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Microbial Respiration and Organic Carbon Indicate Nutrient Cycling Recovery in Reclaimed Soils

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ABSTRACT

Soil quality and the ability of soil to sustain nutrient cycling in drastically disturbed ecosystems will influence the establishment and maintenance of a permanent and stable plant community. We undertook research to evaluate a recently developed method to assess soil quality and nutrient cycling potential in a series of reclaimed soils. The method involves correlating the 3-d flush of microbial respiration after a soil is rewetted against a range of soil biological parameters. Soils were sampled from a number of reclaimed coal mines, a reclaimed uranium mine, and native, undisturbed prairie. All sites were located in semiarid Wyoming. Soils were dried at 55°C, rewetted, and microbial respiration measured at 3 d ($Cmin_{0–3d}$) and 21 d ($Cmin_{0–21d}$). In addition, microbial biomass C (MBC), N mineralization ($Nmin_{0–21d}$), soil organic C (SOC), and total N were also measured. Correlations between $Cmin_{0–3d}$ and the measured soil parameters in reclaimed and native soils were generally strong ($r^2 \geq 0.45$) and highly significant ($P = 0.0001$). Differences between reclaimed and native soils were observed, with native soils exhibiting more variability, possibly due to: differences in soil homogeneity/heterogeneity, the relative lability of the substrates present; different microbial communities; and differences in soil structural properties. Correlations between $Cmin_{0–3d}$ and the measured soil parameters in spoil material, while significant, were less well correlated. We believe this method is a relatively fast, accurate, and economical means by which soil quality and nutrient cycling can be ascertained. We estimated that a minimum concentration of 0.52% SOC or 0.89% soil organic matter (SOM) is necessary to sustain an adequate level of nutrient cycling in these reclaimed soils.

With the enacting of the Surface Mining Control and Reclamation Act in 1977, surface coal mining companies were mandated to maximize reclamation success. This mandate, combined with new technology and research, has greatly enhanced reclamation success in surface coal mines (Schuman, 2002). However, and almost without exception, the requirements for, and evaluation of, successful reclamation have been based solely on characteristics of the re-established plant community. While from many viewpoints this may be considered 'successful reclamation', the soil aspects of reclamation have been, essentially, ignored. There can be little argument though that the quality of the soil resource has a considerable impact on the development of the plant community over both, the short- and long-term. The productivity and biodiversity of the plant community present on a reclaimed area will depend to a large degree on a range of soil physical, chemical, and biological variables (National Research Council, 1994) and the severe perturbations that occur in the strip mining process can severely impact these variables.

Arid and semiarid soils are characteristically low in SOM and nutrients (Jenny, 1930) and this inherently low soil fertility is further reduced by the mining process. In this process, the surface layers of soil (typically the A + B horizons) are removed, potentially stored for a period of time in large stockpiles where plant inputs are often minimal (particularly at depth), and then respread over regraded spoil material on these reconstructed sites. Soils are further altered, especially physically, during seedbed preparation. All of these operations result in the destruction of aggregates (Abdul-Kareem and McRae, 1984) leading to the rapid mineralization and subsequent decline of SOC. This loss of soil C is further exacerbated by the additional dilution of C and nutrients when the soils are salvaged and respread, as the much greater concentration of C and nutrients present in the A horizon are mixed with the B horizon. There is little in the way of literature as to the amount of SOC/SOM lost due to the removal and storage of topsoil, but it has been shown that there can be a decline in SOM (and by implication, N also) of anywhere between ~32 to 85% due to stockpiling (Abdul-Kareem and McRae, 1984). The topsoil salvage process results in SOM levels similar to long-term cropped, dryland systems (Haas et al., 1957).

The loss of SOM during the mining and reclamation processes is an issue that needs to be addressed because of its importance; as a nutrient pool, in determining water holding capacity, in macropore formation, and in micronutrient adsorption: all of which are important factors in establishing a sustainable, reclaimed ecosystem. Thus for many reasons it is important that tools be developed to assist those involved in mined land reclamation to quickly and accurately assess the quality of soil material used in the reclamation process. In conjunction with developing tools to monitor SOM, there is also a need to obtain estimates of the minimum levels of SOM necessary to maintain healthy and adequate nutrient cycling in these inherently infertile, reclaimed ecosystems.

A recent paper by Franzluebbers et al. (2000) reported strong correlations between $Cmin_{0–3d}$ after rewetting a soil, and a suite of other soil parameters (long-term microbial respiration, MBC, N mineralization, SOC, and total N) that are considered to be good indicators of a 'healthy' soil. This led us to postulate that the correlations between

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Abbreviations: $Cmin_{0–3d}$, three-day microbial respiration; $Cmin_{0–21d}$, 21-day microbial respiration; MBC, microbial biomass carbon; N_i, inorganic nitrogen; $Nmin_{0–21d}$, 21-day N mineralization; OM, organic matter; SOC, soil organic carbon; SOM, soil organic matter.

Table 1. Details of the reclaimed mine sites sampled. Sites 1 through 3 were located in the Powder River Basin of north-eastern Wyoming, and Site 4 was located in the Shirley Basin of central Wyoming. Climate data was obtained from the mines as well as from meteorological sites closest to the mine of interest (Wyoming Climate summaries, 2005).

Mine	2001 Precipitation	Mean annual precipitation	Mean max. temperature	Mean min. temperature	Latitude/Longitude
	mm		°C		
1	281	333	13.9	−0.4	N 43°39′/W 105°15′
2	403	396	14.4	0.3	N 44°10′/W 105°27′
3	277	299	13.9	−0.4	N 43°42′/W 105°14′
4	236	390	14.4	−0.9	N 42°17′/W 106°12′

$Cmin_{0–3d}$ and these soil parameters may be of use as a relatively quick, reliable, and economical way in which the quality and nutrient cycling potential of salvaged mine soils could be assessed. A study was initiated on a series of reclaimed surface coal mines located in the semiarid, Powder River Basin region of northeast Wyoming, USA, to determine whether the correlations between $Cmin_{0–3d}$ and these soil parameters could quickly and accurately assess soil quality in these disturbed ecosystems. The intent of this objective was not to investigate the influence of reclamation management techniques on these relationships, but rather whether there were relationships between $Cmin_{0–3d}$ and other standard soil quality assessment parameters, regardless of the management practices employed. The second objective of this study was to estimate the minimum amount of SOC (as a proxy for SOM) required to supply, through mineralization, adequate N for the re-established plant community.

MATERIALS AND METHODS

Field Description and Sampling Methods

The surface coal mines sampled are located in the Powder River Basin of northeastern Wyoming, USA, about 40 to 100 km south of Gillette and approximately 1400 m above sea-level. Climate and location details are shown in Table 1. All mines are currently operational, and the sites sampled were reclaimed using standard reclamation techniques and similar seed mixes of native species. Seed mixes used varied slightly from site to site, but included shrubs (Wyoming big sagebrush, *Artemisia tridentata* ssp. *wyomingensis*; fourwing saltbush, *Atriplex canescens*; rubber rabbitbrush, *Ericameria nauseosa*; winterfat, *Krascheninnikovia lanata*), C_3 grass species (western wheatgrass, *Pascopyrum smithii*; slender wheatgrass, *Elymus trachycaulus*; needleandthread, *Hesperostipa comata*), and the C_4 grass species (blue grama, *Bouteloua gracilis*). The native prairies sampled are classified as northern mixed-grass communities and represent the single largest remaining native grassland in the USA (Coupland, 1992).

In the summer of 2001 we sampled three, operating surface coal mines (Mines 1, 2, 3). At each mine, two permanent sampling sites were chosen to cover a range of reclamation practices. At each of the sites, three, 40-m transects were established. Each of the 40-m transects were sampled at 10-m intervals at soil depth increments of 0 to 2.5 and 2.5 to 15 cm. At each mine we also sampled a native, undisturbed, prairie, control site situated within a few kilometers of the reclaimed sites and that was representative of the reclaimed mine soil. The control sites were sampled in the same manner as the reclaimed sites. Soils were then air-dried and sieved (<2 mm) before analysis.

In addition, a reclaimed uranium mine (Mine 4) located in the Shirley Basin region of south-central Wyoming was sampled in the autumn of 2002. The site sampled on this mine had been reclaimed in the early 1970s using only spoil material and as a consequence, SOC was extremely low (0.10%) as was total N (0.018%) (Schuman et al., 1985). Soils were sampled using the same field design and procedures as used at the coal mine sites.

In 2001, peak production of aboveground vegetation was estimated on the reclaimed and undisturbed, native sites present at Mines 1, 2, and 3 (Table 2). At the 0- and 40-m locations along each of the three transects used to soil sample, all vegetation (with the exception of shrubs) was clipped within a 0.18 m^2 quadrat. Vegetation was placed in a paper bag and dried at 55°C to estimate aboveground biomass.

Laboratory Methods

After air-drying and sieving, all soils were analyzed for organic C, total N, microbial respiration, microbial biomass, and potential N mineralization. Total C and N were determined on a C/N analyzer (NA 2100 Protein, Carlo-Erba Instruments, Italy), after roller-grinding the soils overnight to a fine powder (90% of material passed through a 0.25-mm screen). Inorganic C was measured on a separate subsample of the finely ground soil using a modified pressure-calcimeter method (Sherrod et al., 2002), and organic C was calculated by subtracting inorganic C from total C. Analyses of N mineralization, microbial biomass and respiration were undertaken on soils that had been dried at 55°C for 48 h and then rewetted to a soil-water content of −0.05 MPa, resulting in about 50% water-filled pore space. The reason for drying soils at 55°C was to bring all soils to a more constant soil water content. Using approximately 50 g of soil, microbial respiration was measured using standard base trap methods (Zibilske, 1994) at 3 d ($Cmin_{0–3d}$) and 21 d ($Cmin_{0–21d}$). On a similar amount of soil, MBC was estimated using the chloroform-fumigation incubation method (Horwath and Paul, 1994) using a K_c of 0.41 (K_c is the fraction of MBC decomposed and released as CO_2–C in 10 d; Anderson and Domsch, 1978). Potential N mineralization ($Nmin_{0–21d}$) was determined on the same soil on which $Cmin_{0–21d}$ was measured, by calculating the difference in inorganic N (N_i; NO_3 +

Table 2. Annual aboveground biomass production and plant N-requirements (2001) at a series of reclaimed mine sites located in the Powder River Basin of north-eastern Wyoming.

Mine	Site	Biomass	N requirements
		kg ha^{-1}	kg N ha^{-1}
1	1	815	16.44
1	2	1140	15.42
1	Native	488	6.31
2	1†	978	13.64
2	2†	567	14.55
2	Native	590	10.56
3	1	1289	17.60
3	2	1231	15.20
3	Native	561	7.62

† Grazed before sampled for biomass.

NH_4) between Day 21 and Day 0. Soil N_i was measured on a autoanalyzer (TRAACS 800 System, Technicon Industrial Systems, New York) after extracting 10 g of dried soil (55°C for 48 h) with 50 mL of 1 *M* KCl.

On the 2001 and 2002 samples, and for the purposes of soil description, 40% of soil samples were analyzed for: soil texture using the hydrometer method (Gee and Bauder, 1986), pH was determined on a 1:5 soil/water suspension, and plant available P was evaluated using the bicarbonate-extractable P method (Kuo, 1996).

The dried vegetation was ground and a subsample was then roller-ground and analyzed for C and N using a C/N analyzer (NA 2100 Protein, Carlo-Erba Instruments, Italy). These data allowed us to estimate annual N uptake by the plant communities growing on these reclaimed and native sites.

Data Analyses

As we expected disparate responses from the two soils (reclaimed and native) and spoil material analyzed, because of their different physical, chemical, and biotic properties, separate regression analyses were undertaken for each material. The groupings were; (i) reclaimed soils (Mine-site; 1–1, 1–2, 2–1, 2–2, 3–1, 3–2); (ii) spoil material (4–1); and (iii) undisturbed, prairie soils on all four mines (1-Native, 2-Native, 3-Native, 4-Native). Regression analyses were performed between $Cmin_{0–3d}$ and; $Cmin_{0–21d}$, MBC, $Nmin_{0–21d}$, SOC and total N using the StatView statistical analysis program (Version 5.0; SAS Institute Inc., Cary, NC). The main focus of our evaluation was to investigate whether there were significant relationships between $Cmin_{0–3d}$ and the other soil variables measured in the reclaimed and native soils. As such, we were not interested, per se, as to whether there were significant differences between the relationships for reclaimed soils, native soils, and spoil material. Moreover, we were not interested in examining differences as to how various reclamation and/or management practices influenced these relationships and thus we made no attempt to examine these relationships.

RESULTS AND DISCUSSION

The reclaimed and native soils sampled in this experiment (exception was reclaimed Site 1 on Mine 4 (4–1) which had been reclaimed with spoil material) did not possess any physical or chemical characteristics that would have impeded microbially mediated processes. Soil pH was slightly acidic to slightly alkaline, that is, 5.7 to 8.2 (with most soils in the range of 6.2 to 8.0; Table 3), and SOC, total N, and bicarbonate extractable P of reclaimed soils, while variable, were generally comparable with those of native soils (Table 3). Site 1 located on Mine 4 had been reclaimed some 30 yr earlier using White River spoil material which contained very low inherent amounts of C, N, and P (Schuman et al., 1985). In the intervening years, plant inputs and deposition of aeolian material have increased the SOC and nutrient status of the top 2.5 cm while the lower depths (i.e., 2.5–15 cm) have exhibited little change (Table 3). The increases that did occur, were probably due to inputs from sloughed roots (Bowen, 2003).

The correlations between $Cmin_{0–3d}$ and all of the other parameters measured (Table 4) were significant for both the reclaimed and native soils (Fig. 1–5). While $Cmin_{0–3d}$ was significantly correlated with the other soil quality parameters in spoil material, they always exhibited lower correlations than either the reclaimed or native soils (Fig. 1–5). Correlations in reclaimed soils were generally less variable than the native soils (Fig. 1–5) and a number of possibilities may explain this phenomenon. First, the homogenizing effect of the various procedures associated with mining and reclamation processes. In these processes, the topsoil (A + B horizons) is removed in a single operation, typically stored for a period of time (several months to >20 yr), respread, tilled and then reseeded; all of which lead to a relatively uniform (both

Table 3. Physiochemical characteristics of reclaimed and native soils and spoil material of the Powder River (Sites 1–3) and Shirley (Site 4) Basins of Wyoming. Figures in parentheses are standard deviations.

Mine	Site	Reclamation age†	Topsoil treatment	Soil depth	Organic C	Total N	C/N	Phosphorus	pH	Texture
		yrs		cm	g kg soil^{-1}	g kg soil^{-1}		mg kg soil^{-1}		
1	1	16	Stockpile	0–2.5	46.3 (22.4)	2.34 (1.14)	19.8	14.5	7.3	Sandy clay loam
				2.5–15	8.5 (1.5)	0.51 (0.12)	16.7	3.3	8.2	Sandy clay loam
1	2	4	Stockpile	0–2.5	26.8 (6.5)	1.17 (0.28)	22.9	13.1	7.4	Sandy clay
				2.5–15	9.9 (2.8)	0.70 (0.20)	14.1	5.3	8.0	Sandy clay
1	Native	∞	Native	0–2.5	13.7 (4.6)	1.09 (0.08)	12.6	10.5	6.2	Sandy loam
				2.5–15	7.2 (1.1)	0.75 (0.11)	9.6	4.8	6.2	Sandy loam
2	1	11	Stockpile	0–2.5	20.5 (3.4)	1.47 (0.19)	13.9	8.2	7.6	Clay loam
				2.5–15	7.7 (0.8)	0.84 (0.06)	9.2	1.9	7.8	Clay loam
2	2	6	Directhaul	0–2.5	13.3 (3.9)	1.00 (0.29)	13.3	21.2	7.8	Clay loam
				2.5–15	7.6 (1.6)	0.66 (0.12)	11.5	7.3	7.9	Sandy clay loam
2	Native	∞	Native	0–2.5	14.6 (6.0)	1.35 (0.49)	10.8	9.3	6.5	Clay loam
				2.5–15	9.0 (2.2)	0.92 (0.16)	9.8	3.2	6.7	Clay
3	1	2	Stockpile	0–2.5	10.4 (3.3)	0.80 (0.13)	13.0	5.0	7.3	Sandy loam
				2.5–15	8.1 (3.5)	0.64 (0.10)	12.7	4.0	7.4	Sandy loam
3	2	2	Directhaul	0–2.5	6.1 (1.3)	0.56 (0.09)	10.9	6.0	7.6	Sandy loam
				2.5–15	4.7 (1.1)	0.48 (0.08)	9.8	3.1	7.3	Sandy loam
3	Native	∞	Native	0–2.5	28.6 (7.5)	1.60 (0.31)	17.9	10.3	5.7	Sandy loam
				2.5– 15	10.3 (1.5)	1.09 (0.12)	9.4	3.3	6.3	Sandy loam
4	1	~30‡	Spoil	0–2.5	3.2 (1.9)	0.40 (0.16)	8.0	7.5	7.8	Sandy clay loam
				2.5–15	1.2 (0.9)	0.14 (0.10)	8.6	1.1	8.2	Sandy clay loam
4	Native	∞	Native	0–2.5	16.3 (3.7)	1.62 (0.30)	10.1	16.0	6.9	Sandy loam
				2.5–15	10.5 (1.2)	1.17 (0.11)	9.0	2.5	7.2	Sandy clay loam

† Age of reclamation in 2001.
‡ Age in 2002.

Table 4. Biological variables measured ($Cmin_{0-3d}$, 3-d C mineralization; $Cmin_{0-21d}$, 21-d C mineralization; MBC, microbial biomass C; $Nmin_{0-21d}$, 21-d N mineralization) in series of reclaimed and native soils and spoil material from mines located in the Powder River Basin and Shirley Basin of Wyoming.

Mine	Site	Depth	$Cmin_{0-3d}$	$Cmin_{0-21d}$	MBC	$Nmin_{0-21d}$
		cm	mg C kg soil^{-1}			mg N_i kg soil^{-1}
1	1	0–2.5	353	915	1315	49.7
		2.5–15	73	162	288	8.2
1	2	0–2.5	197	497	760	13.8
		2.5–15	83	172	308	3.5
1	Native	0–2.5	135	368	561	12.6
		2.5–15	57	152	239	3.8
2	1	0–2.5	185	488	906	28.8
		2.5–15	66	160	308	8.0
2	2	0–2.5	127	326	510	16.7
		2.5–15	62	126	200	4.0
2	Native	0–2.5	157	468	846	19.1
		2.5–15	79	216	353	6.9
3	1	0–2.5	167	564	626	13.3
		2.5–15	79	218	380	4.9
3	2	0–2.5	60	261	252	8.9
		2.5–15	36	82	111	1.8
3	Native	0–2.5	140	479	667	25.9
		2.5–15	64	208	289	15.5
4	1	0–2.5	56	208	458	20.8
		2.5–15	28	47	32	1.2
4	Native	0–2.5	114	374	1083	21.7
		2.5–15	66	146	381	8.1

vertically and horizontally) soil mixture. Second, litter (both above- and belowground) present on these reclaimed mine sites is relatively new (mostly ≤16 yr), and the majority of this material is likely to be readily decomposable and mineralizable compared with that observed on native rangeland sites (Six et al., 1998). Third, Beare et al. (1994) observed that macroaggregates that were >2000 μm had the lowest abundance and greatest turnover rate in conventionally tilled soils. With the break up of macroaggregates, a labile pool of nutrients will become more readily available for plant and microbial uptake (Beare et al., 1994; Six et al., 1998). In these cases, C and N are much more likely to be available for microbial mineralization, as observed in the current study where reclaimed soils generally had higher microbial mineralization than the native soils (Table 4; Fig. 1, 3). In contrast, much of the organic C present in the native soils as well as being located in more stable and protected aggregates (Cambardella and Elliott, 1993), is older, and therefore is present in more humified, and subsequently more resistant, organic matter fractions (Schlesinger, 1997). It has also been suggested that over time, small pores (<1 μm diam.) become increasingly occluded with the extracellular microbial by-products that increasingly limit microbes and microbial enzymes to SOM protected in soil aggregate structures (Beare et al., 1994).

Differences between the native and reclaimed soils may also reflect differences in the microbial communities present. A severe perturbation of the soil (such as surface mining) combined with topsoil storage, typically, leads to a decline of fungal communities (as defined by a number of variables, e.g., spores, propagules, hyphae) (Allen and Allen, 1980; Miller et al., 1985; Stahl et al., 1988). The same severe perturbation can have variable effects on microbial communities. It may result in microbial communities declining (Mummey et al., 2002a); increasing

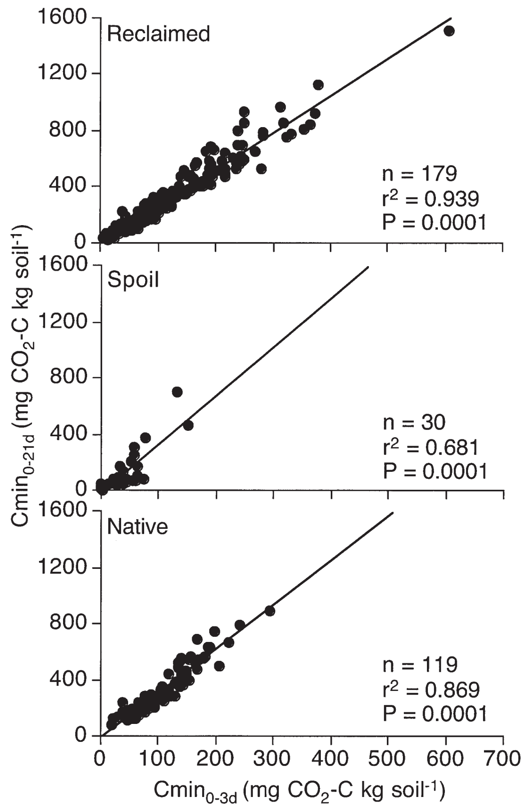

Fig. 1. Relationship between 3 d of microbial respiration ($Cmin_{0-3d}$) and 21 d of microbial respiration ($Cmin_{0-21d}$) for Reclaimed soils; Spoil material; and Native soils.

(Visser et al., 1983); exhibiting little or no change (Persson and Funke, 1988; Williamson and Johnson, 1990); or simply exhibiting a change in the proportions of bacterial groups (Visser et al., 1983; Fresquez et al., 1986; Mummey et al., 2002b). Visser et al. (1983) suggested that bacterial communities present in disturbed soil are less specialized than bacteria in undisturbed land in terms of their nutrient, moisture and temperature requirements and are thus able to take advantage of a much greater range of soil conditions. In this respect the development of a microbial community parallels that of vegetation community characteristics: an initial, early successional microbial community, which over time becomes more diverse as it develops into a later successional population (Fresquez and Aldon, 1984).

Correlations between $Cmin_{0-3d}$ and other measured soil parameters of reclaimed soils were generally comparable with those found by Franzluebbers et al. (2000). These correlations were of particular interest to us as one of the major objectives for initiating this project was to ascertain whether the method of correlating $Cmin_{0-3d}$ with other soil parameters would be of use in semiarid reclaimed ecosystems to quickly, reliably, and economically assess soil quality. As a result of the good correlations observed, we believe this to be an accurate method by which to determine soil quality in reclaimed sites where topsoil (A + B horizons) is used in the reclamation process. For sites where spoil material or alternative substrates for plant growth have been substituted for topsoil (which occurs in some reclamation situations where

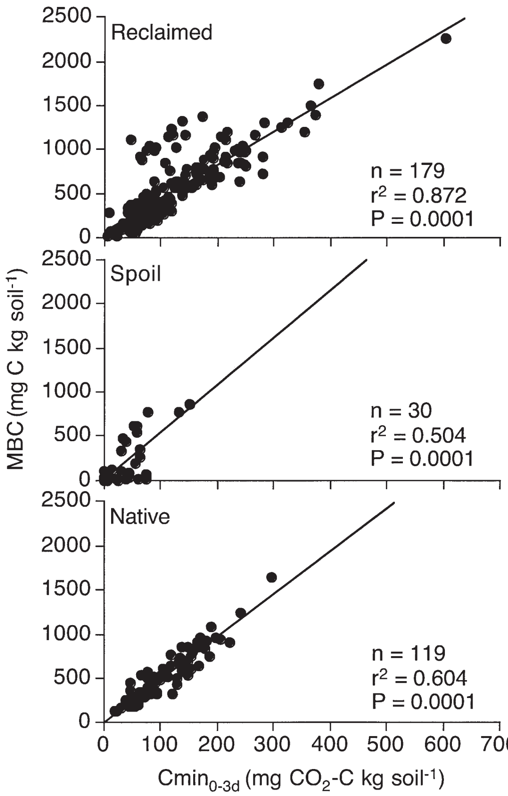

Fig. 2. Relationship between 3 d of microbial respiration ($Cmin_{0–3d}$) and microbial biomass C (MBC) for Reclaimed soils; Spoil material; and Native soils.

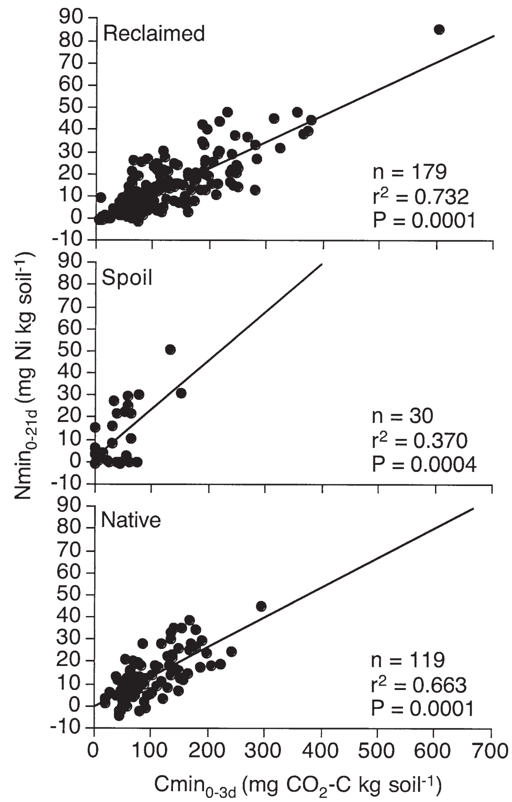

Fig. 3. Relationship between 3 d of microbial respiration ($Cmin_{0–3d}$) and potential N mineralization ($Nmin_{0–21d}$) for Reclaimed soils; Spoil material; and Native soils.

topsoil is limited or not available), we feel this method is of less value due to the inherently low amounts of SOM and microbial activity present in these materials. Franzluebbers et al. (2000) have suggested that correlating soil parameters with $Cmin_{0–1d}$ may be as good as the $Cmin_{0–3d}$ correlation method but we feel the $Cmin_{0–3d}$ method is a more appropriate methodology to determine soil quality in semiarid, reclaimed soils due to relatively low levels of SOM and biological activity present in these soils.

Drying and sieving of the soil undoubtedly has had an impact on microbial activity (i.e., microbial respiration, biomass, and N mineralization) (Seneviratne and Wild, 1985; Sparling and Ross, 1988; West et al., 1989; Franzluebbers, 1999). Previous work, however, has found little difference between estimates of soil microbial biomass regardless of whether biomass measurements were taken on field moist soils or soils that were air-dried and pre-incubated for 10 d before biomass measurements were undertaken (Franzluebbers et al., 1996; Franzluebbers, 1999). We should point out that the aim of our study was not to obtain *absolute* values of the biological parameters of interest but rather to obtain *comparative* values of soil biogeochemical properties. Our overriding interest was in soil biotic activity (rather than physical or chemical properties) since microbes are responsible for many of the important processes (i.e., decomposition, mineralization) by which nutrients are made available for plant uptake and thus, after precipitation, will have the greatest influence on plant growth.

The issue of what constitutes soil quality is somewhat nebulous (see Doran et al., 1994), and the authors would like to point out that we did not intend for this research to define soil quality—either, in a general sense or specifically in regards to semiarid, reclaimed, coal mine soils. The intent of this paper was not to classify whether these reclaimed soils have reached some specific and arbitrarily defined level of soil quality, but whether these soils are able to supply and cycle nutrients, specifically N, over the long-term, to maintain an established, stable, plant community. One of the reasons for sampling undisturbed, native soils was to compare these self-sustaining ecosystems with reclaimed soils. If the trends of the measured values/correlations of the reclaimed soils are similar to native soils, this would imply that reclaimed soils are moving (or have arrived) toward the state, level, or condition of the native soils. That is, these reclaimed ecosystems are well on their way to becoming self-sustaining ecosystems.

The second objective of this research was to estimate the concentration of SOC (as a proxy for SOM) necessary to sustain an adequate level of nutrient cycling in these low N environments. This was a several step process. First, we extrapolated the lab N-mineralization data to a field scenario by using lab $N\text{-}min_{0–21d}$ daily rate and calculating the amount of N mineralized over a 61-d period (assuming that under field conditions, the growing period extends from the 1 May– 30 June; Smoliak, 1956; Rauzi, 1964). Results of this exercise indicate that *potentially*, there is more than sufficient N mineralization to satisfy the requirements of plant communities on

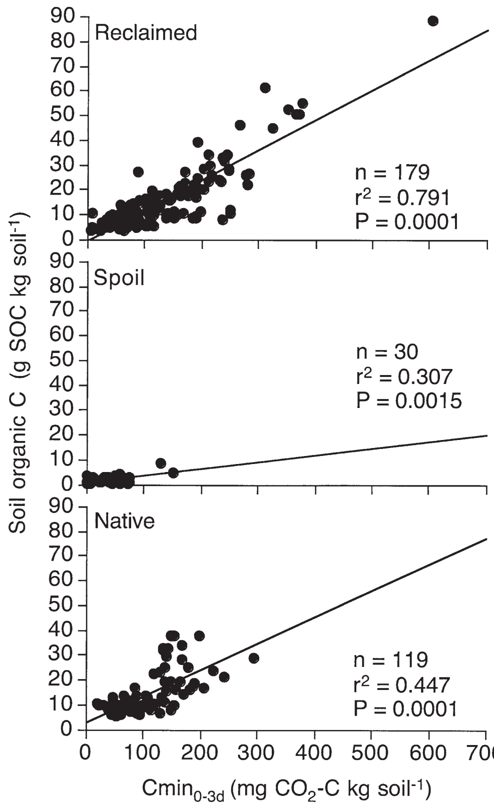

Fig. 4. Relationship between 3 d of microbial respiration ($Cmin_{0-3d}$) and soil organic C (SOC) for Reclaimed soils; Spoil material; and Native soils.

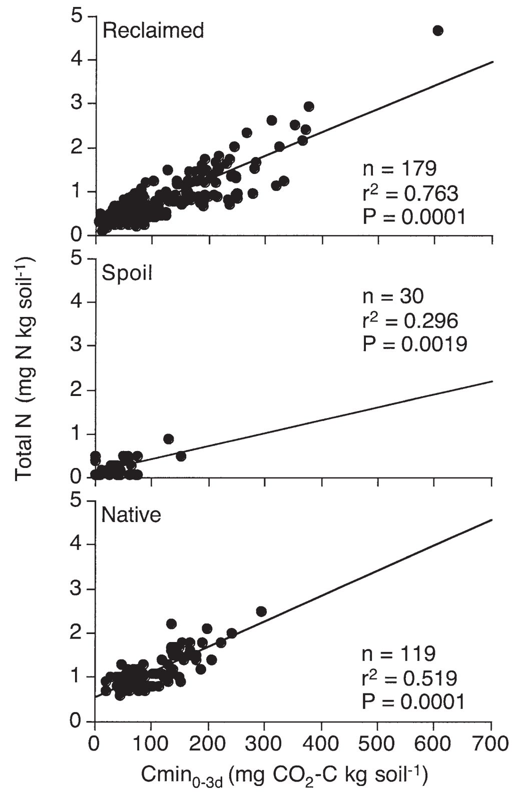

Fig. 5. Relationship between 3 d of microbial respiration ($Cmin_{0-3d}$) and total N for Reclaimed soils; Spoil material; and Native soils.

these reclaimed coal mine sites. We then calculated the rate of N mineralization required to provide exactly the amount of N needed for the growth of the plant communities (Table 2) over the 61-d growing period. By regressing N mineralization against SOC, we could then determine the minimum SOC required to provide the quantity of inorganic N required for plant growth. We estimated that in the order of 0.52% SOC (0.89% SOM) would be required for reclaimed topsoil and 0.68% SOC (1.17% SOM) would be required for native, undisturbed soils, to maintain nutrient cycling over this growing period.

In calculating these estimates, we have made several assumptions: 1. The rate of N mineralization observed in the lab would be comparable with that found in the field, and would occur over the entire course of the defined growing period; 2. Plants would, over time, take up 90% of inorganic N made available by microbes. Numerous studies have shown that while in the short-term (hours to days) microbes are better able to compete for N than plant roots (~86% of available inorganic N; Jackson et al., 1989; Schimel et al., 1989), that in the longer term (and in these semiarid ecosystems the growing season typically lasts for 2 mo due to soil moisture and precipitation patterns; Smoliak, 1956; Rauzi, 1964) somewhere in the order of 85 to 95% of available N is taken up by plants (Kaye and Hart, 1997; Hodge et al., 2000); 3. That ~60% of the N requirements of these mixed-grass plant communities is provided by the retranslocation of N held in plant roots, crowns and rhizomes (Clark, 1977; Woodmansee et al., 1978; Risser and Parton, 1982; Jaramillo and Detling, 1992; Li and Redmann, 1992; Li et al., 1992); 4. A soil bulk density of 1.33 g cm^{-3} in reclaimed soils (P.D. Stahl, unpublished data, 2004).

The 0.52% SOC estimated for the reclaimed soils was within the range of the 0.1 to 0.7% SOC estimated by Woods and Schuman (1986) to maintain nutrient cycling on a reclaimed uranium mine site. Their estimates were based on a study that examined relationships between SOC and microbial biomass, potential N mineralization, and plant N in native soils, topsoil replaced over spoil material, as well as pure spoil material. Our estimate, however, needs to be considered in light of the mounting evidence that plant species are able to take up either directly (see reviews by Lipson and Näsholm, 2001; Schimel and Bennett, 2004), or via mycorrhizae (Marschner, 1999), organic forms of N allowing them to grow without relying solely on inorganic N. Thus our estimate of 0.52% SOC may be higher than what is required to supply sufficient quantities of N for plant growth in these reclaimed ecosystems.

It is of interest to note the differences in the estimated minimum concentration of SOC required to maintain nutrient cycling in the two 'different' soil types (reclaimed, 0.52% vs. native, 0.68%). We speculate that in reclaimed sites, plant inputs are relatively new and therefore unlikely to have become humified and consequently are relatively more labile and available for microbial decomposition. Conversely, undisturbed native soils, having had long-term litter inputs, will contain decomposed plant residues, leading to an increase in chemically recalcitrant aromatic and alkyl carbon compounds (see review article by Krull et al., 2003).

We were unable to differentiate between the mineralizable fraction of SOC (i.e., SOM) and C present in coal (which is only partially mineralizable over the short term), a problem typical of these types of studies (Reeder, 1988; Waschkies and Hüttl, 1999, Krull et al., 2003). Nonetheless, although our measured values for SOC are clearly high in some cases (5–9%; Fig. 4, or SOM of ~9–16%) for a semiarid ecosystem such as these, it may not be a major concern because where SOC was high, microbial activity was also elevated (Fig. 4; Table 3, 4). In any assessment of minimum levels of SOC, it is important to ensure (as much as possible) that coal dust is not a major component of the SOC. In an associated laboratory experiment undertaken at the same time as the experiments reported here, we added increasing amounts of fine particulate coal (0.0, 0.25, 0.5, 1.0, 2.5, 5.0, 10.0, and 100% w/w coal material that had been sieved to <0.25 mm) to a local soil containing no coal material. We found that $Cmin_{0\text{–}21d}$ and $Nmin_{0\text{–}21d}$ was greatest in the 0, 0.25, and 0.5% coal amended samples, with much lower rates of C- and N-mineralization in the other samples (data not shown). The results for microbial biomass were somewhat opposite with little difference between the 0 to 2.5% coal samples but much higher microbial biomass in the 5, 10, and 100% coal amended soil (data not shown). We believe this to be a direct result of the solubilization of C compounds present in coal by the chloroform, and the subsequent release of CO_2 and not an actual measure of microbial biomass per se.

A number of previous studies have, on the basis of various ratios (i.e., MB/Org. C; qCO$_2$; 21-d MR/MB; C mineralization/N mineralization), estimated the 'progress' of soil microbial communities toward some defined state of equilibrium (typically a native, undisturbed ecosystem) (Anderson and Domsch, 1989; Insam and Haselwandter, 1989; Stephens et al., 2001). While we observed a significant correlation ($P = 0.0003$) between reclamation age and qCO$_2$, the low correlation coefficient ($r^2 = 0.052$) indicates that only 5.2% of the variance was explained. We feel that the use of ratios has limitations as an indicator of soil recovery for two reasons; 1. it is well acknowledged that no single method can quantitatively measure the entire mass of soil microbes (Vance et al., 1987; Horwath and Paul, 1994), and any given method will give varying results depending on properties such as soil texture or microbial communities present (e.g., fungi are more susceptible to chloroform vapors than bacteria; Anderson and Domsch, 1978) and, 2. due to varying degrees of coal dust contamination between sites and mines there is potential for ratios to be underestimated. Finally, a review paper by Wardle and Ghani (1995) found that the qCO$_2$ was not a reliable indicator of differences between normal stresses (e.g., drought, nutrient limitations) and more severe perturbations.

Based on the generally strong correlations we observed between $Cmin_{0\text{–}3d}$ and a range of standardized parameters of soil health/quality, we feel that the $Cmin_{0\text{–}3d}$ correlation method provides those involved with mine reclamation a relatively rapid and inexpensive tool to maximize the limited soil resource and ensure SOC quality control in the topsoil salvage and replacement processes. We are presently unable to quantitatively predict the other soil health/nutrient cycling indicators based on $Cmin_{0\text{–}3d}$ alone. We do feel, however, that as a "rule of thumb," semiarid, reclaimed, coal mine soils that respire >72 mg CO_2–C kg soil^{-1} over 3 d after being rewetted, and under ideal conditions, are likely to have sufficient microbial activity to maintain an adequate level of nutrient cycling.

CONCLUSIONS

Using a recently developed protocol that correlates short-term $Cmin_{0\text{–}3d}$ with a range of soil parameters as a method to determine soil quality, we tested a number of soils with different histories (reclaimed coal mine soils; native, undisturbed, prairie soils; and mine spoil material) in a semiarid region. We found correlations between $Cmin_{0\text{–}3d}$ and the soil parameters measured ($Cmin_{0\text{–}21d}$, MBC, $Nmin_{0\text{–}21d}$, SOC, and total N) were highly significant for the three soil types. Reclaimed soils exhibited less variance than for native soils, with spoil material showing the greatest amount of variance. We speculate that reduced variability in reclaimed soils represents a combination of a more homogenous soil system, the addition of new, relatively non-humified plant residues, differences in aggregate structure, and differences in microbial communities. On the basis of the strong correlation we observed between $Cmin_{0\text{–}3d}$ and a range of soil parameters that are considered to be good indicators of soil quality, we believe that the use of the $Cmin_{0\text{–}3d}$ correlation method is a useful methodology/tool to assess the recovery of reclaimed, coal mine soils. Moreover, as the methodology is simple and does not require the use of any highly specialized equipment, it would also be an economical means by which to rapidly (3 d) determine soil quality. While it is not possible using this methodology to quantitatively determine soil quality, it would provide those involved in mine reclamation a means to, at least qualitatively, determine both the quality and nutrient cycling potential of reclaimed soils. Determining the quality and potential nutrient cycling of these soils will assist reclamation specialists in managing the soil material available to them and that will provide a self-sustaining plant community. In addition, we also estimated that in reclaimed soils, a minimum of 0.89% SOM is necessary to supply a sufficient amount of N_i to maintain a stable plant community.

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