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A comparison of the efficacy and ecosystem impact of residual-based and topsoil-based amendments for restoring historic mine tailings in the Tri-State mining district

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HIGHLIGHTS

- Plant yield and metal uptake over 12 years show efficacy of residuals.
- Field small mammal trapping indicate minimal risk of attractive nuisance.
- Physical properties and fertility of residuals are similar to topsoil.
- Ecosystem costs of replacement topsoil show benefit of residuals.

GRAPHICAL ABSTRACT

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ABSTRACT

A long-term research and demonstration site was established on Pb and Zn mine wastes in southwestern Missouri in 1999. Municipal biosolids and lime and composts were mixed into the wastes at different loading rates. The site was monitored intensively after establishment and again in 2012. A site restored with topsoil was also included in the 2012 sampling. Initial results including plant, earthworm and small mammal assays indicate that the bioaccessibility of metals had been significantly reduced as a result of amendment addition. The recent sampling showed that at higher loading rates, the residual mixtures have maintained a vegetative cover and are similar to the topsoil treatment based on nutrient availability and cycling and soil physical properties including bulk density and water holding capacity. The ecosystem implications of restoration with residuals versus mined topsoil were evaluated. Harvesting topsoil from nearby farms would require 1875 years to replace based on natural rates of soil formation. In contrast, diverting biosolids from combustion facilities (60% of biosolids generated in Missouri are incinerated) would result in greenhouse gas savings of close to 400 Mg CO_2 per ha.

1. Introduction

Prior to regulations requiring stockpiling of topsoil, topsoil from above-ground mining operations was typically disposed of with

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overburden (SMRCA, Public Law 95-87). Many of these former mining sites are currently listed on EPA's National Priorities List (NPL), while others are categorized as abandoned mine lands (US EPA AML). It is necessary to source topsoil externally or identify alternatives to naturally developed soils to restore these sites. Restoration of large-scale mining sites often is impeded by the absence of sufficient quantities of replacement topsoil (Titone, 2000). In cases where sufficient topsoil is commercially available, the ecosystem costs of topsoil removal has not been considered in the remedial decision making process. Natural soil formation is a time-intensive process, with soils forming over thousands of years (Banwart, 2011: Brady and Weil, 2002; Montgomery, 2007). Recently, the importance of soil to a range of ecosystem processes has been recognized (Costanza et al., 1997; Robinson et al., 2013; Sauer et al., 2011). Concurrently, a recognition that the health of soils in the United States has been declining with an associated decrease in functionality is noted (Amundson et al., 2003; Banwart, 2011). In limited cases, the value of healthy soil, components of soil or the services associated with soil have been monetized (Dymond et al., 2012; Galinato et al., 2011; Jack et al., 2009). A framework has also been proposed that considers the relative value of different types of soil (Dominati et al., 2009).

Residual-based soil amendments can be a viable alternative to harvested topsoil for restoring large-scale sites. Mixing municipal biosolids with topsoil has been shown to result in greater soil carbon storage with a predicted increase in tree volume for sites restored to forest (Trlica and Brown, 2013). Biosolids are commonly used to restore coal mined lands (Haering et al., 2004; Roberts et al., 1988a, 1988b; Sopper, 1993). Restoration of coal-mined land using biosolids, biosolid-based compost, or other composts is a recommended remedial option in several states (Toffey et al.; Virginia Department of Mines, Mineral, and Energy). The efficacy of residual-based amendments for hard rock mine restoration has been demonstrated for multiple sites, including sites on the NPL (Brown et al., 2004; Brown and Basta, 2007; Madejón et al., 2012; Pepper et al., 2013; Santibáñez et al., 2008; Stuczynski et al., 2007). Studies have shown increased plant cover and diversity, increased microbial activity and nutrient cycling on residual restored sites.

While EPA also recommends the use of residual-based amendments to reclaim disturbed lands, there are few incentives to use this approach rather than conventional sourcing of topsoil (Allen et al., 2007; US EPA Clu-in Ecotools). Once a decision has been reached on the appropriate means to restore a site, there is an expectation that remedial actions will take place as quickly as is feasible. Under current accounting metrics, sourcing of replacement topsoil can be more economical and time efficient than residual-based approaches. Further, large quantities of residuals can be difficult to source over a short time frame, and there is concern about the long-term efficacy of residual based amendments and the potential for sites restored with amendments to create an attractive nuisance. Concerns include the bioavailability of contaminants in restored systems, regulatory requirements relating to the use of residuals and the potential for public opposition to alternative remedies.

A comparison of the ecosystem benefits regarding the use of residuals and the ecosystem costs of topsoil harvesting may result in a different understanding of the relative merits of each approach. Economic factors, regulatory acceptability, and convenience are currently determining factors in decisions to use harvested topsoil. Newer tools, including life cycle assessment (LCA), valuations of natural capital, and environmental economics can provide additional insight to the ramifications of various remedial options and thereby inform the decision-making process (Costanza et al., 1997; Brown et al., 2010; Fenech et al., 2003). Studies have shown that our current rate of topsoil consumption and the use of natural capital are not sustainable (Rockström et al., 2009). However, attempts to quantify the value of soils and to develop tools to institutionalize the valuation of soil services in the decision making process has yet to become broadly adopted (Ranganathan et al., 2008; Robinson et al., 2013).

The historic mining areas in Missouri, Oklahoma and Kansas comprising the "Tri-State mining district" are suitable for this comparison. Mining of Zn- and Pb-rich ores commenced in the area in the mid 1800s. Mining and smelting operations were typically small with over 100 mines and 17 smelters in operation in Jasper County, Missouri. Peak production occurred in 1916 with more than 123 million tons of rocks processed in Jasper County alone (Interstate Technology Regulatory Council Mining Waste Treatment Technology Selection). The area includes multiple sites on the NPL list including the 7000-acre Oronogo-Duenweg Mining Belt (US EPA Oronogo-Duenweg Mining Belt) in Jasper County as well as sites in OK and KS (US EPA Superfund Program Implements the Recovery Act; US EPA Cherokee County Kansas). The entire area encompasses over 607,000 ha.

The Tri-State mining district is close to sources of topsoil. Native soils in most of Kansas and parts of Missouri are classified as Mollisols that are characterized by a high organic matter, nutrient-rich, surface horizon that is 60–80 cm deep (Brady and Weil, 2002). Mollisols are generally considered to be optimal soils for agricultural production and so have high natural capital (Dominati et al., 2009), but large portion of soils in this region were recently classified as "degraded" as a result of decades of conventional agricultural practices (Amundson et al., 2003; Banwart, 2011). Topsoil for reclamation in Jasper County is typically sourced from these local Mollisols. Removal of the top 15–30 cm of these soils would result in further degradation.

1.1. Purpose

This study assessed the long-term efficacy of biosolid- and compost-based amendments to restore Pb and Zn contaminated mine wastes in the Oronogo-Duenweg Mining Belt in southwestern Missouri as an alternative to the standard practice of using harvested topsoil. This data from this portion of the study was then applied to evaluate the ecosystem benefit impact of residual based restoration compared to the traditional practice of topsoil harvesting.

2. Materials and methods

2.1. Site establishment

Seven large-scale demonstration plots were established on mine wastes (tailings and overburden) at the Oronogo-Duenweg NPL site starting in the fall of 1998 with applications complete by June 2001. The site is located at 37°5′3″N and 94°30′47″. Elevation is 306 m. Annual precipitation at the site is 1180 mm with an annual mean low temperature of 8.7 °C and high temperature of 20.7 °C. The primary purpose of these plots was to test the efficacy of residual based amendments to reduce metal availability in situ and to restore a self-sustaining plant cover on amended tailings. Ecosystem transfer of contaminants was a primary focus of this work. Plots ranged in size from 0.4 to 4 ha. Biosolids from Springfield, Missouri (110 to 336 Mg ha^{-1}), mixed with limestone (24 to 48 Mg ha^{-1} $CaCO_3$) mushroom and biosolid based composts, and poultry manure (applied singly at 224 Mg ha) were included in the demonstration. Amendments applied as mixtures were mixed with a front end loader and disked into the top 10–15 cm of soil using a large tiller. Amendments applied singly were surface spread with a loader and similarly incorporated. A subset of the area amended with 110 Mg biosolids and 48 Mg ha limestone was subdivided and seeded with individual grasses or native grass mixtures. Each of the grass plots was approximately 0.5 ha in size. These areas were not replicated. As is typical for historic large-scale, hard-rock mining sites, the wastes were highly variable both in particle size and metal concentrations (Brown et al., 2005; Pepper et al., 2013; Stuczynski et al., 2007). The sites were characterized by a combination of fines (the ground residual material from mineral extraction) and overburden, referred to as "chat." The particle size of the chat is typically greater than 2 mm and derives from silica-based minerals (US EPA, http://www.epa.gov/osw/nonhaz/