An evaluation of *Berkheya coddii* Roessler and *Alyssum bertolonii* Desv. for phytoremediation and phytomining of nickel

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This review is based on field and pot trials carried out on the Ni-hyperaccumulator plants *Alyssum bertolonii* (from Italy) and *Berkheya coddii* (from South Africa), and assesses their potential use for phytoremediation (removal of pollutants from soils) and phytomining, growing a 'crop' of nickel. Fertilization of wild plants of *A. bertolonii* in Italy increased the biomass by a factor of three, to give a yield of 9 t ha^{-1} without consequent reduction of the nickel concentration of 7000 mg kg^{-1} dry mass. This species can thus be used for phytoremediation of soils lightly polluted with nickel. Analogous experiments with *B. coddii* gave a fertilized dry biomass of 22 t ha^{-1} with 5000 mg kg^{-1} nickel in dry biomass. This species would need only half the number of crops required for *A. bertolonii* to remediate weakly polluted soils. A single crop of *B. coddii* could remove about 110 kg ha^{-1} of nickel (worth US$579 in November 2001) compared with 63 kg ha^{-1} by *A. bertolonii*, worth $331. Assuming that only half of the value of the nickel was returned to the grower, the phytomining operation could be potentially economic for *B. coddii* but not for *A. bertolonii*. Sale of the energy derived from combustion of the biomass could improve the economics, but only in the case of a large-scale operation. It is proposed that the economics of phytomining could be improved by selective breeding of plants with greater biomasss and higher metal concentrations as well as by transferring the hyperaccumulating gene to plants of large natural biomass.

Introduction

Plants that accumulate inordinately high concentrations of elements such as nickel are known as hyperaccumulators, defined as containing >1000 mg kg^{-1} (ppm) in dry matter.[1] Since 1977, about 300 nickel hyperaccumulators have been discovered as well as 26 of cobalt, 24 of copper, 19 of selenium, 16 of zinc, 11 of manganese and one each of thallium and cadmium.[2] The disproportionate number of nickel hyperaccumulators is possibly due to the large amount of effort expended on 'serpentine plants' from ultramafic areas. Nine hyperaccumulators (Table 1) have been reported from southern Africa, all confined to the Great Dyke in Zimbabwe and the Barberton/Kaapsehoop region of the Barberton Ultramafic Sequence in South Africa.[1,2]

Removal of elements from soils has been termed *phytoextraction*[3] and may be subdivided into the two associated fields, *phytoremediation* and *phytomining*, each of which will be considered separately below.

Phytoremediation

The origins of the concept of phytoremediation are difficult to establish. Professor K.W. Brown of Texas A & M University, who requested seed of a cobalt hyperaccumulator [*Haumaniastrum katangense* (S. Moore) Duvign. & Plancke] with the object of removing ^{60}Co from radioactively contaminated terrain, is one of the pioneers. The first written reports were by Chaney[4] and Baker and Brooks,[5] who proposed that it should be possible to grow a crop of a hyperaccumulator plant over contaminated soil and remove the contaminant by harvesting the biomass. The first field trials were carried out at Woburn in Britain.[6,7] Research has developed at various centres throughout the world and some reviews now exist.[2,3,8]

The potential of the Italian shrub *A. bertolonii* Desv. (Brassicaceae) for phytoremediation and phytomining was assessed using wild plants near Murlo, in Tuscany,[9] at an altitude of 350 m and about 30 km south of the city of Siena. The soils of Murlo are lherzolitic serpentinites emplaced in gabbro and basalt with pH 6.6–7.4. Mean annual rainfall is 893 mm (37 mm in July to 129 mm in November); mean temperature varies from a minimum of 4.3°C (Jan) to a maximum of 21.7°C (July).

Natural levels of nickel in the wild plants averaged 7000 mg kg^{-1} (0.7%) in dry matter with a maximum of 1.65%. After addition of fertilizers (NKP), the annual biomass increase was *c.* 300% as opposed to only 22% for the unfertilized plants. The nickel concentration in the plant material remained at *c.* 0.7%, so there is clearly advantage to fertilizing the crop. The biomass yield after fertilizing was about 9 t ha^{-1}. Trials in New Zealand yielded a fertilized biomass of 13.0 t ha^{-1} compared with 3.4 t ha^{-1} for unfertilized plants.

From our field trials at Murlo, we envisage that a pilot project might involve the following programme: (1) select a suitable site where the topography permits ploughing, fertilizing of the serpentine soil and harvesting of the crop; (2) seed the site directly or plant out seedlings at a rate of approximately 16 plants per m^2 (160 000 per ha); (3) after a period of 12 months, harvest all vegetation above 10 cm from the ground; (4) incinerate the crop and collect the bio-ore, which could be buried for disposal or sold if of sufficient quantity.

There would be no problem in producing the seedlings, as *A. bertolonii* grows very quickly and produces a large quantity of viable seed that germinates in a few days. There should be no harvesting during the first season, to allow the plants to grow large enough in the second season for sustainable cropping.

If the amount of bio-ore produced is too small to be valuable commercially, some of the costs of phytoremediation could be recouped by recovering some of the energy released during incineration of the biomass (17 500 kJ kg^{-1} for cellulose material). If only 25% of this energy were recovered, US$118 ha^{-1} could be recovered from a 9 t ha^{-1} biomass.[10]

Whereas it would not be possible to phytoremediate natural substrates that are very heavily contaminated by geological pro-

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Table 1. Concentrations of nickel (mg kg^{-1} dry mass) in hyperaccumulator plants from southern Africa.

Species	Location	Max. Ni	Ref.
Berkheya coddii Roessler	Barberton, South Africa	14 000	13,14
B. rehmanii Thell. var. rogersiana Thell.	Barberton, South Africa	17 000	13
Blepharis acuminata Oberm.	Great Dyke, Zimbabwe	2 000	19
Dicoma niccolifera Wild	Great Dyke, Zimbabwe	3 200	19
Merremia xanthophylla Hallier f.	Great Dyke, Zimbabwe	1400	19
Pearsonia metallifera Wild	Great Dyke, Zimbabwe	14 141	19
Rhus wildii R. & A. Fernandes	Great Dyke, Zimbabwe	1 600	19
Senecio coronatus (Thunb.) Harv.	Barberton, South Africa	24 000	20
S. anomalochrous Hilliard	Kaapsehoop, South Africa	4 600	20

cesses, there is scope for use of this technique where anthropogenic causes, such as topdressing with fertilizers or use of sewage sludge over a long period, have resulted in light to moderate contamination. European Union (EU) guidelines for nickel in pastures receiving sewage sludge have been set at a maximum level of 75 mg kg^{-1}, whereas background levels are around 25 mg kg^{-1} for the U.K.[11] It is possible to calculate the amount of nickel that potentially can be removed annually from contaminated pastures using a crop of this species (Table 2).

The high nickel concentration in *B. coddii* has been reported by Morrey *et al.*[12] and Howes[13] in plants from the Barberton Ultramafic Sequence. Trials on phytomining[14] showed that *B. coddii* had some potential for phytoremediation of nickel-contaminated soils. The nickel concentration in this plant is about the same as in *A. bertolonii*, but its biomass is much higher. The number of crops required to decontaminate soils down to the EU limit is about half those needed for *A. bertolonii* (Table 2).

Phytomining

The concept of phytomining (growing a crop of a hyperaccumulator plant to recover the extracted metal) was proposed in 1983[15] and 1989.[5] A patent was granted in 1998.[4]

The first detailed field trials on phytomining were carried out in 1994 by the U.S. Bureau of Mines, Reno, Nevada,[10,16,17] using a naturally occurring stand of a nickel hyperaccumulator, *Streptanthus polygaloides* A. Gray.[18] The soil contained about 0.35% nickel, well below the economic range for conventional mining. It was proposed that a net return of \$513 ha^{-1} to the grower could be achieved, assuming that:

- selective breeding could produce plants with a minimum of 1% nickel in dry mass;
- the world price of nickel was \$7650 t^{-1} (it was \$5260 t^{-1} in November 2001);
- the biomass yield after moderate fertilization was 10 t ha^{-1};
- a quarter of the energy of combustion of the biomass could be turned into electricity for a yield of \$131 ha^{-1}; and
- the return to the grower would be half of the gross yield of \$765 ha^{-1} for the metal plus the energy yield of \$131 ha^{-1}.

This compared well with the average returns from other crops. The viability of nickel phytomining using *S. polygaloides* is now greater due to a higher nickel price. Recouping of the energy dividend depends on the scale of the phytomining operation, whether the combustion plant could be supplied with industrial or domestic waste for the period when no biomass was available and whether there is a market for the energy.

Field experiments with *A. bertolonii*[9] achieved a nickel yield of about 63 kg ha^{-1}. This would have been worth \$332 in November 2001. Assuming that the return to the grower was half of this value and adding the energy bonus of \$118, the gross return would be \$284 ha^{-1} — some way below the price paid to a wheat grower (\$500 ha^{-1}) in the U.S. Without the energy yield, this crop would not be economic.

Plots of *B. coddii* showed that a dry biomass of 22 t ha^{-1} could be achieved after moderate fertilization.[14] The nickel content of the plant was directly related to the extractable fraction of ammonium acetate in a wide range of natural and artificial substrata. Excision of shoots induced a marked increase in the nickel content in the new growth of the whole plant (5500 mg kg^{-1} compared with 1800 mg kg^{-1}). When plants were grown in pots with 0–1% nickel added to the substrate, the metal content of the plants rose to a maximum value of about 1% dry mass.[14]

At the recorded mean concentration of 5000 mg kg^{-1} nickel in field trials in New Zealand, a 1-ha crop of *B. coddii* would remove 110 kg of nickel, worth \$579 in November 2001. Assuming that half of this sum is returned to the grower and adding the energy derived from the combustion of the plant material (\$288), this translates to a total yield of \$755 ha^{-1}, which is above the value of a wheat crop (\$500 ha^{-1}).

Berkheya coddii has several advantages over other phytomining candidates for use in North America and Europe:

- its biomass is higher, and not at the expense of nickel concentration after fertilization;
- it is a perennial that does not need to be resown each year;
- it is hardy, tolerating cool climatic conditions including frost;
- it is easy to grow from fresh seed;
- it could be grown as an annual crop during summer in areas that have severe winters;
- it produces seed readily for future crops and the flowers are easily pollinated by bees; and
- it is resistant to insect attack and soil pathogens when grown on nickel-rich soils.

A model of a possible economic phytomining system differentiates between annual and perennial crops and encompasses the questions of fertilization and soil exhaustion. The success or failure of a project will probably depend on whether or not some of

Table 2. Number of annual crops of *Alyssum bertolonii* (biomass 9 t ha^{-1}) and *Berkheya coddii* (biomass 20 t ha^{-1}) needed to reduce nickel contamination in soils to the EU guideline of 75 mg kg^{-1}. Decontamination times have been multiplied by a factor of two to take into account both the possibility of progressively reduced nickel uptake by sequential crops, and the assumption that plant-available nickel in the soil is not 100%.

Initial Ni conc. (mg kg^{-1})	Crops using *A. bertoloni*	Crops using *B. coddii*
10 000	440	198
5 000	218	98
1 000	42	18
750	30	14
500	19	9
250	8	4
100	1	1

Assumptions: 1, plants both contain 5000 mg kg^{-1} Ni; 2, soil has a density of 1.3; 3, plant roots extend to a soil depth of 15 cm.

the energy of combustion of raw material can be recovered. In the tropics, it should be possible to have crops maturing in each month, so that the incineration plant could be kept busy for the whole year or biomass could be stored in the field or near the incineration plant for burning according to the energy requirement schedule.

If phytomining proceeds beyond the theoretical and pilot plant stages, there are two possible scenarios that can be envisaged. The first of these presupposes a commercial project on a very large scale involving several square kilometres of metal-rich soils such as those derived from ultramafic rocks or low-grade mineralization. The second scenario, perhaps the more likely, could involve phytomining being offered to smallholders throughout a region in which a farmer might grow a few hectares of plant material and have it collected for processing at a nearby facility. This should preferably be close to a large city, where industrial waste could also be used as feedstock for the incineration plant, which in turn could supply steam for supplying electricity to the national grid. A similar system is carried out by the sugar industry in Queensland, where the waste bagasse is burnt to produce electricity that supplies the sugar-processing plant and provides extra energy for sale to local authorities. A country such as Brazil, which has large areas of subeconomic nickel mineralization and ultramafic soils, is an obvious site for this scenario. In Brazil, farmers have sought to grow crops such as soyabean over nickel-rich ultramafic soils and these crops have failed. The surrounding natural vegetation was in contrast quite luxuriant and included several nickel hyperaccumulators that would have grown quite well as an alternative to failed soyabean crops (R.R. Brooks, pers. obs.).

Conclusions

Phytoremediation and phytomining differ from each other in one important respect. The former is not dependent on world metal prices, whereas the latter is heavily dependent on them. Both techniques are essentially 'green' and thereby received more favourably by the general public, provided that the plants are not genetically engineered and are native to the area. Phytoremediation also is potentially less expensive than some of the other alternatives such as on-site vitrification or chemical processes such as washing soils with acids[21] or even physical removal of the contaminated soils.

By far the greatest limitation to phytomining is that its economics are governed by world metal prices. The price per ton of nickel, for example, fell from $7650 to $4000 between 1994 and 1998, then rose to over $10 000 in early 1999. Its price in September 2000 was $8500. Whereas in 1994 there might have been half a dozen plants with the favourable combination of high biomass and elevated nickel concentrations, in 1998 there would have been only one or two species, notably *B. coddii* and perhaps *Alyssum corsicum* Duby, that might have been suitable. This would not, however, preclude growing a crop of metal, burning the biomass and storing the bio-ore until world prices were more favourable.

Selective breeding of plants with higher biomass and/or metal content is another approach that could be favourable for both phytoextractive technologies. Perhaps the ultimate answer is to introduce the gene responsible for hyperaccumulation into high-biomass non-accumulators such as *Brassica napus* L., *B. juncea* Coss. or even other high-biomass crop plants such as *Zea mays* L.

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