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Long term carbon sequestration potential of biosolids-amended copper and molybdenum mine tailings following mine site reclamation

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ABSTRACT

Management and reclamation of industrial mine sites for carbon (C) sequestration is an emerging technique for offsetting anthropogenic C emissions. Land application of municipal biosolids is an effective method for amending closed tailings storage facilities and providing the nutrients to establish a vegetative cover. Biosolids applications can influence the C sequestration potential of tailings and other mine wastes at the onset of reclamation by initiating soil development processes and enhancing primary productivity, thereby leading to increased accumulation of soil organic carbon (SOC) over time. The short term ecological benefits of biosolids applications are well understood, but the long-term (> 10 years) effects of biosolids on reclaimed mine soils are under-researched. The objective of this long-term study was to determine the effects of biosolids applied in 1998 at increasing rates (0, 150 and 250 dry Mg ha^{-1}) on the C sequestration potential of a copper and molybdenum mine tailings site in the southern interior of British Columbia, Canada that is currently undergoing reclamation to a pasture-based ecosystem. We assessed changes in C pools, plant productivity and select soil physiochemical parameters at an established research site at the Bethlehem Tailings Storage Facility over a 13-year period spanning from 1998 to 2011. Tailings total C and N concentrations increased with time and were highest when biosolids were applied at 250 Mg ha^{-1}. Carbon pools increased with increasing biosolids application and ranged from 23 to 155 Mg C ha^{-1} after 13 years of reclamation. The net SOC sequestration rates (i.e. the C sequestration potential) ranged from 0.72 to 6.3 Mg C ha^{-1} yr^{-1} and were highest at the 250 Mg ha^{-1} application rate. The C storage efficiency was higher in the 150 Mg ha^{-1} treatment (0.74 Mg C stored per Mg of biosolids applied), indicating that lower application rates of biosolids are more efficient at storing C than higher application rates. Aboveground plant biomass was substantially higher on biosolid-amended tailings (6 and 6.7 Mg ha^{-1} for B150 and B250, respectively) compared to the unamended tailings (0.39 Mg ha^{-1}), which suggests that the increase in C pools was a direct result of organic matter inputs from enhanced plant productivity. The tailings were naturally high in Cu and Mo, and when amended with biosolids at a rate of 250 Mg ha^{-1}, elevated levels of Zn (as compared to federal soil quality guidelines) were detected. The unamended tailings increased in alkalinity with time, whereas the pH of the biosolid-amended tailings remained stable around neutral. This study demonstrated that a single application of biosolids can facilitate plant production and the accumulation of SOC on mine tailings for more than a decade, and supports the use of biosolids for promoting long-term C sequestration on reclaimed mine sites in similar environments.

1. Introduction

In recent decades, changes in the Earth's climate such as a rise in episodes of temperature extremes, changes in precipitation patterns, and alteration of drought regimes have been observed throughout many regions of the world (Heim, 2015; IPCC, 2014). The observed climate changes are closely associated with increases in anthropogenic carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions since the pre-industrial era, which are being driven by rising populations and rapid economic growth (IPCC, 2014). Human activities, primarily fossil fuel combustion and land use changes, are responsible for an estimated 555 ± 85 Pg of CO_2 released into the atmosphere over the past 200 years (Ciais et al., 2013). These emissions have contributed significantly to the observed 45% increase in the atmospheric CO_2

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concentration (280 ± 20 prior to 1750 to 400 ppm in 2015) (Blasing, 2016; Indermühle et al., 1999). As such, there is a need to generate and implement innovative GHG mitigation strategies.

Management of terrestrial ecosystems for carbon (C) sequestration is one strategy for mitigating increases in atmospheric CO_2 concentration (Shrestha and Lal, 2006). Terrestrial ecosystems are an important component of the global C cycle because they are capable of reducing the concentration of atmospheric CO_2 and storing it in plant biomass and soils as soil organic carbon (SOC). The process where CO_2 is fixed into above-ground (leaves and shoots) and below-ground (roots) biomass through photosynthesis and assimilated into soils by decomposition and microbial activity is known as C sequestration. The amount of C stored in a terrestrial ecosystem is commonly referred to as the terrestrial C sink, or soil C pool. A majority (75%) of the C sequestered in terrestrial ecosystems is found in soils, with the remainder being found in aboveground plant biomass (Houghton, 2003). Estimates of global SOC pools vary, but generally range from 1200 to 1600 Pg for the 0–100 cm depth (Tarnocai et al., 2009). Although C fluxes from terrestrial ecosystems to the atmosphere are a natural biogeochemical process (Golubyatnikov and Svirezhev, 2008), human induced global warming coupled with land use changes such as deforestation and mining can accelerate the decomposition of SOC (Akala and Lal, 2001; Hopkins et al., 2012; Shrestha and Lal, 2011). An estimated total of 100–200 Gt C (1–2 Gt C yr^{-1}) was lost from terrestrial ecosystems as a result of land use changes since the year 2000 (Strassmann et al., 2008). One study in Ohio, USA reported that land disturbance from coal mining caused a 70% decline in the local C sink (Akala and Lal, 2001). In contrast, encouraging C sequestration on such disturbed or degraded ecosystems can lead to replenishing the terrestrial C sink and help mitigate global climate change (Juwarkar et al., 2010; Shrestha and Lal, 2006).

Land disturbances from surface mining include tailings storage facilities, mined lands, waste rock piles, and roadsides. Because the soils on such sites are initially low in SOC, the potential to store C over time is high (Brown and Leonard, 2004). However, plant productivity on these sites is generally difficult to restore due to a variety of physiochemical limitations, beginning with the parent material (Bradshaw, 1987a). For example, tailings (fine waste materials generated from ore processing) are typically characterized by elevated levels of heavy metals, lack of organic matter and plant-essential nutrients, and extreme pH (Gardner et al., 2012, 2010; Mendez and Maier, 2008, 2007; Pedersen et al., 2017), and so they are not a suitable medium for plant growth. Successful reclamation of these mined lands can improve C sequestration and offset some of the emissions caused by mining activities (Shrestha and Lal, 2006). Furthermore, the emergence of C markets may present economic benefits to mining operations that promote C sequestration during reclamation. In one study, C sequestration rates of reclaimed coal mine soils reached up to 3.1 Mg C ha yr^{-1} in a grassland ecosystem and 4 Mg C ha yr^{-1} in a forested ecosystem (Akala and Lal, 2001).

Conventional techniques for reclaiming abandoned mine sites include fertilizer applications and amending the upper surface with stockpiled topsoil, but these methods are often not sufficient to produce sustained plant growth over long periods of time (Sopper, 1993). Organic soil amendments, such as compost and manure, can enhance the long-term productivity of mine tailings, and have been successful in a variety of management scenarios (Brown et al., 2007; Carson et al., 2014; Shrestha et al., 2009). In general, organic amendments improve soil conditions by providing nutrients and organic matter which can have synergistic positive effects on physical, chemical, and biological parameters relating to soil development and ecosystem recovery (Brown et al., 2003; Park et al., 2011; Sheoran et al., 2010; Tarrasón et al., 2014). Municipal sewage sludge, or biosolids, are commonly used as a soil amendment to improve the productivity of degraded agricultural and forested systems (Bai et al., 2017; Pritchard et al., 2010), and have also been used successfully on mine sites (Sopper, 1993; Tian et al., 2009). Biosolids can promote plant production by improving soil chemical properties such as organic C content, plant nutrient availability, cation exchange capacity, and soil pH (Cele and Maboeta, 2016; Gardner et al., 2010). They are also capable of ameliorating harsh physical properties common of tailings such as low porosity, poor moisture retention, and reduced soil aggregation (Drozdowski et al., 2012; Gardner et al., 2010). Furthermore, biosolids can improve nitrogen (N) cycling and soil development by accelerating soil microbial activity (Gardner et al., 2010; Kim and Owens, 2010; Pepper et al., 2012). In addition to the above benefits, increases in above- and below-ground C pools resulting from biosolids application have been measured (Brown et al., 2003; Sopper, 1993). In one study, Trlica and Teshima (2011) showed that biosolids-amended copper (Cu) and molybdenum (Mo) mine tailings in British Columbia, Canada stored more C in the upper 0–15 cm layer than conventionally reclaimed tailings over an 8 year period. As such, the use of biosolids for restoring terrestrial C pools on mine tailings sites is a possible GHG mitigation strategy. Though, potential drawbacks to the use of biosolids for land reclamation have been noted, such as the tendency for metals and other contaminants to accumulate in the ecosystem (Dung et al., 2015; Sopper, 1993), reduction in soil fauna numbers (Brown et al., 2014; Waterhouse et al., 2014) and alteration of microbial communities (Shah et al., 2014), all of which warrant further investigation into the use of biosolids as a C sequestration tool.

To date, few studies have investigated the long-term (> 10 years) effects of biosolids on revegetation of metal mine tailings sites, and whether positive levels of SOC, as well as plant productivity, persist (Brown et al., 2014; Pepper et al., 2013; Trlica and Teshima, 2011). Some research has addressed C sequestration on reclaimed mine lands but many of these studies were conducted on strip-mined areas (Akala and Lal, 2001; Shrestha and Lal, 2006; Tian et al., 2009). Furthermore, most of the biosolids studies conducted specifically on mine tailings sites were short-term (< 5 years) studies (e.g. Brown et al., 2003; Drozdowski et al., 2012; Gardner et al., 2012, 2010). Here we are presented with a unique opportunity to investigate the use of biosolids as a tool for restoring terrestrial C pools on reclaimed mine tailings sites, with the overall goal of reducing atmospheric GHG concentrations and mitigating global climate change.

The purpose of this research was to assess the long-term effects of a one-time biosolids application at three rates (0, 150 and 250 Mg ha^{-1}) on the C sequestration potential of a Cu and Mo mine tailings storage site located in the southern interior of British Columbia, Canada that has used biosolids in its reclamation program. A research site from a previous study (Gardner et al., 2012, 2010) was revisited to investigate changes in C pools, plant biomass yield, and select soil physiochemical parameters spanning a 13-year reclamation period from 1998 to 2011.

2. Materials and methods

2.1. Site description

The research was conducted at Teck-Highland Valley Copper (HVC), an open pit Cu-Mo mine located in the southern interior of British Columbia (BC), Canada, approximately 80 km southwest of the city of Kamloops (Fig. 1; 50°28′23″N 121°01′19″W). Mining operations were first established in the Highland Valley district over 50 years ago, and currently account for around 15% of BC's total Cu production (Mining Association of British Columbia, 2015). The mine processes ore from a low grade (0.4294% Cu over the life of the mine) Cu-Mo porphyry (Casselman et al., 1995).

The study site is located on the Bethlehem Tailings Storage Facility (50°30′43″N 120°58′29″, 1475 m elevation) which is one of three decommissioned tailings sites at HVC that has been reclaimed with biosolids. The tailings site covers an area of approximately 218 ha, with an average depth of approximately 40–50 m and a maximum depth of 90 m (Jaimie Dickson, Teck-Highland Valley Partnership, personal