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Phytostabilization of mine tailings using compost-assisted direct planting: Translating greenhouse results to the field

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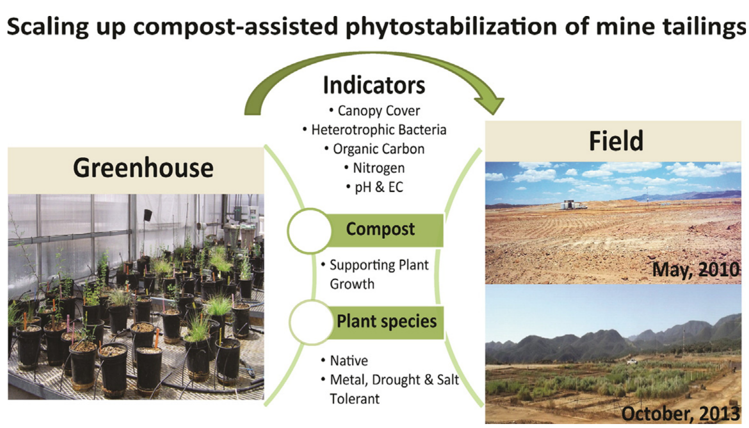
HIGHLIGHTS

- Cap and plant is the current costly standard for mine tailings reclamation
- We assessed direct planting for remediation of acidic metalliferous mine tailings
- 60-day greenhouse pot studies translated successfully to this 41-month field trial
- A single compost application supported plant establishment and soil development
- Direct planting with compost is a viable alternative for treatment of mine tailings

GRAPHICAL ABSTRACT



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ABSTRACT

Standard practice in reclamation of mine tailings is the emplacement of a 15 to 90 cm soil/gravel/rock cap which is then hydro-seeded. In this study we investigate compost-assisted direct planting phytostabilization technology as an alternative to standard cap and plant practices. In phytostabilization the goal is to establish a vegetative cap using native plants that stabilize metals in the root zone with little to no shoot accumulation. The study site is a barren 62-hectare tailings pile characterized by extremely acidic pH as well as lead, arsenic, and zinc each exceeding 2000 mg kg^{-1}. The study objective is to evaluate whether successful greenhouse phytostabilization results are scalable to the field. In May 2010, a 0.27 ha study area was established on the Iron King Mine and Humboldt Smelter Superfund (IKMHSS) site with six irrigated treatments; tailings amended with 10, 15, or 20% (*w*/*w*) compost seeded with a mix of native plants (*buffalo grass*, *arizona fescue*, *quailbush*, *mountain mahogany*, *mesquite*, and *catclaw acacia*) and controls including composted (15 and 20%) unseeded treatments and an uncomposted unseeded treatment. Canopy cover ranging from 21 to 61% developed after 41 months in the compost-amended planted treatments, a canopy cover similar to that found in the surrounding region. No plants grew on unamended tailings. Neutrophilic heterotrophic bacterial counts were 1.5 to 4 orders of magnitude higher after 41 months in planted versus unamended control plots. Shoot tissue accumulation of various metal(-loids) was at or below Domestic Animal Toxicity Limits, with some plant specific exceptions in treatments receiving less compost. Parameters including % canopy cover, neutrophilic heterotrophic bacteria counts, and shoot

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uptake of metal(loids) are promising criteria to use in evaluating reclamation success. In summary, compost amendment and seeding, guided by preliminary greenhouse studies, allowed plant establishment and sustained growth over 4 years demonstrating feasibility for this phytostabilization technology.

1. Introduction

Mine tailings are the main product remaining after ore beneficiation and, if left unreclaimed, can contribute to particulate dispersion into the surrounding environment (Csavina et al., 2011; Mendez and Maier, 2008; Root et al., 2015). In legacy sites, mine tailings particulates often have associated metal(loid) contaminants because extraction technologies 50–100 years ago were not as efficient as those used in modern mining operations. Human health risks arising from dispersion of metal(loid)-containing particulates from legacy sites can result from various routes of exposure including inhalation of particles transported by wind and ingestion of contaminated soil (particularly for children) or food due to the deposition of wind- or water-borne particles onto soil or garden vegetables (Csavina et al., 2011; Henry et al., 2013; Mendez and Maier, 2008; Ramirez-Andreotta et al., 2013).

The US Environmental Protection Agency (EPA) has estimated that remediation costs for National Priority List (NPL) hardrock mining sites will exceed US $7.8 billion for 63 NPL sites inventoried in 2004 with an additional US $16.5 billion needed for future sites using current technologies (Lovingood et al., 2004). The most commonly used technologies are based on constructing an inert or biological cap over the mine tailings (ITRC, 2009). The goal is to have germination and establishment of a vegetative cap followed by plant succession eventually leading to a stable vegetative community on the site. However, such capping strategies can be very expensive (Kempton et al., 2010).

An alternative technology to capping is phytostabilization, which is the use of a vegetation cover planted directly into the tailings that acts to immobilize metals in the rhizosphere and to reduce above ground wind and water erosion processes (Mendez and Maier, 2008; USAEC, 2014). However, direct planting alone is not feasible for many legacy sites because acidic conditions and high metal(loid) content prevent plant germination and growth. A further complication is the need for drought-tolerant plant species which are generally adapted to the alkaline conditions found in most arid environments (Saslis-Lagoudakis et al., 2015). Therefore the phytostabilization process often must be "assisted" through the addition of amendments that may include compost, biosolids, lime, and/or fertilizers (Brown et al., 2004; Clemente et al., 2012; Conesa et al., 2007; Lee et al., 2014; Li and Huang, 2015; Madejón et al., 2010; Santibañez et al., 2012). The vegetative cap created by assisted phytostabilization should result in the phyto-catalyzed stabilization of inorganic contaminants in the root zone driven by organic matter, plant root exudates and the associated rhizosphere microbial community (Mendez and Maier, 2008; Santibañez et al., 2012). Further, there should be limited above ground biomass accumulation of metal(loid)s to prevent the movement of contaminants into the surrounding ecosystem and food chain through grazing or plant death and decay (Henry et al., 2013; Mendez and Maier, 2008; Pérez-de-Mora et al., 2011).

There are few reported field studies that have evaluated the feasibility of assisted phytostabilization of mine tailings in semi-arid environments (Brown et al., 2009; Clemente et al., 2012; Cordova et al., 2011; Pardo et al., 2014; Santibañez et al., 2012). The goal of this study was to determine whether assisted phytostabilization could be successfully implemented at the Iron King Mine and Humboldt Smelter Superfund (IKMHSS) site which has mine tailings that are characterized by extreme acidity and high levels of arsenic, lead, and zinc (Root et al., 2015). We specifically wanted to determine whether successful results from greenhouse trials (Solís-Dominguez et al., 2012) could be scaled to the field. The parameters evaluated in the field trial included percent canopy cover, plant shoot tissue metal(loid) uptake, neutrophilic heterotrophic bacterial counts (NHC), pH, total carbon (TC), total organic carbon (TOC), total nitrogen (TN), electrical conductivity (EC). These parameters were used to assess progress in transitioning the original mine tailings ecosystem to include soil properties more characteristic of a plant-sustaining matrix.

2. Materials and methods

2.1. Site description

The IKMHSS was active from the late 1800s until 1969 producing gold, silver, copper, lead, and zinc, leaving behind a mine tailings pile comprising approximately 62 ha adjacent to the town of Dewey-Humboldt, Arizona (North 34°31′57″, West 112°15′9″) (USEPA, 2010) (Fig. 1). The top of the mine tailings pile is at an elevation of 1464 m and the surface of the site is an orange gossan zone that is vulnerable to erosion (Hayes et al., 2014; USEPA, 2010). The surficial tailings are characterized by low pH and nutrient content and elevated concentrations of a range of metal(loids) including arsenic, lead, copper, cadmium, chromium, and zinc as well as pyrite (Tables 1–3). In contrast, the surrounding area is a Chaparral biome influenced by three ephemeral waterways with *Balon gravelly sandy clay loam* (BgD) as the predominant soil type. Vegetation in the area is dominated by rubber rabbitbrush (*Ericameria nauseosa*), shrub live oak (*Quercus turbinella*), and broom snakeweed (*Gutierrezia sarothrae*) among other plants. White willow (*Salix spp*), Arizona walnut (*Juglans major*), and cottonwood (*Populus fremontii*) are present in riparian areas (USEPA, 2009).

2.2. Site preparation

In May 2010, a compost-assisted phytostabilization trial was established on a 0.27 hectare area on the IKMHSS mine tailings. The six treatments tested (with four replicates each) were: (1) unamended control; (2) 10% compost - seeded with buffalo grass and mesquite; (3 and 4) 15% and 20% compost respectively - unseeded; (5 and 6) 15% and 20% compost respectively, seeded with a mixture of six native plants. All treatments were laid out in a randomized block design with the exception of the controls which were located at the far corners of the study area (Fig. 1, controls are labeled with the number 1). This was done to prevent contamination of the control plots with compost during site preparation and tilling of compost into the subsurface.

A tractor was used to rip and till the site to a depth of about 38 cm and divided into 24 experimental plots (9.6 m × 15 m per plot) each bermed to about 50 cm to prevent cross contamination between treatments. A dairy manure-green waste compost from Arizona Dairy Compost LLC (Anthem, AZ) was weighed using a truck scale and added to each plot according to treatment: the 10% compost treatment received 228 t ha^{-1}; 15% compost treatments received 342 t ha^{-1}; and 20% compost treatments received 456 t ha^{-1}. The compost was tilled into each plot to a depth of 15 cm.

Plots were then seeded according to treatment based on preliminary greenhouse results (Solís-Dominguez et al., 2012). The six native desert plants used in this study and their seeding rates were: grasses, 90 kg ha^{-1} buffalo grass (*Buchloe dactyloides*); 56 kg ha^{-1} arizona fescue (*Festuca arizonica*); shrubs, 56 kg ha^{-1} quail bush (*Atriplex lentiformis*), 11 kg ha^{-1} mountain mahogany (*Cercocarpus montanus*); trees, 0.15 kg ha^{-1} mesquite (*Prosopis juliflora*), and 1 kg ha^{-1} catclaw acacia (*Acacia greggi*) (seed source: Desert Nursery, Phoenix, AZ). The 10% compost treatment, considered a suboptimal rate (Solís-Dominguez et al., 2012), received only seeds from the two plants that grew most successfully in the greenhouse as measured by biomass production (buffalo grass and mesquite). The 15 and 20% compost treatments received a mixture