Gold phytomining in arid and semiarid soils

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Abstract
Metals such as gold, copper and lead can be found in soil at high concentration at many desert locations. However, adverse weather conditions, specifically a lack of moisture, limit the range of applicable technologies to recover these metals. A number of plant species have been tested under both laboratory and field conditions to determine their potential for use in the phytoextraction of metals such as gold. Recorded gold extraction and dry matter yields suggest that phytomining in arid and semiarid zones might be viable if plant species are used that can to adjust to the conditions of these regions.

Key Words
Induced hyperaccumulation, hyperaccumulator plants, mine tailings.

Introduction
Environmental conditions such as weather and humidity limit the practice of activities that generate the livelihoods necessary for the survival of desert communities. One of the economic activities that has developed in desert regions is mining. This activity has been conducted in desert regions for centuries (Grattan *et al.* 2004). Various metals such as gold, copper, lead are hosted in desert sites around the globe. The enduring adverse climates (Kondos 2009) and other conditions that prevail in arid and semiarid desert regions often limit the application of appropriate technologies for metal recovery. Despite the limitations, mining activities for certain metals (particularly copper) have developed in some desert areas on an immense scale (Grattan *et al.* 2004). Recent studies reveal the existence of areas of gold mineralization in desert areas around the world (Reid *et al.* 2009). The same conclusion can be made for lead and chromium (Pyatt *et al.* 1999). These arid-zone mineral deposits could be exploited through application of appropriate mining technologies.

Induced hyperaccumulation of gold in plants
Since the early of 20th century, there have been reports about the accumulation of gold by plants, particularly trees (Warren and Delavault 1950). These studies showed that coniferous trees can accumulate quantities of gold that are in the order of parts per billion in their tissues (Warren and Delavault 1950). Some mining companies use plant species as bioindicators of the presence of gold in soil. However, no plant species have been identified that can hyperaccumulate gold naturally. Gold, under natural conditions, is highly insoluble. This reduces its bioavailability and thus limits the potential for phytoextraction; bioavailability is one of the most critical factors for plant uptake of metals (Gardea-Torresdey *et al.* 2005). Scientists have suggested procedures to force hyperaccumulation by applying chemical compounds that promote metal solubility to the substrate of a growing plant. This technique is known as induced hyperaccumulation and provides the basis for the development of phytomining, which is a novel extraction technique to exploit precious metal resources from soil. Phytomining is the use of live plants to recover valuable metals from waste mining substrates (tailings) or mineralized soils. Phytomining has been applied to areas where the metal concentration is not suitable for viable extraction using conventional technologies (Anderson *et al.* 1998). In 1994, scientists conducted the first field trials of induced hyperaccumulation for lead using maize (*Zea mays* L.) and other species (Huang and Cunningham 1996). More recent studies have shown that thallium and nickel are metals for which phytomining may also be economically viable using natural or non-induced hyperaccumulation (Robinson *et al.* 2009).

Laboratory trial for gold phytoextraction
In 1998, Anderson and his research group in New Zealand reported, for the first time, results describing the induced hyperaccumulation of gold in plants (Anderson *et al.* 1998). In this work, Indian mustard (*Brassica juncea* Czern.) was induced to accumulate gold concentrations in leaf tissues as high as 57 mg/kg of dry matter (Anderson *et al.* 1998).

Experiments to extract gold from hydroponic solutions using the species *Medicago sativa* L., were published in 1998 and 2002 (Gardea-Torresdey *et al.* 2002). In these reports, thiourea was used to induce gold hyperaccumulation. The data showed that the species could be used for the phytoextraction of gold particles dissolved in hydroponic solutions. In subsequent studies, laboratory tests using the crop plants radish (*Raphanus sativus* L.), onions (*Alluim cepa* L.), beet (*Beta vulgaris* L.) and carrot (*Daucus carota* L.) cultivated in a silica sand containing 3.8 mg/kg gold showed that gold concentrations greater than 200 mg/kg of plant tissue could be achieved (Msuya *et al.* 2000).

In 2005, a study was published in which the species *Chilopsis linearis* Cav. that grows in the deserts of Chihuahua, Mexico, was used to extract gold particles from hydroponic solutions. The results showed the viability of this species to be used in the absorption of gold using ammonium thiocyanate to increase the solubility of metallic gold (Gardea-Torresdey *et al.* 2005).

In 2007 a study conducted in Australia was reported in which the following plant species were tested for gold phytomining: *Eucalyptus polybractea* R.T.Baker (Blue Mallee), *Acacia decurrens* Willd. (Black Wattle), *Sorghum bicolor* L. Moench. (Sorghum) *Trifolium repens* L. (White clover cvs. Tribute and Prestige), *Bothriochloa macra* (Steud) S.T.Blake (Red grass), *Austrodanthonia caespitosa* (Gaudich.) H.P.Linder (Wallaby grass) and *Microlaena stipoides* (Labill.) R.Br. (Weeping grass). The reported results showed that *Trifolium repens* L. *cv*. Prestige could be induced to accumulate gold concentrations higher than 27 mg/kg of dry matter, when cultivated on mine tailings and where sodium cyanide was used as the inducing agent (Piccinin *et al.* 2007).

Greenhouse trial for gold phytoextraction
During 2006 studies were conducted in Mexico where plants were tested for their ability to extract gold from spiked sand. In this work the following species were used: *Amaranthus spp* (amaranth), *Sorghum halepense* L. Pers. (Johnson grass), *Helianthus annuus* L. (Sunflower), *Sesamum indicum* L. (Sesame), *Gossypium hirsutum* Tod. (Cotton), *Brassica campestris* L. (Indian mustard) and *Amoreuxia palmatifida* Moc. & Sessé ex DC. (Mexican yellowshow) (Wilson-Corral 2008). Results showed that it is possible to induce gold concentrations above 304 mg/kg of dry matter in *B. campestris* growing in gold-enriched silica sand and using ammonium thiocyanate as the inducing agent for gold hyperaccumulation.

In early 2008, a trial was performed in order to evaluate the gold extraction potential of *Sorghum halepense* L. Pers. cultivated on mine tailings in a greenhouse. Sodium cyanide, thiourea, ammonium thiocyanate and ammonium thiosulfate were used to induce gold hyperaccumulation. These trials revealed that sodium cyanide could induce gold concentrations up to 23.9 mg/kg of dry matter (Rodriguez-Lopez *et al.* 2009a).

During 2009, a test was conducted in which the species *Kalanchoe serrata* Mannoni & Boiteau was grown. This species can grow in high temperature and scarce water conditions that can prevail in deserts (Rodriguez-Lopez *et al.* 2009b). This study revealed that, through application of sodium cyanide to the growing media, it is possible to induce a gold concentrations higher that 9 mg/kg of dry matter in this species.

Field trials for gold phytoextraction
During 2003 the first field trial for gold phytoextraction from mine tailings was conducted using sodium cyanide and ammonium thiocyanate as chemicals to induce gold hyperaccumulation (Anderson *et al.* 2005). In this work B*rassica juncea* Czern. (Indian mustard) and *Zea mays* L. (maize) were used to recover gold from rock with a gold concentration of 0.6 mg/kg. The results showed that it is possible to achieve a gold concentration of up to 39 mg/kg of dry matter in Indian mustard under field conditions. This trial showed that potentially between 10 and 20% of the gold present in the substrate can be removed in any one crop.

Towards the end of 2006, researchers at the Centro de Innovacion y Desarrollo Educativo (CIDE AC) conducted field trials in Mexico where plants of *Brassica juncea* Czern. were cultivated in mine tailings. The results showed that it was possible to obtain biomass yields in excess of 8 ton/ha under field conditions (Wilson-Corral, 2008). Finally, in 2009, a field trial was conducted to establish the potential of the species *Helianthus annuus* L. to recover gold from mine tailings. A plot of 50 m^2 was constructed. The average gold concentrations for leaves, stems, and roots, were 16, 21, and 15 mg/kg of dry mater, respectively after cyanide treatment of the mature biomass (unpublished).

Technical assessments

Scientists at the University of Sydney have evaluated the technical feasibility and the economic viability of nickel and gold phytomining in Australia. In this work possible sites were identified and plant species most suited to these regions and methods of recovering the metals from the plants were suggested. The indicative profitability for a Ni phytomine in Australia was predicted to be 11,500 AU$/ha/harvest, using the hyperaccumulator *Berkheya coddii* Roessler on nickel rich serpentine soils and with energy generation from the harvested biomass. For Au, a profit of 26,000 AU$/ha/harvest was predicted using induced accumulation (with thiocyanate) with a crop of *Brassica juncea* L. coupled with energy generation from the harvested biomass (Harris *et al.* 2009).

Conclusions

Tests are ongoing in Mexico under both greenhouse and field conditions to assess the economic returns that could be generated by the implementation of phytomining to extract gold from waste produced by mining activities in this country. Considering the scientific studies reported in this manuscript, the following objectives are being actively researched: a) systems to evaluate the potential of ore, tailings or waste produced by mining activities in arid and semiarid regions for gold phytomining; b) tests to identify plant species that can be used in these areas for gold phytomining; c) economic assessment to determine potential profits that could be gained through applying the technology in arid and semiarid regions; and d) the implementation of commercial scale phytomining operations.

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References

Anderson C, Brooks RR, Stewart RB, Simcock R (1998) Harvesting a crop of gold in plants. N*ature* **395**, 553-554.

Anderson C, Moreno F, Meech J (2005) A field demonstration of gold phytoextraction technology. *Minerals Engineering* **18**, 385-392.

Gardea-Torresdey JL, Parsons JG, Gomez E, Peralta-Videa J, Troiani HE, Santiago P, Jose-Yacaman M (2002) Formation and growth of Au nanoparticles inside live alfalfa plants. *Nano Letters* **2**, 397-401.

Gardea-Torresdey JL, Rodriguez E, Parsons JG, Peralta-Videa JR, Meitzner G, Cruz-Jimenez G (2005) Use of ICP and XAS to determine the enhancement of gold phytoextraction by *Chilopsis linearis* using thiocyanate as a complexing agent. *Analytical and Bioanalytical Chemistry* **382**, 347-352.

Grattan JP, Gillmore GK, Gilbertson DD, Pyatt FB, Huntf CO, McLareng SJ, Phillips PS, Denman A (2004) Radon and 'King Solomon's Miners': Faynan Orefield, Jordanian Desert. *The Science of the Total Environment* **319**, 99-113.

Harris AT, Naidoo K, Nokes J, Walker T, Orton F (2009) Indicative assessment of the feasibility of Ni and Au phytomining in Australi. *Journal of Cleaner Production* **17**, 194-200.

Huang BJ, Cunningham (1996) Lead Phytoextraction: species variation in lead uptake and translocation. *New Phytologist* **134**, 75-84.

Kondos P (2009) Gold Extraction: Practices and Challenges. *In* ' 5ta International Conference: Science, Technology and Applications of Gold '. Hiedelberg, Germnay. (Ed. H University), p. 31. (World Gold Council (WGC)).

Msuya FA, Brooks RR, Anderson C (2000) Chemically-induced uptake of gold by root crops: Its significance for phytomining. *Gold Bulletin* **33**, 134-137.

Piccinin RCR, Ebbs SD, Reichman SM, Kolev SD, Woodrow IE, Baker AJM (2007) A screen of some native Australian flora and exotic agricultural species for their potential application in cyanide-induced phytoextraction of gold. *Minerals Engineering* **20**, 1327-1330.

Pyatt FB, Barker GW, Birch P, Gilbertson DD, Grattan JP, Mattingly DJ (1999) King Solomon's Miners Starvation and Bioaccumulation? An Environmental Archaeological Investigation in Southern Jordan. *Ecotoxicology and Environmental Safety* **43**, 305-308

Reid N, Hill SM, Lewis DM (2009) Biogeochemical expression of buried gold mineralization in semi-arid northern Australia: Penetration of transported cover at the Titania Gold Prospect, Tanami Desert, Australia. *Geochemistry: Exploration, Environment, Analysis* **9**, 267-273.

Robinson BH, Banuelos B, Conesa HM, Evangelou MWH, Schulin R (2009) The Phytomanagement of Trace Elements in Soil. *Critical Reviews in Plant Science* **28**, 240-266.

Rodriguez-Lopez M, Wilson-Corral V, Anderson C, Lopez-Perez J (2009a) Chemically Assisted Gold phytoextraction in *Sorghum halepense*. *In* '5ta International Conference: Science, Technology and Applications of Gold '. Heidelberg, Germany. (Ed. Heidelberg University), p. 353. World Gold Council.

Rodriguez-Lopez M, Wilson-Corral V, Lopez-Perez J, Arenas-Vargas M, Anderson C (2009b) Aplicacion Potencial de *Kalanchoe serrata* en Tecnologías de Mineria Ambientalmente Sostenibles In 'Primer Congreso Internacional de Ciencias de la Ingeniería'. Los Mochis, Sinaloa. (Ed. CP Barrios Durstewitz) pp. xxx-xxx. (Universidad Autonoma de Sinaloa).

Warren HV, Delavault RE (1950) Gold and silver content of some trees and horsetails in British Columbia. *Geological Society of America Bulletin* **61**, 123-128.

Wilson-Corral V (2008) Hiperacumulación de oro inducida químicamente en ocho especies vegetales (*Brassica juncea, Brassica campestris, Helianthus annus, Amaranthus spp., Sesamum indicum, Sorghum halepense, Amoreuxia palmatifida y Gossypium hirsutum*). PhD Thesis. Centro de Estudios Justo Sierra (CEJUS).