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Research paper

Growth and metal uptake of canola and sunflower along a thickness gradient of organic-rich covers over metal mine tailings

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ABSTRACT

We completed a field-scale experiment to determine the thickness thresholds of covers of organic residuals required to grow biofuel crops over low-sulfur metal mine tailings with high metal content. An organic-rich mix made of municipal yard waste composts and wood waste was spread up to ~70 cm thick over low sulfur Ni-Cu tailings. We seeded and fertilized biofuel crops of canola and sunflower across this gradient. We measured biomass production and concentrations of nutrients and trace metals in tailings, organic residuals, and plants. Below the threshold organic cover thickness of 15 cm, macronutrient content was reduced and bioavailable Fe, Ni and Cu were 5–50 times higher as compared to thicker organic covers, apparently as a result of tillage. Bioavailable K and Na increased by an order of magnitude and Mo doubled with increasing thickness of organic covers from 5 and 70 cm thick. The plants showed limited uptake of Ni and Cu, with bioconcentration factors of near 1 for sunflower and 0.6 for canola. Biomass production was not affected by the thickness of the organic cover. Plant rooting depth was deeper over thin organic covers, extending up to 15 cm into the tailings. Low stem Fe in plants over thin covers indicated a potential interaction between trace metals and Fe nutrition. These results support the use of covers of organic residuals as thin as 15 cm thick to grow biofuel crops over circumneutral metal mine tailings. Thin covers will make this approach more economical for mine reclamation managers.

1. Introduction

Organic-rich residual wastes such as biosolids, municipal composts and pulp and paper sludge are increasingly being used as amendments to reclaim and revegetate metal mine tailings facilities (Alvarenga et al., 2009; Brown et al., 2003; Forsberg et al., 2008; Gardner et al., 2010; Hargreaves et al., 2012; Lock et al., 2010; Madejon et al., 2010; Van Rensburg and Morgenthal, 2003; Verdugo et al., 2011). Such organic amendments (i) decrease bulk density of the tailings and provide structure; (ii) improve water holding capacity; (iii) favour root penetration; (iv) provide slow-release nutrients for vegetation and microorganisms; (v) have high cation exchange capacity for nutrient retention; (vi) boost microbial activity through the decomposition and release of labile organic compounds; and (vii) limit the bioavailability of trace metals and metalloids through adsorption, complexation, reduction and volatilization (Larney and Angers, 2012; Park et al., 2011). Organic amendments can also increase the solubilisation of trace metals in tailings (Ribet et al., 1995; Schwab et al., 2007), but the use of circumneutral or alkaline organic amendments, or their mixing with a liming agent, limits the solubility of many trace metals and their bioavailability (Alvarenga et al., 2009; Forsberg et al., 2008; Van Rensburg and Morgenthal, 2003).

Organic residuals may be mixed into the tailings (Alvarenga et al., 2009; Forsberg et al., 2008; Gardner et al., 2010; Madejon et al., 2010; Verdugo et al., 2011) or they may be added as covers on top of mine tailings to act as the principal rooting medium, thus limiting contact with the underlying tailings (Brown et al., 2003; Hargreaves et al., 2012; Lock et al., 2010). If thick enough, covers of organic residuals may also limit oxygen and water ingress into tailings, potentially limiting acid-mine drainage in susceptible tailings (Peppas et al., 2000).

Researchers and reclamation managers primarily use organic residuals on metal mine tailings as part of a phytostabilization strategy, with the intent to establish low productivity vegetation that limits wind and water erosion of the tailings, limits plant metal uptake and brings biodiversity benefits (Alvarenga et al., 2009; Brown et al., 2003; Gardner et al., 2010). In contrast, managers in coal mining and aggregate industries have for decades used organic residuals to reclaim surface mine spoil toward high productivity agricultural land (Sopper,

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1992). Only recently have researchers used organic residuals to target high-productivity agricultural endpoints on metal mine tailings (Hargreaves et al., 2012; Lock et al., 2010), for non-food uses such as biofuel crops. These latter trials have used thicker covers of organic residuals, 40–100 cm thick, to limit water and oxygen ingress into the tailings and minimize plant uptake of contaminants. However, tailings management areas of metal mines can exceed hundreds of hectares, so managers would need plentiful and inexpensive sources of organic residuals for such thick covers. Thin covers of organic residuals would be more economical, but little is known on the potential of using compost covers < 40 cm for biofuel crop production over metal mine tailings. Thinner covers may limit available nutrient pools and increase metal uptake by plants, both of which could affect plant biomass production. Growing oil seed crops such as canola (*Brassica napus* L.) and sunflower (*Helianthus annuus* L.) on thin covers of organic residuals may offer a complementary strategy since both crops are metal-tolerant and have been used to phytoremediate metal-contaminated soils (Lai et al., 2010; Marchiol et al., 2004; Mohammadzadeh et al., 2014; Rivelli et al., 2012; Shaheen and Rinklebe, 2015).

Here we present a field-scale study to test whether growing crops of canola or sunflower on thinner covers of organic residuals over low sulfur Ni-Cu mine tailings affects the availability and uptake of nutrients and contaminants of concern and the production of crop biomass. We constructed a thickness gradient of organic residuals from < 5 to ~70 cm over the metal mine tailings, and then we prepared, seeded and fertilized crops of sunflower and canola across this gradient over two growing seasons. We were interested in identifying the minimum threshold thickness of organic covers that affect nutrients and contaminants in substrates and crop plants and also affect crop growth. We predicted that: (i) the availability of contaminants would increase and nutrients would decline below threshold thicknesses of covers made of organic residuals; (ii) the plant uptake of contaminants would increase below these thresholds; and (iii) the productivity of oilseed crop plants would also drop below these thresholds. Knowing these thresholds thicknesses would allow managers to limit the quantity and cost of organic covers for the reclamation of metal mine tailings facilities to biofuel cropland, while at the same time limiting environmental risks.

2. Materials and methods

The study took place at a Ni-Cu mine tailings facility within the northwest part of the City of Greater Sudbury, Ontario, Canada in the summer 2013, after a preliminary 2012 season. The region has a humid continental climate, with an average annual temperature of 4.1 °C, July average temperature of 19.1 °C, 943.6°-days above 10 °C and 903.3 mm of precipitation annually (Sudbury A station, 41 km E; 1981–2010 climate normals; Environment Canada, 2017). Average temperature and precipitation for July and August 2013 were within half a standard deviation of the climate normals for these months. The tailings facility is ~65 ha in size and flat to very gently domed, with deep tailing deposits (maximum > 15 m) and surrounded by the rolling landscape of Precambrian shield. The tailings originated as waste from the processing and extraction of Cu and Ni-rich phases of massive pentlandite, chalcopyrite, pyrrhotite and pyrite-bearing sulfide deposits (Rousell et al., 2002). The raw sulfide-rich tailings are capped by ~1.5 m of low sulfur tailings produced through a desulfurization process. The surface tailings were slightly alkaline (pH 7.8 ± 0.2), had low organic matter content (0.3 ± 0.1%) and low cation exchange capacity (CEC; 15.7 ± 2.7 cmol (+) 100 g^{-1}; n = 5; mean ± SD; K. Nicholls, unpublished data). They also had very low total content of C, N, and P, high total content of Ca, Mg, Fe and Al, and high total content of several elements of concern, namely Ni, Cu, Cr, Mo and Se, well above Canadian environmental guidelines (Table 1).

The mining company applied a cover of organic residuals over these low sulfur tailings in the fall and winter of 2011–2012. The organic cover was prepared from Greater Toronto municipal yard waste compost (> 95%) blended with composted wood and bark fiber from northeastern Ontario lumber operations (< 5%). They spread the organic residual by bulldozer in the spring of 2012 over an area of 225 m by 125 m, (~3 ha), producing a thickness gradient of organic residuals from ~70 cm along the eastern edge to < 10 cm along the western edge. After spreading, the organic cover had a circumneutral pH (7.4 ± 0.2), high organic matter content in the < 2 mm fraction (26.3 ± 2.6% dry content), and high CEC (27.1 ± 1.7 cmol (+) 100 g^{-1}; mean ± SD; n = 10; K. Nicholls, unpublished data). The composts had low total content of the elements of concern, except for total Mo which just surpassed the agricultural guideline and total Se which was much higher than the industrial guideline (Table 1).

Table 1
Total concentrations of selected nutrient, major elements and minor elements (μg g^{-1}) within low sulfur tailings (n = 160) and organic covers (n = 39), as determined from ICP-AES (Smith 2012), as compared to Canadian soil quality guidelines for agricultural and industrial uses (CCME, 2016). Bolded mean values in the tailings exceed agricultural soil quality guidelines.

Element	Low sulfur tailings		Organic cover		Soil quality guideline	
	mean	SD	mean	SD	Agricultural	Industrial
P	339	104	1780	577		
K	5560	903	3960	1000		
Ca	12900	2140	40400	9270		
Mg	10800	855	11400	1800		
Fe	32800	4090	13800	1060		
Al	20000	2070	11990	1110		
As	5.7	4.8	3.7	2.5	12	12
B	239	107	–	–		
Cd	< 0.03		0.4	0.1	1.4	2.2
Co	15.7	5.3	7.3	1.7	40	300
Cr	**156**	21	30	7.5	64	87
Cu	**388**	108	60	23	63	91
Mn	444	47	491	72		
Mo	**131**	81	**8.9**	20	5	40
Na	844	158	1050	250		
Ni	**1050**	229	26	7	45	89
Pb	32.1	4.4	32	12	70	600
Se	**495**	67	**170**	36	1	2.9
Zn	66.5	26.7	174	47	200	360

A farmer prepared, seeded and fertilized the organic covers in 2012 and 2013. He prepared the substrate using a tiller-mulcher, followed by an S-tine cultivator with double rolling basket harrows to remove weeds and break up clods. In early July in both years, the farmer seeded canola (DEKALB® 73-75 RR; 0.1 M seeds ha^{-1}) or sunflower (Dupont Pioneer® 63A21; 1.6 M seeds ha^{-1}) onto the freshly cultivated organic residuals using a broadcaster in alternating 3 m wide strips, parallel to the thickness gradient of organic residuals, in an east-west direction. Each year, he applied fertilizer at seeding using a broadcaster, first with 10-20-20 NPK at a rate of 247 kg ha^{-1} and second with 34-0-0 NPK as ammonium nitrate, again at a rate of 247 kg ha^{-1}. He used a harrow and chains to lightly cover the seed and fertilizer. In mid-July 2013, he again applied ammonium nitrate (34-0-0 NPK) at a rate of 247 kg ha^{-1}.

On September 19, 2013, we sampled plants and substrates at 16 locations for each crop species, with eight locations per crop on the thicker organic covers and eight per crop on thinner covers, in alternate crop strips. At each location, we randomly selected an individual plant, measured the exact thickness of the organic residual cover, and collected a bulk sample of the organic residuals within the rooting zone. We carefully excavated roots to determine the maximum rooting depth and rooting width and then collected the aboveground parts of each plant. We also sampled the top 10–15 cm of underlying tailings from locations below the thick and thin organic residuals (n = 7).

We air-dried the organic residual and tailing samples, passed them through a 4 mm sieve, and selected 50–100 g subsamples for chemical analysis. We broke up aboveground plant parts, air-dried and then

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