



Phytoextraction: an assessment of biogeochemical and economic viability

Brett Robinson^{1,2,3}, José-Enrique Fernández², Paula Madejón², Teodoro Marañón², José M. Murillo², Steve Green¹ & Brent Clothier¹

¹HortResearch, Private Bag 11 030, Palmerston North, New Zealand. ²IRNAS. Avenida de Reina Mercedes 10, Apartado 1052, 41080 Sevilla, Spain. ³Corresponding author*

Received 8 November 2001. Accepted in revised form 12 July 2002

Key words: decision support system, model, economic, phytoextraction, phytomining, phytoremediation

Abstract

Phytoextraction describes the use of plants to remove metals and other contaminants from soils. This low-cost technology has potential for the *in situ* remediation of large areas of contaminated land. Despite more than 10 years of intensive research on the subject, very few commercial phytoextraction operations have been realised. Here, we investigate the viability of phytoextraction as an effective land-treatment technology. A Decision Support System (DSS) was developed to predict the effect of phytoextraction on soil metal concentration and distribution, as well as the economic feasibility of the process in comparison to either inaction or the best alternative technology. Changes in soil metal concentration are mechanistically predicted on the basis of plant water use, metal concentration in soil solution, soil density, plant root distribution and our so-called root-absorption factor. The root-absorption factor is a 'lumped parameter' describing the xylem/soil solution metal concentration quotient. Phytoextraction is considered to be a viable option if it can satisfy environmental regulations and simultaneously be shown to be the most cost-effective technology, either alone, or in combination with other remediation technologies. To date, commercial phytoextraction has been constrained by the expectation that site remediation should be achieved in a time comparable to other clean-up technologies. However, if phytoextraction could be combined with a profit making operation such as forestry, then this time constraint, which has often been considered to be the Achilles heel of phytoextraction, may be less important.

Introduction

Ever since pioneering studies on plants that hyperaccumulate heavy-metals (Brooks et al., 1977; Jaffré et al., 1976), their potential use for the extraction of heavy-metals from soils has been investigated. Studies by McGrath et al. (1993) and Baker et al. (1994) demonstrated that the hyperaccumulator *Thlaspi caerulescens* had potential use for the *in situ* remediation of zinc-contaminated soils. Since these initial reports, a whole suite of articles have appeared proposing the use of plants to remove heavy-metal contamination from soils. The technology, termed *phytoextraction*, involves the repeated cropping of plants on heavy-

metal contaminated soils until the soils' metal concentrations have reached acceptable levels. After each cropping, the plant biomass is removed from the area and may be burned to reduce its volume whereupon it can be stored in an appropriate area that does not pose a risk to the environment.

Nicks and Chambers (1994) reported a second potential use for hyperaccumulator plants: for economic gain in the mining industry. This operation, termed *phytomining* includes the generation of revenue by extracting saleable heavy-metals from otherwise sub-economic ore bodies.

Phytoextraction has several advantages over other remediation and metal extraction technologies. First, and foremost, is the low cost of the operation. Competing technologies such as soil removal, capping and *ex-situ* cleansing can cost around \$US 1 million per

* FAX No: +64(6)-3546731.

E-mail: brobinson@hortresearch.co.nz

hectare, as compared to an estimated US\$ 60 000 to 100 000 per hectare for phytoextraction (Salt et al., 1995a). Other benefits of phytoextraction include the ultimate fertility of the cleansed site and the high public appeal of 'green' technology.

Basic plant physiology, nonetheless, limits the scope of phytoextraction. Only surface contamination can be removed, and the clean-up is restricted to areas that are amenable to plant growth. Most importantly, it may take a long time for site remediation to be effective.

The mass of metal that can be removed by a single crop of plants sets a limit on the speed of any phytoextraction operation. Hyperaccumulator plants can achieve a high metal concentration in their biomass, yet their biomass production is usually inferior to non-hyperaccumulator plants. For some common metals, such as lead (Pb), there are no reliable reports of any hyperaccumulator species. A possible solution to these problems is the use of *induced hyperaccumulation*. Non-hyperaccumulator plants can be made to take up metals such as lead, or even gold, by the addition of solubilising agents to the substrate (Anderson et al., 1998). Such additions increase the mobility of the metal in the soil, allowing it to be taken up more easily by the plant. At the same time, however, there is the possibility that some of the metals might leach down the soil profile, possibly entering groundwater. Physical soil processes such as preferential flow may exacerbate metal leaching (Bundt et al., 2000), and these soil amendments may also persist in the environment creating additional and unforeseen problems. Environmental concerns may limit the use of induced hyperaccumulation to hydraulically isolated treatment sites where the connection to receiving waters has been 'broken'.

More promising work is being conducted where high biomass plants are being genetically altered to extract larger amounts of metal from soils (Rugh et al., 1998), or where the potential biomass of smaller varieties of hyperaccumulator plants is being improved (Ow et al., 1998).

To date, there are very few field demonstrations of the potential success of phytoextraction. Blaylock (2000) showed an impressive decrease in soil lead concentration over two years at two sites in the United States using a combination of *Brassica juncea* and EDTA to induce accumulation. Unfortunately, the mass balance of lead was not shown for that operation. It is therefore uncertain just how much lead the plants removed, and how much leached through

the soil profile. It is well known that chelators such as EDTA can act as chemical ploughs, redistributing surface contamination down the soil profile thereby causing an observed reduction in concentration near the soil surface, but having little effect on the total amount of contaminant in the soil profile.

The aim of this study was to create a Decision Support System (DSS) that would use simple theory to quantify both biogeochemical and economic factors and which could be used to assess the viability of phytoextraction as a land treatment option under a range of soil contamination scenarios.

A simple model for phytoextraction biogeochemistry

Metal accumulation as a function of transpiration and bioavailable metal

Fundamental to the success of phytoextraction technology is the ability of plants to accumulate metal in the above-ground portions of their biomass. Phytoextraction relies on plants working as solar-driven 'biopumps'. The soil solution is drawn from the root zone through the plants' roots and stems to the leaves, where it is lost via transpiration. Any metal taken up in the soil solution that enters the roots will accumulate in either the roots or the shoots of the plant. High metal concentrations in the roots can result from plant water uptake inducing metal migration, via mass flow, to the root surface where they are precipitated (Zhao et al., 2000). Not surprisingly, in the above-ground portions, the highest concentrations are often found in the leaves as they are the major water sink. It is well documented that metal translocation from the roots to the shoots is driven by plant water uptake (Hinchman et al., 1996; Salt et al., 1995b). For the purpose of modelling, we consider the amount of metal (M) removed by the plant is therefore proportional to the transpiration rate (T) over a given period of time (t).

$$M \propto \int_0^t T dt \quad (1)$$

Any water that is taken up by the plants' roots must first pass through the surrounding soil. During this time, only some fraction of the metal present in the bulk soil will be in solution (Echevarria et al., 1998; Gérard et al., 2000). The remainder is likely to be bound to mineral particles and the organic matter in the soil. So bound it is therefore unavailable for

uptake. Hence, the total amount of metal that accumulates in the plant is related to the metal concentration that is in the soil solution (Robinson et al., 1997a,b, 1998, 2000), rather than the total metal concentration in the bulk soil. Thus, we consider M to be proportional to the metal concentration in soil solution (C).

$$M \propto [C] \quad (2)$$

Root absorption factor

The total amount of metal that accumulates in the plant does not usually equal the accumulated product of the soil-solution concentration times the volume of water transpired by the plant. For a metal to be translocated to the aerial parts of a plant, it has to enter the root, either via the symplastic or apoplastic (Marschner, 1995) pathways where some active or passive filtering may occur.

Here, we define the root absorption factor (ϕ) as a dimensionless lumped parameter that represents the root xylem/soil solution metal concentration quotient.

$$\phi = \frac{[C]_r}{[C]}, \quad (3)$$

where $[C]_r$ is the soluble metal concentration (mg L^{-1}) in the root xylem and $[C]$ is the soluble metal concentration (mg L^{-1}) in the soil solution.

The parameter ϕ is a simple lumped parameter intended to remove the need to measure the plethora of complex, and often poorly understood, biogeochemical factors that influence the passage of metals from the soil into the roots. Rhizobiological activity, root exudates, temperature, moisture, pH and the concentration of competing ions will affect ϕ . The issue is further complicated by the fact that ϕ could change depending on the metal concentration in the soil solution. This would be particularly pronounced for essential elements such as iron, copper, zinc and manganese.

Root absorption factor and plant responses to heavy metals

Baker (1981) divided plants species into three groups according to their above-ground metal concentrations in relation to the metal concentration in the soil. These three groups are delineated in our model using ϕ . For non-essential elements such as cadmium, nickel and arsenic, plants having a very low ϕ (active exclusion)

are termed as being 'excluders'. Most plants that occur naturally on metalliferous soils are recognised as being excluders.

Plants that have a relatively constant ϕ over a wide range of metal concentrations in soil solution are known as 'indicators'. In this case, the concentration in the plant has a near linear relationship to the metal concentration in soil solution. Plants that do not occur naturally on metalliferous soils usually behave as 'indicators' when grown in the presence of the non-essential elements.

The third category of plants are those who tolerate very high concentrations of metal in their aerial parts or have an active uptake mechanism for the non-essential metal (high ϕ). These plants are known as 'hyperaccumulators'.

For both excluders and hyperaccumulators, ϕ is constant over just a narrow concentration range. There can be a sudden increase in plant metal concentration at high soil-solution concentrations. At this point, the metal uptake control mechanisms break down, and metal 'floods' into the plant in the transpiration stream. The actual phenomenon may be an overload of the regulatory mechanism, or a break down of the plasma membrane at the apoplast/symplast interface. When this phenomenon occurs, the plants show toxicity symptoms and biomass production is reduced.

This change in ϕ over a concentration range can be modelled by adding a decay constant K

$$\phi(C) = \frac{\phi_1 C_1}{C_1 + K(C - C_1)}, \quad (4)$$

where $\phi(C)$ equals root adsorption factor at soil solution concentration C (mg L^{-1}), ϕ_1 equals the measured root adsorption factor at concentration C_1 (mg L^{-1}), and K ($0 \leq K < 1$) is the decay constant.

Estimating the root absorption factor

The plant specific ϕ can be approximated using the plant's total water use, above-ground dry biomass, and the metal concentration in soil solution. We assume the following relationship holds:

$$\phi \cong \frac{MB}{TC} \quad (5)$$

ϕ equals the Root Absorption Factor for the metal (dimensionless) M equals the metal concentration in the above-ground dry biomass (mg kg^{-1}), B equals above-ground dry biomass (kg), T equals the total water use (L) and C equals the concentration of metal in soil solution (mg L^{-1}).

Metal uptake from a metalliferous soil

The distribution of metals in a contaminated soil is never uniform, and in most agricultural soils the highest concentrations are usually found near the soil surface. Urban and industrial soils are usually more heterogeneous with high metal concentrations 'hot spots' occurring at depth. For simplicity, our DSS considers the soil to be divided into three zones:

1. a 'contaminated' zone where the surface soil has the maximum metal concentration.
2. an 'intermediate' zone where there is a mixing of contaminated and uncontaminated soils.
3. an 'uncontaminated' zone where the soil is unaffected by contamination and assumed to have 'background' levels for the metals.

Phytoextraction induced change in soil metal concentration over time

The local concentration of metal in soil solution and hence the potential amount of metal entering the plant roots, will be depth-dependent. The plant-root density also varies with depth. Most of the plant roots are near the surface and root density decreases with increasing depth. We assume potential metal uptake depends on root density.

Plant metal-uptake causes a change in soil metal concentration (mg kg^{-1}) at depth d , and this change is calculated as:

$$\Delta[M]_z = \frac{1}{\rho_z} \int_0^\tau R_z T C \phi dt, \quad (6)$$

where: $\Delta[M]_z$ =change in contaminant metal concentration (mg kg^{-1}) at depth z , ρ_z =bulk density of the soil (g cm^{-2}) at depth z , t =time (days), R_z =root density fraction (root mass at depth z)/(total root mass), T =water use (L day^{-1}), C =concentration of metal in soil solution (mg L^{-1}), ϕ =root absorption factor for the metal. The metal concentration in soil solution (C) needs to be measured using a consistent physical or chemical techniques such as those described in Ernst (1996). It is imperative that a consistent technique be used, as differing methods will give different values of (C) and therefore ϕ will need to be recalculated (5).

It is clear from the above equation that the phytoextraction process can be enhanced by increasing the concentration of metal in the soil solution (C). This may be done by using soil amendments such as chelates.

Alternatively, ϕ or the transpiration rate can be enhanced by selective breeding, or by gene manipulation.

Change in metal bioavailability after successive croppings

Over time, as more metal is removed from the soil by successive croppings, the soluble metal concentration will decrease. In some situations, the change may be approximately linear, however in most cases there could be a logarithmic decay upon successive annual croppings (Robinson et al., 1999).

Return of metals to the soil via leaf-fall

If phytoextraction is utilising trees with a cropping rotation of greater than 1 year, then it can be assumed that the leaves are being recycled back onto the ground and their associated metal is being reincorporated into the bulk soil at the surface. The effect of plant biomass re-entering the soil can concentrate even more metal in the upper soil profile. The low mobility of heavy-metals in the soil means that as successive generations of leaves are dropped, there can be an accumulation of metals near the surface. This might then be readily removed simply by Surface Scraping. It could, however, also provide a new exposure pathway for the metals (Perronnet et al., 2000).

Limitations of the model

The model (6) is analytically simple, yet has a rationally convenient description of the whole plant-metal uptake processes. Environmental conditions that may prohibit plant-growth, such as drought, are not considered. Root absorption factors for metal-uptake by a given species could well be different when the plant is grown in different soils. This is because at a single solution concentration, the ease with which a metal enters the plant's symplast will be affected by the cocktail of ions that are present in soil solution, as well as other factors such as soil pH, moisture and temperature. The model can be modified, on the basis of more information, to include a more mechanistic approach of root uptake. Such complexity, however, could decrease usability.

Upon entering the root, the model assumes that all the metal will be translocated to the above-ground portions of the plant. Analysis of the root material invariably shows that this assumption is not correct due to the presence of the metal in the root tissue.

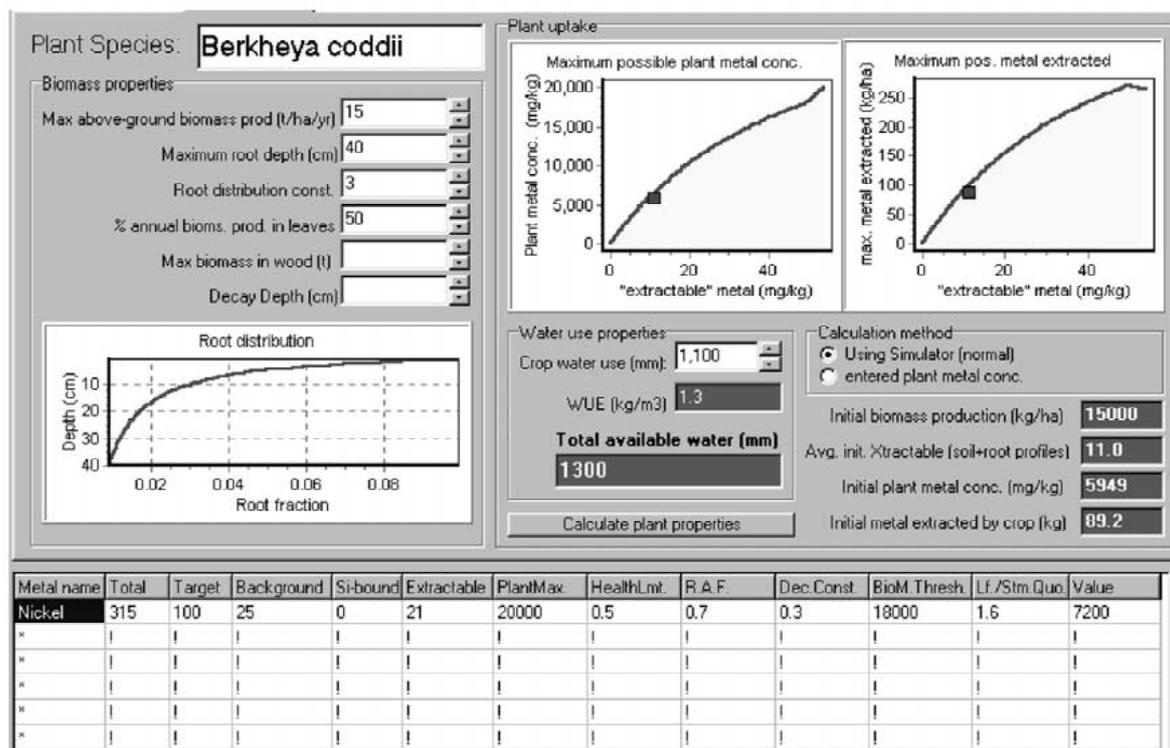


Figure 1. A screen printout of the phytoremediation DSS showing plant uptake parameters for *Berkheya coddii* growing on a nickel contaminated soil. 'Extractable' metal indicates the soluble nickel (mg kg^{-1}) in a 1 M ammonium acetate extractant. PlantMax. indicates the maximum possible nickel (mg kg^{-1} dry mass) concentration in living plant tissue, BioM. Thresh. is the maximum nickel concentration in plant tissue before growth is adversely affected. R.A.F. is Root Adsorption Factor, Dec. Const. is decay constant. HealthLmt., Lf./Stm.Quo., Value, % annual bioms. Prod. in leaves, Max biomass in wood and Decay Depth are not used in this simulation. The green squares on the graphs indicate the initial values for the crop.

Stephan and Scholz (1993) demonstrated that metals in the aerial plant parts could be further translocated within in the phloem. Any relocation of metals back to the below-ground portions via the phloem will result in an over estimation of the amount of metal that is extracted.

The depth-wise distribution of fine roots does not always equate with total root uptake, even for water. Roots tend to be more active when the surrounding soil is moist (Clothier and Green, 1997). The model, for simplicity and utility, considers a uniform moisture distribution in the soil. Given these shortcomings, the model may indicate a slightly shorter time for remediation than actually occurs in the field. Caution must therefore be applied, especially in a commercial sense, to not mislead clients on the necessary time for remediation.

Predicting the effect of phytoextraction on future soil metal concentration

The DSS is used here to assess the phytoextraction of nickel from a contaminated soil with a total concentration of 315 mg kg^{-1} , and the time needed to reduce the concentration down to a limit of 100 mg kg^{-1} using the nickel hyperaccumulator *Berkheya coddii*. The depth of contaminated soil was taken at 315 mg kg^{-1} for 0.05 m linearly decreasing down to 25 mg kg^{-1} at 0.2 m. The plant-uptake parameters are shown in Figure 1. In this example, the total, and extractable metal concentrations were determined experimentally, and the other parameters taken from the literature (Robinson et al., 1997b). Figure 2 shows the soil concentration profile after 10 years of phytoremediation, the minimum time needed to reduce the maximum soil concentration to 100 mg kg^{-1} . The concentration profile shown in Figure 2 predicts that the amount of

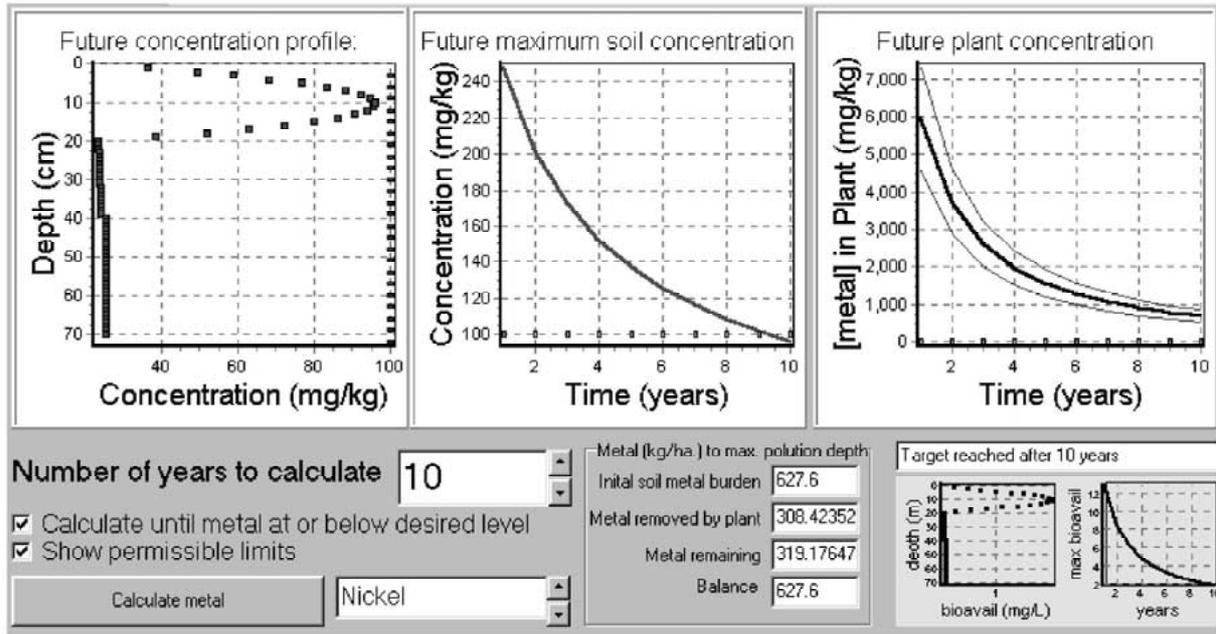


Figure 2. Outputs from the phytoremediation DSS showing (from left to right), (1) the predicted soil concentration profile after 10 years of phytoextraction, (2) the predicted maximum soil concentration over time, and (3) the predicted plant concentration over time. The three lines on (3) represent from top to bottom, leaves, whole plant, and stems respectively.

soil with around 100 mg kg^{-1} nickel is very small. This result indicates that ploughing the soil would further reduce the maximum nickel concentration by way of dilution. The time needed for remediation could thus be greatly reduced by ploughing, or alternatively a change in regulation that considers the amount of nickel in the concentration profile rather than its maximum concentration. Figure 2 also shows that the plant nickel concentration rapidly decreases after successive croppings. Such an operation could be sped up by adding soil amendments, such as sulphur, to increase plant-metal uptake (Robinson et al., 1999).

The DSS tool offers the potential to estimate the minimum time needed for the effective phytoextraction of any metal using a range of plants. However, this information alone cannot be used to assess the viability of phytoextraction as a land treatment option. How long is too long? We need to factor in the economic viability.

Economic viability: when should phytoextraction be used?

If phytoextraction is ever going to be commercially implemented, it must meet two basic criteria. Firstly

it must satisfy environmental legislation. The plants must be able to grow to minimise the risk of contaminant movement offsite from the affected zone. Secondly, phytoextraction will only be used if it is an economically attractive option for the organisation responsible for the land's remediation or the land's owner.

To determine the economic viability of phytoextraction it must be compared to the best alternative technology and the economic cost of inaction. Phytoextraction will be implemented only if it is the most financially attractive long-term option. The cost of phytoextraction V (US\$) can be determined by:

$$V = A \times \int_0^t (C1 + C2 - P1 \times V1 - P2 \times V2) dt + \sum_{x=1,2,3\dots t} \int_0^x (C1 + C2 - P1 \times V1 - P2 \times V2) dt \times \frac{I}{100}, \quad (7)$$

where A =total area (ha) $C1$ =cost of planting (US\$/ha), $C2$ =cost of production (US\$/ha), $P1$ is the production of saleable biomass (t/ha), $V1$ is the value of the biomass (US\$/t), $P2$ is the production of bio-ore

(t/ha) and V_2 is the value of the bio-ore (US\$/t) and I =interest rate (%).

The cost of phytoextraction can be compared with the cost of the best alternative technology over the same period of time. If the alternative technology results in the land being remediated in a shorter period of time, then the cost of this technology (V_a) will be offset by the now-enhanced earnings off the land.

$$V_a = A \times \left(C \left(1 + \frac{1}{100} \right)^{t_1} - L \left(1 + \frac{1}{100} \right)^{(t_2 - t_1)} \right), \quad (8)$$

where A =total area (ha), t_1 =time needed for conventional technology to remediate land (yr), t_2 =time taken for phytoextraction to remediate land (yr), C =cost of alternative technology (US\$/ha), I =interest rate (%) and L =earnings off the land (US\$).

The cost of these two technologies must also to be compared with the cost of doing nothing. The cost of inaction is largely due to legislation, however, loss of income off the land, reputation/goodwill, and any future costs will also play a role. The value of reputation/goodwill can be difficult to quantify as it is highly dependent on the stakeholder. Reputation/goodwill may include anything from the political cost of inaction through to loss of earnings due to the refusal of other countries to import produce. Future costs may also be significant if the contaminant is mobile and has the potential to eventually affect groundwater, or other land areas. The cost of inaction (V_i) compared to phytoextraction may be determined by:

$$V_i = (LG + RP + LE + FC) \left(1 + \frac{1}{100} \right)^{-1}, \quad (9)$$

where LG =cost of legislation (US\$), RP =the cost of loss of reputation/goodwill (US\$), LE =loss of earnings off the land (US\$/yr), FC =future costs (US\$), I =interest rate (%) and t =the time taken for phytoextraction.

The unimportance of time in the economic viability of phytoextraction

The importance of the time needed for effective remediation, long hailed as the Achilles heel of phytoextraction, may not decrease its attractiveness as a land treatment option, especially if the cost of the operation is sufficiently low, or phytoextraction is combined

with a profit making operation. The productivity from land remediated using conventional techniques often falls well below any interest accrued on the capital outlay of the operation. If the cost of phytoextraction falls within this margin of the interest, or even turns a profit, then the time needed for the operation becomes less important.

Here, we use the DSS to assess the viability of using forestry for the remediation of lands contaminated by the 1998 Aznalcóllar mine tailings-dam disaster in Southern Spain (for an overview of the environmental impact caused, see papers in Grimalt and Macpherson, 1999). Tree species that could be used for silviculture such as *Pinus pinaster* and *Populus alba* are able to thrive on the contaminated soils (Consejería de Medio Ambiente, 1999). Our calculations using our DSS indicate that the time needed to phytoextract the heavy-metal contamination down to acceptable levels using forestry in 30-year rotations, is in the order of hundreds of years. The best alternative technology, the physical removal and storage of the contaminated soil, would take around 2 years. The cost of the soil removal (top 0.3 m) is estimated at US\$ 500 million for the approximately 4300 hectares affected (Consejería de Medio Ambiente, 1999). This equates to \$US 116 000 per hectare. The cost of inaction is estimated at around US\$ 10 000 per hectare, largely due to a damaged reputation as a food producer and the potential loss of tourism from the nearby Doñana World Heritage Park. Phytoextraction using forestry for wood production would produce a small profit, currently estimated at \$US 2000 per hectare, every 30 years. The elevated heavy-metal concentration contained within the wood is unimportant for human health. Wood is often tannilised with high concentrations of heavy-metals to prevent rotting. Figure 3 shows the estimated cost of the three operations over the next 60-years. The calculations used an interest rate of 4% p.a. Clearly phytoextraction using forestry is predicted to be a financially attractive option. It should be noted that the accuracy of these predictions will be affected by variables such as fluctuating interest rates and land value.

Conclusions

At present, commercial applications of phytoextraction are being hindered by the legal acceptance of this technology as an effective land treatment option. This is due to the perception that it may require an excess-

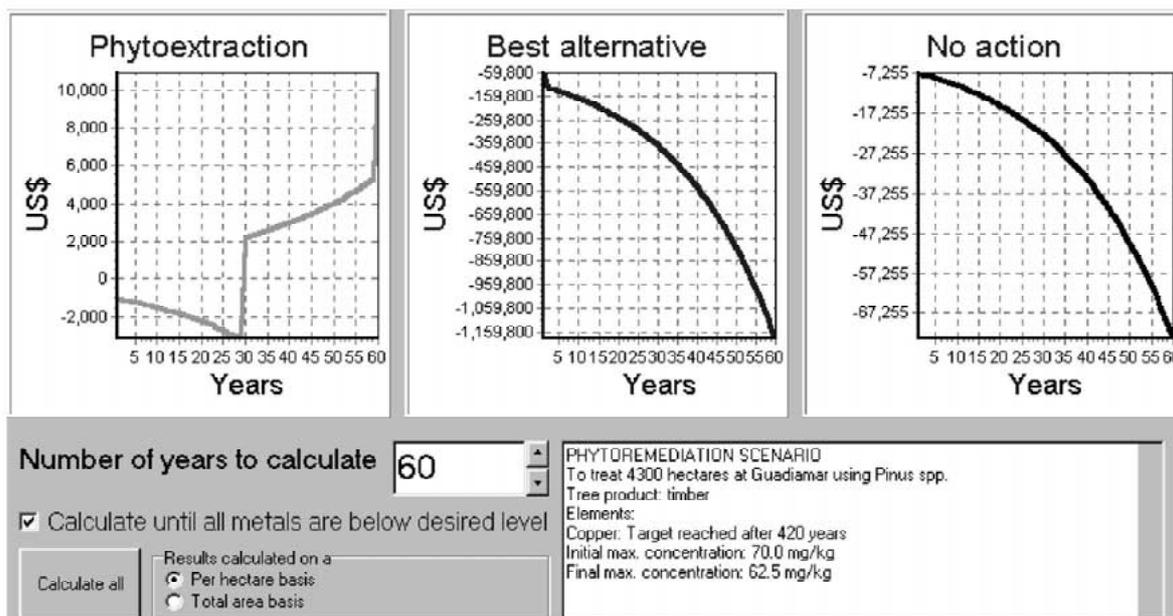


Figure 3. Predicted costs in US\$ per hectare, of phytoextraction, soil removal (the best alternative) and no action over 60 years for cleanup of soils contaminated following the mine tailings collapse at Aznalcóllar, Southern Spain.

ive amount of time for phytoextraction to be effective. This legal constraint may be circumvented if it can be demonstrated that the risk to the environment is minimal during the phytoextraction operation because of the stabilising action of plants on soil. The use of chelators significantly increases the risk of contaminant leaching and will do little to enhance the ability of phytoextraction to meet the demands of current environmental legislation.

The route to market for phytoextraction may be shortened if this technology is combined with a profit making operation that is unaffected by any elevated plant-metal loadings. Such operations may include forestry and bio-energy production. Bio-energy is taking on increasing importance due to the increasing global concern on carbon dioxide emissions and could be a profitable way to use contaminated lands.

A full validation of the DSS tool will be considered, and the tool will be further improved. Future work that is critical will involve developing easy methods for the quantification of variables affecting the root absorption factor.

Acknowledgements

The senior author gratefully acknowledges the receipt of an OECD fellowship for the duration of this

work. P.M., T.M. and J.M.M. were supported by the PICOVER program from the Consejería de Medio Ambiente, Sevilla, Spain.

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