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Abstract. Harvesting metals from hyperaccumulator biomass (or 'metal crops') may be implemented either as an alternative type of agriculture by farmers (agromining), or implemented on mined-out or degraded land (phytomining). Scientific experiments and field trials relating to agromining/phytomining are being developed at various locations around the world. Large-scale commercial application of the technology has not yet happened however, and to build the case for investors or to seek industry adoption, a large-scale demonstration is urgently needed. We outline current developments in the agromining/phytomining field on the basis of research undertaken by our team.

Keywords: bio-ore, hyperaccumulator, nickel, trials.

1 Agromining and Phytomining

Growing and harvesting selected hyperaccumulator plants on agronomical scale followed by metallurgical processing of the bio-ore may produce economically valuable trace elements (Chaney et al. 1998). This technology may be termed either 'agromining' or 'phytomining' depending on the type of application (Van der Ent et al. 2015a). Whereas phytomining takes place on degraded or mined land as part of a rehabilitation strategy, agromining takes place on low-productivity agricultural soils to generate economic returns to farmers.

2 Feasibility

Agromining or phytomining may be undertaken to produce As, Se, Cd, Co, Mn, Ni, Tl or Zn, as suitable hyperaccumulators are known for these trace elements. However, economic feasibility ultimately depends on the element market price, the annual yield per unit area and the availability of surface areas enriched in the target element (Van der Ent et al. 2015a). Considering these factors the technology will be especially feasible for Ni, Se and Tl, but large surface areas with enrichment exist only for Ni and Se. Other factors to be considered in feasibility assessments include: (i) total development costs through trial stages to full operation; (ii) predicted operating costs; (iii) land ownership or lease costs; and (iv) price of the target metal on world markets (Van der Ent et al. 2015a). In the tropical context, phytomining will take place in mining leases funded by mining companies, whereas agromining works via arrangements with farmers and landowners to manage crop production and harvest, with payment on the basis of the Ni contained in the harvested crop.

3 Suitable soils for implementation

Recent research in Malaysia demonstrates that not all ultramafic soils are suitable for agromining/phytomining as the potential Ni yield depends on the soil available Ni pools (Van der Ent et al. 2013). Tropical Ni hyperaccumulator plants in Sabah (Malaysia) are distributed on circum-neutral serpentinitic and saprolite soils with high Ni plant-availability (Van der Ent et al. 2015b). The landscapes after conventional Ni strip-mining appear promising for phytomining because the chemical characteristics match this natural habitat. The potential lifetime of a phytomining operation may be estimated by considering the Ni concentration in 1 ha (total Ni concentration of 2000 mg kg^{-1} over 1 meter of which 10% is plant-available) and with a metal crop producing a yield of 100 kg Ni ha^{-1}. Given this scenario the agromining operation could last for 30 years.

4 Current developments

The development of agromining/phytomining is currently progressing in several areas around the world, specifically with extensive field trials undertaken over a number of years in Albania, the future trials planned in Spain and Greece, and recent reconnaissance and experimental work in Malaysia, Indonesia and Zambia. Below we outline the present status of some of these developments:

4.1 DR Congo and Zambia (Cu, Co)

The Copper-Cobalt Belt of the DR Congo and Zambia is one of the most important metallogenic regions and, without doubt, the richest metallophyte location in the world. To date, over 600 metallophytes have been described from the Copper-Cobalt Belt, including many species that occur nowhere else (Brooks et al. 1985; Baker et al. 2010). These metallophytes occur on isolated copper-mineralised hills spread throughout the Copper-Cobalt Belt. The existence of more than 30 Cu-Co hyperaccumulator plants is a special feature of this region, and these plants accumulate extraordinarily high concentrations (up to 2%) of Cu and Co metal in their living tissues (Reeves and Baker 2000).

The concomitant occurrence of Cu-Co hyperaccumulator plants and large areas with metal-enriched and metal contaminated soils makes a compelling case for developing these phytotechnologies in Zambia. Although the phenomenon of abnormal accumulation of Cu-Co in certain plants from the Copper-Cobalt Belt has been known since the 1950s, no study to date has elucidated metal speciation and distribution in these Cu-Co hyperaccumulator plants. Funded by the International Mining for Development Centre (IM4DC) in Australia a fieldwork campaign was successfully completed in Zambia in November 2014. During the fieldwork a range of active and abandoned mines and tailings storage facilities were visited in the Copperbelt Region of Zambia. Three Cu-Co hyperaccumulator plants were sampled for ongoing micro-PIXE and synchrotron XAS studies in South Africa and Australia respectively.

4.2 Experimental studies in Malaysia (Ni)

Tropical Ni phytomining trials are currently setup in Sabah (Malaysia) near Kinabalu Park. Using two native Ni hyperaccumulator species, *Rinorea bengalensis* and *Phyllanthus securinegoides*, experimental studies are undertaken to establish optimal agronomic practises to stimulate biomass production and Ni yield. This work aims to identify operational agronomics and provide 'real-life' evidence for attainable yields. In a parallel strategy handheld X-ray Fluorescence (XRF) technology is being applied to screen tens of thousands of herbarium specimens held at major tropical herbaria for hyperaccumulators of Ni and other elements to increase the number of possible species for application in agromining/phytomining. Adding greater numbers of hyperaccumulators to the knowledge base increases the options for selection of species with optimal characteristics to match local conditions. These characteristics include he ability to re-spout after pruning, inherent growth rate, irrigation requirements, nutrient needs and Ni allocation in different fractions of the aboveground biomass.

4.3 Exploration in Indonesia (Ni)

In partnership with Eramet/PT Weda Bay Nickel, tropical Ni phytomining is currently being developed in Halmahera Island in the Maluku Provide of Indonesia. The extremely high plant diversity of the rainforest on Halmahera Island, in combination with over 5000 km^2 of ultramafic soils, offers both high potential for the discovery of Ni hyperaccumulator plants, but also a great challenge as information on the occurrence such plants is virtually non-existent at present. Therefore the first stage of the current project is to identify native Ni hyperaccumulator plants in Halmahera Island. In order to be considered suitable or application as 'metal crops' in future phytomining operations, attention focuses on finding plants with at least 1% foliar Ni (so-called 'hypernickelophores'). One such plant has already been recorded on the basis of herbarium collections; *Rinorea bengalensis*, the same species that is subject of ongoing experimental work in Sabah (Malaysia).

Rapidly re-establishing plant growth on ultramafic soils after Ni mining is necessary to reduce soil run-off. However, establishing vegetation on mined soils is challenging because of the extreme physical and chemical properties of the saprolite materials. Therefore, appropriate matching of native Ni hyperaccumulator species to local soil and climatic conditions is critical. This process must be repeated in different bioclimatic regions and on different soils.

4.4 Other elements and possible opportunities

Phytomining may also be a possibility for a number of other valuable trace elements present in some types of minerals wastes such as tailings. Current research activities with collaborators include experimental work with *Berkheya coddi* for extraction of platinum group elements (PGEs) from minerals wastes in South Africa, the possibility of extraction of Tl from Zn-Pb-Cu tailings in Australia, and rare earth elements (REE) from minerals wastes in China.

5 Conclusions and outlook

Although agromining/phytomining technology has been successfully demonstrated in academia, no large-scale implementation has yet been seen. This may result from a lack of awareness of the technology in the minerals industry. However, the expiry of the patents this year may stimulate renewed interest from commercial entities and investors. Current research activities are centred on parallel strategies in the Mediterranean Region and in Australasia. The combined efforts are now gaining momentum and significantly advance our knowledge on the success factors critical to agromining/phytomining.

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