

Review

Phytoextraction to promote sustainable development

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Abstract: Mining makes a positive contribution to the economy of Indonesia. Significant earnings accrue through the export of tin, coal, copper, nickel and gold. Of these commodities, gold carries the highest unit value. But not all gold mining is regulated. Indonesia has a significant Artisanal and Small Scale Gold Mining (ASGM) industry, defined as any informal and unregulated system of gold mining. These operations are often illegal, unsafe and are environmentally and socially destructive. New technology is needed to support the sustainable exploitation of gold and other precious metal resources in locations where ASGM is currently practised. This technology must be simple, cheap, easy to operate and financially rewarding. A proven option that needs to be promoted is phytoextraction. This is technology where plants are used to extract metals from waste rock, soil or water. These metals can subsequently be recovered from the plant in pure form, and sold or recycled. Gold phytoextraction is a commercially available technology, while international research has shown that phytoextraction will also work for mercury. In the context of ASGM operations, tailings could be contained in specific 'farming areas' and cropped using phytoextraction technology. The banning of ASGM operations is not practicable or viable. Poverty would likely become more extreme if a ban were enforced. Instead, new technology options are essential to promote the sustainable development of this industry. Phytoextraction would involve community and worker engagement, education and employment. New skills in agriculture created through application of the technology would be transferrable to the production of food, fibre and timber crops on land adjacent to the mining operations. Phytoextraction could therefore catalyse sustainable development in artisanal gold mining areas throughout Indonesia.

Keywords: *Artisanal and Small Scale Gold Mining, gold phytoextraction, poverty*

Introduction

Phytoextraction is a practical example of phytoremediation, defined as the use of plants to manage or to clean up the environment, and in this sense is a classical industrial biotechnology (Robinson et al., 2009). The concept is not new; plants have been used for hundreds of years to treat human waste, limit soil erosion and to protect water quality. But it is only in the last 30 years that phytoremediation as a defined system has entered the world of science and technology. To make phytoremediation work, plants act as biological pumps or 'biopumps' using the sun's energy to move water and contaminants from the soil into their leaves and stems. At the same time they return some of the products of photosynthesis, such as sugars, to the root-zone. Transpiration is thus the driving force of phytoremediation. By removing water from degraded soil, plants limit the potential for erosion, runoff and leaching. They thereby manage the off-site movement of soil contaminants. Some contaminants are removed along with water. These are stored in plant

tissues, or can be metabolised *in situ*. Just the simple action of drying a soil has positive environmental benefits; the volume of soil will be reduced proportional to the amount of water removed, and an oxygen-rich zone is created where life is enhanced. Carbon returned to soil in the form of sugar and decaying root matter will further stimulate biological activity. This biological activity is crucial to phytoremediation and is in fact a defining property of soil. Without soil health there is no remediation, and the best way to create biological activity is to grow plants. To summarise this first section then, phytoremediation works when plants are grown in a degraded environment. The choice of plant is dependant on the type of environment and the target contaminant, but once growing, the sun provides the fuel for remediation.

The different roles of phytoremediation

There are many sub-technologies that make up phytoremediation. The important ones are briefly described here.

Phytostabilisation is where plants immobilise contaminants in the root-zone. This generally refers to leachate reduction and erosion control and can also be described as hydraulic isolation. Perhaps the greatest application for phytostabilisation is to manage wastewater and leachates that are generated by landfills, land-based effluent disposal systems, and intensive farming. High water use trees can be strategically planted and used to stop leachates entering ground water (otherwise known as Riparian buffer zones). A simple operation such as revegetation can be considered an application of phytostabilisation. A revegetated polluted site looks good and will reduce off-site contaminant movement, while deep-rooted trees can lower a water table. Revegetation has been shown effective in Australia as a way to reverse the problem of soil salinity brought about through deforestation (Bell, 1999). The simple act of revegetation will increase biodiversity; the planting of native trees and shrubs will provide habitat for native animals. The transformation of a dead and polluted industrial site into a living green zone can, in this way, generate significant economic, social and political value through increase land prices, public good will and through improved perception of landowners and regulatory agencies.

Phytodegradation describes the breakdown of contaminants in the root-zone. Degradation may be a chemical process due to root exudation, or a metabolic process, as soil microbes degrade some contaminants. Again this application highlights the importance of biological activity. Phytodegradation can be an effective way to clean-up soil contaminated with organic pollutants such as cyanide, petroleum, TNT, perchlorates, organochlorines and some polycyclic aromatic compounds. But not all organics are susceptible to phytodegradation. Plants, for example, do not breakdown DDT (Robinson et al., 2003 and references therein).

Phytoextraction describes the use of plants to *remove* contaminants from the soil. The contaminant is stored in leaves, shoots and stems and can be harvested and removed from site. Repeated cropping will reduce soil contamination to a safe level. Some plants used for phytoextraction are called hyperaccumulators, and these are plants that accumulate very high concentrations of certain metals as they grow. Plants will accumulate other metals if we can find a way to increase their solubility in soil, and we call this process 'induced hyperaccumulation'. To highlight a couple of examples, the chemical EDTA will cause plants to accumulate lead when irrigated on soil (Huang and Cunningham, 1996), while thiocyanate, thiosulphate and cyanide will all cause plants to accumulate gold (Anderson, 2005). But it's not just contaminated soil that can be cleaned using phytoextraction.

Radioactive nuclides of strontium and caesium have been removed from polluted water near the site of the Chernobyl nuclear disaster using common sunflowers (see Brooks, 1998). There are other technologies in the phytoremediation family, such as **phytovolatilisation** where contaminants such Hg, Se and trichloroethane are volatilised from the soil to the atmosphere by plants, and **phytomining** where plants are used to recover valuable metals such as gold for economic profit. This last example is an applied use of phytoextraction and is sometimes referred to as phyto-reclamation.

Research groups in several laboratories around the world are trying to unlock the genetic secrets of phytoremediation. Genetic modification could allow the genes for metal accumulation to be transferred to high-biomass plants such as corn, in effect creating an easy to grow super-plant. The genes responsible for mercury volatilisation have been identified and transgenic plants can be used for mercury phytovolatilisation (Meagher et al., 2000), but transgenic phytoextraction remains largely in the laboratory.

The pros and cons for phytoremediation

Phytoremediation has a key advantage over conventional remediation technology. Phytoremediation is lower cost, low technology and low maintenance; the system is an agricultural one. Conventional remediation such as soil removal or capping can cost in excess of 1M\$ per hectare. Compare this to phytoremediation, which may cost in the order of 0.1M\$ per hectare (Salt et al., 1995). But there are other benefits to consider. Phytoremediation leaves a site green and fertile, and 'green' solutions generally have high public acceptability. Some operations can yield valuable products from harvested plant material, offsetting remediation costs and in some cases generating a profit.

An obvious product is the plant material itself. Phytoremediation could be combined with forestry, and the harvested wood used for pulp or timber. Tradeable carbon credits as defined under the Kyoto Protocol could be realised from the sustainable use of biomass. Alternatively, vegetation could be combusted by incineration or gasification to produce renewable energy. Another possibility is to use plants with elevated levels of essential trace elements such as zinc, cobalt or boron as organic mineral supplements for crops, livestock or even humans. The possible business opportunities for nutraceutical and bioactive extracts from such plants have yet to be explored in detail.

It is possible to recover economic quantities of some industrially important metals from plants, such as nickel or even gold. It is possible to design a phytoremediation operation where the revenue

generated from processing valuable metals out of a crop of plants can pay for the management of serious pollutants such as arsenic or mercury. Spin-off benefits that indirectly generate positive revenue such as employment and education can also be realised under this scenario. And this is a scenario which will be more fully developed in this paper.

But we must realize that phytoremediation is not a solution for all polluted land. Phytoremediation relies on plant-physiology, and this is a limiting factor. Plants will only target surface contaminants and clean-up is restricted to soil and climates that will support plant growth. We must also consider the timeframe for phytoremediation.

For an example, consider the permissible EU limit for nickel in soil, which is set at 75 mg/kg or ppm. Using *Berkheya coddii*, a nickel hyperaccumulator that can remove 200 kg of nickel per crop from a hectare of land, soil with a concentration of 250 ppm would be safe after 4 years; 1000 ppm after 18 years; or 10,000 ppm after 138 years (Robinson et al., 1997). Clearly for lightly contaminated soil phyto is a viable option, but for land with 1% metal contamination, conventional soil excavation would be a better solution if re-zoning of the land for residential or commercial development is the target land use. If the land is to remain undeveloped then the time-scale is less important. Perhaps under this scenario long-term management using phytoremediation is a viable option for even mid to high-level pollution. A managed forested ecosystem could lock-up the pollutants in perpetuity. The intended eventual land-use for a polluted site must therefore be considered during assessment of the merits of phytoremediation for soil clean up or management. Of note is the fact that nickel phytoremediation using *Berkheya coddii* has been successfully used by the Anglo Platinum Company at their Rustenburg Base Metal Refinery in South Africa (Howes et al., 1998).

A key question that arises is what to do with the harvested biomass. Anglo Platinum feed the material into their metal smelter, but these are few and far between. This question must be addressed for every operation, but the consensus is that plant material should be burnt, reducing the amount of waste to between 5 and 10% of the initial volume. Safely managing a small volume of ash that is enriched in metal is then a more viable prospect than safely managing a large volume of soil.

One has to also consider potential exposure pathways for soil contaminants into the food chain. Animals and humans could consume metal-rich plants, while insects might become contaminated through the pollination of metal-rich plants. These concerns become particularly relevant if plants are genetically modified to accumulate metals. In this scenario there is potential for cross-pollination with

crop species. These are real issues to consider as phytoremediation becomes an established technology. Risk assessment is a critical part of any investigation into the site-specific suitability of phytoremediation for the clean up or management of polluted soil.

In this next part of the paper the specific application of phytoextraction as a technology to promote sustainable development at artisanal and small-scale gold mining areas is described.

Artisanal and Small-scale Mining

The term 'artisanal mining' describes an informal and unregulated system of small-scale mining prevalent in many of the world's poorest countries and communities. Artisanal miners do not make large profits; they strive to make sufficient money to support their immediate family. Many metals and minerals are mined using artisanal methods, but high value commodities such as precious metals and gemstones provide the greatest return.

Artisanal mining is practiced in the developing nations of Africa, Asia and South and Central America. An estimated 20 to 30 million artisanal-small scale miners operate in 55 countries. Each miner is thought to generate income for a further 10 people (ILO, 1999). Artisanal operations are often illegal and poorly regulated. Miners have no title to the land they are working and thus there is no incentive for sustainable land management. Environmental destruction is the most visible outcome of artisanal mining. Problems include acid mine drainage, deforestation, soil erosion, river silting and the pollution of soil and water with toxic compounds.

Abhorrent health and social problems are typical of many artisanal communities. Primitive and low-cost technologies lead to high levels of work-place hazard; fatal accidents are common. Workers migrate from mine-site to mine-site, creating friction, resentment and social instability. Gambling and prostitution increase the prevalence of HIV infection in mining areas. In some areas in Africa the incidence of HIV affects 50% of the artisanal mining communities. Poor infrastructure for water, sanitation, education and law and order are all manifestations of the illegal industry.

Artisanal mining is characterised by a vicious poverty cycle: discovery, migration, and relative economic prosperity are followed by resource depletion, out-migration and economic destitution. After depletion of easily exploitable gold reserves, sites are abandoned, and the miners who remain contend with a legacy of environmental devastation and extreme poverty. These people have little opportunity to escape their circumstances (Veiga and Hinton, 2002).

Despite the negativity, artisanal mining plays an essential role in developing societies. Small mines can be a major source of revenue for rural communities, and can provide income for investment. Artisanal miners can exploit a mineral deposit considered uneconomic by modern industry. Every \$1 generated through artisanal mining generates about \$3 in non-mining jobs. In the words of Sir Mark Moody Stewart, the President of the Geological Society of London during a November 2003 conference on sustainable mining, "Artisanal mining should be encouraged; however, the associated poor health, safety and environmental conditions must be improved."

Artisanal gold mining

Artisanal gold mining (ASGM) accounts for around 50% of the world's artisanal and small-scale mining. Mercury amalgamation is the preferred gold extraction method used by artisanal miners worldwide. Amalgamation is simple and cheap, leading to quick profits, but is inefficient and will discharge mercury and gold into the environment. A common legacy of artisanal gold mining is mercury pollution.

ASGM has perhaps been more extensively studied in Brazil than in any other country, due, in part, to the infamy of the Serra Pelada mine that was operating in the 1980s where about 80,000 miners extracted 90 tonnes of gold from an open pit. There are approximately 2000 artisanal mines in the Amazon region of Brazil alone, producing around 20 tonnes of gold per year. About 2 million people owe their jobs to these mines (Veiga et al., 1995). One tonne of mercury is typically released to the environment for every tonne of gold produced. When the cumulative calculations are made, the level of mercury discharge is staggering. Anywhere between 3000 and 4000 tonnes of metallic mercury have been released into the Amazon region since the beginning of the gold rush in the 1980's. A high proportion of this mercury finds its way into the atmosphere, but 20% commonly ends up in the waste soil and rock of a mining operation (tailings).

Mercury in tailings can transform into methylmercury, and accumulate in the food chain. Methylmercury is the sixth most toxic of six million compounds known to mankind (Malm, 2001). Plants and animals, in particular fish, a major food source, are contaminated by methylmercury. Many mine workers and their families show elevated mercury concentrations in their blood and urine, and neurological disorders have been linked to these high mercury concentrations. Although technology is available to manage mercury pollution, it is

expensive, and therefore unattractive to artisanal communities.

Phytoextraction: a new technology for artisanal communities

A developing project of the International Research Centre for the Management of Degraded and Mining lands is the implementation of a phytoextraction scenario where revenue can be generated from a crop and used to pay for the clean-up of less valuable metals or contaminants that are removed or broken down in the degraded land at the same time. Theatres for the application of this scenario can be found around the world. But research in New Zealand has investigated a system where gold and mercury are recovered by the same crop of plants from soil or tailings at an ASGM location elevated in both of these metals (Anderson et al., 2005; Moreno et al., 2005).

In this scenario the target for cleanup is mercury, but gold accumulated by plants along with mercury could be sold and thus provide revenue for the environmental operation.

Phytoremediation and phytomining are being developed and offered as a commercially viable environmental technology by many groups. Massey University has an international reputation for conducting novel and important phytoremediation research at historic and active mine sites in New Zealand, Australia, Fiji, China, USA, Mexico, Brazil and South Africa. Massey University scientists have many years of experience in the design and application of phytoremediation projects. A New Zealand company that has a research relationship with Massey University has proprietary expertise in the processing of plant biomass to recover metals, including gold; gold phytomining is a commercially available technology.

Our proposed system has three key steps. First we plant polluted mercury and gold waste with a fast-growing and high-biomass plant species. Once the crop has reached maturity, we apply an amendment to the soil that will make a proportion of the mercury and gold soluble. The soluble metal will accumulate in the roots, shoots and leaves of our crop as it continues to grow. Finally, after one-to-two weeks of metal accumulation, the crop is harvested and processed to recover the metal.

The aim of this system is to remediate mercury-polluted land, but there is a crucial advantage, the value of gold in the harvested crop. We know from the United Nations Development Programme Sustainable Livelihoods Project that miners will show little interest in environmental initiatives if there is no quantifiable and immediate payback. Our system addresses this critical issue. The gold value of the

crop may provide a cash incentive to artisanal farmers who clean up their land.

Where implemented in Indonesia the aim of the system would be as an agricultural strategy at ASGM locations to manage the environmental burden of amalgamation and cyanidation tailings. Phytoextraction could generate revenue from what is currently a waste product. Upskilling of workers with modern agricultural techniques during the operation would lead to a newly educated workforce within ASGM communities that could protect the environment, and generate produce for community consumption and external trade from land more suitable for agricultural production. The mechanism by which this change could be created is the extraction of gold and mercury from ASGM waste using plants. The gold value of the crop should

provide a cash incentive to artisanal farmers who clean up their land.

Artisanal mining can clearly benefit communities while resources are rich. What is needed is a livelihood that can sustain the environment during these times, and generate alternative income when resources are poor or depleted. The livelihood identified to break the poverty cycle is agriculture. Education and training paid for by gold revenues could empower communities to farm their land efficiently. Farming might then be seen as a more attractive alternative livelihood for migrant workers. Gold could be a catalyst to bring about sustainable agriculture.

The research would specifically contribute to Indonesian efforts to meet Target 7a of Millennium Development Goal Seven

‘Integrate the principles of sustainable development into country policies and programmes; reverse loss of environmental resources’.

Working scenario..... ‘Local co-operatives’ train artisanal farmers with the agronomic skills necessary to farm metals. Co-operatives then employ and subsidise farmers to carry out the metal recovery operation, and purchase the metal-rich biomass upon harvesting. Environmentally sound processing would recover the mercury for disposal or recycling. Recovery and sale of the gold would make the operation economically viable. A newly empowered farming community would eventually utilise the clean soil and their new skills for agricultural production.

Mercury removal and productive land use: environmental sustainability...
Gold removal and agricultural development: economic sustainability...
Employment and education for the artisanal community: social sustainability

The economic case for farming mercury and gold

Soils polluted through ASGM operations have mercury concentrations as high as 6000 mg/kg mercury (unpublished Indonesia data), and gold concentration as high as 10 mg/kg. Field experience shows that under optimal conditions, a single crop of plants will remove approximately 15-20% of the gold present in the soil. This means that soil with a 3 mg/kg gold concentration can yield a crop with a 100 mg/kg (dry weight) plant concentration. Assuming we harvest 10 tonnes of dry biomass from a hectare of land (can be multiple small areas summing to one hectare), and that we can recover all of this gold from the plant material, our final product is 1 kg of gold per hectare unit of land.

At a gold price of \$1,000 USD an ounce, 1 kg of gold is worth \$32,150 USD. The modeled costs to grow, treat and process 10 tonnes of plant material are approximately \$16,000 USD. The balance available for artisanal training, salaries, subsidies and mercury disposal is greater than \$16,000. Gold is currently significantly above US\$1,000 an ounce, but to be conservative, this value is often used.

The target for mercury uptake is similar (concentration of 100 mg/kg), yielding again 1 kg of mercury per hectare. This would reduce the soil-mercury concentration by 0.5 mg/kg. The amount of gold in the soil will also reduce with each crop, as will the gross return per crop. However, all infrastructure is established during the first crop, thus costs will reduce significantly for subsequent harvests. The environmental risk of mercury in soil will be reduced with each harvest as mercury is removed, or contained within the treatment area. In this way, phytoextraction could sustainably manage the risk of mercury interacting with the ecosystem at ASGM locations.

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