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Aggregate and organic matter dynamics in reclaimed soils as indicated by stable carbon isotopes

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ABSTRACT

Recovery of belowground ecosystem processes, such as soil aggregation and organic matter (OM) accumulation, in reconstructed soils is crucial to successful reclamation of disturbed lands. Objectives of this study were to track soil aggregate recovery in combination with aggregate associated OM on a chronosequence of reclaimed surface mine sites and a native, undisturbed reference site. Macroaggregate and micro-within-macroaggregate proportions increased with reclamation age, while microaggregate proportions decreased. Organic carbon (C) and total nitrogen (N) concentrations increased with reclamation age for each aggregate fraction and were higher in the OM fraction observed within soil aggregates than in the free OM fraction found between soil aggregates. Naturally occurring isotopic signatures of ^{13}C decreased rapidly with reclamation age, indicating over 50% of total aggregate C to be new C from predominately C_3 plant community inputs after 26 years of reclamation. Soil aggregate size distribution trends of increasing macroaggregation and micro-within-macroaggregates along with rapid rates of OM accumulation with time indicated that reclaimed soils had recovered structurally towards a native soil condition after a period of 10–15 years.

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1. Introduction

Research on soil aggregation in reclaimed mine lands has generally focused on soil stability (or resistance to erosion) rather than influences of aggregation on reclaimed soil structure and function, i.e. organic matter (OM) protection and dynamics (Vogel, 1987). Structurally, aggregation directly influences soil properties such as, but not limited to, bulk density and pore size distribution (Hillel, 1982). Soil OM indirectly contributes to soil structure by serving as a nucleus for aggregate formation (Six et al., 1998). Aggregation is also closely tied to soil function by physically protecting OM (which provides a metabolic energy pool for microbes and macronutrients for plants) and therefore is one regulator of microbial decomposition and nutrient availability (Essington, 2004). Reclaimed mine soils present a unique system for detailed examination of soil processes such as aggregation and OM protection.

It is generally understood that OM is greatly reduced and diluted with topsoil stripping and/or storage prior to mining from increased microbial activity and soil horizon mixing (Ussiri et al., 2006; Lorenz and Lal, 2007). In reclaimed soils, most macroaggregates are also destroyed as a result of topsoil removal, storage, replacement, and tillage prior to re-vegetation as the roots and fungal hyphae holding macroaggregates together are disrupted. Soil OM (measured as soil organic carbon, SOC) has been found to rapidly accumulate in reclaimed soils (Stahl et al., 2003), but there is not always a corresponding increase in soil macroaggregation (Malik and Scullion, 1998). However, it is hypothesized that recovery of aggregation in reclaimed soils could be important for OM accumulation because physical protection by soil aggregates is considered to be a major mechanism protecting OM from microbial mineralization in these systems (Ingram et al., 2005). Additionally, inputs from reclaimed plant communities, which are often more productive than native communities (Wick et al., 2007), could result in greater contributions of OM and root exudates to the soil, leading to more aggregate formation and protection of OM within soil aggregates. Soil aggregate recovery, its relationship with OM accumulation and the rate of recovery towards pre-disturbance conditions in drastically disturbed lands are important factors for ecosystem function and reclamation success (Lyle, 1987; Jastrow et al., 1998).

Though the relationship between OM and aggregates is important, the dynamics associated with incorporation of OM into soil aggregates is a poorly understood component of reclaimed soil recovery. Stable carbon (C) isotopes can be used to track the incorporation of "new" OM (approximately 48% of which is C; Brady and Weil, 2002) into soil aggregates following a land use

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conversion if the plant community has changed from warm season (C_4) grasses ($\delta^{13}C$ of -12 to $-16‰$) to cool season (C_3) grasses ($\delta^{13}C$ of -25 to $-29‰$), or vice versa (O'Leary, 1988). Many studies have used this technique to observe OM incorporation, dynamics and aggregate hierarchy in agricultural or land use change soils (Jastrow et al., 1996; Six et al., 2000; Lobe et al., 2005; Schwendenmenn and Pendall, 2007).

Mining disturbances in eastern Wyoming often result in a change in plant community composition from an undisturbed native C_4/C_3 plant community with the dominant species being *Bouteloua gracilis*, *Pascopyrum smithii*, and *Artemisia tridentata* to a reclaimed C_3 plant community consisting of *Pascopyrum smithii*, *Nassella viridula*, and *Hesperostipa comata*. Undisturbed, northern mixed-grass plant communities found in northeastern Wyoming consist of approximately 70% C_3 and 30% C_4 plants compared to reclaimed communities which typically contain less than 2% C_4 plants (Wick et al., 2007). Utilizing stable C isotopes to understand OM incorporation and accumulation in reclaimed systems will increase our understanding of C cycling in reclaimed soils.

Objectives of this research were to: (1) quantify aggregate size distributions through time, (2) quantify changes in organic C and total N in aggregate size classes and (3) quantify and determine the location of new OM within each aggregate size class. We hypothesize: (1) macroaggregation will increase with time since reclamation to approach native soil conditions, (2) aggregate organic C and total N will increase with reclamation age, (3) soil macroaggregate $\delta^{13}C$ values will be most similar to root signatures under reclaimed plant communities, and (4) microaggregate $\delta^{13}C$ values will remain similar to native, undisturbed soil $\delta^{13}C$. We also expect a more rapid rate of new C incorporation into the macroaggregate fraction compared to the microaggregate fraction.

2. Materials and methods

2.1. Site information and field sampling

A chronosequence of three reclaimed strip mine sites and one native undisturbed reference site were sampled at the Belle Ayr Coal Mine, a surface mine located in the Powder River Basin, WY, USA. The <1 year 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 and the undisturbed, native rangeland site (N 44° 04.997′, W 105° 26.016′) had not been impacted by mining. A topsoil stockpile was selected for the <1 year old site because of lack of available new reclamation sites at the Belle Ayr Mine. Removal of topsoil from an undisturbed site and relocation to a stockpile followed by drill seeding for stockpile stabilization was similar to the disturbance associated with direct haul of topsoil from an undisturbed site to a reclaimed area during reclamation efforts. A native undisturbed reference site, though imperfect for comparison purposes, was included to provide an example of aggregation, C and N concentrations in relatively undisturbed semiarid soils. Average annual precipitation for the area is 376 mm and the mean annual air temperature is 6.7 °C (Laurel Vicklund, personal communication). Each site selected for sampling was relatively flat and approximately 0.5 ha in size. Direct haul topsoil replacement (where soil is stripped from an area about to be mined to an area in the process of being reclaimed) was used for all reclaimed sites. Similar cool season (C_3) grass species were observed [*Pascopyrum smithii* (Rydb.) A. Löve, *Nassella viridula* (Trin.) Barkw., and *Hesperostipa comata* (Trin. & Rupr.) Barkw.] on all sites. The 26 year old site had a small component (<2% cover) of C_4 grasses, including *Bouteloua gracilis* (H.B.K. Lag. Ex Steud) (Wick et al., 2007).

Soil samples were collected at each site in May, 2005. The top 5 cm of soil (where C changes occur the fastest; Grandy and Robertson, 2007) was collected with a trowel at four points along each of three randomly oriented, 45 m transects. At the native site only, samples were also collected from the 5–15 and 15–30 cm depths using a 2.5 cm diameter step probe to represent soil mixing with topsoil stripping and to better serve as a reference for isotopic signatures. Five samples from the 0–5 cm depth were collected for bulk density (BD) and five samples for root biomass at each site using a double cylinder, hammer driven core sampler (Grossman and Reinsch, 2002).

2.2. General soil properties

Samples were air dried and dry sieved to 2000 μm to remove large roots and break apart soil clods while leaving structure <2000 μm intact. Particle size distribution was determined on a subset of samples (four per site age) using the hydrometer method (Gee and Or, 2002). Electrical conductivity (EC) and pH were determined on a 1:1 soil:water mixture using an Oakton con 100 series EC probe (Vernon Hills, IL) and a Fisher Scientific Accument Basic pH meter with a glass electrode (Pittsburgh, PA). Root cores of known volume were immersed in deionized water overnight to slake aggregates and washed on nested 2000 and 250 μm sieves to separate roots from soil. The 250 μm sieve was used only to collect small root pieces that may have been broken off larger roots during sampling. Roots remaining on the sieves were combined, dried at 55 °C and weighed to calculate root biomass. Visual estimations of dead root biomass were determined at this point.

2.3. Aggregate size distribution

Water stable aggregate size distribution of soil was determined on the 2000 μm sieved samples using a wet sieving protocol described by Six et al. (1998). In summary, 100 ± 0.02 g of air dried soil were submerged in deionized water for 5 min at room temperature on a 250 μm sieve. Water stable macroaggregates (250–2000 μm) were separated from the whole soil by moving the sieve 3 cm up and down 50 times in 2 min. Material (water plus soil) that passed through the sieve was transferred to a 53 μm sieve and the above process repeated. Material collected from each sieve (250–2000 and 53–250 μm) was dried at 55 °C until a constant weight was achieved. Samples were then weighed and stored. The fine fraction (<53 μm) was determined by subtracting aggregate weights from the starting sample weight of 100 g. The fine fraction was collected, dried and weighed for 10% of total samples analyzed to assure >98% sample recovery throughout the sieving process.

Sand the same size as macro- and microaggregates is not likely to be part of an aggregate and will vary across site ages (Elliott et al., 1991). Aggregate samples were corrected for sand content according to Denef et al. (2001); where 5 g of each aggregate sample was dispersed with 0.5% sodium hexametaphosphate on a shaker for 18 h. Following shaking, dispersed samples were sieved with 250 and 53 μm nested sieves for macroaggregates and a 53 μm sieve for microaggregates. Sand on the sieves was collected, dried and weighed. Sand corrected aggregate weights were determined according to Eq. (1).

$$\text{Sand corrected weight} = \text{aggregate weight} - [(\text{sand weight}/5\text{g}) \times \text{aggregate weight}] \quad (1)$$

2.4. Micro-within-macroaggregate isolation

Micro-within-macroaggregates were isolated according to a method described by Six et al. (2000). Macroaggregate samples