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# The potential of the high-biomass nickel hyperaccumulator *Berkheya coddii* for phytoremediation and phytomining

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**Abstract**

Pot trials and tests in outside plots were carried out on the South African Ni hyperaccumulator plant *Berkheya coddii* in order to establish its potential for phytoremediation of contaminated soils and for phytomining of Ni. Outside trial plots showed that a dry biomass of 22 t/ha could be achieved after moderate fertilisation. Pot trials with varying soil amendments with nitrogen and phosphorus fertilisers showed enhanced uptake of Ni with increasing nitrogen addition, though there was no reaction to phosphorus. The Ni content of the plant was directly related to the ammonium acetate extractable fraction of Ni in a wide range of natural and artificial substrates. Excision of shoots induced a dramatic increase in the Ni content in the new growth (5500 μg/g compared with 1800 μg/g Ni). When plants were grown in pots with Ni added to the substrate (0–1%), the Ni content of the plants rose to a maximum value of about 1% dry mass. The data from this last experiment were used to calculate the probable Ni yield (kg/ha) of plants grown in nickel-rich soils in different parts of the world. It was calculated that moderately contaminated soils (100 μg/g Ni) could be remediated with only two crops of *Berkheya coddii*. The potential of this species for phytomining has also been evaluated and it is proposed that a yield of 100 kg/ha of Ni should be achievable at many sites worldwide. Phytomining is also discussed in general terms for other metals as well as Ni. © 1997 Elsevier Science B.V.

*Keywords:* *Berkheya coddii*; phytoremediation; phytomining; hyperaccumulator of nickel

## 1. Introduction

*Berkheya coddii* is an asteraceous perennial plant that typically grows to a height of 1.5 m. It is found naturally only on serpentine soils in southern Africa. *Berkheya coddii* belongs to a group of very unusual plants termed *hyperaccumulators* (Brooks et al., 1977). Hyperaccumulator plants accumulate heavy metals from the soil into the aerial parts to concentrations in excess of a threshold of 1000 μg/g (ppm) set by Brooks et al. (1977) for dry biomass. In the case of Zn, the threshold has been set at 10000 μg/g. There are known hyperaccumulator plants for As, Cd, Co, Cu, Mn, Ni, Pb, Se and Zn, of the order of 700 species in all, of which more than half are Ni hyperaccumulators. *Berkheya coddii* falls into this latter category, with foliar Ni concentrations reported in excess of 11,600 μg/g (1.16%) dry mass (Morrey et al., 1992).

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A potential practical use for hyperaccumulators was first suggested by Chaney (1983) and later by McGrath et al. (1993) who showed that these plants might be used to remove metals from polluted soils. The process would involve growing repeated crops of a hyperaccumulator on the polluted area. The plant material would be burnt to produce a 'bio-ore'. This metal-rich ash, typically only 7% of the weight of the dried plant material, could be stored in a safe area or even conceivably be sold as feedstock to a smelter to recoup some of the cost of the operation. This technique has been termed *phytoremediation* and is now the subject of many studies (Brooks, 1998).

A potential new use for hyperaccumulator plants was proposed Nicks and Chambers (1995, 1998), who showed that the Californian hyperaccumulator *Streptanthus polygaloides* could extract over 100 kg of Ni per hectare from serpentine soils. In this operation termed *phytomining*, the objective was to grow commercial crops of Ni, on soils that are too nickel-poor for direct extraction by mining.

A study by Robinson et al. (1997) reported earlier in this journal, showed that the Ni hyperaccumulator *Alyssum bertolonii* from central Italy could potentially be used to phytomine Ni commercially, though the operation was nearing the low end of economic feasibility. It was found that the Ni content of the plants was correlated positively with the ammonium acetate extractable fraction of Ni in the soil.

It has been proposed that adding a compound to the soil that solubilises non-available heavy metals, would increase metal yields in the plant. Evidence for this comes from Blaylock et al. (1997) who showed that Indian mustard (*Brassica juncea*) plants accumulated Pb to a level of 1.5% (dry mass) in the aerial parts one week after addition of EDTA to the soil. The plant rapidly died, but this is not important for a phytoextraction operation as dead tissue can be harvested and burnt as easily as live material. The disadvantage with this strategy is the cost involved in adding such compounds and the risks that metals may pose to the environment.

So far, the problem with most potential phytoextraction operations has been that the hyperaccumulator plants that would be used, often have a low biomass production. If recourse is made to high-biomass plants, the advantage is offset by a lower degree of metal accumulation compared with hyperaccumulators. One strategy for increasing metal yields at present is, as mentioned above, to try to induce high biomass non-accumulator plants to accumulate a higher concentration of metal by adding chelating agents to the soil, or in the longer term by inducing the plant to produce its own complexing agents, by introducing genes from other hyperaccumulating species.

It is clearly desirable on economic grounds to discover high-biomass hyperaccumulators for phytoremediation/phytomining operations. An initial study of *Berkheya coddii* in its natural environment by some of us (RRB and AWH) showed that this plant certainly combines a high biomass (individual plants averaged 300 g d.w. at a site in Barberton, South Africa) with a high Ni content (up to 1.7% Ni in dried leaves). We have now grown this plant experimentally in New Zealand for two years in which we studied the effect of climate, shoot excision, soil amendments (including chelating agents) and varying Ni contents in the substrate. These studies were performed both in plant growth units and outside under field conditions and had the purpose of establishing the suitability of this species for phytomining and/or phytoremediation.

## 2. Materials and methods

### 2.1. Environmental control and growth media

All experiments, except the biomass estimation, were conducted in glasshouses at the Plant Growth Unit, Massey University, New Zealand. The temperature was controlled year-round within the limits of 15°–25°C. Plants were watered daily. The biomass production experiments were conducted out-of-doors in experimental plots at Massey University during a 12-month period. Plants were also grown outside for 24 months in order to study their resistance to frost during the winter.

In Palmerston North mean maximum and minimum temperatures for July (winter) are 12.1° and 4.0°C. For January (summer) the values are 22.3° and 13.1°C. In the winter a rare ground frost could be as cold as −5°C.

Various growth media (Table 1) were used. These included a serpentine soil from Red Hills in Califor-

Table 1
Elemental concentrations (total) and pH of natural and artifical growth media used in the experiments

| Growth medium | Mg (%) | Fe (%) | Ni (μg/g) | Cr (μg/g) | Co (μg/g) | pH |
|---|---|---|---|---|---|---|
| Bark [a] | 0.0001 | 0.001 | < 1 | < 1 | < 1 | 6.2 |
| Serpentine mineral (Te Kuiti) | 23.0 | 4.8 | 1880 | 910 | 96 | 9.2 |
| Bark : serpentine (v/v) [b] | | | | | | |
| 10 : 1 | 3.83 | 0.8 | 313 | 152 | 16 | 7.0 |
| 5 : 1 | 6.57 | 1.4 | 537 | 260 | 27 | 7.4 |
| 4 : 1 | 7.67 | 1.6 | 626 | 303 | 32 | 7.4 |
| 3 : 1 | 9.20 | 1.9 | 752 | 364 | 38 | 7.7 |
| 2 : 1 | 11.5 | 2.4 | 940 | 455 | 48 | 8.1 |
| 1 : 1 | 15.3 | 3.2 | 1253 | 606 | 64 | 8.3 |
| Bark : serpentine : gravel (1 : 1 : 2)(v/v/v) [b] | 6.57 | 1.4 | 537 | 260 | 27 | 7.9 |
| Bark : californian serpentine soil 1 : 1 (v/v) [b] | 10.7 | 6.5 | 2226 | 1027 | 116 | 6.5 |
| Californian serpentine soil (Chinese Camp) | 16.1 | 9.7 | 3340 | 1540 | 174 | 6.5 |
| South Island serpentine rubble (Rai Valley) | 15.9 | 23.4 | 6090 | 7850 | 540 | 7.6 |
| South African serpentine soil (Barberton) | 5.26 | 16.1 | 3000 | 6200 | – | 6.7 |

N.B. All artifical growth media had been amended with 'Osmocote' slow-release fertilisers.
[a] The bark contained 10 μg/g N and 2 μg/g P. [b] Mixtures prepared with fresh bark on a volume basis. On a weight basis, the dry bark had half the mass of the fresh material.

nia, and a serpentine soil from South Island, New Zealand. Other growth media were artificial 'serpentine soils' prepared from additions of a serpentine mineral ('Te Kuiti Serpentine') to either garden soil or finely sieved (< 2.0 mm) bark.

Fertilisation was carried out by addition of 'Osmocote' slow-release fertilisers at the rates recommended by the manufacturers.

### 2.2. *Estimation of annual biomass production*

Two adjacent 1 × 1 m plots, containing a 3 : 1 mixture of bark : crushed serpentine rock to a depth of 20 cm (see Table 1) and fertilised with 'Osmocote', were each planted with 16 individual seedlings. The boundaries of these plots were surrounded with 1 m high shade cloth. This was added to reduce edge effects: i.e. extra peripheral light and the effects of wind. One year after planting, the plants were excised approximately 5 cm above ground level. The plants were dried and the weight of the stems, leaves and flowers from each plant were recorded and their Ni concentrations determined.

### 2.3. *Effect of fertiliser additions on nickel uptake*

The effect of nitrogen and phosphorus on Ni uptake was studied by growing specimens of *Berkheya coddii* in 500-ml plastic pots for a period of 20 weeks in a 3 : 1 bark : serpentine mineral mixture (see Table 1) to which was added incremental amounts of nitrogen and phosphorus from calcium ammonium nitrate and superphosphate fertiliser. There was a total of nine different amendments with replicates of five plants within each group. The amendments were as follows: $N_0P_0$, $N_0P_1$, $N_0P_2$, $N_1P_0$, $N_1P_1$, $N_1P_2$, $N_2P_0$, $N_2P_1$ and $N_2P_2$; where $N_0$–$N_2$ were 0, 100 and 200 μg/g nitrogen as N, and $P_0$–$P_2$ were 0, 50 and 100 μg/g phosphorus as P. The leaves of the plants were excised after 20 weeks and analysed for Ni.

### 2.4. *Effect on soil nickel concentration, soil nickel solubility and excision on nickel uptake*

Nickel was added as the nitrate to a standard commercial seed compost to give concentrations of 0, 14, 41, 123, 370, 1111, 3333, and 10,000 μg/g.

In a further experiment, mixtures were also prepared with crushed serpentine rock : bark in the following ratios: 1 : 1, 1 : 2, 1 : 3, 1 : 4, 1 : 5, 1 : 10 and pure bark. Californian serpentine soil (from Red Hills near Chinese Camp), and a 1 : 1 mixture of bark/Californian serpentine was also used. Five replicates were prepared for each treatment. Plants were grown in 500-ml pots for 6 months then excised at ground level and analysed. The re-growth of the plants in the same mixtures were re-sampled and re-analysed after two months.

### 2.5. Effect of citric acid and EDTA on plant metal uptake

Forty plants were grown in pots containing 500 g of a 3 : 1 mixture of bark : crushed serpentine rock (see Table 1) for a period of 5 months. The plants were divided into five groups of eight and the following treatments prepared for each specimen: control, 5 g citric acid, 10 g citric acid, 2 g EDTA, and 2 g EDTA and 5 g citric acid. Citric acid was added as a 20% solution, and the EDTA added as a 5% solution of the trisodium salt. Leaf samples were taken after the first and third weeks after treatment, and the entire plant harvested one month after treatment.

### 2.6. Determination of the nickel content of the plants

Plant material was placed in a drying cabinet at 70°C until a constant weight was reached. Approximately 0.1 g samples of plant material were weighed accurately into 15-ml borosilicate test tubes. The samples were ashed overnight at 500°C. A 5-ml volume of warm (80°C) 2 *M* HCl was added to each, and the samples were mixed and shaken to dissolve the ash. Nickel in the solutions was determined by flame atomic absorption spectroscopy (FAAS).

### 2.7. Determination of the solubility of nickel in the soil

Soils were dried at 35°C. Soil samples (2 g) were weighed accurately into 50-ml centrifuge tubes and 20 ml of 1 *M* ammonium acetate (pH 7.0) was then added to each. This extractant was used so that the results could be compared with those of other studies (e.g. Robinson et al., 1997) that had shown that the ammonium acetate extract could be used to predict the nickel content of a plant grown in the extracted soil. The tubes were agitated for 24 h and the mixtures filtered. Nickel was determined in these extracts by graphite furnace atomic absorption spectroscopy (GFAAS).

## 3. Results and discussion

### 3.1. The biomass production of Berkheya coddii

After one year's growth from seed, the total above-ground dry biomass of plants in the two 1 × 1 m plots were 2.08 and 2.20 kg respectively. This translates to a mean biomass production of 21.4 t/ha per year. Plants were on average 180 cm tall and are shown in Fig. 1. This biomass was achieved with moderate addition of Osmocote slow-release fertilisers. However, field observations indicate that the plant attains this height in its natural habitat. Poorer soils may, however, need fertiliser addition for optimal production. Table 2 compares the biomass production of *B. coddii* with some other plant species, both non- and hyper-accumulating. The value of 21.4 t/ha is among the highest reported for any natural hyperaccumulator species, and over twice as high as the biomass production of *Alyssum bertolonii* (9 t/ha per year) that has been shown by Robinson et al. (1997) to have the potential of being able to provide an economic crop of nickel.

### 3.2. Effect of fertiliser amendments on nickel uptake by Berkheya coddii

Chemical analysis of leaves collected in these experiments showed no statistically significant relationship between the nickel content of the plants and the phosphorus content of the medium when the nitrogen content was constant. If, however, the experimental samples were considered as three separate populations with treatments $N_0$, $N_1$ and $N_2$ (i.e. ignoring the P treatments), there was a significant increase of Ni content with increasing addition of N (Fig. 2). The mean Ni content rose from 2300 μg/g d.w. for zero addition of N, to 3250 for the $N_1$ treatment and to 4200 μg/g for the $N_2$ amendments (see also Fig. 2).

### 3.3. The nickel concentration of Berkheya coddii in relation to soil nickel solubility

Nickel concentrations in the plants grown in various substrates as detailed in Table 1, ranged from 31 to 7880 μg/g (Fig. 3). The values represent the whole of the aerial parts of the plants as calculated

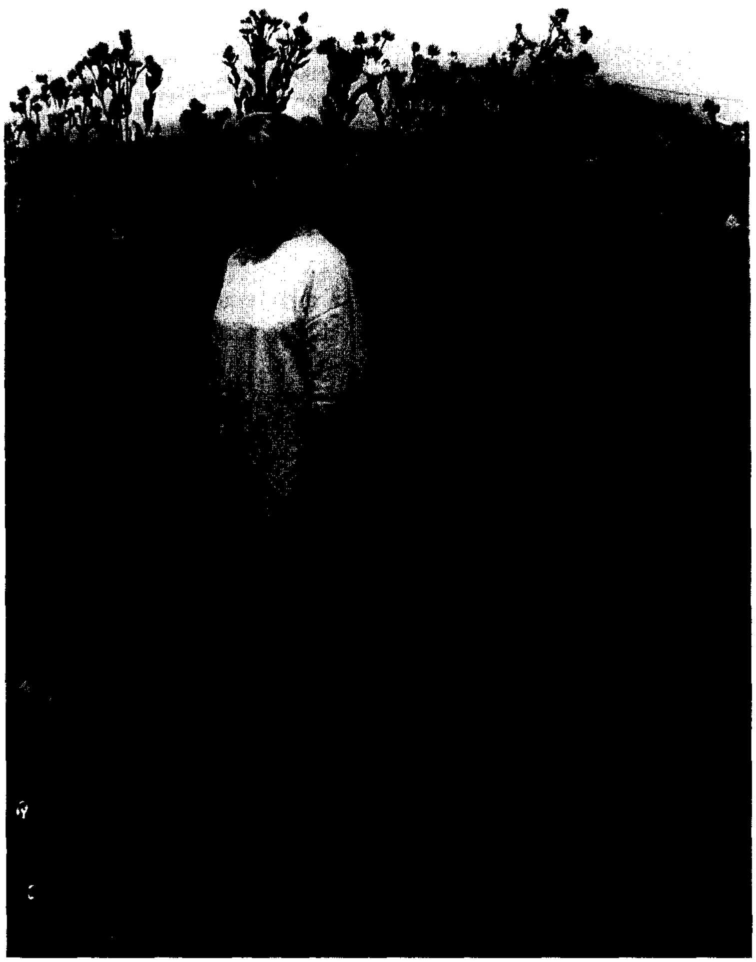

Fig. 1. Experimental out-door stand of *Berkheya coddii* with a biomass of 22 t/ha and height of about 1.8 m.

from analyses of leaves, flowers and stems (percentages being 49, 19, and 32 by weight, respectively).

No significant correlation was found between the total metal content of the soil and that of the plants. This was almost certainly due to the fact that it is the soluble Ni fraction in the soil which determines plant uptake (Robinson et al., 1997). This hypothesis is supported by the fact that there was a very highly significant ($P < 0.001$) positive correlation between the metal content of the plant and the soluble Ni concentration as determined by extraction into a 1 *M* ammonium acetate solution (Fig. 3). This concurs with results obtained by Robinson et al. (1997) in which the Ni content of *Alyssum bertolonii* had a significant positive correlation with the extractable Ni concentration in the supporting soil. These results indicate that the concentration of extractable Ni in a

Table 2
Fertilised biomass, mean metal content and extraction potential of various hyperaccumulators of metals

| Species | Fertilised biomass/ha | Mean metal content (μg/g) | Metal extracted (kg/ha) |
|---|---|---|---|
| *Homalium kanaliense* (Ni) | 36 | 556 [a] | 20 |
| *Zea mays* (Ni) | 30 | 1 | 0.03 |
| *Alyssum tenium* (Ni) | 23 | 3391 | 78 |
| *Berkheya coddii* (Ni) | 21.4 | 7880 | 168 |
| *Alyssum lesbiacum* (Ni) | 15 | 10000 | 150 |
| *Alyssum murale* (Ni) | 13.8 | 7101 | 98 |
| *Alyssum bertolonii* (Ni) | 9 | 7500 | 68 |
| *Haumaniastrum katangense* (Co/Cu) | 7.5 | 2266 | 17 |
| *Thlaspi caerulescens* (Zn) | 5.1 | 30000 | 153 |
| *Cardaminopsis hallerii* (Zn) | 2.6 | 3846 | 10 |

[a] Leaves have 7000 μg/g Ni but the stems have much less; hence the low extraction yield.

soil is a better indicator of the probable metal content of the plant than is the total concentration of Ni in the soil.

### 3.4. Prediction of the probable nickel content of *Berkheya coddii* grown on various serpentine soils

From Fig. 3 it will be observed that there is a linear relationship between the Ni content of *Berkheya coddii* and the extractable fraction of this element in the soil. The Ni content of *B. coddii* growing on a nickeliferous soil can therefore be predicted by the extractable Ni as determined by use of ammonium acetate solutions. Obviously there are other factors involved in Ni uptake such as the pH of the soil, nutrient availability, and the concentration of other heavy metals; however, the predictions should give a rough guide to a soil's suitability for phytomining or phytoremediation.

It is important to mention, however, other considerations that would need to be addressed before *B. coddii* were to be introduced to an area intended for phytomining or phytoremediation. All the plants in our experiments, as well as plants growing naturally in South Africa, were not under water stress. It has yet to be determined how *B. coddii* would tolerate

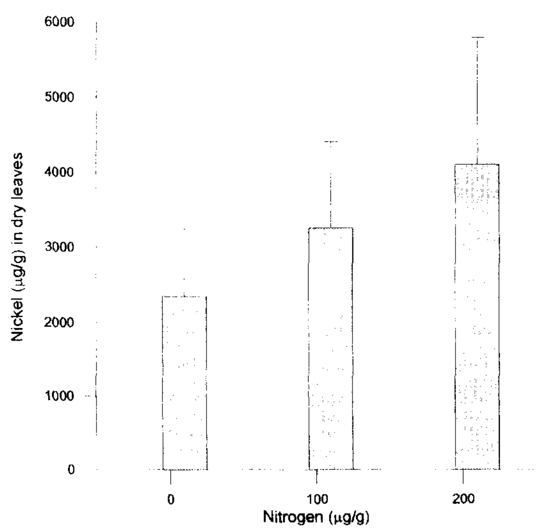


Fig. 2. Effect of nitrogen fertiliser on the nickel content of *Berkheya coddii*.

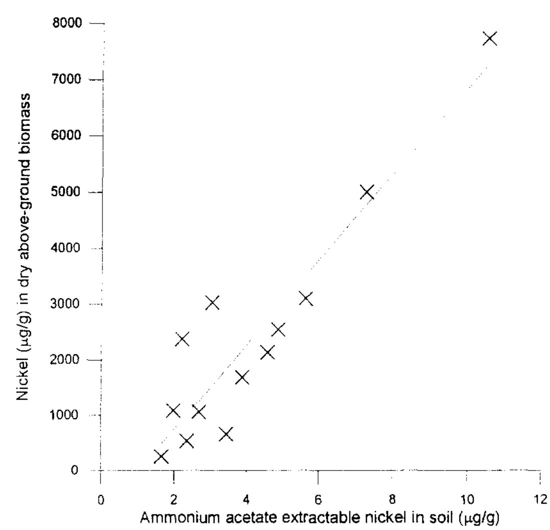


Fig. 3. The nickel content of dry biomass of *Berkheya coddii* as a function of extractable (ammonium acetate) nickel in the substrate.

xeric conditions. The plants in our outside plots withstood ground frosts of up to −5°C, though growth will undoubtedly suffer in very cold climates.

The question arises as to whether *B. coddii* could potentially become a weed. The rapid growth rate, and the production of large quantities of wind-borne seeds could in theory make the species invasive of surrounding areas, thus outcompeting native vegetation. Even though this plant is entirely confined to ultramafic environments in South Africa where the limiting factor may indeed be lack of competition from non-serpentine plants, it should not be assumed that there is no risk of its becoming a weed in other environments and this question should therefore be addressed in future field trials in other countries.

### 3.5. The effect of excision

Plants that were excised at ground level rapidly grew new foliage. This new growth had a much higher Ni concentration than the original plant (Fig. 4). The difference is on average over three times greater in the optimum range of 600–1000 μg/g in the soil. The same behaviour has been noted by Varennes et al. (1996) for the Ni hyperaccumulator *Alyssum pintodasilvae*.

Enhanced Ni uptake after excision could be due to two factors. The plant may be removing more Ni from the soil, or it may simply be translocating existing Ni in the plant to the new growth structures. The higher Ni in the new growth would be advantageous to the plant if it inhibited its predation by folivores (Boyd and Martens, 1994). Were the plant to be extracting more Ni from the soil, it may be possible to induce increased Ni uptake by removal of the apical meristem for example, or the addition of Ni-binding compounds to the soil. This could be tested by measuring the change in the Ni concentration of the regrowth over time. No significant de-

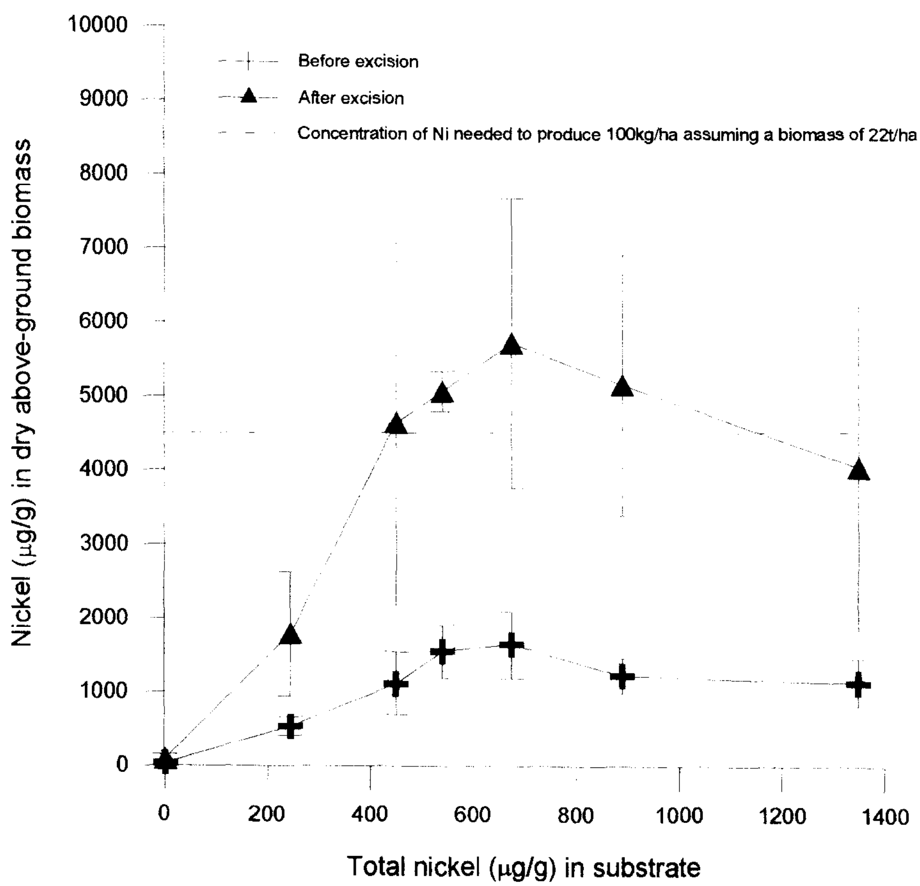


Fig. 4. The effect of excision on enhancement of the nickel content of fresh shoots of *Berkheya coddii*.

crease in Ni would indicate increased uptake of the metal by the plant. Whichever mechanism is responsible for the increase in Ni, the new growth could be harvested as another high Ni crop a few months after the original cropping, or the plant may be cropped once a year, removing the need to resow the plants.

### 3.6. Nickel in plants as a function of total nickel in the substrate

The results of experiments in which two-month-old whole plants of *B. coddii* were grown in standard seed mix containing incremental concentrations of Ni (0–10,000 μg/g) are shown in Fig. 5. The plants would not grow in substrates containing more than 3333 μg/g available Ni and the highest level of just over 10,000 μg/g Ni in the plants grown in pot trials is probably a limiting value. Although under natural conditions the plant can have up to 17,000 μg/g (1.7%) of this element in its dry leaves, the whole plant has a nickel content around 0.8% and this is of the same order as our experimental value of 1% in pot trials.

### 3.7. The effect of chelating agent addition on the metal uptake of *Berkheya coddii*

Compounds to be added to augment metal crops in a phytoextraction operation necessarily have to be cheap and relatively non-toxic as large amounts may need to be added. Citric acid was used in these experiments to lower the pH of the soil. This increase of acidity has been shown by Robinson et al. (1996) to increase metal solubility. Citric acid costs around US$ 20 per kilogram, and is rapidly broken down in the soil. EDTA has been shown by Blaylock et al. (1997) and by Huang and Cunningham (1996) to induce hyperaccumulation of Pb in crop plants such as *Zea mays* and *Brassica juncea* that do not usually hyperaccumulate this element. EDTA is a well known chelating agent which bonds with many metals including Ni. It costs around US$ 40 per kilogram, and is degraded in the natural environment in a few months (Means et al., 1980).

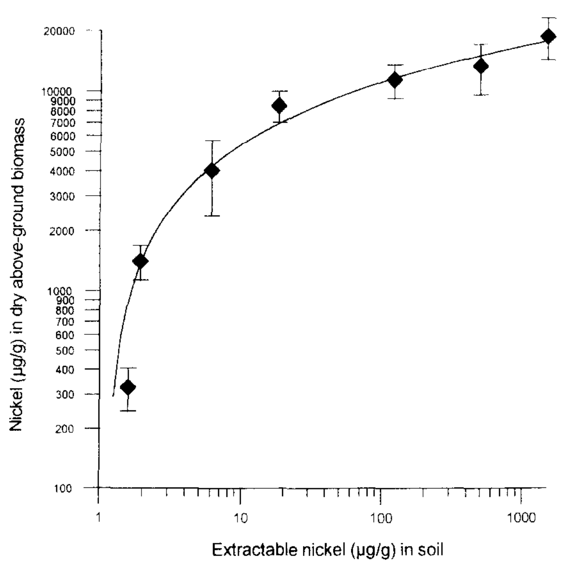


Fig. 5. Results of pot trials showing the relationship between nickel in *Berkheya coddii* and the available (ammonium acetate extractable) nickel content of the substrate.

Table 3
Effect of various treatments on metal uptake (μg/g d.m.) by *Berkheya coddii*

| Treatment ($n = 8$) | Ni | Co | Cr |
|---|---|---|---|
| Control | 3480 | 38 | 0.9 |
| 5 g citric acid | 1612 [a] | 121 [a] | 1.0 |
| 10 g citric acid | 770 [a] | 149 [a] | 7.9 [b] |
| 2 g EDTA | 1559 [a] | 29 | 1.1 |
| 2 g EDTA + 5 g citric acid | 1306 [a] | 44 | 1.7 |

[a] Very highly significant difference from the mean ($P < 0.001$) as determined by *t*-test.
[b] Significant difference from the mean ($P = 0.037$) as determined by *t*-test.
All other values showed no significant differences from the mean.

The relationship shown in Fig. 3 implies that the Ni content of the plant might be increased by increasing the availability of Ni in the soil. Citric acid and EDTA (trisodium salt) were added to plants in an attempt to augment their uptake of Ni and other metals. Table 3 shows the effect of these additions.

Surprisingly, the addition of both citric acid and EDTA caused a highly significant decrease ($P < 0.001$) of Ni content in all relative to the control. This was in spite of an increase in the extractable Ni content of the soils. However, there was no noticeable reduction in the biomass yield. A possible explanation for reduced Ni is that the compounds added to the soil compete with the plant's own nickel-binding agents causing the Ni to diffuse out down its concentration gradient. This is consistent with an active Ni uptake system, which can be contrasted to the passive uptake of Pb by *Zea mays* (Huang and Cunningham, 1996). In the latter system, the addition of EDTA solubilises large quantities of Pb from the soil, which then diffuses down its concentration gradient into the plant root, or is taken up by mass flow. More evidence for this comes from the fact that addition of citric acid caused a significant increase in concentrations of other elements not normally accumulated by *B. coddii*. The uptake of the other elements upon the addition of citric acid, though significant, is not sufficient to make their phytoextraction an economic means of increasing the value of a metal crop. Unlike in the case of Pb, there is thus no advantage in adding citric acid or EDTA to the soil, if Ni extraction is the aim of the operation.

## 4. Discussion of the potential role of *Berkheya coddii* in phytoremediation and phytomining

### 4.1. Phytoremediation of nickel-contaminated soils

The combination of high biomass and high Ni content of *Berkheya coddii*, together with its ease of propagation and culture as well as its tolerance of cool climatic conditions, should render this species a suitable agent for phytoremediation. Sites highly polluted with Ni are less numerous than those contaminated with Pb and Zn. There is, however, a need for some degree of remediation of several sites throughout the world where pollution from Ni is a problem. S.P. McGrath (pers commun.) has described the problem of Ni pollution of the environment. Apart from the obvious local pollution from smelters, a significant problem arises from addition of Ni to pastures via sewage sludges. At Beaumont Leys (UK) for example, the Ni content of surface soils at a sewage farm was found to be as high as 385 μg/g.

European Community guidelines for Ni in pastures receiving sewage sludge have been set at a maximum level of 75 μg/g where background levels are around 25 μg/g for UK (McGrath, 1995). Assuming a biomass of 22 t/ha for *Berkheya coddii* and a soil depth of 15 cm and density of 1.3, it is possible to calculate the amount of Ni that could potentially be removed annually from contaminated pastures using a crop of this species. Using the data from Fig. 5, an estimate can be made for the probable Ni content of a *Berkheya* crop growing over polluted soils. It must be remembered, however, that the experiments portrayed in Fig. 5 were carried out with substrates containing Ni as the totally soluble nitrate, though a high proportion of this Ni would have been absorbed by complexing with the organic matter of the substrate. In applying these data to a hypothetical situation involving a contaminated soil in which the availability of the Ni might not be known in advance, we have adopted a conservative approach that assumes that only half of the metal burden of the soil would be available to the plants.

The number of annual crops of *Berkheya coddii* that would be required to reduce the Ni burden of soils down to the EU level of 75 μg/g is summarised in Table 4. For moderate Ni contamination (100 μg/g) two crops would be sufficient to reduce the metal content to well below the 75 μg/g of the EU guidelines. Even at 250 μg/g (few polluted sites would exceed this value) only four crops of *Berkheya coddii* would be needed.

Current EU guidelines (CEC, 1986) permit an annual addition of only 3 kg/ha Ni when sewage sludge is used as fertiliser for pastures and cropping. One crop of *Berkheya* (Table 2) would remove the equivalent of 24 years of annual fertiliser additions assuming that only half of the Ni is extractable.

Table 4
Number of annual crops of *Berkheya coddii* required to reduce nickel contamination in soils to the EU guideline of 75 μg/g

| Initial Ni in soil (μg/g) | Content after one year | Number of crops to decontaminate |
|---|---|---|
| 10000 | 9918 | 138 |
| 5000 | 4925 | 74 |
| 2000 | 1932 | 34 |
| 1500 | 1435 | 26 |
| 1000 | 939 | 18 |
| 750 | 691 | 14 |
| 500 | 445 | 10 |
| 250 | 200 | 4 |
| 100 | 59 | 2 |

Assumptions: 1 = biomass of 22 t/ha, 2 = only half the Ni is extractable, 3 = Ni content of the plant, and hence its extractive power, is a function of the extractable Ni content of the soil as determined from Fig. 5.

### 4.2. *Phytomining for nickel*

The concept of phytomining has not yet been thoroughly tested under field conditions. The first paper on the subject by Nicks and Chambers (1995) involving the Californian Ni hyperaccumulator *Streptanthus polygaloides* proposed a yield of 100 kg/ha of metal, worth at today's prices about US$ 720. A fertilised biomass yield of 10 t/ha would provide 175 GJ of energy with a value of US$ 3 per GJ. Assuming that 25% of this energy could be recovered, the incineration process would provide an additional US$ 131/ha. The total yield would therefore be US$ 851. If half of this sum could be returned to the grower, the yield would be about US$ 425 compared with the US$ 333 net return of a crop of wheat.

The figure of 100 kg/ha quoted by Nicks and Chambers (1995) as the minimum quantity of Ni per hectare in an economic phytomining operation would require a minimum plant Ni content of about 4500 μg/g in *Berkheya coddii* assuming a biomass yield of 22 t/ha as found in our experiments. Our experiments and field observations in South Africa indicate that this limit should be easy to reach.

At the highest recorded concentration of 7880 μg/g, a 1-ha crop of *Berkheya coddii* would remove 168 kg of Ni. This combined with the energy derived from the combustion of the plant material (US$ 288) translates to 1260 + 288 = US$ 1548 per hectare. If half of this sum could be returned to the producer (US$ 774), this is about twice the value of a wheat crop.

Some caution must be applied in extrapolating to large-scale metal farming, the results of pot trials and limited field trials. We have not been able to achieve experimentally the 7880 μg/g Ni found in wild plants and believe from our experimental studies that a more conservative level of 5000 μg/g Ni seems more realistic. This could provide 110 kg/ha Ni worth US$ 792 at today's prices. Adding the energy 'profit' and assuming a 50% return to the operator, the value of the crop then becomes US$ 540, still well above that of a wheat crop.

*Berkheya coddii* has several advantages over other phytomining candidates:

1. its biomass production is superior to that reported of any other hyperaccumulator except perhaps *Alyssum lesbiacum* (McGrath et al., 1993) and is not at the expense of Ni content;
2. the plant is a perennial that can be harvested and regrown the following year without need of re-sowing;
3. preliminary observations indicate that the Ni content of regrowth tissue is significantly higher than in the original first-year's growth;
4. *Berkheya coddii* is an exceptionally hardy plant that will tolerate cool climatic conditions including frost. It is easy to grow from seed but does not propagate from cuttings;
5. although the plant is tolerant of the relatively mild New Zealand winter, this would probably not be the case for North America; however, it could conceivably be grown as an annual crop in North America during say the March–September period;
6. *Berkheya coddii* produces seed readily for future crops and the flowers are easily fertilised by local honey bees and bumble bees, though in South Africa they appear to be fertilised by a local species of flying beetle;
7. finally, *Berkheya* appears to be resistant to insect attack and soil pathogens; we have had very few failures in pot trials even when growing plants in non-serpentinic substrates where soil pathogens and fungi might be expected to flourish.

It must be emphasised at this stage, that phytomining is at present only a theoretical concept advanced by only two previous reports (Nicks and Chambers, 1995; Robinson et al., 1997).

The first requirement is that there should be a terrain with extensive areas of subeconomic Ni mineralisation (often lateritic). The Ni yield of such phytomining operations would be governed by a number of factors such as climate and the degree of plant-availability of the Ni. This latter factor is of supreme importance as we have established from the above experimentation. We have determined the Ni extractability (using ammonium acetate) of eleven serpentine soils from throughout the world. Relating this extractability to the projected Ni content of *Berkheya coddii* (see Fig. 3), we have calculated the probable Ni yield of crops of this species grown in various parts of the world as is shown in Table 5. It is possible that economic crops of Ni could be phytomined from those sites with > 98 kg Ni/ha

Table 5
Predicted nickel yields for crops of *Berkheya coddii* grown on nickel-rich soils throughout the world

| Country/State | Location | *N* | A | B | C |
|---|---|---|---|---|---|
| New Caledonia | Plaine des Lacs | 1 | 30.8 | 1.00 [a] | 200 [a] |
| California | Red Hills (Chinese Camp) | 2 | 26.3 | 1.00 [a] | 200 [a] |
| New Zealand | Coppermine Saddle | 6 | 19.3 | 1.00 [a] | 200 [a] |
| Italy | Monte Pelato | 40 | 14.4 | 1.00 [a] | 200 [a] |
| New Zealand | Dun Mountain | 5 | 11.7 | 0.82 | 164 |
| South Africa | Barberton | 2 | 10.5 | 0.73 | 146 |
| Italy | Monte Murlo | 76 | 7.46 | 0.49 | 98 |
| Argentina | Vitali Quarry, Cordoba | 1 | 3.40 | 0.18 | 39 |
| Morocco | Taafat | 1 | 2.91 | 0.14 | 31 |
| New Zealand | Cobb asbestos mine | 5 | 2.46 | 0.11 | 24 |
| Portugal | Bragança | 1 | 1.63 | 0.05 | 10 |

[a] It is assumed that there is a limiting value of 1% Ni in *B. coddii* irrespective of the extractable Ni in the soil.
*N* = number of soil samples tested, A = extractable soil nickel (%), B = estimated nickel content of plant (μg/g), C = estimated nickel yield (kg/ha).
Assumptions: 1 = biomass of 22 t/ha, 2 = Ni content of the plant, and hence its extractive power, is a function of the extractable Ni content of the soil as determined from Fig. 5.

projected yields from *B. coddii*, provided of course that other factors were favourable, not the least of which would be a sufficiently large area for economic metal farming. Although some of the soils show extractable Ni levels well in excess of the maximum of 10.5 μg/g shown in Fig. 3, we have chosen not to extrapolate beyond this level since as is shown in Fig. 5, Ni levels in *Berkheya* tend to level off at just over 1% in dry matter.

The most obvious regions on earth where metal farming with *Berkheya* might be possible are the ultramafics of California/Oregon, Central Brazil in Goiás State, New Caledonia, Anatolia, and Western Australia. The next step in the development process would be the establishment of a pilot scheme in one of these or other suitable territories.

### 4.3. Phytomining for other metals

The practical limits of phytomining have already been discussed by Robinson et al. (1997). The main variables that control the economic feasibility of phytomining are metal price, plant biomass, and the metal content of the plant. These variables are highlighted in Table 6. The metal values extend from US$ 13,600,000/t for Au to US$ 817/t for Pb. A plant with a biomass of 20 t/ha such as *Berkheya* would need to contain 1.8 μg/g Au or 4.08% Pb at the two extremes. To achieve either of these extremes would require some type of substrate modification such as EDTA as natural concentrations of these two elements do not usually exceed 0.1 μg/g for gold and 50 μg/g for Pb. It is true that the Pb content of *Zea mays* with a biomass of 30 t/ha can be raised to close to the limit of 2.04% by addition of EDTA to the substrate (Blaylock et al., 1997);

Table 6
Metal concentrations (μg/g d.m.) in vegetation required to provide a total US$ 500/ha return [a] on hyperaccumulator crops with varying biomass

| Metal | (US$/t) | Biomass production (t/ha) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 10 | 15 | 20 | 25 | 30 |
| Au | 13,600,000 | 36.8 | 18.4 | 12.3 | 9.2 | 7.4 | 3.7 | 2.5 | 1.8 | 1.5 | 1.2 |
| Pd | 4,464,000 | 112.0 | 56.0 | 37.3 | 28.0 | 22.4 | 11.2 | 7.5 | 5.6 | 4.5 | 3.7 |
| Ag | 183,000 | 2732 | 1366 | 911 | 683 | 546 | 273 | 182 | 137 | 109 | 91.0 |
| Co | 48,000 | 10417 | 5208 | 3472 | 2604 | 2083 | 1042 | 694 | 521 | 417 | 347 |
| Tl | 15,000 | 33333 | 16667 | 11111 | 8333 | 6667 | 3333 | 2222 | 1667 | 1333 | 1111 |
| Ni | 7,485 | 66800 | 33400 | 22267 | 16700 | 13360 | 6680 | 4453 | 3340 | 2672 | 2227 |
| Sn | 6,200 | 80650 | 40323 | 26882 | 20161 | 16129 | 8065 | 5376 | 4032 | 3226 | 2688 |
| Cd | 3,750 | 133333 | 66667 | 44444 | 33333 | 26667 | 13333 | 8889 | 6667 | 5333 | 4444 |
| Cu | 1,961 | 254970 | 127485 | 84991 | 63743 | 50994 | 25497 | 16998 | 12749 | 10199 | 8499 |
| Mn | 1,700 | 294120 | 147060 | 98039 | 73529 | 58824 | 29412 | 19608 | 14706 | 11765 | 9804 |
| Zn | 1,007 | 496520 | 248260 | 165506 | 124130 | 99305 | 49652 | 33102 | 24826 | 19861 | 16551 |
| Pb | 817 | 612000 | 306000 | 204000 | 153000 | 122400 | 61200 | 40800 | 30600 | 24480 | 20400 |

[a] Excluding any profit from sale of the energy of biomass incineration.

however, the cost of the EDTA alone would exceed the value of the Pb yielded from the soil.

To be realistic, we may assume that phytomining, if ever realised as a commercial enterprise, will be confined to metals such as Co and Ni that lie in the price range of US$ 7500 to US$ 48,000 per tonne and which are known to have plant hyperaccumulators of them.

Finally, there is the possibility of simultaneous extraction of two different metals with the same plant species since some plants (e.g. the Co/Cu hyperaccumulators of former Zaïre in Central Africa) can accumulate two metals of which the lesser priced of the two could contribute to the financial return, though neither might be economically viable in its own right.

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