THE INFLUENCE OF MANAGEMENT ON MICROBIAL BIOMASS AND SOIL ORGANIC CARBON IN RECLAIMED SURFACE COAL MINES OF WYOMING[1]

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Abstract. This study was conducted to determine the long-term influence ($\geq$11 years) of a number of reclamation management practices on the concentration microbial biomass carbon (MBC) and the concentration and mass of soil organic carbon (SOC) in reclaimed soils from a number of surface coal mines located in Wyoming. We compared a number of commonly used reclamation management practices (grazed vs. un-grazed; stockpiled topsoil vs. direct hauled topsoil; hay-crimp mulch vs. stubble mulch; grass seed mixture vs. shrub seed mixture) at five surface coal-mines. In addition, a native, undisturbed prairie soil was also sampled at each of the five coal-mines native sites. Reclamation management practices compared in this study, with the exception of stubble mulching, did not have significantly different long-term effects on SOC concentrations. Microbial biomass C was more influenced than SOC by the compared practices in the soils examined. In more than half of the sites analyzed, reclaimed soils had SOC concentrations similar to undisturbed soil reflecting the potential to accumulate C in reclaimed coal-mine soils.

Additional Key Words: C sequestration, topsoil handling, seed mixtures, grazing, mulching, reclamation management, semiarid, surface mining

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Introduction

It has been proposed that sequestration of C in soil as organic matter (OM) would be a desirable, workable, and effective means by which CO_2 concentration in the atmosphere can be reduced (Paul et al., 1997). Further, the potential to sequester C in disturbed soils, such as those presently being reclaimed after surface coal mining or those abandoned after surface coal mining (prior to the passage of Surface Mining Control and Reclamation Act in 1977), appears to be particularly great. Soil disturbance associated with surface mining results in loss of organic C (OC) through increased mineralization, erosion and leaching (Lal et al., 1998). Reclaimed minesoils, however, have the potential to accumulate soil organic matter (SOM) rapidly and therefore sequester C from the atmosphere (Stahl et al., 2003; Akala and Lal, 2001).

Land management practices are known to have important effects on amounts of C and micro-organisms in soil by modifying environmental conditions and affecting C cycling dynamics, e.g. rates of decomposition and primary productivity (Doran and Linn, 1994; Stahl et al., 1999). This is critical because it is well established that OC and other organic nutrients in soil (i.e., SOM) are among the most important soil components influencing ecosystem processes and properties. A host of management practices are known to affect controls on soil organic C (SOC) turnover including irrigation, fertilization, tillage, fire, grazing and vegetation alteration, amongst others (Paustian et al., 1997). Reclamation management methods used on surface mines such as topsoil salvage and replacement, revegetation, grazing and mulching are commonly believed to have an impact on the success and quality of mined land remediation (Harris et al., 1996; Ries and Nilson, 2000).

Previous studies of reclaimed soils on mined lands indicate that microbial communities may take 20 years or longer to recover, in terms of biomass and diversity, to that found in similar undisturbed soil (Insam and Domsch, 1988; Sawada, 1996). The slow recovery of microbial biomass production seems contradictory to the reported observations of rapid accumulation of SOM in many reclaimed soils (Stahl et al., 2003). Because of the critical importance of these two soil components to ecosystem function and reclamation success, it is crucial to understand how their recovery is influenced by reclamation management practices.

The primary objective of this study was to examine and compare the influence of different surface mine reclamation management practices on SOC and MBC in a series of reclaimed sites on surface coal mines in Wyoming, USA. Secondary objectives were to 1) compare amounts of SOC in reclaimed and disturbed soils, and 2) estimate carbon sequestration potential of reclaimed areas examined.

Materials and Methods

Study sites

All mines were located in semiarid regions of north-east and south-central Wyoming with varying elevation (1,220 – 2,067 m) and precipitation (mean annual precipitation, 216 – 390 mm; Western Regional Climate Centre, 2004). The site in south-central Wyoming had the lowest elevation and rainfall. Prior to disturbance, soils were classified as fine-loamy, mixed, mesic Ustic Haplargids at Mines 2 and 4 (Westerman and Prink, 2004) as well as at Mines 1 and 5 (Munn and Arneson, 1999) and coarse-loamy, mixed, Ustic Haplargids at Mine 3 (Munn and Arneson, 1999). Reclamation sites had been seeded with native grasses, forbs and shrubs in an attempt to establish plant communities similar to those found prior to disturbance.

Experimental design

Comparisons of reclaimed soils on surface mined lands are inherently complicated by a lack of reclamation histories, differences in parent material and overburden and changes in regulatory requirements over the years. With this in mind, every attempt was made to find sites in which all variables were similar between comparisons except the compared management practices.

For each of the four commonly used reclamation practices, we sampled soils from a site at each of two different surface mines. A suitable second site for comparison of the mulching practices could not be located. Reclamation practices were paired by age of reclamation and topsoil depth (Table 1). Along with reclamation practice comparisons, undisturbed soils, adjacent to the reclaimed areas, were sampled to serve as references.

At all sites (reclaimed and undisturbed), three 100 m transects were randomly established and four sampling points were located along each of these transects. At each sampling point, soil samples were taken at depth increments of 0-5, 5-15 and 15-30 cm, resulting in a total of 36 soil samples per site. All soil samples were sieved to < 2 mm, air-dried and stored at 4˚C. In addition, at two points along each of the transects, soil cores of a known volume were excavated at 0-5, 5-15 and 15-30 cm depth increments for determination of bulk density (Blake and Hartge, 1986). These were used to calculate C mass on a per hectare basis.

Laboratory methods

All soils were analysed for pH (Thomas, 1996), electrical conductivity (EC) (Rhoades, 1996) and soil texture (Gee and Or, 2002) to determine basic soil physiochemical characteristics. Soil organic C was calculated as the difference between total C and inorganic C (IC). Total C was analysed using an elemental analyser (NA 2100 Protein, CE instruments, Italy) and IC was analysed by means of a modified pressure calcimeter method (Sherrod et al., 2002). Microbial biomass C was quantified by the chloroform fumigation extraction method (Vance et al., 1987). Soil extractions were analysed for soluble organic C with a Phoenix-8000 UV-persulfate total C analyser (Techmar-Dohrman, Mason, Ohio). Microbial biomass C were calculated using a correction factor of K_{EC} = 0.35 (Horwath and Paul, 1994).

Differences in soil parameters between practices as well as between reclaimed and undisturbed, native soil were undertaken using a two-way analysis of variance (Minitab, 2000).

Results

Soil texture was similar between paired reclamation comparisons and undisturbed soils within each mine (Table 1). The only exception was Mine 4 where the undisturbed soil was a sandy clay loam and the reclaimed soils were clays. Electrical conductivity and pH were also similar among soils examined; both between compared practices and undisturbed soils (Table 1).

Weighted means of SOC concentrations ranged from a low of 1.9 g C kg^{-1} soil, at Mine 1 direct haul site, to a high of 32.0 g C kg^{-1} soil, at Mine 2 undisturbed site (Table 2). Microbial biomass C concentrations ranged from a low of 0.017 g C kg^{-1} soil, at Mine 2 grazed site, to a high of 0.654 g C kg^{-1} soil, at Mine 4 shrub site (Table 2).

Table 1. Site information and soil texture, pH, electrical conductivity (EC), bulk density (BD), total N (TN) and C:N ratios in undisturbed and reclaimed soils of surface coal mines in Wyoming. The data presented were calculated as a weighted mean of the 0-5, 5-15, and 15-30 cm depth increments and the figures in parentheses are standard errors of the mean.

Mine	Site	Reclamation Age (yrs)	Depth of replaced topsoil (cm)	Soil texture	Clay (%)	pH	EC (dSm^{-1})	TN (%)	C:N[1]
Mine 1	Undisturbed	∞	-	Sandy Clay Loam	27.1	6.2	0.33 (0.02)	0.107	7.2
	Grazed[2]	26	30	Sandy Clay Loam	25.0	6.5	0.57 (0.11)	0.048	21.7
	Ungrazed	26	30	Sandy Loam	16.0	6.3	0.58 (0.14)	0.043	23.7
	Shrub	11	45	Sandy Clay Loam	18.8	7.6	0.31 (0.01)	0.040	6.3
	Grass	11	45	Sandy Clay Loam	17.0	7.7	0.36 (0.01)	0.042	7.6
	Stockpile[3]	11	45	Sandy Clay Loam	17.0	7.7	0.36 (0.01)	0.042	7.6
	Direct Haul	11	45	Sandy Clay Loam	19.0	7.7	0.34 (0.01)	0.036	6.4
Mine 2	Undisturbed	∞	-	Sandy Clay Loam	18.4	6.2	0.34 (0.01)	0.114	7.9
	Grazed[4]	11	55	Sandy Clay Loam	18.1	7.2	0.41 (0.01)	0.063	9.2
	Ungrazed	11	55	Sandy Clay Loam	22.9	7.0	0.35 (0.01)	0.067	7.9
Mine 3	Undisturbed	∞	-	Sandy Loam	16.8	8.0	0.63 (0.14)	0.133	6.9
	Direct Haul	19	35	Sandy Loam	19.2	8.1	0.39 (0.03)	0.063	13.1
	Stockpile[5]	19	35	Loam	24.9	8.0	0.37 (0.01)	0.064	10.9
Mine 4	Undisturbed	∞	-	Sandy Clay Loam	34.1	6.6	0.42 (0.02)	0.115	8.3
	Shrub	11	55	Clay	54.8	7.9	0.55 (0.08)	0.123	8.5
	Grass	11	55	Clay	52.1	7.5	1.27 (0.23)	0.121	8.8
Mine 5	Undisturbed	∞	-	Sandy Loam	20.3	7.8	0.42 (0.07)	0.080	10.6
	Hay	14	60	Sandy Loam	16.3	8.1	0.36 (0.02)	0.047	14.4
	Stubble	14	60	Sandy Loam	13.0	8.0	0.38 (0.03)	0.061	15.9

[1] Organic C data were taken from Table 2, Total N data is not shown
[2] Grazed for *ca.* six years at a long duration (July – October) and low to moderate stocking rate
[3] Topsoil was stockpiled four years before reclamation was initiated
[4] Grazed for *ca.* five years at a short duration (two - 3 days periods) and high stocking rate (10 cattle ha^{-1})
[5] Topsoil was stockpiled five years before reclamation was initiated.

Table 2. Means of soil organic carbon (SOC) and microbial biomass carbon (MBC) by whole soil (0-30), 0-5, 5-15 and 15-30 cm depth increments. Means, by mine, in columns not followed by the same letter are statistically different at $P < 0.05$. Standard errors are shown in parentheses.

	Mine 1		Mine 2		Mine 3		Mine 4		Mine 5	
	SOC	MBC	SOC	MBC	SOC	MBC	SOC	MBC	SOC	MBC
	g C kg^{-1} soil									
0-30 cm										
Undisturbed	7.7 (0.8)^{b}	0.128 (0.009)^{a}	13.5 (1.3)^{b}	0.092 (0.022)^{b}	9.2 (1.4)^{a}	0.108 (0.009)^{a}	9.5 (0.7)^{a}	0.167 (0.009)^{a}	8.5 (0.7)^{ab}	0.110 (0.008)^{b}
Grazed	10.5 (1.2)^{b}	0.128 (0.014)^{a}	5.8 (0.5)^{a}	0.037 (0.006)^{a}						
Ungrazed	10.2 (1.4)^{b}	0.105 (0.014)^{a}	5.3 (0.4)^{a}	0.095 (0.006)^{b}						
Directhaul	2.3 (0.1)^{a}	0.109 (0.036)^{a}			8.2 (0.7)^{a}	0.146 (0.017)^{a}				
*Stockpiled	3.2 (0.2)^{a}	0.075 (0.004)^{a}			7.0 (0.5)^{a}	0.135 (0.018)^{a}				
*Grass mix	3.2 (0.2)^{a}	0.075 (0.004)^{a}					10.7 (0.8)^{a}	0.140 (0.016)^{a}		
Shrub mix	2.8 (0.1)^{a}	0.242 (0.011)^{b}					10.5 (0.5)^{a}	0.528 (0.049)^{b}		
Hay									6.7 (0.6)^{a}	0.051 (0.01)^{a}
Stubble									9.7 (1.0)^{b}	0.082 (0.01)^{ab}
0-5 cm										
Undisturbed	17.9 (3.3)^{b}	0.323 (0.037)^{b}	32.0 (4.3)^{b}	0.259 (0.060)^{b}	9.5 (1.7)^{a}	0.217 (0.045)^{a}	23.3 (2.6)^{b}	0.315 (0.043)^{a}	10.6 (0.9)^{b}	0.206 (0.022)^{b}
Grazed	14.0 (1.4)^{b}	0.219 (0.018)^{a}	14.0 (1.6)^{a}	0.092 (0.011)^{a}						
Ungrazed	16.0 (1.4)^{b}	0.136 (0.009)^{a}	9.9 (0.8)^{a}	0.216 (0.038)^{b}						
DirectHaul	3.3 (0.3)^{a}	0.179 (0.042)^{a}			13.2 (1.7)^{a}	0.339 (0.042)^{a}				
*Stockpiled	5.4 (0.5)^{a}	0.162 (0.018)^{a}			11.7 (1.4)^{a}	0.287 (0.049)^{a}				
*Grass mix	5.4 (0.5)^{a}	0.162 (0.018)^{a}					16.3 (1.3)^{a}	0.260 (0.035)^{a}		
Shrub mix	4.1 (0.5)^{a}	0.173 (0.025)^{a}					17.3 (1.1)^{a}	0.654 (0.059)^{b}		
Hay									6.4 (0.3)^{a}	0.120 (0.017)^{a}
Stubble									7.8 (0.9)^{a}	0.204 (0.054)^{b}
5-15 cm										
Undisturbed	7.8 (0.7)^{b}	0.118 (0.010)^{a}	11.6 (1.0)^{b}	0.081 (0.023)^{a}	9.2 (1.4)^{a}	0.099 (0.012)^{a}	8.1 (0.7)^{a}	0.208 (0.026)^{a}	7.5 (0.5)^{a}	0.112 (0.011)^{c}
Grazed	11.7 (1.6)^{c}	0.143 (0.017)^{a}	5.0 (0.7)^{a}	0.039 (0.009)^{a}						
Ungrazed	11.4 (1.9)^{c}	0.124 (0.016)^{a}	4.7 (0.4)^{a}	0.092 (0.038)^{a}						
DirectHaul	2.3 (0.2)^{a}	0.079 (0.034)^{a}			9.0 (1.0)^{a}	0.140 (0.017)^{a}				
*Stockpiled	2.9 (0.3)^{a}	0.063 (0.006)^{a}			6.5 (0.3)^{a}	0.132 (0.021)^{a}				
*Grass mix	2.9 (0.3)^{a}	0.063 (0.006)^{a}					9.9 (0.7)^{a}	0.123 (0.012)^{a}		
Shrub mix	2.4 (0.1)^{a}	0.223 (0.019)^{b}					10.0 (0.9)^{a}	0.459 (0.049)^{b}		
Hay									6.2 (0.4)^{a}	0.029 (0.004)^{a}
Stubble									7.0 (1.3)^{a}	0.066 (0.009)^{b}

15-30 cm										
Undisturbed	5.6 (0.6)[b]	0.069 (0.009)[a]	8.5 (1.0)[b]	0.045 (0.023)[a]	8.5 (1.9)[a]	0.057 (0.008)[a]	5.6 (1.7)[a]	0.098 (0.008)[a]	8.5 (0.9)[a]	0.077 (0.009)[b]
Grazed	8.6 (1.6)[b]	0.087 (0.019)[a]	3.6 (0.3)[a]	0.017 (0.003)[a]						
Ungrazed	7.5 (2.1)[b]	0.083 (0.021)[a]	4.7 (0.6)[a]	0.056 (0.020)[a]						
DirectHaul	1.9 (0.1)[a]	0.107 (0.004)[a]			6.0 (0.5)[a]	0.085 (0.014)[a]				
*Stockpiled	2.6 (0.2)[a]	0.053 (0.004)[a]			5.9 (0.5)[a]	0.087 (0.013)[a]				
*Grass mix	2.6 (0.2)[a]	0.053 (0.004)[a]					9.1 (1.1)[a]	0.112 (0.022)[a]		
Shrub mix	2.6 (0.3)[a]	0.278 (0.017)[b]					8.5 (0.5)[a]	0.532 (0.059)[b]		
Hay									7.3 (1.0)[a]	0.041 (0.007)[a]
Stubble									12.1 (1.9)[b]	0.052 (0.009)[a]

*This site (comprised of stockpiled topsoil that had been seeded with a grass seed mix)is represented twice but compared separately against two different management comparisons; a site which had grass mix seeded into direct haul topsoil site and a shrub seed mixture site which received stockpiled topsoil.

Grazing

Soil OC concentration was not significantly different in grazed, ungrazed, and undisturbed soils at Mine 1 except in the 5-15 depth increment where both grazed and ungrazed reclaimed soil had greater SOC content than undisturbed soil. At Mine 2, there was no difference in SOC concentration of the grazing treatments. Both of these reclaimed soils, however, were significantly lower in SOC through the whole profile to 30 cm than the nearby, undisturbed soil. There was no significant difference in MBC at Mine 1 between grazed, ungrazed and undisturbed soils for the entire soil profile, but undisturbed soils were significantly higher in MBC than either of the grazing treatments for the 0-5 cm increment (Table 2). At Mine 2, grazed soils had significantly lower MBC, for both the entire soil profile as well as the 0-5 cm depth increment, than both undisturbed and ungrazed soils (Table 2).

Topsoil handling

There was no difference in SOC between topsoil handling treatments at Mine 1, but both had significantly lower SOC, for the entire profile and for each depth, than undisturbed soil. At Mine 3, no differences were found in SOC concentration between topsoil handling treatments and undisturbed soil either for the profile or for a given depth increment (Table 2). There were no statistical differences in soil MBC concentration in sites reclaimed with stockpiled or direct hauled topsoil (Table 2) at either site where this comparison was made. With the exception of the 0-5 cm depth increment at Mine 1 where MBC was greater in undisturbed soil than either of the reclaimed topsoil treatments, there was no difference between undisturbed and topsoil handling treatments (Table 2).

Seed Mixtures

Shrub and grass seed treatments at Mine 1, while not different from one another, had significantly lower SOC, both overall and at each depth, than undisturbed soil. At Mine 4, there was no difference in SOC for the entire profile or the 5-15 and 15-30 increments between seeding treatments or undisturbed soil. However, at the 0-5 cm depth, undisturbed soils had a greater concentration of SOC (Table 2). Microbial biomass C was significantly greater in soil at the shrub seeded sites for the entire profile and at all depth increments compared to grass seeded sites at both mines 1 and 4. In addition, MBC was generally greater in the reclaimed shrub seeded soils than undisturbed soils (Table 2).

Mulching

Stubble mulched soil contained more SOC than hay crimped soil for the entire profile and this was attributable to a significant increase in SOC at the 15-30 cm depth (Table 2). There was no difference in SOC concentration of undisturbed soil and either of the mulch treatments for the entire profile, but undisturbed soil had significantly more SOC at the 0-5 cm depth than either mulch treatment and significantly less SOC than the stubble mulched soil at the 15-30 cm depth. Stubble mulched soils had significantly greater MBC content than hay crimp soil at the 0-5 and 5-15 cm depths but there was no differences between the two practices for the entire profile. Undisturbed soil had significantly greater MBC than both mulch practices soils at the 5-15 and 15-30 cm depth increments (Table 2).

Discussion

Soil texture, pH and EC were similar in paired reclaimed and undisturbed soils within mines. Over the long term, reclamation practices compared in this study do not appear to have influenced pH, EC or soil texture. Other studies have reported similar findings (Foster, 1986). Thus, it is unlikely that any differences observed in these variables would negatively influence microbial productivity or SOC accumulation.

Our results indicate that the reclamation management practices compared in this study, with the exception of mulching practices, had minimal different effects on SOC concentration or mass of reclaimed soils 11 – 26 years after reclamation was initiated (Table 2, 3). Lack of differences may be because the sites examined were reclaimed for >11 years and the natural processes and environmental factors contributing to the formation and accumulation of SOC had more influence over time than the management practices compared (Sawada, 1996; Foster, 1986; Akala and Lal, 2001). It is probable that compared practices result in only short-term differences in SOC and over the long-term (>10 yrs) processes and environmental factors associated with 'natural' recovery override differences in reclamation practices (with the exception of stubble mulching) and seem to occur relatively rapidly (≤ 10 yrs).

While the results of the grazing comparisons appear to be somewhat contradictory, disparities in grazing practices used at the two mines probably explain these differences. The reclaimed area examined at Mine 1 was moderately grazed while the area examined at Mine 2 was heavily grazed. Heavy grazing has often been shown to lead to a reduction in SOC relative to lightly grazed sites (Dormaar et al., 1990; Fuhlendorf et al., 2002) particularly when grazing occurs under drought conditions (Morgan et al., 2004; Schuman et al., 2005). In contrast, lightly grazed sites often show an increase in SOC compared to native, undisturbed grasslands (Ayuba, 2001; Eldridge and Robson, 1997; Schuman et al., 2005).

Differences in MBC between sites can also be explained in a similar manner. In general, heavy grazing has been observed to lead to a reduction in MBC compared to grazing at more moderate rates which, in turn, result in an equal or greater measured MBC than ungrazed sites both in arid and semiarid climates (Holt, 1997; Ingram et al., 2004; Stahl et al., 2004). Thus, it is critical that specific grazing practices be considered carefully due to their potential to negatively impact MBC and the subsequent implications this may have on nutrient cycling and C sequestration.

Although there were no differences in SOC content of grass and shrub seeded sites, the different seed mixtures used had a considerable effect on MBC at both locations. Vegetation communities derived from shrub seed mixtures appear to be facilitating greater microbial productivity than plant communities resulting from the grass seed mixtures used on these semiarid reclamation sites. The spatial distribution of shrubs in semiarid ecosystems results in concentrations of nutrients being significantly higher in soils near shrubs (Charley and West, 1975; Doescher et al., 1984) leading to the term "islands of fertility". The impact of shrubs on the spatial distribution of resources and organisms in reclaimed soils has previously been reported in regards to SOM, NH_4, MBC, and FAME biomarkers (Mummey et al., 2002a). In addition, snow accumulation around shrubs (Burke et al., 1989) and the hydraulic redistribution of water from deeper to shallower depths (Leffler et al., 2004) (both of which result in an increase in soil moisture), when combined with the greater availability of nutrients, greatly enhance microbial activity and biomass production.

While MBC was greater in soils seeded with the sagebrush mix, there was no significant difference in the concentration of SOC between the grass and sagebrush seeded sites (Table 2). We speculate this can be explained by the sagebrush sites are more productive, resulting from both a high density of sagebrush (> 1 plant m^{-2}) and a large mass of grass. Although litter was greater in the sagebrush sites, the higher amounts of MBC resulted in greater rates of decomposition and increased microbial respiration.

The stubble mulch soil had significantly greater overall SOC though the soil profile (0-30 cm) than did the crimped mulch site. This difference was due entirely to differences at the 15-30 cm depth. Stubble mulching increases SOC accumulation at depth by root inputs while hay-crimp mulch only applies hay to the surface of the soil. Though just one year's input of cereal root biomass from stubble mulching was added to the system 14 years previously, it appears to have had a considerable long-term effect. Additionally, stubble mulching has been reported to increase infiltration through improvement of soil physical characteristics from deep rooting stubble mulch as well as facilitating seeded grass reestablishment when compared to hay-crimp mulching (Pinchak et al., 1985; Schuman et al., 1985); both of which lead to greater vegetation production and C sequestration.

Because topsoil stockpiling is known to result in a decline in SOC (Akala and Lal, 2001) and adversely impact soil organisms (Miller et al., 1985), it can be hypothesized that sites reclaimed with directly hauled topsoil would have greater concentration of SOC and MBC than sites reclaimed with stockpiled topsoil. No differences, however, were found in SOC or MBC between sites reclaimed with directly hauled or stockpiled topsoil at either mine where this comparison was made. Use of directly hauled topsoil may avoid or minimise some of the problems associated with long-term topsoil storage. These problems include a decline in fungal and bacterial populations (Miller et al., 1985; Johnson et al., 1991) and significant losses of C (~32-85%) (Abdul-Kareem and McRae, 1984; Foster, 1986).

Data on MBC suggests that microbial community productivity may have recovered in most of the reclaimed soils examined in this study. Of the 13 reclaimed sites investigated, 12 had MBC contents (whole soil profile to 30 cm) not significantly different or greater than MBC content of nearby undisturbed soil (Table 2). We also observed that MBC in most reclaimed soil profiles have recovered to levels found in undisturbed soils. Other studies with similar climatic conditions (< 500 mm precipitation $year^{-1}$) have recorded varying results. Some studies have observed that reclaimed areas (1-32 years) have not yet recovered to similar levels of MBC found in undisturbed soils (Visser et al., 1983; Anderson et al., 2002; Mummey et al. 2002b), whereas, others have reported sites with highly variable (greater, comparable or lower relative to a undisturbed soils) values for MBC (Mummey et al. 2002a; Ingram et al. 2005; this study). It appears then, that as a general rule, while MBC appears to recover slowly to levels found in undisturbed soils in these semiarid regions (<500 mm precipitation $year\text{-}^{1}$), it is to some degree, site specific, making it difficult to predict the rate of recovery in any given reclaimed area.

We hypothesized that the relationship between SOC and MBC would be different in reclaimed and undisturbed soil based on differences in environmental conditions in these soils (e.g. impacted physical structure, different or limited soil biota, vegetation differences, etc.) and because SOC (as a proxy for soil organic matter) is accumulating in reclaimed soils. Regression analyses we conducted (StatView ver. 5.0, SAS Institute) on data from each site (whole profile, 0-30 cm) examined in this study did not support this hypothesis. Overall, both native (n=179, r^2=0.191, P<0.0001) and reclaimed (n=483, r^2=0.111, P<0.0001) soils were significantly, though poorly correlated. There was no significant difference in the relationship between MBC and SOC in undisturbed and disturbed soils. On a site-by-site basis, we found highly significant positive linear relationships between SOC and MBC at 8 of 13 reclaimed sites and at all 5 of the undisturbed sites (data not shown). Examination of scatter plots and regression equations revealed no patterns to differentiate relationships between MBC and SOC in reclaimed and undisturbed soils. While we would have hypothesized that MBC and SOC would have greater correlations, our results are generally comparable to those reported in other studies, which have described similar relationships (Insam and Domsch, 1988; Sawada, 1996; Ingram et al., 2005).

It is estimated that there are 0.63 M ha of surface-mined land in the U.S. that could be reclaimed with the potential to accumulate C at a rate of 1,000-3,000 kg C ha^{-1} yr^{-1}, resulting in a potential annual accumulation of 0.63-1.89 Mt C (Follett et al., 2001). Three of the five mines we studied had reclaimed soils that had sequestered, on average, 8,800 kg C ha^{-1} (range 4,000-16,000) above that found on comparable, undisturbed soils (Table 3). While we can not tie any given reclamation management practice to high rates of C sequestration (with the possible exception of mulching), it appears Wyoming reclaimed coal mines may potentially be able to sequester large amounts of atmospheric C.

Table 3. Age of reclamation site and soil organic carbon (SOC) as a ratio to the undisturbed value. Figures in bold indicate that the data (SOC or MBC) for the reclaimed site of interest is greater than the comparable undisturbed, prairie value.

Mine	Site	Age	SOC[1] (kg C ha^{-1})	SOC[2]
Mine 1	Undisturbed	∞	30000 ± 3000	-
	Grazed	26	**46000 ± 5000**	**1.53**
	Ungrazed	26	**43000 ± 6000**	**1.43**
	Direct Haul	11	10000 ± 1000	0.32
	*Stockpiled	11	13000 ± 1000	0.43
	*Grass mix	11	13000 ± 1000	0.43
	Shrub mix	11	13000 ± 1000	0.43
Mine 2	Undisturbed	∞	50000 ± 5000	-
	Grazed	11	25000 ± 2000	0.50
	Ungrazed	11	22000 ± 2000	0.73
Mine 3	Undisturbed	∞	37000 ± 5000	-
	Direct Haul	19	34000 ± 2000	0.92
	Stockpile	19	29000 ± 2000	0.78
Mine 4	Undisturbed	∞	38000 ± 2000	-
	Grass mix	11	**42000 ± 3000**	**1.11**
	Shrub mix	11	**42000 ± 2000**	**1.11**
Mine 5	Undisturbed	∞	34000 ± 3000	-
	Hay	14	30000 ± 3000	0.89
	Stubble	14	**41000 ± 4000**	**1.21**

[1] Calculated as a weighted average based on depth increments (0-30 cm) and bulk density per depth

[2] Calculated as a weighted average and divided by undisturbed value

* Same site listed twice for ease of comparison

Conclusions

Reclamation practices compared in this study did not have significantly different effects on the concentration of OC in soil ten or more years after reclamation was initiated, except for stubble mulching which was found to result in an apparently long lasting input of C at the 15-30 cm soil depth. Microbial biomass C was more affected by the compared management practices than SOC, and in particular by seed mixes and grazing treatments. Our data indicates that although significant amounts of OC were initially lost from soils impacted by surface coal mining, reclaimed soils accumulated OC at a substantial rate and may accrue more C than nearby undisturbed soils. Although a significant positive linear relationship between MBC and SOC was observed for both reclaimed and undisturbed soils, we believe differences in the environmental control of this relationship is leading to the relatively high rate of C accumulation in reclaimed soils.

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