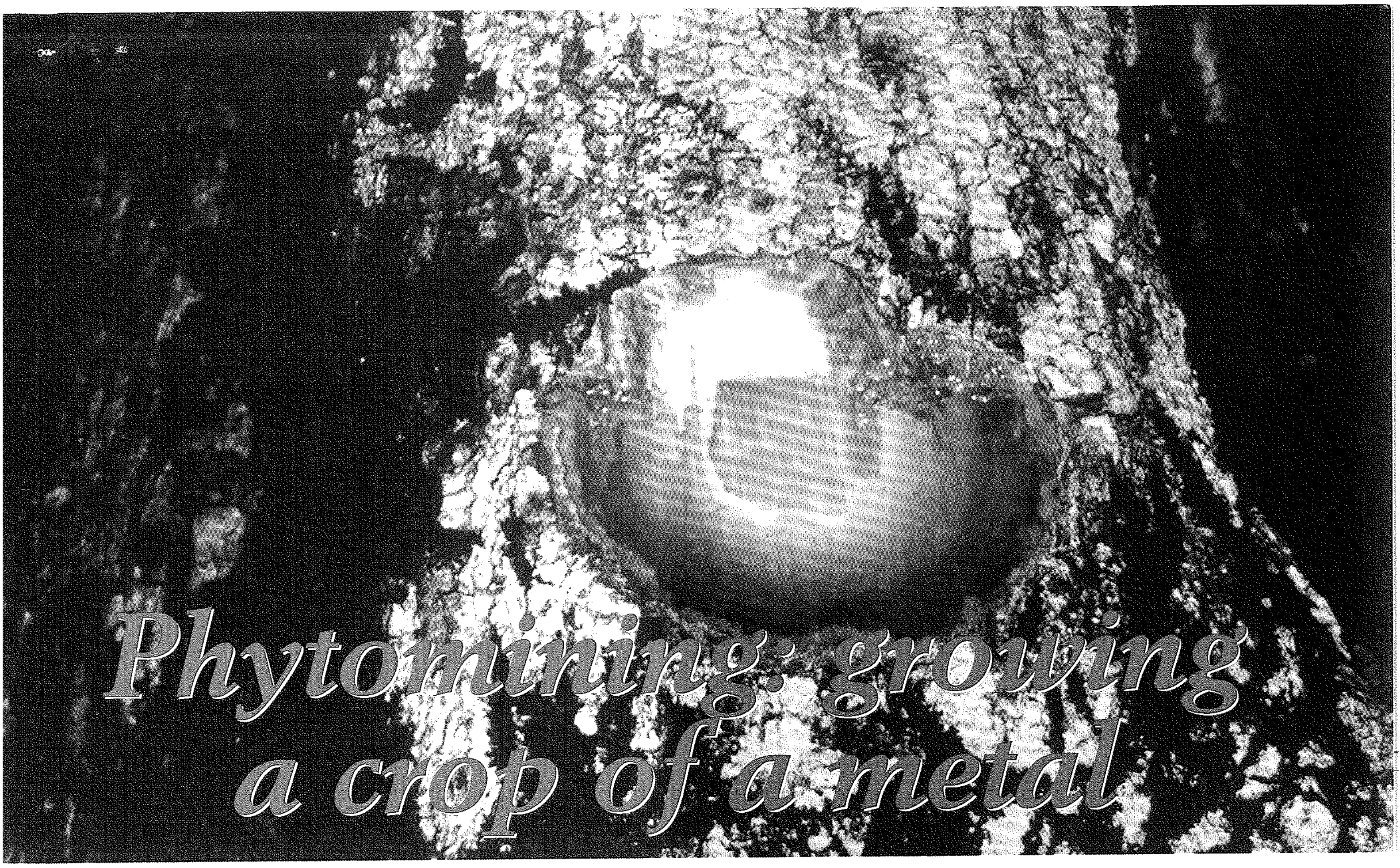

Phytomining: growing a crop of a metal

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Some plants are able to hyperaccumulate heavy metals such as nickel, cobalt, cadmium, zinc or even gold. Such plants could be used to extract metals from soils or ores that are subeconomic for conventional mining. This proposed new technology is known as phytomining.

In the early 1970s, T. Jaffré discovered a tree in New Caledonia, *Sebertia acuminata,* that exudes a sap containing 26% nickel in its dry mass. It is known locally as *sève bleue* (blue sap). The question immediately arose in people's minds, 'what if it had been gold that exuded so freely from the trunk?'. One could imagine tapping it like a rubber tree for its golden harvest. A whole decade was to pass before others saw the possibility of phytomining for nickel and other elements. Growing a crop for its metal was first proposed by Chaney (1983) and later by Baker and Brooks (1989), but it was not until the mid-1990s that field trials were carried out. Nicks and Chambers (1995), working from Nevada, grew a crop for nickel in California, over nickel-rich 'serpentine' soils. These serpentine, or more correctly ultramafic (ultra-magnesium-ferric) soils are derived from ultramafic rocks that cover about 1% of the Earth's land surface and contain high concentrations of nickel, chromium, cobalt and magnesium. In the preliminary trials, the researchers used the nickel-hyperaccumulating plant *Streptanthus polygaloides* (Figure 1), which can contain over 1% of this metal in its dry matter. In 1998, Chaney and his co-workers took out a patent on phytomining for nickel.

Phytomining and its better-known, associated technology, phytoremediation, depend on the use of hyperaccumulator plants; these are classified as containing over 100 times higher elemental concentrations than non-accumulator species, even when the latter grow on mineralised soils. Hyperaccumulation is a relatively rare event; so far, about 400 species have been found worldwide to hyperaccumulate nickel, but the total for other elements, such as copper and zinc, is much less. It is also possible to induce hyperaccumulation in plants by the addition of a chemical to the soil that solubilises the target element. This is known as induced hyperaccumulation.

Pioneering field trials

The early study by Nicks and Chambers calculated that the net return to a phytominer would be $US513 per ha per annum, assuming a nickel price of $US7650 per tonne, a biomass yield of 10 t/ha, containing 1% Ni, and the return to the grower of $US131 per ha, derived from the energy obtained from combustion of the biomass. This latter activity is not unique – the same strategy is now used in the sugar cane industry, where electricity generated from

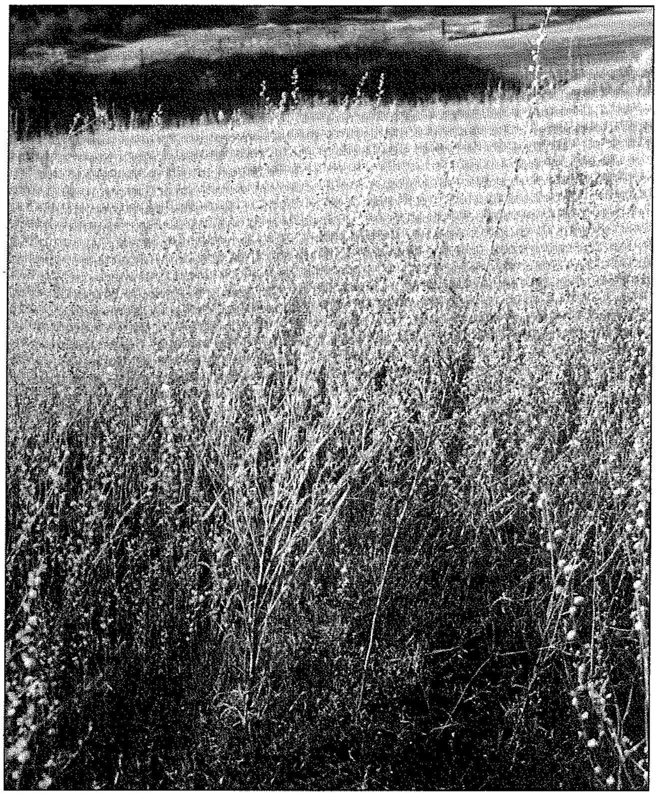

Figure 1. A crop of nickel in Streptanthus polygaloides, *growing in California.*

burning the *bagasse* (biomass remaining after sugar extraction) is used to run the factory and provide surplus energy to the national grid.

The next set of field trials was performed by Robinson *et al.* (1997a), who looked at natural stands of *Alyssum bertolonii* (Figure 2) growing in Tuscany, Italy. They found that moderate fertilisation of the soil gave a threefold biomass increase without concomitant loss of nickel content of 0.8% (8000 mg/kg) in the dry plant material. Later field trials in New Zealand, using the same species, showed that a biomass of 12 t/ha could be achieved by moderate fertilisation of the serpentine substrate. This yield, together with a nickel concentration of 0.8% would have produced 96 kg/ha of nickel, which is comparable with the yield from *S. polygaloides* in California.

Pot and field trials for nickel phytomining have also been performed with the South African hyperaccumulator *Berkheya coddii*. After moderate fertilisation, Robinson *et al.* (1997b) obtained a biomass yield of 22 t/ha, containing about 5500 mg/kg (0.55%) nickel. This would have provided 121 kg/ha of nickel, together with a potential energy yield of $US288. The world price of nickel fell to about $US4000 per tonne, but has now recovered to $US7200. The value of the nickel in the crop would therefore be $US871. If half of this sum represented the net profit to the phytominer, and adding the energy dividend, the net return would be $US723, which is well above the $US322 per ha obtained by an American wheat farmer in 1996, even without the energy dividend.

Berkeya coddii is at present probably one of the best candidates for phytomining for nickel; it has a high biomass, and is easy to grow from seed, it is a perennial, so that it does not need to be resown each year, it is tolerant of frost and cool weather, and readily produces seed for future sowings. In climates with severe winters, it could be grown as an annual crop.

Thallium and gold

Although most of the pioneering work on phytomining has been performed with nickel, there is no reason why other metals should not be extracted in the same manner. In New Zealand and in France, we have initiated experiments with *Iberis intermedia* (candytuft) from southern France; this contains over 2000 mg/kg (0.2%) thallium in its dry mass (Leblanc *et al.,* 1999). This highly toxic metal has a world price of $US300 per tonne at present, and is obtained from a single mine in southern Macedonia, near the Greek border. The biomass of the *Iberis* (Figure 3) is about 5 t/ha, and could produce up to 10 kg/ha of thallium, worth about $US3000.

The *Iberis* could also be used to phytoremediate thallium-contaminated soils, in which the crop is grown specifically to remove the pollutant without consideration of the marketable value of the crop (McGrath *et al.,* 1993). Nearly all the recent papers on phytoextraction of heavy metals by plants have been focussed on phytoremediation; here, the aim of the project is decontamination of polluted soils, while production of an economic bio-ore is a possible bonus and not the main objective. The phytoremediation of nickel-polluted soils by *Alyssum bertolonii* and *Berkheya coddii* has previously been discussed by Robinson *et al.* (1997a; b).

As mentioned above, another way to use natural plant hyperaccumulators of metals is in induced

Figure 2. Alyssum bertolonii *– a nickel hyperaccumulator from Tuscany, Italy. The dried leaves contain on average about 1% (10,000 mg/kg) nickel.*

hyperaccumulation. Blaylock *et al.* (1997), for example, grew crop plants to full size on lead-polluted soils for the purpose of phytoremediation. Lead is not taken up by plants because it occurs in soils as highly insoluble salts. However, addition of EDTA to the soil solubilised the lead, so that crop plants such as maize took up as much as 1% Pb (dry mass), thus enabling removal of lead from the contaminated substrate.

An interesting development of this work with lead was the discovery by Anderson *et al.* (1998) that plants such as Indian mustard (*Brassica juncea*) were able to hyperaccumulate up to 57 mg/kg gold from various auriferous substrates, following the addition of ammonium thiocyanate to the growth medium (Figure 4). It was suggested that this method might be used to recover gold from mine wastes too impoverished to be economically viable for extraction by conventional recovery techniques. This induced hyperaccumulation of gold was carried out using various auriferous substrates, including crushed gold ore, native gold dispersed in silica sand, and an artificial growth medium consisting of finely disseminated colloidal gold in silica sand.

Figure 3. Iberis intermedia *growing over thallium-rich mine tailings in southern France. This plant can contain up to 2000 mg/kg (0.2%) thallium in its dry leaves.*

Economics

A model of a proposed economic scheme for phytomining is shown in Figure 5. This system applies to either natural or induced hyperaccumulation. In the latter case, the cost of the reagent has to be taken into account. The economics of the operation are dependent on a number of factors, such as the metal content of the plant, its biomass production per annum, and whether or not the energy of combustion of the biomass can be recovered and sold. The most important factor, however, is the world price of the metal being phytomined. A classic example of this is nickel, which has almost halved in price since 1994. Similarly, gold has fallen from $US400 per oz to less than $US300 per oz during the same period. This problem is highlighted in Table 1, which shows metal concentrations (mg/kg dry mass) required to provide a $US500 per ha return for phytomining crops of different biomass, excluding the sale of energy from combustion of the plant material.

In 1994, at the time of the early field trials, the world price of nickel was $US7650. It then halved, but has recently recovered, to $US7200. The halving of this price since then can be expressed in terms of the economics of phytomining. In 1994, *Berkheya coddii* with a biomass of 20 t/ha needed only 3340 mg/kg nickel in dry mass (easily attainable) to recoup $US500 per ha, not counting the sale of energy of combustion. In 1998, it would have required 6162 mg/kg for the same yield. Sale of energy in a phytomining operation is obviously a *sine qua non* for a successful outcome of the project. It must be appreciated that this energy dividend also has to be set against agronomic costs such as site preparation, fertiliser application (if needed) and seed. It is clear that phytomining, unlike the related phytoremediation, will be dependent on commodity world prices, just like any other type of mining.

Although phytomining is now marginal for nickel, this may not be true for other metals, whose prices also rise and

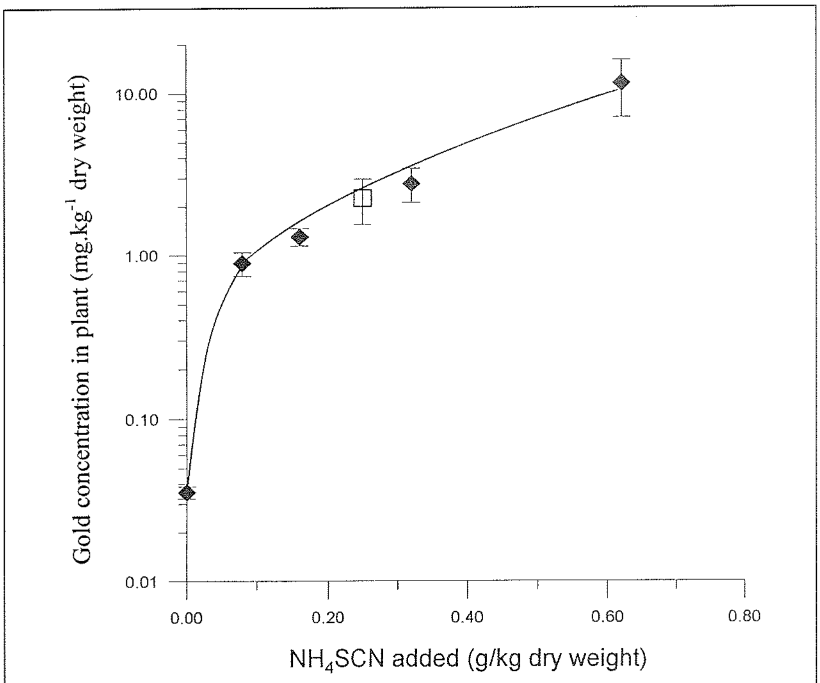

*Figure 4. Thiocyanate-induced uptake of gold by Indian mustard (*Brassica juncea*) from finely disseminated (solid diamonds) and native (open square) gold substrates containing 5 mg/kg (ppm) gold.*

Table 1. Metal concentration (mg.kg-1 dry mass) in vegetation of different biomass needed to provide a crop with a value of $US500 per ha, excluding sale of energy of biomass combustion

		Biomasss yield (t/ha)				
Metal	**$US per t-**	**1**	**10**	**15**	**20**	**30**
Platinum*	12 500 000	40	4.0	2.7	2.0	1.3
Gold*	10 714 000	47	4.7	3.2	2.3	1.5
Palladium*	3 787 000	131	13.1	8.8	6.6	4.3
Thallium	300 000	1667	167	111	83	56
Silver*	152 113	3278	328	218	164	109
Cobalt	48 000	10 417	1042	694	521	347
Uranium	22 000	22 728	2273	1515	1137	758
Tin*	5580	88 715	8871	5914	4435	2957
Nickel	7200	69 018	6901	4600	3451	2345
Cadmium	3750	133 333	13 333	8889	6687	4444
Copper	1964	254 970	25 497	16 998	12 749	8499
Manganese	1700	294 120	29 412	19 608	14 706	9804
Zinc	1192	417 076	41 707	27 805	20 853	13 902
Lead*	577	869 040	86 904	57 936	43 452	29 968

*Induced hyperaccumulation probably required.

fall in the cycles of world markets. The proposed technology does have a number of unique features that should be emphasised.

1. It offers the possibility of exploiting ores or mineralised soils that are quite uneconomic by conventional mining methods. For example, nickel can easily be phytomined from soils containing only 0.5% Ni and which cover vast areas throughout the world.

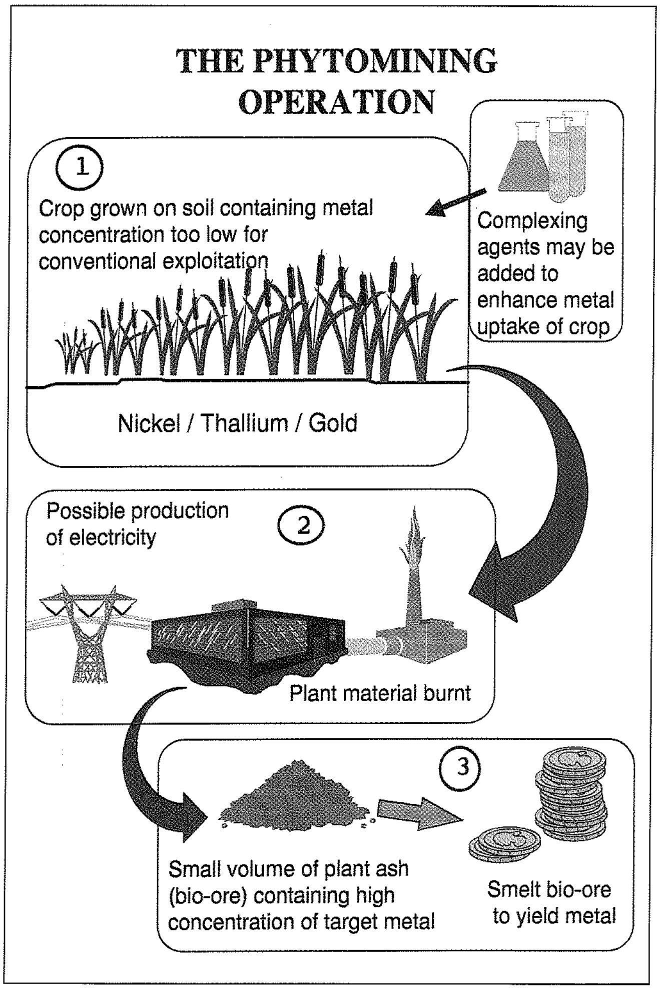

Figure 5. Model of a proposed system for phytomining for metals.

2. 'Bio-ores' are virtually sulphur-free and their smelting will require less energy than sulphidic ores, which contribute greatly to the problem of acid rain.

3. The metal content of a bio-ore is usually much greater than that of a conventional ore, and therefore requires less storage space. For example, we have found 22% Ni in the ash of the Zimbabwean hyperaccumulator *Pearsonia metallifera.*

4. Phytomining is a 'green' technology, which should appeal to the conservation movement as an alternative to opencast mining of low-grade ores.

There are environmental concerns related to adding complexing agents or other chemicals to soils or tailings. Despite its low toxicity relative to cyanide, use of thiocyanate would have to be strictly controlled to prevent leaching of this chemical into water tables and local waterways. There is also the potential problem of birds and grazing animals ingesting vegetation or seeds contaminated with heavy metals. For the purpose of the phytomining operation, the leaching of gold solution out of the root zone is certainly not desirable.

It has been suggested (C. French, pers. comm.) that it might be possible to use transgenic plants which express a bacterial thiocyanate-degrading system to extract gold from auriferous substrates. This approach would solve the problem of thiocyanate toxicity to plants and perhaps allow them to extract more gold. The idea of transferring 'hyperaccumulation' or other types of gene into non-accumulating plants is being studied worldwide; for example, genetically modified *Arabidopsis thaliana* plants are able to convert mercury ions into the volatile metal and might therefore be used to remove mercury from contaminated soils.

Induced hyperaccumulation of gold, as reported by Anderson *et al.* (1998), is the first evidence of significant non-hydroponic gold uptake by any plant. The true potential of phytomining has yet to be established. It has not yet been trialed on a commercial scale and much research remains to be carried out, particularly in the field of increasing metal uptake by plants, either by genetic manipulation or addition of specific reagents to the soil. It is only then that we will know whether phytomining is just a temporary aberration in the long history of scientific progress, or a new idea whose time has come.

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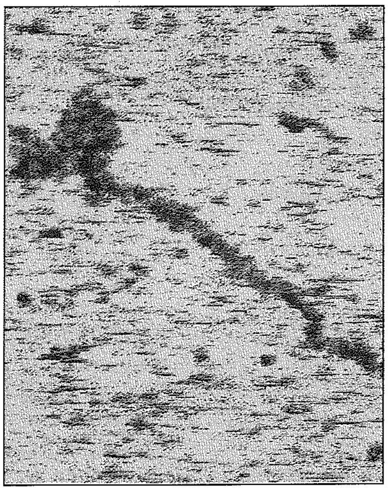

Myosin molecule
The smallest object portrayed in the exhibition. A scanning probe microscope image of a single myosin molecule, showing the two 'heads', which are involved in the ratchet mechanism of muscle contraction.
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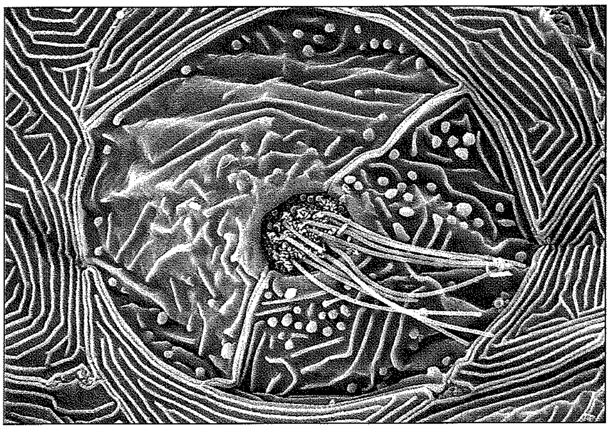

Fish lateral line system
A scanning electron micrograph of a neuromast organ in the zebrafish lateral line system, showing the hair cells. These are similar to those in the human cochlea.
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