respiratory activities.

The level of WFPS or matric potential to achieve maximum SMBC and specific respiratory activity of SMBC was unaffected by clay content (data not shown). Compression of soil had no effect on the level of WFPS to achieve maximum SMBC and specific respiratory activity of SMBC in comparison with soil under naturally settled conditions, but increased the matric potential to achieve maximum SMBC. Coefficients of variation of the levels of WFPS and matric potential to achieve maximum SMBC and specific respiratory activity of SMBC were higher than for cumulative C and net N mineralization.

3.5. Selection of a common level of WFPS or matric potential

In many soil ecological studies it would be of interest to determine a suite of biological properties, including cumulative C and net N mineralization, SMBC, and specific respiratory activity of SMBC to understand better the active organic matter dynamics. The level of WFPS or matric potential to achieve maximum microbial activity and biomass varied mostly due to the biological property under investigation, to some extent on the incubation period and level of compaction, and to the least extent on the clay content. For example, if the level of WFPS were selected to maximize SMBC of soil under naturally settled conditions (i.e., 0.76 $m^3 m^{-3}$ or −4 kPa), net N mineralization would have been only 32±19% of its maximum potential based on WFPS and 76±7% based on matric potential, resulting in serious discrepancies.

The level of WFPS to achieve estimates of maximum microbial biomass and activity was rarely affected by level of bulk density, suggesting that bulk density under naturally settled condition in the laboratory could be used as a standard method. Further, variation in optimum WFPS was usually less under naturally settled compared with compressed condition. Maximum microbial biomass and activity under naturally settled conditions in the laboratory should

Table 3
Effect of soil bulk density (BD) and selection of a common level of WFPS, ($m^3 m^{-3}$) and matric potential (ψ, kPa) on the fraction of maximum microbial activity and biomass (n=15 for each property and BD)

	Naturally settled (BD=1.1±0.1 Mg m^{-3})		*T*-test	Compressed (BD=1.3±0.1 Mg m^{-3})	
	WFPS=0.5	S.D.		WFPS=0.5	S.D.
CMIN (0–3 d)	0.97	0.06		N.D.	N.D.
CMIN (3–10 d)	0.96	0.03	**	0.99	0.01
CMIN (10–24 d)	0.90	0.08	*	0.84	0.16
CMIN (0–24 d)	0.97	0.04	*	0.95	0.05
NMIN (0–10 d)	0.96	0.03	NS	0.96	0.03
NMIN (10–24 d)	0.94	0.06	*	0.77	0.28
NMIN (0–24 d)	0.96	0.02	*	0.90	0.11
SMBC	0.88	0.10	NS	0.81	0.11
SRAC	0.97	0.05	NS	0.91	0.12
	ψ=−33	S.D.		ψ=−33	S.D.
CMIN (0–3 d)	0.99	0.01		N.D.	N.D.
CMIN (3–10 d)	0.99	0.01	NS	0.99	0.01
CMIN (10–24 d)	0.99	0.02	NS	0.99	0.01
CMIN (0–24 d)	0.99	0.01	NS	0.99	0.01
NMIN (0–10 d)	0.99	0.01	***	0.96	0.03
NMIN (10–24 d)	0.97	0.03	*	0.94	0.05
NMIN (0–24 d)	0.99	0.01	***	0.96	0.03
SMBC	>0.99	<0.01	NS	0.99	<0.01
SRAC	>0.99	<0.01	NS	0.99	0.01

CMIN is carbon mineralization, NMIN is nitrogen mineralization, SMBC is soil microbial biomass carbon, and SRAC is specific respiratory activity of SMBC.
*, ** and *** indicate significance at $p \leq 0.1$, $p \leq 0.01$, and $p \leq 0.001$, respectively.

therefore, be related to those under field conditions. However, the phenomenon of lower C and N mineralization under compression compared with naturally settled conditions needs to be investigated further to understand the difference in processes under disturbed and undisturbed conditions.

Selection of a WFPS level of 0.5 m^3 m^{-3} or a matric potential of -33 kPa was optimum for most microbial properties under varying conditions of incubation period, bulk density, and clay content (Table 3). Although adjusting soil water content based on a common matric potential (e.g., -33 kPa) may be thermodynamically more appropriate than based on a common level of WFPS (Sommers et al., 1981), adjustment of soil water content based on WFPS is a simpler, and yet, acceptable alternative that can be used for soils collected from eroded landscapes with large variations in clay and organic matter contents. The results from this study could be extended to encompass comparisons of microbial biomass and activity from different geographical regions with various soil textures, organic matter contents, and structural integrity, since clay and soil organic matter contents varied widely in this study and are the main determinants of water availability to microorganisms among soils. Determination of soil water content at a common matric potential for soils varying in clay and organic matter contents would be a time-consuming prerequisite in spatially diverse ecological studies. WFPS, however, requires only that the volume of soil be known, which can be readily determined.

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