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Growth of selected plant species in biosolids-amended mine tailings

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ABSTRACT

Biosolids stockpiles from sewage treatment plants are a valuable source of organic matter which could be utilized to improve the nutritional status and physical properties of Au mine tailings and support the growth of vegetation planted in the tailings. However, biosolids often contain elevated concentrations of heavy metals including Hg while Au mine tailings would usually contain residual Au. Therefore, it would be beneficial to select plants capable of both tolerating and phytoextracting Hg and/or Au.

This paper reports on a glasshouse-based screening study which examined the growth of plant species known for their ability to phytoextract Hg and/or Au which can grow on substrates consisting of biosolids, Au mine tailings, or different combinations of both. The germination and establishment of plants over 8–12 weeks were monitored for *Brassica juncea* (Indian mustard), *Daucus carota* (carrot), *Lupinus albus* (white lupin), *Beta vulgaris* (sugar beet), *Solanum tuberosum* (potato), and *Manihot esculenta* (cassava).

Each plant species exhibited differential responses in terms of germination, seedling quality, leaf area, specific leaf area, root and shoot biomass, and percentage dry matter partitioning to the roots. Both the Indian mustard and carrot grew successfully in the biosolids-mine tailings substrate combinations while white lupin, sugar beet, cassava, and potato failed to grow in most of the substrate combinations. The most suitable biosolids-mine tailings combination was determined to be 75% biosolids – 25% mine tailings, wherein most of the abovementioned growth parameters did not differ significantly from those of the plants grown in the control potting mix.

1. Introduction

The use of plants to remove, detoxify, and contain heavy metals is called phytoremediation (Chaney et al., 1997). Phytoextraction is a type of phytoremediation wherein metals in the growth substrate are effectively extracted in large amounts into the aboveground harvestable parts. The most desirable characteristics for a plant used for metal phytoextraction, is that it should be able to take up and sequester the pollutant in harvestable aboveground tissues and must also be able to tolerate the presence of the pollutant while maintaining normal growth and development. In some phytoextraction efforts a hyperaccumulating plant species is utilized. A metal hyperaccumulator plant is typically defined as a plant species that accumulates a metal to a concentration in the aboveground tissues 100-fold higher than what is normally observed for plants. The accepted criteria for heavy metal hyperaccumulating plants are at least 100 mg/kg (0.01% dry wt.) for Cd or As; 1000 mg/kg (0.1 dry wt.) for Co, Cu, Cr, or Pb; and 10,000 mg/kg (1% dry wt.) for Zn, Mn, or Ni (Reeves and Baker, 2000). Some hyperaccumulating plants are often small plants that can be challenging to use in larger scale field phytoremediation efforts. High biomass plants capable of moderate accumulation of metals in their aboveground tissues can also be used for phytoextraction (Salt et al., 1995; Ebbs and Kochian, 1998; Clemente et al., 2005; Ghosh and Singh, 2005). An advantage of using these high biomass, moderately accumulating plants is that they are often agronomic plants with readily available sources of seed that are easier to propagate.

Mine tailings are generally the fine-grained solid material remaining after the metals and minerals have been extracted from mined ore and the process water. In the case of gold ore, the tailings can contain residual gold which can be extracted using a variation of phytoextraction called phytomining (Anderson et al., 1999; Piccinin et al., 2007). However the success of phytoextraction or phytomining depends first and foremost on whether that substrate can support plant growth. Mine tailings often have physicochemical characteristics that are not conducive to plant

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growth. Trying to grow plants in mine tailings is difficult because of the lack of oxygen supply to the roots, the poor physicochemical characteristics of the tailings, and the lack of key plant nutrients. There has been considerable work showing that tailings can be improved if blended with other substrates (Madejón et al., 2010). The use of soil amendments like composts, sewage sludge, manure and plant cover is the basis of cost-effective and environmentally sustainable methods to manage landscapes in mined areas (Tordoff et al., 2000; Wong, 2003). In a study by Moreno et al. (2004), pumice was added to improve drainage of the fine-textured mine tailings. The use of fungal endophytes and biosolids enhanced the growth of native grasses on sulfidic arsenical mine tailings (Madejón et al., 2010).

Industrialized gold mining in the Stawell gold fields involved extraction and crushing of sulfidic quartz veined gold ore followed by extraction using carbon in the pulp cyanidation process. This recovery method dates back to the 1880's as a replacement for mercury amalgamation of gold (Lougheed, 1987). Characteristic of the Goldfields region of Victoria, the tailings contain significant quantities of arsenic, present in solid solution in pyrite and arsenopyrite form (Oldmeadow, 2008). This is in contrast to the soils near the mine which show greater concentrations of As, Cr and Pb than those near a regionally determined background. This is attributed to the combination of a natural geochemical halo around mineralization and anthropogenic dispersion due to mining and urbanization. Total As concentrations were between 16 and 946 mg kg^{-1} near the mine in a regional background of 1–16 mg kg^{-1} (Noble et al., 2010). Previous geochemical testing of mine rocks near the historic mine working from where the tailings were obtained showed high sulfur content (>5% S) and a low but significant acid neutralizing capacity (Oldmeadow, 2008). The net acid generation (NAG) tests confirmed that the sulfides were reactive with a final NAG pH of 2.6 indicating a high risk of acid generation in these materials.

Historical gold mining activities especially in the state of Victoria have also left a legacy of Hg contamination of soils, surface and sediments with concentrations up to 130 mg kg^{-1} in soils of residential areas of mining towns (Bycroft et al., 1982). Normal, non-polluted soils usually contain 20–150 μg Hg kg^{-1} (WHO, 1976). In a later report, the concentration of Hg in natural soils, which comprise 93% of all land surfaces, was reported to be approximately 0.05–0.08 mg kg^{-1} (World Bank Group, 1998). Because of the elevated levels of Hg in gold mine tailings in the goldfields, exposure to this heavy metal has been considered a potential health risk. Mercury is also very phytotoxic (Boney, 1971; De et al., 1985; Godbold and Huttermann, 1986; Suszcynsky and Shann, 1995; Israr et al., 2006; Zhou et al., 2007; Shiyab et al., 2008, 2009). The physiological processes of plants exposed to Hg-contaminated soil, water, or air are generally negatively affected. Toxic metal ions act mainly by blocking functional groups and/or displacing other vital metal ions in plant biomolecules. The biochemical phytotoxicity of Hg is based on its high affinity to sulfhydryl (—SH) groups and disulfide bonds (—S—S—) (Kabata-Pendias, 2011). In a study of exposed two-day-old sporelings of *Plumaria elegans* (red algae) to $HgCl_2$, 50% growth inhibition occurred after 6, 12 and 24 h at concentrations of 1.0, 0.5, and 0.25 mg Hg L^{-1}, respectively (Boney, 1971). Mercury has also been shown to reduce dry weight, decrease chlorophyll, protein and RNA contents, as well as decrease catalase and protease activity, all of which accelerate leaf senescence. This has been observed in *Pistia stratiotes* (water cabbage) when exposed to $HgCl_2$ at concentrations between 0.05 and 20.0 mg Hg L^{-1} for 2 days (De et al., 1985). The pattern of Hg phytotoxicity is virtually the same in terrestrial plants where changes in root tip cell membrane integrity have been observed in *Picea abies* (spruce seedlings) treated with 100 nM $HgCl_2$ and 1.0 nM CH_3HgCl (Godbold and Huttermann, 1986). Inhibition of root and shoot growth occurred in *Nicotiana miersii* exposed to 1.0 mg $HgCl_2$ L^{-1} for 10 days (Suszcynsky and Shann, 1995). Hence, if Hg is also present in tailings targeted for Au phytomining, then Hg phytotoxicity could limit plant growth.

Biosolids are stabilized organic solids, resulting from the treatment of domestic and industrial wastewater (Bright and Healey, 2003). The reuse of biosolids is being promoted due to the excessive space taken up by these materials in treatment plants and landfills, not to mention the large cost of disposal. Typical biosolids are rich in organic matter as well as macro- and micronutrients essential for plant growth and development. Currently, the main use of biosolids is as fertilizers or composts in land applications to improve and maintain soil productivity and stimulate plant growth. Biosolids can also be used to re-establish and sustain vegetation at mine sites (Tian et al., 2006). Reutilization of biosolids also reduces or eliminates issues associated with their disposal (Fresquez et al., 1990). However, there are environmental and public health concerns related to biosolids applications. These are mainly related to the presence of pathogenic microorganisms and hazardous compounds (Oliver et al., 2005). Heavy metals and metalloids are of particular concern as they are frequently present at elevated concentrations in biosolids. The toxicity and potential mobility of these metals can result in surface and groundwater contamination. Heavy metals can also be translocated into plants and further transferred into animal and human food chains (Lavado et al., 2005; Oliver et al., 2005). Among the heavy metals frequently present in biosolids, Hg is arguably of the highest environmental and public health concern. This is due to the extreme toxicity of both the organic and inorganic Hg species and their potential for bioaccumulation (Sloan et al., 2001). Gold can also be present in biosolids as a result of the discharge of waste materials from manufacturing processes (Reeves et al., 1999).

Mining activities produce large quantities of waste materials and tailings that frequently contain toxic concentrations of heavy metals and metalloids. Currently, many strategies and health and safety policies are used to minimize the production, emission and dispersion of pollutants from mine sites. Biosolids stockpiles from sewage treatment plants are a valuable source of organic matter which could be utilized to improve the nutritional status and physical properties of sulfidic tailings.

Most plants are sensitive to heavy metals, especially Hg. However, certain plant species can grow on contaminated habitats because they have developed a range of avoidance and/or tolerance mechanisms by which the excess of heavy metals can be rendered harmless. Mercury compounds have very limited solubility in soil leading to low Hg availability for plant uptake. In addition, Hg does not have any known biological function (Beauford et al., 1977). This may explain why any Hg-hyperaccumulating plant has yet to be identified. Limited uptake of Hg has been shown in mosses, lichens, fungi and in wetland, woody and crop plants (Patra and Sharma, 2000). Other studies on the phytoremediation of mercury in contaminated soils have been reported using different plant species such as *Atriplex canescens* (saltbush) (Patra and Sharma, 2000), *Rumex induratus* and *Marrubium vulgare* (common horehound) (Moreno-Jiménez et al., 2006), white lupin (Ximenez-Embun et al., 2001), *Tritcum aestivum* (wheat) (Cavallini et al., 1999), *Pisum sativum* (pea) (Beauford et al., 1977; Godbold and Huttermann, 1986), *Sorghum bicolor* (sorghum) (Patra and Sharma, 2000), *Chrysopogon zizanioides* (vetiver grass) (Wong, 2003), *Azolla caroliniana* (an aquatic fern) (Bennicelli et al., 2004), and *Oryza sativa* (rice) (Du et al., 2005). Few studies however, have been carried out on biosolids phytoremediation and Hg was found mainly in the roots of the nine plant species tested with very low translocation to the shoot (Lomonte et al., 2010a). In order to find the best plant species for future phytoextraction or phytomining studies, several candidate plant species known for Hg and/or Au