Phytoextraction of gold and copper from mine tailings with *Helianthus annuus* L. and *Kalanchoe serrata* L.

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A B S T R A C T

To examine the feasibility of gold phytoextraction, and the corresponding uptake of copper that is induced at the same time, field and laboratory scale experiments were carried out using mine tailings from the Magistral mine in Sinaloa State, Mexico. The locally available plant species *Helianthus annuus* L. (sunflower) and *Kalanchoe serrata* L. (magic tower) were used in this work, in combination with the chemical amendments: sodium cyanide (NaCN), ammonium thiocyanate (NH₄SCN), ammonium thiosulphate (NH₄)₂S₂O₃, and thiourea [SC(NH₂)₂] to promote gold uptake. The results show that for *K. serrata*, average copper concentrations were increased to above 4 mg/kg and gold concentrations to above 9 mg/kg in the dry matter of aerial tissues. For *H. annuus* average copper concentrations were increased to 116 mg/kg in roots, 141 mg/kg in stem and, 119 mg/kg in leaves while average gold concentrations were increased to 15 mg/kg in leaves, 16 mg/kg in roots and, 21 mg/kg in plant stems. Poor health of plants after treatment with chemicals to induce gold uptake could be a function of toxic concentrations of other trace elements such as copper in the plants. Our results confirm that phytoextraction technology can be used to recover precious metals from mine tailings, and that at the current market price for gold, this recovery may be economic. However, our results also highlight the differential response of plant species to copper and gold in the ground, and the importance of choosing the correct chemical to induce metal uptake.

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1. Introduction

Specific plants, known as hyperaccumulators, are recognized in many ecological environments around the world for their ability to accumulate metals that are not essential for living processes, to concentrations that are similar to those of the macro nutrients (0.1–1%). Brooks and colleagues, in the late 1970s, were the first scientists to use the term hyperaccumulation to describe plants that absorb nickel to concentrations exceeding 1000 mg/kg (0.1%) of dry matter when growing on serpentine soils (Brooks et al., 1977; Jaffre et al., 1976). Later, hyperaccumulator plants were defined as those that accumulate metal to concentrations that are 10–100 times the concentrations found in plants called “normal” (Chaney, 1983). These concentrations are an order of magnitude higher than concentrations found in other plants that grow in the same environment. Today, 440 hyperaccumulator plant species are known, of which 75% are nickel hyperaccumulators (Reeves, 2006). The remaining plant species hyperaccumulate arsenic, cadmium, manganese, sodium, thallium and zinc.

1.1. Practical application of hyperaccumulation of metals into plants

Since the early years of the 20th century, there have been reports about the accumulation of gold by plants, particularly trees (Warren and Delavault, 1950). These studies have shown that coniferous trees, in particular, can accumulate quantities of gold that are in the order of parts per billion in their tissues. Since three decades ago, hyperaccumulators plants have been suggested as a viable mining technique called phytomining (Brooks and Robinson, 1998). Phytomining is the use of live plants to recover valuable metals from waste substrates including mine tailings or mineralized soils. Phytomining can potentially be applied to areas where the metal concentration in the ground is not suitable for extraction using conventional mining technologies, and has been suggested as a possible way to recover the metals nickel, thallium and gold from...
the soil, ore or waste rock (Anderson et al., 1999a; Robinson et al., 2009).

Despite the reported studies into metal accumulation by plants, no hyperaccumulator plant species have been identified for gold. The hyperaccumulation of gold is not a natural trait of plant species (Anderson et al., 1999b). This is because gold, under natural conditions, is highly insoluble, and therefore has low bioavailability. This subsequently hampers the potential for phytoextraction of the element (Gardea-Torresdey et al., 2005). Although gold is known to be relatively immobile it may be solubilised from minerals and soils by microbial activity (Korobushkina et al., 1983) and by cyanogenic plants (Girling and Peterson, 1980).

The technique used to promote increased uptake of metals not normally accumulated by plants is known as induced hyperaccumulation, where the bioavailability (solubility) of metals in soil is promoted using chemicals. In 1996, scientists reported the first field trials of induced hyperaccumulation for lead using Zea mays L. (Maize) and other species (Huang and Cunningham, 1996). Later the initial discovery (October 1997) that plants could be induced to accumulate gold from ‘soil’ was published (Anderson et al., 1998). From this initial observation, work has intensified with an aim to increase the level of accumulation of gold in plants.

Chemicals used as solubilizing agents to promote the solubility of heavy metals during induced hyperaccumulation have been varied. One of the most representative works investigating the induced hyperaccumulation of gold was developed during 2001, when an artificial gold-bearing soil was prepared to contain a gold concentration of 5 mg/kg. The chemicals used as to induce gold uptake in this work were NaCN (Sodium cyanide), KCN (Potassium cyanide), KI (Potassium iodide), KBr (Potassium bromide), and (NH4)2S2O3 (Ammonium thiosulphate). The plant species take in this work were NaCN (Sodium cyanide), KCN (Potassium cyanide) and the element (Gardea-Torresdey et al., 2005). Although gold is considered the third most commonly used metal around the world. During recent years Cu phytoextraction has received considerable scientific attention due to the potential for this technology to clean-up or manage copper contamination of land. Reports about the copper recovery using plants are abundant in the scientific literature (Almeida et al., 2008; Murakami and Ae, 2009; Wang et al., 2010).

Given the general association of copper with gold in waste rock and tailings, it is important to consider the interactive effect of copper on gold phytoextraction. Therefore, the current study comprised three objectives, each of which sought to provide further background data on the viability of gold phytoextraction: (a) to evaluate the field potential of the drought tolerant species Helianthus annuus (Sunflower) cultivated in mine tailings for gold phytoextraction, (b) to examine the feasibility of gold phytoextraction in the laboratory using the desert species Kalanchoe serrata, and (c) to evaluate the interactive effect of tailings copper concentration on gold phytoextraction by both species.

2. Materials and methods

2.1. Substrate for plant growth

Field and laboratory research was conducted using mine tailings from the Magistral mine, in Sinaloa State, Mexico. Research using H. annuus was conducted at an in situ plot on the Magistral tailings deposit, while tailings were collected and transported to greenhouse facilities in Guasave, Sinaloa State for the K. serrata study. Chemical and physical characteristics of these tailings are shown in Table 1.

The Magistral mining district is located in the northern portion of Sinaloa State, 100 km N and 25 W of the city of Culiacan and 19 km N and 25 E of Mocorito township within the municipality

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>2.15</td>
<td>mg kg⁻¹</td>
</tr>
<tr>
<td>Cu</td>
<td>40.0</td>
<td>mg kg⁻¹</td>
</tr>
<tr>
<td>Ag</td>
<td>0.65</td>
<td>mg kg⁻¹</td>
</tr>
<tr>
<td>pH</td>
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</tr>
<tr>
<td>Ca</td>
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<tr>
<td>Mg²⁺</td>
<td>425</td>
<td>mg kg⁻¹</td>
</tr>
<tr>
<td>Na⁺</td>
<td>525</td>
<td>mg kg⁻¹</td>
</tr>
<tr>
<td>CO₃⁻</td>
<td>0</td>
<td>mg kg⁻¹</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>73.2</td>
<td>mg kg⁻¹</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>1056</td>
<td>mg kg⁻¹</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>277</td>
<td>mg kg⁻¹</td>
</tr>
<tr>
<td>Organic matter</td>
<td>0.28</td>
<td>%</td>
</tr>
<tr>
<td>Sand</td>
<td>30</td>
<td>%</td>
</tr>
<tr>
<td>Clay</td>
<td>6</td>
<td>%</td>
</tr>
<tr>
<td>Silt</td>
<td>64</td>
<td>%</td>
</tr>
</tbody>
</table>
of the same name (Fig. 1). This mining district is considered young in the context of mining in Mexico, as mining references only appear in records since the nineteenth century. Although there is no readily available data on the production history of this mining district, it is estimated that the current infrastructure should have produced approximately 60–80 tons of milled ore daily for cyanidation (Zawada, 2009).

2.2. Field trials for copper and gold phytoextraction

For the field trial, a small research plot (5 m × 10 m × 0.30 m) (Fig. 2) was established at the Magistral mine. The average annual temperature at the mine site is 24.2 °C, with a maximum of 44 °C and a minimum of 0.5 °C, while the average annual rainfall is 697.1 mm (maximum recorded 1101.2 mm and minimum of 523.5 mm). Mocorito municipality has two types of climate: a warm-temperate climate with a wet savanna with well-marked dry season, representative of the valleys, low-zones of plains and hills, and in the foothills of the mountain regions, and a mild/cold climate which occurs in the highland areas of the municipality. The plot area was lined, and tailings excavated from the tailings pile and placed on top of a plastic liner according to the design of Anderson et al. (2005). The plot was fertilized with chemical fertilizers (N–P–K) at a rate of 100 kg/ha for each nutrient before the species *H. annuus* was seeded in rows spaced 50 cm apart. Irrigation was applied daily using above-ground spray irrigation heads. Plants were cultivated during 11 weeks and then the substrate was treated with a solution of NaCN at a rate of 1 g/kg reported by Piccinin et al. (2007). One week after treatment, the plants were harvested. Plant samples were dried at 70 °C over 12 h then milled.

2.3. Laboratory trials for copper and gold phytoextraction

For the laboratory trial, living plants of *K. serrata* belonging to the family of Crassulaceae (Fig. 3) (with an important level of tolerance to drought and to high and low temperatures), with four weeks of growth and five centimeters of average height were collected in the field near Guamuchil city in Sinaloa State. Plants were transplanted into pots containing one kilogram of substrate. A total of 25 pots were prepared.

The laboratory trial was developed in a greenhouse in the Guasave Municipality. The municipality has an average annual rainfall of 392.8 mm, with a reported maximum of 760.3 and a minimum of 231.1 mm. The average day time temperature for this part of Mexico is 25.1 °C, with a reported maximum of 43.0 °C and minimum of 3.0 °C. The hottest months are June–October and the coldest November–March.

After transplant, the plants were cultivated for 6 weeks in a greenhouse with a daily temperature range of 20–34 °C. At the end of the six-week growth period, each pot was assigned one of five treatments to induce gold uptake (five replicates per treatment): control, sodium cyanide (NaCN), ammonium thiocyanate (NH₄SCN), ammonium thiosulphate (NH₄)₂S₂O₃ and thiourea [SC(NH₂)₂]. The first three of these gold solubilizing agents was recently used and reported for solubilization of heavy metals from gold-bearing ores (Ebbs et al., 2010). Treatment application rates in Moles of chemical per kg of tailings and g of chemical per kg of tailings are presented in Table 2. Each treatment was applied as 150 mL of solution. The dose of NaCN used for this trial was
reported by Piccinin et al. (2007). For NH4SCN, we used a dose equivalent to double that reported by Anderson et al. (1998). The dose of 2 g/kg of (NH4)2S2O3 was reported in a greenhouse study (Msuya et al., 2000). Finally, the dose of SC (NH2)2 used in this study is equivalent to double the dose used and reported by Rodriguez et al. (2006). Two weeks after treatment the plants were harvested. Plant samples were dried at 70 °C over 12 h and then milled.

2.4. Gold and copper analysis

For analysis, approximately 0.2 g subsamples (triplicate) of each milled plant sample was accurately weighed into 10 mL borosilicate test tubes in the Soil and Earth Sciences Laboratory, Massey University, Palmerston North, New Zealand. These tubes were subsequently ashed at 550 °C overnight in a muffle furnace. The following day the ash was digested using a water bath in 5 mL of aqua regia (3:1 mix of concentration hydrochloric nitric acids), then made to 10 mL.

The copper concentration in each digest solution was analysed using atomic adsorption spectroscopy (GBC Avanta). The gold concentration in the digest solutions of K. serrata was analysed using atomic adsorption spectroscopy; the gold concentration in the digest solutions of sunflower was analysed using Graphite Furnace Atomic Absorption Spectroscopy (Perkin Elmer AAnalyst 600). For graphite furnace analysis a 5 mL aliquot of the digest solution was extracted into an equal volume of methylisobutylketone (MIBK). To ensure accuracy of analysis, blank solutions were run and standard solutions were freshly diluted from 1000 mg/L. For quality control purposes, an internal Massey University biomass reference sample was analysed in triplicate with each set of samples (Anderson et al., 2005). Average values were within 20% of the previously published value for gold, and 18% of the previously published value for copper.

3. Results and discussion

3.1. Field study

The gold concentrations in the leaves, stems, and roots of control plants was higher than expected given a general background concentration of gold in plants of less than 0.05 mg/kg, but this may be due to adsorption of gold onto the exterior of plant tissues. The high root concentration for the control plants supports this theory (there is limited evidence for translocation of root gold to stems). It is very difficult to fully remove gold adhered to the exterior of plant surfaces, without destroying the structure of the plant.

Cyanide increased the gold concentration of each plant organ, however the results were very variable (high standard deviation). This may reflect a non homogenous distribution of gold in the mine tailings, and uneven distribution of the soluble gold cyanide complex throughout the root zone of the plants. The maximum gold concentrations recorded were in excess of 50 mg/kg for the roots and stem of sunflower, and in excess of 30 mg/kg for the leaves of this species. The maximum gold values recorded for this field experiment were slightly higher than those recorded by Anderson et al. (2005), during their field experiment in Brazil.

The copper concentration for the sunflower plants harvested from the field trial is presented in Table 4. Cyanide induced a significant increase in copper uptake for sunflower. The average uptake concentration was increased by a factor of 4 for roots, over 2 for leaves, and by 8 for the stems. The copper concentration in sunflower correlates with the gold concentration in this species after treatment with cyanide (Table 4).

The growth of sunflower at the Magistral mine site was limited due to the dry conditions apparent over the summer period. Growth could only be sustained through regular irrigation. However, in any practical application of the technology, a more drought tolerant specie may be preferable. To further test this hypothesis, the desert plant K. serrata was subsequently grown in the Magistral tailings during a follow-up pot trial. Four chemicals were used to investigate the response of this plant species to gold made soluble in the plant root zone.

3.2. Laboratory study

Gold and copper concentrations in K. serrata from the laboratory study are presented in Tables 5 and 6. Gold and copper uptake by this species, induced by the tested chemicals, was limited relative to data published for other plant species such as Brassica campestris L. (Field mustard) (Wilson-Corral et al., 2008), and Brassica juncea (L.) Czern. (Indian mustard) (Anderson et al., 2005), but similar to reported for stems of Eucalyptus polybractea (Blue mallee), stems of Acacia decurrens (Black wattle), Sorghum bicolor (Sorghum), Bothriochloa macra (Red grass), and Microlaena stipoides (Weeping grass) (Piccinin et al., 2007).

The concentration of gold in the control plants was significantly higher than would be expected in a normal plant (less than 0.05 mg/kg), but again it is unknown whether the high gold concentration for the control plants represents accumulation, or contamination of the exterior of plant organs with soil and dust.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>n</th>
<th>Average Au concentration (mg/kg)</th>
<th>Standard deviation</th>
<th>Maximum Au concentration (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td>Average Au concentration (mg/kg)</td>
<td>Standard deviation</td>
<td>Maximum Au concentration (mg/kg)</td>
</tr>
<tr>
<td>Leaves</td>
<td>5</td>
<td>1.01</td>
<td>0.58</td>
<td>1.64</td>
</tr>
<tr>
<td>Stems</td>
<td>5</td>
<td>1.72</td>
<td>1.53</td>
<td>3.50</td>
</tr>
<tr>
<td>Roots</td>
<td>5</td>
<td>7.81</td>
<td>7.99</td>
<td>21.30</td>
</tr>
<tr>
<td>NaN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaves</td>
<td>8</td>
<td>19.2</td>
<td>10.6</td>
<td>34.2</td>
</tr>
<tr>
<td>Stems</td>
<td>8</td>
<td>21.5</td>
<td>17.5</td>
<td>55.5</td>
</tr>
<tr>
<td>Roots</td>
<td>8</td>
<td>14.9</td>
<td>15.2</td>
<td>55.6</td>
</tr>
</tbody>
</table>

Note: Au concentration is expressed in mg of gold per kg of dry matter of sunflower plants.
The apparent efficacy of thiosulphate to induce uptake suggests the tested chemicals is the least toxic and most environmentally friendly, as compared to thiourea. Uptake induced by the thiosulphate combination in phytomining. Uptake induced by thiourea was no different to the control uptake; thiourea has no apparent ability to induce gold uptake in this species under neutral to alkaline pH conditions, while thiocyanate is expected to induce gold uptake under acid conditions. This is due to the relevant gold complexes being stable under different geochemical conditions (Anderson, 2005). The neutral to mildly alkaline pH value for the Magistral tailings (7.7) suggests that uptake should be promoted with both cyanide and thiosulphate, not thiocyanate. The high gold concentration induced into sunflower in the field using cyanide is explained through the stability of the formed soluble gold-cyanide complex. It is based on the high stability of gold cyanide that this chemical finds application in both hydrometallurgy and phytomining. Thiocyanate, however, was the first chemical used to induce gold uptake in plants. In later years, researchers have focused on cyanide, as this chemical is actually less toxic to plants. We are unable to propose, at this time, an explanation for the unexpected efficacy of thiocyanate to induce gold uptake in K. serrata relative to cyanide. Thiourea, of all the tested chemicals is the least toxic and most environmentally benign. The apparent efficacy of thiosulphate to induce uptake suggests further research should be conducted into the use of the K. serrata thiosulphate combination in phytomining. Uptake induced by thiourea was no different to the control uptake; thiourea has no readily apparent ability to induce gold uptake in this species under the conditions of this research.

None of the chemicals used had a significant effect on the copper concentration in K. serrata; there was no significant increase in the copper concentration in this species after treatment. This observation is in contrast to previously published reports that show a significant increase in copper uptake after cyanide treatment, for example corn and Indian mustard, Anderson et al. (2005), and is in contrast to the recorded observation for sunflower in the current work.

### Economic and practical considerations

Anderson et al. (2005), predicted that gold phytomining could be an economic activity, assuming a target concentration of 100 mg gold/kg dry biomass could be induced into plants. In addition, a study published in 2009 has suggested that gold phytoextraction could produce a profit of 26,000 AU$/ha/harvest, using induced accumulation (with thiocyanate) with a crop of B. juncea coupled with energy generation from the harvested biomass (Harries et al., 2009). In the current research, the target of 100 mg/kg was not reached. However, the gold price in 2005 was approximately US$400 per ounce, in contrast to over US$1500 per ounce in April 2011. Assuming costs have not changed significantly in the past 5 years, it is possible that a gold target as low as 30 mg/kg might be economic today. Values in excess of this target were reached using sunflower growing on the Magistral mine tailings.

The gold concentration in the plant is not the only important variable. The total amount of gold recovered from an area of land is a product of the gold concentration and the harvested dry biomass. In this trial, the field biomass yield from the Magistral mine site was low. The crop was grown over the northern hemisphere summer of 2008. An irrigation system was set up, however the irrigation rate used was insufficient to support optimal biomass growth. The gold concentration in the plant is not the only important variable. The total amount of gold recovered from an area of land is a product of the gold concentration and the harvested dry biomass. In this trial, the field biomass yield from the Magistral mine site was low. The crop was grown over the northern hemisphere summer of 2008. An irrigation system was set up, however the irrigation rate used was insufficient to support optimal biomass growth.

## Table 4

Copper concentration in H. annuus cultivated in the Magistral mine tailings plot.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>n</th>
<th>Average Cu concentration (mg/kg)</th>
<th>Standard deviation</th>
<th>Maximum Cu concentration (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>5</td>
<td>20.4</td>
<td>4.85</td>
<td>27.1</td>
</tr>
<tr>
<td>NaCN</td>
<td>5</td>
<td>34.5</td>
<td>9.07</td>
<td>43.5</td>
</tr>
<tr>
<td>NH4SCN</td>
<td>5</td>
<td>10.15</td>
<td>2.83</td>
<td>13.1</td>
</tr>
<tr>
<td>(NH4)2S2O3</td>
<td>5</td>
<td>17.1</td>
<td>3.63</td>
<td>20.7</td>
</tr>
</tbody>
</table>

Note: Cu concentration is expressed in mg of gold per kg of dry matter of sunflower plants.

## Table 5

Gold concentration in K. serrata cultivated in Magistral mine tailings.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>n</th>
<th>Average Au concentration (mg/kg)</th>
<th>Standard deviation</th>
<th>Maximum Au concentration (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>5</td>
<td>4.02</td>
<td>2.67</td>
<td>6.94</td>
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<tr>
<td>NaCN</td>
<td>5</td>
<td>4.81</td>
<td>3.73</td>
<td>10.0</td>
</tr>
<tr>
<td>NH4SCN</td>
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<td>9.53</td>
<td>3.60</td>
<td>13.8</td>
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<tr>
<td>(NH4)2S2O3</td>
<td>5</td>
<td>10.15</td>
<td>2.83</td>
<td>13.1</td>
</tr>
</tbody>
</table>

Note: Au concentration is expressed in mg of gold per kg of dry matter of K. serrata plants.

## Table 6

Copper concentration in K. serrata cultivated in the Magistral mine tailings.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>n</th>
<th>Average Cu concentration (mg/kg)</th>
<th>Standard deviation</th>
<th>Maximum Cu concentration (mg/kg)</th>
</tr>
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<tbody>
<tr>
<td>Control</td>
<td>5</td>
<td>20.4</td>
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<td>NaCN</td>
<td>5</td>
<td>34.5</td>
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<td>NH4SCN</td>
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<tr>
<td>(NH4)2S2O3</td>
<td>5</td>
<td>17.1</td>
<td>3.63</td>
<td>20.7</td>
</tr>
</tbody>
</table>

Note: Cu concentration is expressed in mg of gold per kg of dry matter of K. serrata plants.
production. Sunflower has proven to be more tolerant to dry conditions than corn or mustard and was thus used for this work. However, the species does require regular irrigation. *K. serrata*, on the other hand, is a desert plant tolerant of very dry environmental conditions that would likely require no irrigation in the field environment. This is particularly true for Mexico, a country with land that could potentially be exploited by phytomining. A low maintenance plant with low to no irrigation requirements is of much greater applicability that a high water use species. The trade of, however, is decreased biomass relative to an irrigated, commercial crop. It is for these reasons that *K. serrata* was investigated for its potential to uptake gold in the current research.

The other important variable controlling the economic viability of gold phytomining is the gold grade of the tailings, ore or waste being worked, and the constituent concentration of other elements. A higher gold grade in the ground will yield a higher gold concentration in the plant. It is estimated that 10–20% of the gold in the root zone can be taken up by plants in any one phytomining cycle, and therefore a sufficient concentration of gold needs to be in the root zone to allow for an economic recovery or metal (Anderson et al., 2003). The Magistral tailings have a high gold concentration (2.35 mg/kg) relative to tailings that can be found in countries like New Zealand, Australia and the USA. This relatively high concentration is, however, representative of many areas of tailings in Mexico and in other developing countries around the world. For example, some studies have estimated that the Kolar Gold Fields located in Karnataka, India, which contain up to 33 million tons of tailings that have accumulated over many years, may be a source of 24 tonnes of gold (Mohanty, 2005). Tailings with less that 1 mg/kg gold are unlikely to have sufficient gold to justify economic phytomining. But tailings with more than 1 mg/kg should be targets for development. An issue associated with this requirement is resource acquisition. In 2009, plans were made to repeat the Magistral field trial with a more robust irrigation system. However, due to changing ownership issues, access to the mine site in 2009 was not granted. A developing issue for researchers working on gold phytomining is the ability to negotiate access to suitable resource on which to develop field applications of the technology. Our research group in Mexico is currently searching for a new site on which to conduct a final and conclusive trial into the concentration of gold that can be induced into a crop of plants with a quantified, harvested, biomass.

The presence of other metals in the substrate that can also be more susceptible and accumulated by plants is a likely important variable that will affect the metal uptake concentration. Assuming gold uptake is by mass flow, and that a plant has no mechanism to block gold uptake, accumulation will continue as long as the plant is viable and continues to transpire. Evapotranspiration rates will decrease as the plant concentrates metals such as copper in roots, stems and leaves to phytotoxic levels (Anderson et al., 2005). It is well known that many metals are essential for life, e.g. Na, K, Cu, Zn, Co, Ca, Mg, Mn and Fe, but all can exert toxicity when present above certain threshold concentrations (Gadd, 2010). A recent literature review regarding the phytotoxicity of trace metals shows a trend as follows (from most to least toxic): Pb > Hg > Cu > Cd > As > Co > Ni > Zn > Mn (Kopittke and Blamey, 2010). Sunflower in the field experiment accumulated significantly higher concentrations of copper after cyanide treatment, although levels were lower than those reported by Anderson et al. (2005), for the Brazil field trial. It is unknown whether the levels of copper in sunflower were phytotoxic; however the plants did show signs of visible stress in the days after treatment with cyanide.

The physiological mechanisms of resistance to some heavy metals such as Cu include internal detoxification and exclusion of the metals via root carboxylate exudation (Qin et al., 2007). Photosynthetic reactions, both photochemical and biochemical are key physiological functions of a plant that can be inhibited by many heavy metals and in particular Cu (Kupper et al., 2009). Recent studies have shown that toxicity symptoms in poplar roots will occur at Cu concentrations of 30 μM in solution and above (Qin et al., 2007). While this value may not be directly attributable to crop species such as sunflower, this does provide a background value for future study. The increase in copper accumulation by *K. serrata* after cyanide and other chemical treatment was, in contrast to sunflower, very low. This species may have some better mechanism to block copper uptake. This species could therefore potentially be used to accumulate gold over a much greater timeframe, using a very dilute solution of chemical lixiviant, as copper uptake does not appear to be promoted. Thiosulphate, the lixiviant which promoted the highest uptake concentration in *K. serrata* is not toxic, and could be used much more freely than cyanide or the other thio-chemicals.

There does appear to be some variability in the potential of different plant species to accumulate gold. The authors of this paper believe that mass flow is the driving mechanism for uptake. However, there may be some genetic control over the final gold yield in a plant. In a country like Mexico, with edaphically challenging conditions, crop plants may not be the best choice to operate phytomining in arid to semi-arid ecosystems. The results of our work indicate that more research needs to be conducted to better understand the interaction of different species with different chemicals and metals that are commonly associated with gold in soil. Phytomining has good potential to become an economically viable gold recovery technology in certain locations around the world; although the system will never compete with conventional mining. Phytomining could assist with the sustainable closure of mine sites, as gold is recovered from plants generating revenue from the initial stages of revegetation and rehabilitation. Cropping of waste land will increase levels of soil carbon, nutrients and biological activity, thereby increasing the success rate of subsequent native planting strategies. But phytomining is potentially also a niche technology to recover gold from areas of waste rock, ore or tailings that are too small, or located too far from a conventional processing facility. In these scenarios the costs of transport or infrastructure may make exploitation of the resource uneconomic by conventional technology. However, in these same scenarios, a well-designed phytomining operation, with a species chosen based on climatic conditions, and a chemical chosen with consideration of geochemical and environmental restrictions, may represent an economically viable alternative technology.

The data from this research shows that economic concentrations of gold can be induced into plant tissues using the system known as gold phytomining. Our results support previously reported studies. However further and more extensive field studies are necessary to examine the long-term economic viability of the technology.

4. Conclusions

The concentration of gold accumulated by sunflower was sufficiently high to potentially make phytomining of Magistral tailings an economically viable operation. However, based on a single treatment, the gold concentration in *K. serrata* was too low.

The results of our study confirm that there is an associated increase in copper uptake by some plants when treatment is applied to soil to induce gold uptake. However, this response does not appear to be true for all species. In a comparison of *H. annuus* and *K. serrata*, *K. serrata* appears to restrict copper uptake. The two species also show a differential gold uptake response to chemicals. Sunflower responded to cyanide treatment of Magistral mine tailings, while, *K. serrata* responded to thiosulphate treatment of this substrate.
The current (2011) world gold price has increased interest in gold phytomining as a viable metal recovery technology. However, the science underpinning this technology must be better understood if economic returns are to be realized. The results of our study have highlighted the variability in uptake that can be apparent when different plant species or soil treatments are used to promote gold uptake.

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