AGGREGATE SIZE DISTRIBUTION AND STABILITY UNDER A COOL SEASON GRASS COMMUNITY CHRONOSEQUENCE ON RECLAIMED COAL MINE LANDS IN WYOMING[1]

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Abstract: Evaluation of mine reclamation success is based on examination of aboveground ecosystem components. Recovery of belowground constituents and processes, such as soil structure and nutrient cycling, is crucial to successful reclamation of disturbed lands. Inadequate recovery of belowground ecosystem structure and function during reclamation can lead to future site degradation. Our objective in this study was to test the hypothesis that recovery of plant community properties on reclaimed surface mine land accurately reflect recovery of soil structure, more specifically aggregate size distribution. In this study, above- and belowground constituents were sampled on reclaimed mine sites representing various ages (native rangeland, a 4 month old topsoil stockpile, 14, 26, and 29 year old reclamation) located in northeastern Wyoming. Cool-season grass (native and reclaimed) communities were sampled for aboveground biomass production, cover and species diversity according to Wyoming Department of Environmental Quality standards. Soil samples were analyzed for water stable aggregate size distribution with wet sieving. Soil structure appears to be recovering through time. An increase in macroaggregates (250-2000µm) on a weight basis and a decrease in free microaggregates (53-250 µm) and free silt and clay (<53 µm) on reclaimed sites with time was observed, indicating incorporation of free silt and clay and free microaggregates into macroaggregates. Aboveground biomass production and macroaggregate formation showed a significant relationship ($R^2 = 0.457$); however, no relationship was evident for microaggregate formation. No significant relationship existed among total cover and species diversity with respect to macro- and microaggregate formation. These preliminary results suggest that soil structural recovery is most closely related to plant biomass production, while other plant community properties do not necessarily reflect this recovery.

Additional Key Words: reclamation, macroaggregate, microaggregate, recovery

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Introduction

Recovery of drastically disturbed lands along an ecological trajectory towards defined native ecosystem characteristics is an essential concept in restoration ecology and land reclamation (Whisenant, 1999). Mineland reclamation goals should include recovery of plant community structure and ecosystem function. To ensure long term reclamation success, we need to understand soil processes such as structure, nutrient cycling, and microbial community recovery (Ingram et al., 2005; Whisenant, 1999). The state of Wyoming evaluates reclamation success based on reestablished plant communities, with little consideration of belowground ecosystem recovery (WDEQ, 2002). Inadequate recovery of soil structure and function can lead to future site degradation because plant community productivity and diversity are highly dependent upon soil physical, chemical and biological properties (National Research Council, 1994).

Impacts of tillage disturbance on soil structure have been extensively studied in agricultural systems, but until recently, have not been a focus of reclaimed mine land research. Soil structural properties, mainly water stable aggregate size distribution, are important factors influencing rates of nutrient cycling, plant community development and soil stability (Six et al., 1998; Jastrow, 1987; Valmis et al., 2005). Aggregates physically protect soil organic matter (SOM) from microbial decomposition, resulting in reduced organic matter (OM) turnover rates and a steady release of plant available nutrients. With disturbance, macroaggregates (>250 µm) break apart and release microaggregates (53-250 µm) as well as silt and clay particles (<53 µm) into the soil making once protected OM susceptive to higher rates of microbial decomposition (Six et al., 1998). Through time, as microbial polysaccharides, root exudates and OM are added to the soil, macroaggregates form from recent and old OM, free microaggregates, silt and clay (Six et al., 1998; Tisdall, 1996). Within stable macroaggregates, microaggregates will develop through the binding of complex OM, silt and clay. This type of microaggregate is extremely stable and provides a mechanism for long term carbon (C) storage. In addition to nutrient cycling and C dynamics, soil aggregation also influences gas exchange between the soil and atmosphere, soil water movement, plant root development, microbial development and soil stability (Jastrow et al., 1998; Kay, 1998). Soil structural recovery in drastically disturbed lands is important for ecosystem function and reclamation success.

The objectives in this study were to observe aggregate recovery through time and study relationships between reestablished plant communities and soil structural recovery to determine whether current reclamation success standards adequately reflect recovery of this particular soil function. We hypothesize that (1) the amount of 250-2000 µm size aggregates increases with reclamation age at all soil depths, (2) the amount of free microaggregates (53-250 µm) and free silt and clay decreases with site age at all soil depths, and (3) plant community properties reflect soil structural recovery.

Methods and Materials

Site Information

A chronosequence of reclaimed sites (5) were sampled at Belle Ayr Mine in the Powder River Basin, WY, USA. The four month old site (N 44˚ 04.613’ W 105˚ 25.520’) was a topsoil stockpile established in March of 2005, the 14 year old site (N 44˚ 05.696’ W 105˚ 22.564’) was reclaimed in May of 1991, the 26 year old site (N 44˚ 06.333’, W105˚ 22.4476’) was reclaimed in October of 1979, the 29 year old site (N 44˚ 05.890’, W 105˚ 22.330’) was reclaimed in

November of 1976, and the native site (N 44˚ 04.997', W 105˚ 26.016') has not been impacted by mining. Each site is approximately 0.5 ha in size. Direct haul topsoil replacement was used for all three reclaimed sites and similar cool season grass seed mixes were used at each site. Reclaimed sites have been grazed by cattle in a three year rotation.

Soil Sampling and Lab Analysis

Soil samples at each site were collected in 2005. The top 5 cm of soil was collected with a trowel and the 5-15 and 15-30 cm depths with a 2.5 cm diameter step probe at four points along three randomly oriented, 45 meter transects. Five samples for each of the three depths were collected for bulk density (BD) at each site using a double-cylinder, hammer driven core sampler (Blake and Hartge, 1986). Samples were air-dried and dry-sieved to 2000 µm to break apart soil clods and leave structure <2000 µm intact. Soil texture was determined on a subset of samples using the hydrometer method (Gee and Bauder, 1986). Electrical conductivity (EC) and pH were determined on all samples with 1:1 mixtures (5 mL of deionized water and 5 grams of soil). An Oakton con 100 series EC probe and an Accument Basic pH meter with a glass electrode were used for analysis. C and Nitrogen (N) values were obtained with an Elementar Variomacro Analyzer (Hanau, Germany). Inorganic carbon (IC) was determined with the modified pressure calcimeter method (Sherrod et al., 2002). General soil characteristics for each site are given in Table 1.

Table 1. Soil characteristics for stockpile, reclaimed and native sites at the Belle Ayr Mine, WY.

Site	Depth	Texture				pH	EC	BD	C/N	Org C	Tot N
		sand	silt	clay	class						
yrs	cm	g 100 g^{-1} soil					S m^{-1}	g cm^{-3}		g ha^{-1}	(10^2) g m^{-2}
0.3	0-5	38	26	36	clay loam	7.83	0.052	1.26	9.99	5.46×10^8	55.9
0.3	5-15	37	24	39	clay loam	7.68	0.056	1.35	10.74	1.19×10^9	119
0.3	15-30	38	25	37	clay loam	7.59	0.062	1.51	10.35	1.76×10^9	174
14	0-5	38	19	43	clay	7.63	0.037	1.20	15.61	5.50×10^8	82.8
14	5-15	38	17	45	clay	8.10	0.037	1.33	18.67	1.39×10^9	190
14	15-30	38	16	46	clay	8.12	0.057	1.26	9.60	1.49×10^9	180
26	0-5	38	27	35	clay loam	7.04	0.041	1.21	13.64	9.62×10^8	72.2
26	5-15	37	25	38	clay loam	7.82	0.031	1.38	14.89	9.68×10^8	104
26	15-30	37	14	49	clay	7.96	0.035	1.26	15.33	3.04×10^9	261
29	0-5	39	16	45	clay	6.57	0.033	1.13	13.27	3.98×10^8	51.4
29	5-15	35	27	38	clay loam	7.73	0.085	1.30	14.73	1.00×10^9	107
29	15-30	39	18	43	clay	7.75	0.134	1.37	15.28	6.16×10^9	413
Native	0-5	37	40	23	loam	6.03	0.019	1.33	10.37	1.47×10^9	143
Native	5-15	38	33	29	clay loam	6.27	0.010	1.27	13.86	1.94×10^9	140
Native	15-30	39	22	39	clay loam	6.57	0.017	1.34	10.65	2.09×10^9	198

Water stable aggregate size distribution was determined using wet sieving protocol described by Six et al. (1998). In summary, 100 ± 0.02 grams of air-dried soil was submerged in dionized water (room temperature) for 5 minutes on a 250 µm sieve. Water stable macroaggregates (250-2000 µm aggregates resistant to slaking) were separated from the bulk soil by moving the sieve 3 cm up and down 50 times in 2 minutes. Material (water plus soil) which went through the sieve was transferred to a 53 µm sieve and the above process repeated. Material collected from each sieve (250-2000 µm, 53-250 µm and <53 µm) was dried at 55˚C until a constant weight was achieved. Samples were then weighed and stored.

Sand is the same size as 250-2000 and 53-250 µm aggregates. Sand corrections were determined for a subset of samples according to Denef et al. (2002). Five mL of sodium hexametaphosphate and 10 mL of water was added to 5 grams of the 250-2000 µm sized aggregates. The same was done for 53-250 µm sized aggregates. Samples were shaken on a reciprocal shaker for 18 hours and sieved with 250 and 53 µm sieves. Samples collected on each sieve were dried and weighed to determine a sand correction value (weight basis).

Vegetation Sampling and Analysis

Vegetation samples were collected in late June 2005 according to Appendix A of the Wyoming Department of Environmental Quality standards for determination of reclamation success (WYDEQ, 2002). Briefly, five aboveground biomass production plots were established using a stratified random method from a baseline (Chambers and Brown, 1983). Vegetation rooted within 1 m^2 plots was clipped and separated by species. A 50 m transect was randomly directed from each aboveground biomass production plot to determine cover at meter increments with an ocular device (ESCO Associates Inc, 0.05 mm accuracy). Cover was recorded for one point on either side of the transect at each meter for a total of 100 points. Diversity was determined along the same 50 meter transect, by recording each species within one meter of either side of the transect. Samples collected in the field were dried in a forced air oven at 55˚C for 24 hours, or until a constant weight was reached.

Statistical Analysis

Statistical analysis was conducted using JMP version 4.0.4 (JMP, 2001). Data were analyzed with one way analysis of variance to determine differences among reclamation ages, student's t-tests to determine significance, and simple regressions for soil-plant relationships within a reclamation age. All statistical analyses were accomplished at $P \leq 0.05$.

Results and Discussion

Aggregate Size Distribution

Two general trends were observed in the data, both suggesting soil structure is recovering on reclaimed mine lands. The first observation was a significant increase in the proportion of 250-2000 µm size aggregate fraction with time and a significant decrease in the proportion of 53-250 µm free microaggregates and <53 µm free silt and clay for the 0-5 cm depth of the reclaimed soils (Figure 1). This was attributed to incorporation of 53-250 µm size free aggregates, and free silt and clay into 250-2000 µm aggregates through time (Tisdall and Oades, 1982). On the reclaimed sites, soil structure appears to be recovering. However, we would have expected to see the highest proportion of 250-2000 µm in native sites compared to disturbed sites (Tisdall, 1996), but this was not evident. The fact that the native site did not have the highest proportion of 250-2000 µm aggregates can be explained by significantly lower aboveground biomass production on the native site (98.3 g m^{-2}) compared to reclaimed sites (averaging 184.1 g m^{-2}). We can assume that belowground biomass production was also lower on the native site, meaning that less fine roots and root exudates were aiding in formation of 250-2000 µm size aggregates. Higher above- and belowground biomass production on reclaimed lands compared to native lands also adds more plant residue to the soil. Plant residue serves as a nucleation site for aggregation, fungi and microbial biomass growth. Extracellular polysaccharides released by fungi and microbes bind primary particles into 250-2000 µm size aggregates and soil particles are physically entangled in fungal hyphae (Jastrow et al., 1998; Tisdall et al., 1997). Malik and Scullion (1998) found that carbohydrate inputs and microbial biomass are highly correlated with aggregate formation on reclaimed mine lands. In addition to plant biomass, soil texture effects aggregate formation. The native soil had less clay (23%) compared to the reclaimed sites (>35%) which could have caused the lower proportion of 250-2000 and 53-250 µm size fractions of aggregates in the native soil (Lado et al., 2004). Clay is important in the physical formation of macroaggregates (Degens et al., 1996) in addition to altering soil pore space and creating microhabitats for microbes (Denef and Six, 2003). Fungal hyphae contribute more to macroaggregate formation than bacteria in soils higher in sand compared to more clayey soils where both bacteria and fungi aide in aggregate formation (Degens et al., 1996). The combined effects of fungi and bacteria activity on macroaggregate development in higher clay soils, could explain the decreased macroaggregate formation in the native soil. Similar trends were observed in 5-15 and 15-30 cm depths (Figures 2 and 3, respectively).

A second observation was that the mass of the 250-2000 µm size fraction increased from the stockpile site to the 14 year old site followed by a decrease in amount of macroaggregates with site age with exception of the 29 year old site (Fig. 1). This decrease could signify macroaggregate turnover (Jastrow et al., 1996). As microbial and fungal communities recover through time, macroaggregate formation increases. Microbial and fungal activities persist until OM within the aggregate becomes too complex for most microbes. At this point, microbial activity decreases and the macroaggregates turnover (Six et al., 2000). Once protected microaggregates, highly degraded OM, and silt and clay are released into to the soil (Six et al., 2002). This trend was observed in sites (14 year, 26 year, and native) dominated (44, 55, 39% of total vegetation production, respectively) by the rhizomatous grass, western wheatgrass (*Pascopyrum smithii)*. Crested wheatgrass (*Agropyron cristatum*) is a bunch grass and

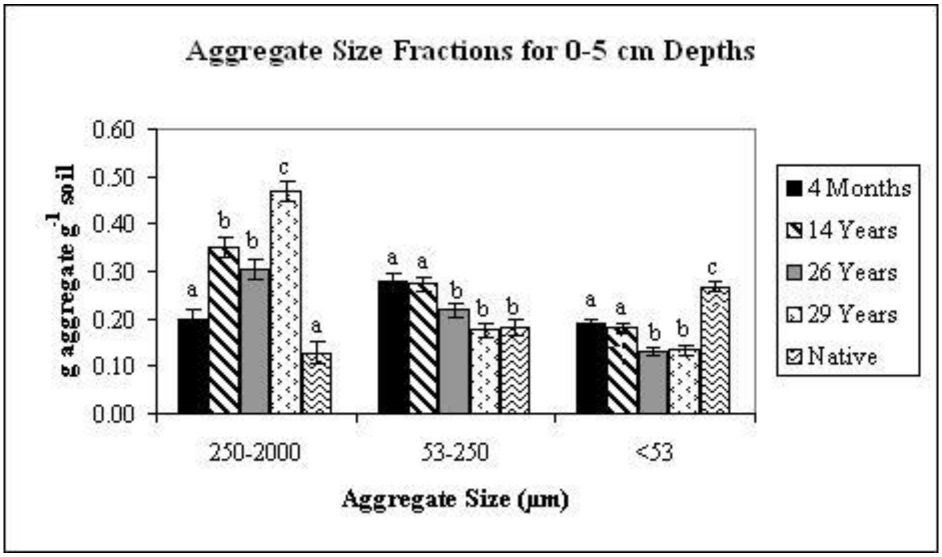

Figure 1. Aggregate size distribution for 0-5 cm depths of reclaimed and native sites at Belle Ayr Mine, WY.

dominates (78% of total vegetation production) the 29 year old site, potentially causing differences in macroaggregate formation based on root type and root exudation. A more fibrous root system under crested wheatgrass could lead to an elevated macroaggregate formation in the 29 year old site and more coarse roots under western wheatgrass could lead to more root penetration and break up of macroaggregates at the other sites (Six et al., 2004). Again, this same general trend was observed in the 5-15 and 15-30 cm depths (Fig. 2 and 3).

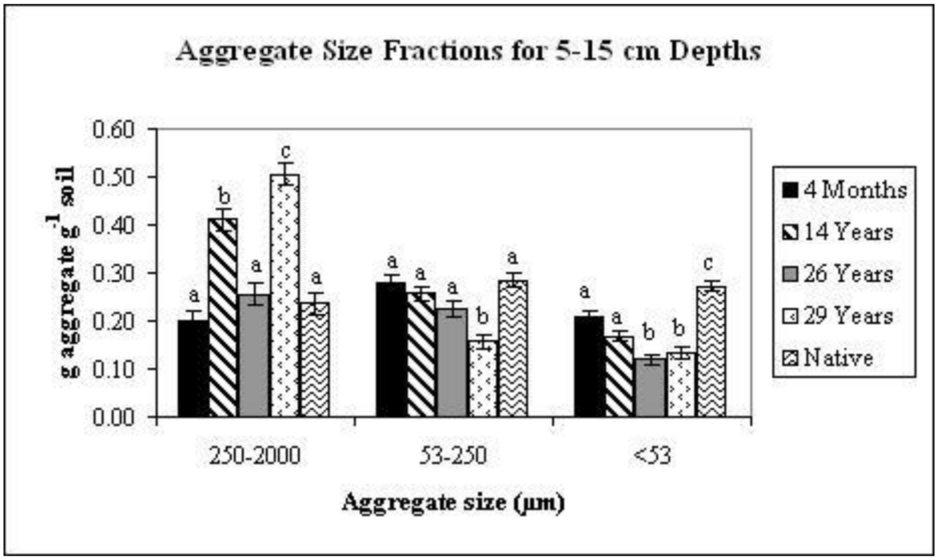

Figure 2. Aggregate size distribution for 5-15 cm depths of reclaimed and native sites at Belle Ayr Mine, WY.

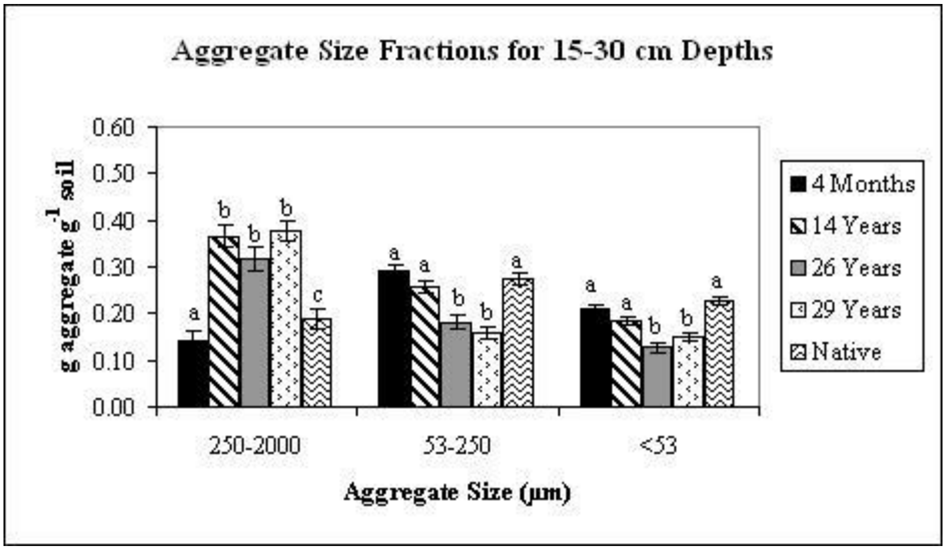

Figure 3. Aggregate size distribution for 15-30 cm depths of reclaimed and native sites at Belle Ayr Mine, WY.

Aggregate Size Distribution and Plant Community Properties

As reclamation age increased, there was a decrease in cool season grass and annual forb production and an increase in warm season grasses and perennial forb production (Table 2). Jastrow (1987) and Jastrow et al. (1998) suggest that warm season (C_4) plants and perennial forbs contribute more to macroaggregate formation than cool season (C_3) plants in tall grass prairie ecosystems. As the C_4 grass component increased (Table 2) through time, we would expect to see macroaggregate formation increase as well. An unexpected decrease in macroaggregate formation was observed under a mix of C_4 and C_3 grasses in the native plant community.

Table 2. Percentage of plant life forms based on aboveground biomass production data.

Site	% Cool Season Grass	% Warm Season Grass	% Annual Forbs	% Perennial Forbs	% *Bromus tectorum*
4 Month	100.0	0.0	0.0	0.0	0.0
14 Years	60.8	0.0	30.5	0.0	8.7
26 Years	60.2	0.0	32.6	4.4	2.8
29 Years	81.5	1.5	16.2	0.6	0.2
Native	72.4	14.8	1.0	9.4	2.4

A significant relationship between aboveground biomass production and macroaggregate formation ($R^2 = 0.457$) was observed; however this relationship did not exist for microaggregate formation. Plant roots, fungal hyphae and excretion of microbial polysaccharides are major components of macroaggregate formation. Microbial community diversity and time are major components of microaggregate formation. As plant and microbial communities become less productive and more diverse over time (Visser et al., 1983), microaggregate formation becomes dominant. Total aboveground biomass production values for the reclaimed sites (14, 26 and 29 yr old sites) were not significantly different, but were significantly higher than the native and topsoil stockpiled sites.

Percent total cover and species cover was higher on the 14 yr old reclamation and the native site compared to the other reclaimed sites (Fig. 4). Cover on the 14 yr old site was higher than other reclaimed sites because of higher vegetation production and invasion of cheat grass (*Bromus tectorum*) (Table 2). Cheat grass accounted for 11% of the cover on the 14 yr old site compared to 2% for the other sites. There was not a significant relationship between cover and macroaggregate recovery or cover and microaggregate formation.

Diversity was significantly higher on the native site compared to reclaimed sites. This was expected because diversity is one of the most difficult plant community properties to re-establish on reclaimed mine lands. There was no relationship between diversity and aggregate size distribution.

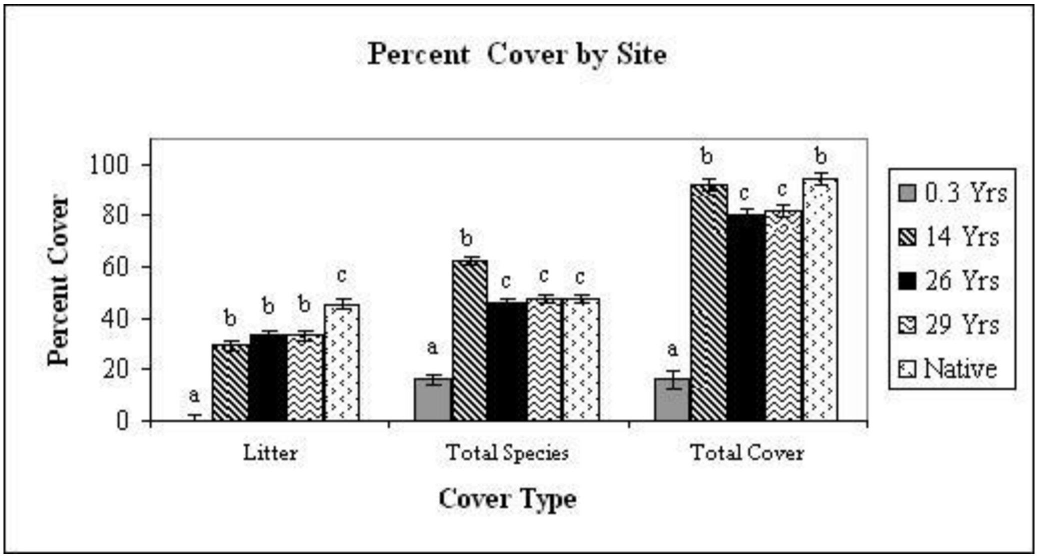

Figure 4. Percent cover by site at the Belle Ayr Mine, WY.

Conclusions

Macroaggregates and microaggregates are showing recovery though time (weight basis), but this recovery is not reflected by all three plant community properties evaluated in this study. There was a significant relationship between aboveground biomass production and macroaggregate recovery due to probable influence of roots on macroaggregate formation. Fine roots entangle soil particles, release exudates, form associations with fungi and influence dry-wet cycles in the rhizosphere, which all increase water stable aggregate formation. Vegetation cover and diversity parameters exhibited signs of recovery through time, but they did not appear to be related to the recovery of soil structural. An understanding of belowground ecosystem recovery in relation to aboveground ecosystem properties is essential for long term reclamation success.

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