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Review article

Phytoextraction: Where's the action?

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ABSTRACT

Many articles concerning phytoextraction of trace elements state that it is "an emerging technology that can be used for the low-cost clean-up of contaminated land…". Given the lack of commercial phytoextraction operations or even successful field trials, we sought to determine whether phytoextraction could ever compete with existing technologies to clean up soil within a realistic time-frame, say <25 years. We also investigate why phytoextraction has not found commercial use for the phytomining of valuable metals. Calculations reveal that bioaccumulation coefficients of >10 are required to reduce the total metal concentration in soil by 50% within 25 years, under conditions that are ideal for phytoextraction. Heterogeneity of both the target element, nutrients, and water in soil, as well as heterogeneity of plant roots has a large, but as-yet unquantified effect on remediation time. Variations in climatic conditions, including drought and flooding can also reduce metal extraction rates. Unlike phytoextraction for soil cleansing, phytomining could theoretically produce valuable crops of metal. However, phytomining suffers from a low efficiency of metal extracted per unit of land. Ironically, phytomining may have a larger ecological footprint than conventional mining. Currently, lack of infrastructure limits its implementation. While our review shows that phytoextraction for soil cleansing and phytomining is currently impractical, it is not our intention to discourage research in this area. The best rebuttal of our analyses would be full-scale field operations. However, investigations of new plants/soils/soil conditioner combinations should at least demonstrate how phytoextraction could work by providing convincing basic mass-balance calculations.

Contents

1. Introduction

Over thirty years have passed since pioneering work by Rufus Chaney indicated that plants might be gainfully employed to improve

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soils that are contaminated with one or more trace elements (TEs) (Chaney, 1983). Baker et al. (1994) described experiments showing that hyperaccumulator plants such as *Thlaspi caerulescens* (now *Noccaea caerulescens*) could extract significant amounts of Zn from a contaminated soil. Repeated cropping, it seemed, could potentially reduce the soil's Zn burden to acceptable levels. The biomass would be removed from the site and burned to reduce its volume. There was also a possibility of recovering metal from the ash. This idea lead to another related technology, phytomining (Nicks and Chambers, 1994), where the goal of the operation was to extract valuable amounts of TEs from low-grade ore bodies.

As of June 2014, over 6500 articles have appeared on Web of Science that deal with some aspect of phytoremediation. Of those, 535 use the word "phytoextraction" in the title and many others investigate metal uptake by plants with a view to their eventual use to clean up contaminated soil or to phytomine TEs for profit. Many of these articles include the mantra "…phytoremediation is an emerging technology that can be used for the low-cost clean-up of contaminated land…". Frequently, these articles investigate:

- The metal uptake by a new species/soil combination
- Genetic factors affecting metal uptake/gene manipulation and report that the shoot concentration of a target metal can be increased
- Soil amendments, such as chelators or biological inocula that can increase plant TE uptake.

While there are numerous examples of using plants to improve degraded environments, there has been a conspicuous absence of published clean-up operations, where plants have reduced the total TE concentration in soil to below threshold values (Dickinson et al., 2009). Nor has phytomining transformed low-grade ore bodies into verdant landscapes of metal farming. A potential explanation for this is that academic studies resulting in phytoextraction publications are necessarily limited by the funding cycle, which is usually <5 years. Longer-term studies, undertaken by industry, may not be published. However, it is unlikely that industry would not advertise a successful new technology.

The lack of success to date is not a reflection on the quality of the science contained in many of the aforementioned articles. On the contrary, there have been tremendous advances in the understanding the interactions of TE with plants and all manner of innovative experiments and ideas to increase plant TE-uptake. The conceptual framework it provided significantly advanced knowledge soil chemistry and plant biology. Nevertheless, the challenges of successful phytoextraction (Robinson et al., 2006; Van Nevel et al., 2007) have still not been met. Some workers in the area of soil remediation erroneously equate phytoremediation with phytoextraction and conclude that "it does not work", potentially tarnishing other "phyto" technologies, many of which have demonstrable successes (Conesa et al., 2012a).

If achievable, phytoextraction for soil cleansing would compete directly with other soil rehabilitation technologies, i.e. chemical or physical processes that either clean up the soil, bury, or remove the contaminating layers. Non-biological treatments are routinely used for the remediation of urban areas and small contaminated-sites that pose a disproportionate environmental or political risk. Existing soil remediation technologies are prohibitively expensive for low-value land.

We aim to determine whether phytoextraction could ever achieve "the low-cost clean-up of contaminated land…" by reducing the total TE concentration in soil to below threshold levels and investigate barriers that have prevented the implementation of phytomining. We seek to elucidate the most important factors that should be considered in studies that conclude that a particular plant or technique "has the potential to be used for the low-cost clean-up of contaminated land". Furthermore, it is our intention to show that the discoveries and scientific endeavours associated phytoextraction have applications in other phytotechnologies and beyond.

1.1. A reasonable time-frame

Successful phytoextraction can be guaranteed by removing the time constraint of the operation. As long as the rate of TE removal is greater than any TE inputs, the soil's contaminant burden will eventually be reduced to acceptable levels. Clearly, any costs of phytoextraction increase in proportion to the time taken, unless the biomass is used to produce profit (Robinson et al., 2003; Thewys et al., 2010a,b). This is not just the costs of planting and maintaining the site, but also the cost of taking land out of productive use. Biomass produced could be used for non-food products such as bioenergy (Licht and Isebrands, 2005), timber (Pulford et al., 1995), or even as animal fodder that is fortified in the target TE (Fassler et al., 2010b). In this latter case, care must be taken to ensure non-essential elements are not present at excessive concentrations (Fassler et al., 2010a). Such long-term operations are included in the umbrella term of "phytomanagement", where the phytoextraction of TEs for soil cleansing is relatively unimportant compared to the goal of producing a profit from contaminated land, while mitigating environmental risk (Robinson et al., 2009).

1.2. Shifting the goal posts

Phytoextraction would always succeed in hypothetical "soil polishing" (Dickinson et al., 2009). Here, phytoextraction would be deployed on a soil that has a TE concentration fractionally above a target value and reduce the average concentration of the soil to below guidelines. While soil polishing may satisfy environmental regulation and have the appeal of a green technology, it hardly constitutes the clean-up of a contaminated soil. Arguably, a soil amendment such as compost may dilute the TE below target values at a lower cost and with the added benefit of reducing TE solubility.

More promising is the use of phytoextraction to reduce the soluble, plant-available TE in soil, thereby reducing the environmental risk, a technique known as "bioavailable contaminant stripping" (Hamon and McLaughlin, 1999). Pot trials have revealed that the As hyperaccumulator plant *Pteris vittata* reduces the uptake of this non-essential element by rice plants (Ye et al., 2011). Similarly, Herzig et al. (2014) demonstrated that crops of sunflower and tobacco could reduce soluble Zn in a contaminated soil to below Swiss regulatory values. In these scenarios the rate of removal of soluble TE from the soil is greater than the immediate rate of recharge of the labile pool of TE from non-labile soil fractions. The length of time over which this reduction in soluble TE concentration is apparent should be considered, as should the bioaccessability of the contaminants to other organisms that may interact with the soil through dermal contact or direct ingestion.

1.3. Phytoextraction for soil cleansing – the challenge

The successful deployment of phytoextraction in competition with chemical or physical methods for cleansing TE-contaminated soil, requires that it be cheaper than the best alternative technology and crucially, cheaper or more viable than the cost of inaction (Robinson et al., 2003). Phytoextraction might also be deployed, successfully or not, as a result of legislation designed to promote "green" technologies. The cost of "conventional" clean-up technologies can be >US$ 1 M per hectare (Salt et al., 1995; USEPA, 2014b). For example, considering a site where the top 20 cm of soil is contaminated, i.e. in the rootzone of the plants that would be used for phytoextraction, there are some 2600 tonnes of soil (assuming a density of 1.3 t/m^3). The offsite disposal of this soil in a landfill costs US$100–200 per tonne (USEPA, 2014a), equating to US$520,000 excluding transport and costs of amendments to rehabilitate the subsoil. While the clean-up is rapid and all contaminants are removed, there are also environmental issues associated with the disposal of large volumes of soil. The question is whether phytoextraction can do better than this in a reasonable time-frame. To distinguish phytoextraction from phytomanagement, we define "reasonable" as one human generation of <25 years. Certainly the costs are likely to be lower (ca. US$100,000/ha) (Salt et al., 1995). However, cost does not include the opportunity cost of having the land out of use for 25 years. The opportunity cost is greatest for land in high-value areas, such as occurs in urban environments. For low value land, such as occurs in rural settings, the cost of phytoextraction may be greater than the land value. In such cases, only regulators can force land owners to remediate the land (Robinson et al., 2007) and the regulators need to be convinced that phytoextraction will provide a solution (Conesa et al., 2012b). Cundy et al. (2013) propounded the need for effective stakeholder engagement when implementing "gentle" plant-based remediation approaches.

1.4. Beyond the beguilingly simple

Phytoextraction research focuses on increasing the metal extracted per hectare, X (g/ha), by increasing either the crop biomass B (tonnes/ha) or the crop metal concentration P (g/tonne) (Eq. (1)). Of critical importance is the *bioaccumulation coefficient* (B_C), which relates P to the metal concentration in the soil, M (Eq. (2)).

$$X = BP \tag{1}$$

$$B_C = \frac{P}{M} \tag{2}$$

For example, if the 2600 tonnes/ha of soil were contaminated with a TE at an average concentration of 5 mg/kg, then there would be a total of 13 kg of TE per hectare. Reducing this concentration to below a threshold level of 2 mg/kg would require the removal of 7.8 kg in 25 years. Thus a crop where $B = 10$ tonnes/ha would need to have a TE concentration (P) of 31.2 mg/kg of TE in the shoots each year, which represents a bioaccumulation coefficient (plant/soil concentration quotient) of just over 6. This seems reasonable, as there are numerous reports of plants having bioaccumulation coefficients of this magnitude for elements such as Cd e.g. (Robinson et al., 2000). However, numerous authors, e.g. Mertens et al. (2005), have pointed out that TE uptake is a function of the soil TE concentration and therefore uptake decreases as the metal concentration in soil decreases. Therefore, the time to clean up the soil, t (years) requires a parameter that describes the changing concentration of the plant-available TE around the root, E (g/t), as described in Eq. (3) (Robinson et al., 2006).

$$t = \frac{M_i - M_f}{P(E)B(E)} \tag{3}$$

where M_i is the initial TE burden (g ha^{-1}) in the affected area, and M_f is the target TE soil burden (g ha^{-1}). Assuming that the biomass production B is unaffected by the soil metal concentration, and that the metal concentration in the plant P, is directly proportional to the total metal concentration in the soil, which is usually not the case (Robinson et al., 2009), then the initial plant concentration P required to clean up the aforementioned soil in 25 years would be 47 mg/kg, representing a bioaccumulation coefficient of just under 10. If the soluble (plant – available) TE concentration decrease more rapidly than the total concentration (as described by Langmuir or Freundlich isotherms), then the required bioaccumulation coefficient would increase beyond 15.

Such high bioaccumulation coefficients have been demonstrated in pot trials where a single cropping has been carried out on a plant growing in homogenized soil (Granel et al., 2002). However, as demonstrated by Bañuelos et al. (1998), TE concentrations in the field are often lower than in pot trials. This is because in the field situation, TEs are distributed heterogeneously over a wide range of scales, from the soil colloid to the entire site (French et al., 2006; Rees et al., 2012). Plants in the field may have a uniform distribution of roots within the target zone of contamination, or the root growth may be limited in contaminant hot spots. Rooting density is spatially affected by the distribution of water and nutrients in soil, which are themselves highly heterogeneous. Since TE uptake is greatest in zones of high root density, the plants themselves create heterogeneities of the TE in soil over successive crops. The plant-available TE, E, at a given point x (latitude, longitude) is thus described by Eq. (4) (Robinson et al., 2009).

$$E(x) = \int_0^z \int_0^t R(t',z) C(M(t',z)) dt' \; dz \tag{4}$$

where z is depth (m), R is the root fraction (dimensionless) that is in contact with the soluble TE, C (g t^{-1}), which is a function of M. Eq. (4) can only be solved numerically. Increasing the contaminant and root heterogeneity in Eq. (4) almost invariably increases extraction times because localized soil contaminant concentrations will be higher than the average for the site and hence require longer remediation times. In our example above, a site with an average soil TE concentration of 5 mg/kg may have localized areas where the concentration is 10 mg/kg. Cleansing this site in 25 years would now require a plant with a bioaccumulation coefficient >20. A small minority of plants with roots that forage contaminant hotspots, such as *Thlaspi caerulescens* (Whiting et al., 2000), would remove TEs at a greater rate than the vast majority of plants with root systems that are indifferent or avoid contaminant hotspots (Breckle and Kahle, 1992; Dickinson et al., 1991).

1.5. Setting the target

Eqs. (3) and (4) can be solved numerically to calculate minimum bioaccumulation coefficients (B_C) required for various degrees of soil cleansing in the scenario described above (Table 1). These values are likely to at least double in the field situation where contaminants and roots occur heterogeneously.

It must also be noted that the arbitrary conditions used to calculate the values shown in Table 1 represent an ideal case for phytoextraction: uniform and superficial contamination of a single contaminant. Many, if not most contaminated sites contain more than one contaminant. In such cases, successful phytoextraction requires that adequate bioaccumulation coefficients exist for all the contaminants present if the operation is not to exceed the reasonable timeframe of 25 years. The co-occurrence of organic contaminants, such as Polycyclic Aromatic Hydrocarbons (PAHs) can reduce both the growth and TE uptake of plants (Carlo-Rojas and Lee, 2009). While plants that accumulate high concentrations of some elements, such as Ni, Cd, Zn, As, Se and Tl are known, there are other elements for which there are no reliable reports

Table 1
Minimum bioaccumulation coefficients to reduce the Trace Element concentration in a soil by (% cleansing) in a 25-year period. Assumes a cleansing depth of 0.2 m, a soil density of 1.3 (g/cm^3) and a homogeneous distribution of the TE. Note that the required bioaccumulation coefficients will increase in proportion heterogeneity of the TE in soil and with increasing heterogeneity of the plants' root distribution.

	Biomass production		
% Cleansing	5 tonnes/ha	10 tonnes/ha	20 tonnes/ha
10	2.3	1.1	0.6
20	4.8	2.4	1.2
30	7.7	3.8	1.9
40	11.0	5.5	2.7
50	14.8	7.4	3.7
60	19.5	9.7	4.9
70	25.4	12.7	6.4
90	47.6	23.8	11.9

of natural accumulators. These include Cr, Pb, and Hg (van der Ent et al., 2013a).

Similarly, the depth of contamination here is within the root zones of most plants. If the contaminated zone is shallower, then much of the plant's roots will be present in uncontaminated soil (Turner and Dickinson, 1993) and therefore not phytoextract the contaminants. If the zone of contamination is deeper, then the lower rooting density of the plants at depth will result in deeper zones not being cleaned-up as quickly.

1.6. Hitting the target

There are several strategies to achieve the bioaccumulation coefficients shown in Table 1. These are described in detail in numerous reviews e.g. (Nowack et al., 2006; Robinson et al., 2009; Sheoran et al., 2011), which we will not repeat. Briefly, phytoextraction may employ hyperaccumulator plants (Brooks et al., 1977), which accumulate inordinate concentrations of one or more trace elements as part of their normal metabolism (Reeves, 2006). Hyperaccumulator plants have lower biomass productions than crop plants, which is unsurprising as there is a metabolic cost to hyperaccumulation. When not grown in their native environments, hyperaccumulators may be difficult to procure, exhibit reduced growth, and suffer from weed competition (Fig. 1).

An alternative strategy is developing/inducing standard crop plants to accumulate high TE concentrations by selective breeding, gene manipulation, soil conditioners such as biological inocula (Lebeau et al., 2008) or TE-mobilising agents such as chelants (Shahid et al., 2014). The addition of chelants such ethylenediaminetetraacetic acid (EDTA) or ethylenediamine-N,N'-disuccinic acid (EDDS) either fails to result in sufficient TE uptake, or resulted in groundwater contamination or both (Bolan et al., 2014). A large excess of chelant is required to solubilize the target metal due to the co-solubilisation of Ca and Fe. Soil solution chelate concentrations of at least several mM are required to induce appreciable shoot concentrations. Nowack et al. (2006) reported that at such soil solution concentrations, plants will remove only a small fraction of the solubilized metals. Leaching, exacerbated by preferential flow processes, is unavoidable unless the operation is conducted *ex situ* on an impermeable liner (Robinson et al., 2009).

Whatever strategy is used to procure plants with high bioaccumulation coefficients, target values, such as those reported in Table 1, should be used to determine whether any resulting operation would be successful. Where these targets cannot be met, conclusions need to state that phytoextraction using these plants would be limited to soil polishing, rather than soil cleansing in a reasonable 25-year timeframe. That said, the minimum bioaccumulations coefficients calculated using Eqs. (3) and (4) multiplied by the heterogeneity of the system indicates that phytoextraction for soil cleansing in a reasonable time-frame, are not likely to be achieved without a quantum leap in techniques to increase plant metal uptake (Table 2).

1.7. Changing the target: phytomining

Phytomining is the phytoextraction of economically valuable TEs from environments where the target metal concentration is too low for conventional mining, or, where the surface volume of mineralized soil is insufficient to justify the capital expenditure of the necessary processing, despite target metal concentrations in excess of minimum grades. Here, the goal is profit. Bioaccumulation coefficients are less important. There need not be any clean-up goal, although there may be secondary environmental goals. For example, in the case of Hg-contaminated artisanal and small-scale gold mining waste, Au phytomining may generate revenue that can pay for or subsidise the phytoremediation of an insidious environmental pollutant (Krisnayanti et al., 2012). For any given crop, the key value for phytomining, *PM (US$*/ha), is metal extracted per hectare multiplied by the value of the metal, *V* (US$), (Eq. (5)).

$$PM = BPV \tag{5}$$

As with Eq. (1), there is no time component in Eq. (5). This becomes important for successive crops, which are discussed later. Early studies (Nicks and Chambers, 1994, 1995) showed that the Ni hyperaccumulator *Streptanthus polygaloides* grown on ultramafic soils in California, could remove up to 100 kg ha^{-1} of Ni in their biomass. This was worth US$550 ha^{-1} at the prices at that time. Profit could also be gained from converting the biomass to energy (ca. $219/ha). These revenue streams were comparable to that obtained from a crop of wheat. Moreover, phytomining could be used to turn a profit on the vast swathes of Earth that are covered in ultramafic soil, upon which it is problematic to grow conventional crops. Subsequent studies (Chaney et al., 2007) have reported that using *Alyssum* species to phytomine Ni could give a return of US$ 16,000 ha^{-1}, a figure related to the high value of Ni at that time. Bani et al. (2015) showed that native populations of *Alyssum murale* in Albania, when fertilized, could phytoextract an economically-viable crop of Ni.

Other studies have shown the potential for phytomining precious metals such as Au (Anderson et al., 1999), In (Nguyen Thi Hoang et al., 2011) and Re (Bozhkov et al., 2012). Studies involving the uptake of precious metals usually require a lixivant to solubilize the metal and induce plant uptake. It is propounded that these operations could be conducted using the model of heap-leach mining techniques, in the form of a 'phyto-leach' pad (Hunt et al., 2014). The value of the proposed operation may not come directly from the precious metal, but the plant-metal matrix, which when processed, may have valuable properties as catalysts (Haverkamp et al., 2007). Hunt et al. (2014) propose that

Fig. 1. Difficulties cultivating the Ni-hyperaccumulator *Berkheya coddii* as shown by (A) C. Anderson observing the growth of 9-month-old *B. coddii* plants on ultramafic soil in New Zealand compared to (B) a verdent crop of *Berkheya coddii* growing in its native South Africa as part of a phytoextraction trial.

Table 2
Example biomass production and bioaccumulation coefficients of various soil/plant combinations.

Class of plant	Target element(s)	Biomass production (t/ha)	Typical soil conc. (mg/kg)	Typical plant conc. (mg/kg)	Typical B_C	Reference(s)
Ultramafic hyperaccumulators	Ni, Mn	2–23	1000–5000	1000–30,000	1–5	(Brooks, 1998; van der Ent et al., 2013b)
*Thlaspi caerulescens*and other calamine	Zn, Cd	2	Up to 1% in native range	Ca. 1%	1–15	(Robinson et al., 1998)
Pteris vittata and As-hyperaccumulating ferns	As	<2	Up to 3%	Up to 6030	<1–18.6	(Luu Thai et al., 2014)
Salix species	Zn, Cd	Up to 30	variable	Up to 100	1–15	(Robinson et al., 2000)
Induced hyperaccumulation in crop species	Pb	Up to 30	200–600	Up to 1.5%	Up to 25	(Blaylock et al., 1997)

plants containing platinum-group elements could be turned into high-value catalysts for specific industrial and chemical reactions.

Unlike phytoextraction for soil cleansing, which suffers from prohibitively long clean-up times, the reason why phytomining has not found widespread commercial application is not immediately apparent. Potential limiting factors are:

1.8. Agronomic limitations

Ultramafic soils, where Ni phytomining would occur, are usually nutrient poor and have poor soil structure (Chiarucci et al., 1998). While native ultramafic vegetation is adapted to such environments, the biomass production in its natural habitat is well below the requirements of phytomining (Robinson et al., 1997). Fertiliser and irrigation requirements for ultramafic soils are higher than other soils because of their low ability to retain water and nutrients. Using soil amendments such as compost to improve the water and nutrient holding capacities may lessen the plant-availability of the target metal and hence reduce profits. That said, Chaney et al. (2007) concluded that although phytomining crops require special fertilisation, this would not be prohibitively expensive. Irrigation may be critical. Whereas large crop-growing areas often have collective irrigation schemes, areas to be phytomined may be geographically distant and not have easy access to water. Similarly, disused mine sites or mine tailings where phytomining may occur generally have low fertility, and may have salinity and acidity issues.

Unlike conventional cropping, there are, as yet, no large-scale suppliers of seeds for hyperaccumulator plants that would be used in phytomining. Suppliers would doubtless appear if phytomining were to find widespread use. However, given the difficulties (Fig. 1) and ecological concerns of growing hyperaccumulator plants outside their normal range, phytomining would most likely employ local species, each of which would have distinct propagation and fertilization requirements.

Agronomic challenges also exist for phytomining operations that rely on the use of chelants to promote metal uptake in non-hyperaccumulator plants. Crops species are generally not suited to growth on edaphically challenging environments. Furthermore, efficiency in the use of the chelants to target specific elements is poorly optimised. Risk mitigation to ensure that phytomining of gold, for example, does not cause secondary environmental harm will be needed before this technology can be implemented in applied scenarios (Anderson et al., 2013).

1.9. Biomass and metal processing: economics of scale

Phytomining is the production of metal rich biomass that could provide revenue through conversion to energy and recovery of the metal from the plant ash (bio-ore) or through green chemistry, where plant-borne metals form part of valuable phytochemicals grown for harvest (Hunt et al., 2014). Li et al. (2003) and Zhang et al. (2014) demonstrated the feasibility of Ni recovery from the bio-ore of crops from the genera *Alyssum*, *Leptoplax* and *Bornmuellera*. These bio-ores from Ni hyperaccumulator plants contain Ni concentrations of 6 - 20% (Koppolu et al., 2004; Zhang et al., 2014), which is significantly higher than normal Ni-ores (ca. 3%). Bio-ores have low concentrations of Mn, Fe and Si oxides that are problematic in Ni recovery from conventional ores (Li et al., 2003). Bio-ore generated from *Berkheya coddii* can contain high Ca concentrations (34%), which may reduce the efficiency of Ni recovery from the bio-ore (Boominathan et al., 2004).

While energy production and metal recovery are theoretically feasible, in practice this could only happen if phytomining occurs in proximity to existing energy conversion facilities or to infrastructure that is actively processing metal (for example a Ni smelter). However, incineration destroys the original structure of metals in a plant (oxidation) and therefore negates many of the stated opportunities to use in vivo metal nanoparticles in catalysis.

In the event where phytomining is not conducted near to existing infrastructure, long-distance transport of the biomass would greatly reduce any profits. Alternatively, phytomining could be conducted over very large areas that justify the construction of purpose-build facilities. This would require significant capital outlay, and may not be feasible without government help. Scale-up of phytomining to field scenarios and models for the construction of the necessary infrastructure are lacking. The definition of viable and working engineering solutions to process metal-rich biomass is an area that is ready for development.

1.10. Clean-green phytomining?

The environmental impacts of conventional mining are well-documented (Conesa and Schulin, 2010). Intuitively, phytomining, which would produce green landscapes, would appear to have a lower environmental impact. However, from an environmental perspective, the comparison needs to be made on the relative effects of phytomining on ecosystem functioning and human health. While conventional mining leaves a visible scar on the landscape, it can extract a much greater mass of metal per unit area than phytomining. The theoretical maximum nickel harvest from phytomining of 0.4 t/ha per year (Chaney et al., 2007) can be obtained from just 15 tonnes of conventional ore in just a few hours (Robinson et al., 2009).

While the land used for phytomining is under vegetation, this is most likely to be a monoculture that is receiving high rates of fertiliser inputs, which due to the low water and nutrient holding capacity of ultramafic soils, may contaminate receiving waters with plant nutrients. Most low fertility of ultramafic soils are not currently under crop production and instead support native ecosystems with plants that are often locally endemic (Brooks, 1998; Erskine et al., 2012). Phytomining would require clearing of most of this vegetation and replacement with a hyperaccumulator species, which may itself be exotic.

If phytomining and its associated infrastructure were established on a large scale, there are only a limited number of profitable crops that a metalliferous soil can support before plant metal concentrations drop below profitability. After 3–18 phytomining crops (Robinson et al., 1999a), continuation of economically-viable phytomining would require the removal of the topsoil or alteration of its geochemical properties to release more plant-available Ni. Such actions would not only be expensive, but also result in environmental perturbation on a massive scale.

1.11. Potential role of phytomining

More promising is the combination of phytomining with mine rehabilitation, where the revenue generated from phytomining crops can offset the cost of remediation. Here, plants could be used to recover metals from tailings or waste rock that have metal concentrations too low for conventional processing. In such cases, the infrastructure to recover the metals may already be in place. The role of the hyperaccumulator plants would be to initially tolerate the adverse conditions on the tailings, thereby stabilizing the substrate and introducing organic matter that permits the subsequent establishment of native species. Associated with this scenario could be development opportunities in mining areas. Many large-scale mines are in rural areas of poor countries where agriculture is a primary livelihood. Where farmers are cultivating crop species on mineralized soils, yields are generally low as pointed out by Brooks and Robinson (1998) for Brazilian farmers growing Soy Bean on ultramafic soil. A phytomining operation could create opportunities to train rural communities in modern agricultural skills. Such skills would be essential to ensure that phytomining crop yields meet targets, and these same skills could be applied by farmers to the cultivation of suitable crop species on adjacent but non-mineralised land. Anglo Platinum's Ni phytomining work at the Rustenburg Base Metal Refinery in South Africa in the early part of this century exemplified this model well (Fig. 1). The company contracted local farmers to collect seeds of *Berkheya coddii* growing throughout the surrounding area. Farmers then raised seedlings of the hyperaccumulator and planted these onto contaminated land. The farmers tended the crop throughout the growth season, and collected seeds at the end of summer for subsequent planting. The biomass was then harvested by hand, tied in bundles and fed directly into the Ni smelter. Through this process the land was remediated, Ni from the biomass was incorporated into the bulk metal product, and farmers were employed and provided with training on how to better grow plants. This could, perhaps, be considered as the best-recorded example of the potential of phytomining to effect environmental, economic and social development.

1.12. Where to for phytoextraction?

It is clear that phytoextraction faces perhaps insurmountable challenges to ever find widespread application to decontaminate soil in <25 years. Nevertheless, research on mechanisms of plant TE-uptake as well as techniques to engineer increases in plant uptake has the potential for widespread applications in various related technologies that will benefit humanity.

Zhao and McGrath (2009) pointed out the synergisms between phytoextraction for the remediation of contaminated soil and enhancing the concentration of essential TEs in food crops. Knowledge from phytoextraction studies may provide effective tools for biofortification, which seeks to increase the concentration of this essential micronutrient in crop plants, pre-harvest, by agronomic means or genetic modification (Cakmak, 2008). Zinc deficiency affects between a quarter and a third of humanity, with deficiency rates ranging from 4 to 73% (Hotz and Brown, 2004) in various countries. Some 10% of the population in the United States consume less than half the recommended dietary allowance for Zn (Ho, 2004).

Similarly, phytoextraction technology may be used to improve livestock nutrition. Pasture often has lower TEs concentrations compared to trees and shrubs (Robinson et al., 2005). Cobalt accumulators in the genus *Nyssa* could provide stock with an adequate source of this essential micronutrient when grown on deficient soils (Robinson et al., 1999b). Similarly, willow clones that have been investigated in relation to Zn phytoextraction have been shown to cause a significant increase in the Zn concentration in the blood of grazing animals (Anderson et al., 2012).

2. Conclusions

Our analyses show that phytoextraction for the clean-up of TE-contaminated soils is not “an emerging technology that can be used for the low-cost clean-up of contaminated land” and that phytomining is inefficient and likely to have a lager ecological footprint than conventional mining. However, it is not our intention to discourage research in this area. The best rebuttal to this analysis would be publication of TE mass balances in full-scale field operations. That said, scientific articles investigating new plants/soils/soil conditioner combinations should at least demonstrate how phytoextraction could work by providing basic mass balance calculations. Continuing to tout phytoextraction as a low-cost alternative for soil clean-up when, clearly it is not, tarnishes all “phyto” technologies. To a large extent, this has already happened. The broadest term, ‘phytomanagement’, encompasses a range of land management activities, many of which only affect the plants indirectly. The challenge before the phyto community is to find a new ‘non-phyto’ term that describes the betterment of the stressed environments through biological manipulation, perhaps shifting the focus from clean-up to palliative care.

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