RECENT ADVANCES IN DEVELOPING TROPICAL NICKEL AGROMINING

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ABSTRACT

Hyperaccumulator plants can be utilized as 'metal crops' in agromining operations. This emerging technology produces 'bio-ore' by growing 'metal crops' on sub-economic ore materials, such as natural ultramafic soils. In a typical application plant material is periodically harvested, followed by air-drying and incineration to produce the bio-ore intermediate. The bio-ore is of very high grade (>15 wt. % nickel), and of high purity, and may be processed into a number of different products (including nickel metal, nickel-based catalysts and pure nickel salts). Current research efforts from our team focus on Mediterranean climate field trials (Albania, Spain) and tropical climate field trials (Malaysia, Indonesia). Field-scale demonstrations are required to provide evidence of real-life performance and of economic viability. If the trials are successful, agromining may in the near future support local livelihoods with income opportunities as an alternative type of agriculture: to farm nickel.

KEYWORDS

Agromining, Phytomining, Nickel, Strip-mining, Tropical Ultramafic Soils.

INTRODUCTION AND BACKGROUND

Hyperaccumulators, plants with the exceptional ability to uptake and concentrate trace elements in their shoots, can be utilized as 'metal crops' in agromining operations (Van der Ent et al., 2013a; Chaney et al., 1998; 2007; Baker et al., 2010). Agromining produces 'bio-ore' from harvested 'metal crops' grown on unconventional resources such as natural ultramafic soils (Van der Ent et al., 2015a). The bio-ore is a high purity and very high-grade (>15 wt. % nickel) product intermediate that may be turned into a range of different nickel products (nickel metal, nickel-based catalysts and pure nickel salts). The potential for agromining is greatest in tropical regions (Asia-Pacific Region: Indonesia, Malaysia, Philippines, Papua New Guinea and New Caledonia) where very large expanses of ultramafic soils exist (Van der Ent et al., 2013b). Agromine operations may replace existing marginal agriculture on poor ultramafic soils, for example oil palm plantations that require high fertilizer inputs to be profitable, or take place under a co-cropping regime. The ability of 'metal crops' to achieve high nickel concentrations in biomass (and hence in harvested bio-ore) from soils with just <0.5 wt. % nickel, makes it possible to access non-conventional resources, not accessible by traditional mining techniques. For example, agromining could be implemented both on the large 'halo' around the mine leases, and as part of the progressive rehabilitation process after conventional resource extraction. As with all methods for resource extraction, agromining will be finite due to the diminishing concentrations of nickel in the zone accessible by plant roots (Chaney et al., 2014). Nevertheless, considering soil materials with 0.2 wt. % nickel and 'metal crops' with a yield of 100 kg nickel ha^{-1} the agromining venture may be sustainable for decades (Van der Ent et al., 2015a).

Substantial progress is currently being made in developing nickel agromining in the Asia-Pacific Region by our research team. Immediate priority is intensive screening for potentially suitable 'metal crops' in the region. The recent discovery of >50 new hyperaccumulator plant species in Sabah (Malaysia) and Halmahera (Indonesia) by our team is indicative of the very high potential of this untapped resource in the Asia-Pacific Region (Van der Ent et al. unpublished data,). On the basis of the range of different hyperaccumulator plant species that have been discovered, suitable 'metal crops' are now being selected for agronomic trials to assess growth performance, fertilizer requirements and sustained nickel yields of the crops when successively harvested.

CURRENT RESEARCH ACTIVITIES AND EXPERIMENTS

The application of agromining is envisaged to provide opportunities for an income source for communities in Malaysia, Indonesia and the Philippines as an alternative type of agroforestry ('farming for nickel'). The land targeted for setting up such operations consists of ultramafic soils of poor normal agricultural utility. In Sabah (Malaysia) in excess of 3500 km^2 of ultramafic soils exists, whereas in Sulawesi (Indonesia) over 15 000 km^2 of ultramafic soils are present (Van der Ent et al., 2013b). Criteria to consider for use of land for agromining include the ownership arrangements, location outside any protected areas/nature reserves, road accessibility, slope aspect, availability of (gravity) irrigation, local soil properties, etc. Clearly the majority of the geological expanses in the Asia-Pacific Region would not be suitable for agromining on the basis of these criteria, but even if a conservative estimate of 10% of this ultramafic landmass were suitable, this would represent an enormous potential for developing agromining. It should be emphasised that it is not anticipated that the development of agromining poses a threat to existing biodiversity by increasing land clearing, as large areas of degraded land (from logging, forest fires, etc.) already exist in Indonesia and Malaysia. There is evidence that degraded land, where topsoil has eroded, is more suitable for agromining than (recently) forested soils. There are indications for this in the fact that most nickel hyperaccumulator plants are naturally found in secondary, disturbed habitats, often on ridges, landslides and in riparian zones (Van der Ent et al., 2015b). In tropical regions, the topsoil ('limonite') is generally depleted in nickel that is further enriched in the subsoil. The chemical speciation of nickel in the subsoil ('saprolite') is also qualitatively different and hyperaccumulator plants are thought to better access the nickel-bearing phases in this material, compared to the limonitic topsoil (Van der Ent et al., in press). This also has implications for implementation of agromining (or more strictly defined as phytomining, see Van der Ent et al., 2015a) on mined substrates after conventional strip-mining, where the saprolite has been exposed after extraction of limonite ore. It is anticipated that the leftover material in the mined landscape is especially suitable for establishing 'metal crops'.

In partnership with Sabah Parks a research station has been setup at the Monggis sub-station of Kinabalu Park in Sabah, Malaysia. The principal purpose of this 'Hyperaccumulator Garden' is to serve as a living collection/gene bank of all known hyperaccumulator plant species in the region, many of which are exceedingly rare and potentially threatened due to habitat loss. In addition, the station is used for applied research on hyperaccumulator plants. Currently, experimental studies are undertaken to establish optimal agronomic practises to stimulate biomass production and nickel yield in *Phyllanthus* cf. *securinegoides* (Phyllanthaceae) and *Rinorea bengalensis* (Violaceae). These two plant species were selected as the most promising 'metal crops' after an evaluation process taking their relative growth rates, nickel accumulation, and effective propagation methods into account. The large pot trial, with these to species, consists of a solution-based chemical treatment injected in each pot at 4-month intervals to adjust soil pH and to provide additions of nickel, calcium, sulphur, nitrogen, potassium and phosphorus (in a randomised block design).

At the nearby village of Pahu, a hectare-scale field trial has been set up with *Phyllanthus* cf. *securinegoides* and *Rinorea bengalensis* to provide 'real-life' evidence for attainable yields using these 'metal crops' over a number of years in a long-term study. The field trial is aimed to clear the barriers to successful implementation of agromining by delivering the critical insights in the suitable combinations of soil amendments to obtain optimal growth conditions. Relevant parameters will be recorded and monitored e.g. growth rate, biomass production by unit surface area, nickel concentrations in harvested biomass, etc.

INTENSIFYING EFFORTS FOR POTENTIAL 'METAL CROP' DISCOVERY

Discovery of greater numbers of tropical hyperaccumulator plant species is necessary to increase the options for selection of possible 'metal crops' with optimal characteristics. Only hyperaccumulator plant species that accumulate in excess of 1 wt. % nickel in their biomass, but preferably >2 wt. %, are in principle suitable as a 'metal crop'. Desirable other traits include a high growth-rate and high biomass of the shoot, the ability to thrive in exposed conditions, low irrigation requirements, ease of mass propagation, resistance to disease, and so forth.

One of the most effective new methods for mass discovery of hyperaccumulator plants is the use of handheld X-ray Fluorescence (XRF) instruments to screen tens of thousands of herbarium specimens. This has recently been undertaken at a major tropical herbarium (the Forest Research Centre, Sepilok, Sabah, Malaysia) where >10 000 specimens were measured for a wide range of elements, which led to the identification of numerous hitherto unknown hyperaccumulator species of nickel and other elements (including for cobalt, manganese and zinc). This exercise has added a multitude of species with >1 wt. % nickel in their leaves, adding to the five such ('hypernickelophore') species already known from Sabah, Malaysia (Van der Ent et al., 2015b). Our team is in the process of expanding this approach by undertaking massive herbarium XRF scanning at other global herbaria.

The process of hyperaccumulator discovery has to be undertaken anew in different geographic regions to permit appropriate matching of local nickel hyperaccumulator species to local soil and bioclimatic conditions. Some regions, including Southeast Asia and Cuba are home to numerous candidate 'metal crop' species (ostensibly meeting the criteria as described earlier), but other regions including Brazil and New Caledonia, despite having many hyperaccumulator species, have no or very limited numbers of suitable 'metal crop' candidates. In Brazil over 40 hyperaccumulator species are presently known, but the highest concentrations are found in species such as *Pfaffia sarcophylla* (Amaranthaceae) that have (very) low biomass (Reeves et al., 2007). In New Caledonia, 65 hyperaccumulator have been described to date, and several have among the highest nickel concentrations in the shoot of any plant known globally, for example the famous *Pycnandra acuminata* (Sapotaceae) with its green nickel-rich latex (Jaffré et al., 2013). However, this species, and others such as *Psychotria gabriellae* (Rubiaceae, with up to 6.4 wt. % nickel) and *Hybanthus austrocaledonicus* (Violaceae, with up to 2.5 wt. % nickel) (Jaffré et al., 2013) are rainforest understorey shrubs presumed to be slow growing. Nevertheless, several *Phyllanthus*-species, most notably *Phyllanthus favieri* (*serpentinus*) with up to 4.2 wt. % nickel (Jaffré et al., 2013), may be 'metal crop' candidates. Australia only has three known nickel hyperaccumulator species, including *Stackhousia tryonii* (Celastraceae, with up to 4.1 wt. % nickel) (Reeves, 2003) and *Hybanthus floribundus* (Violaceae, with up to 1.4 wt. % nickel) (Cole, 1973), but neither of these are suitable 'metal crops' due to their slow growth rates and low biomass. In contrast, in Cuba 130 hyperaccumulator species are presently known, of which numerous (53) species with >1 wt. % nickel in their shoots, especially in the genera *Buxus, Phyllanthus* and *Leucocroton* from the Buxaceae, Phyllanthaceae and Euphorbiaceae families respectively (Reeves et al., 1996; 1999).

There are two species, *Alyssum murale* (Brassicaceae) originating from the Balkans and *Berkheya coddii* (Asteraceae) originating from South Africa, that may be regarded as universal 'metal crops' with applicability in Mediterranean and Steppe climates respectively. Extensive greenhouse and field trials since the 1990s have demonstrated the performance of these two species in agromining at various locations around the world (Bani et al., 2015; Chaney et al., 2007; Li et al., 2003; Robinson et al., 1997). Although it is generally preferable to utilize native species for agromining, rather than imported exotic species to reduce biosecurity risks, these two species may nevertheless be used as a 'metal crops' in cultivation outside of their natural ranges. Careful climatic matching remains important, as the failed experiment with *Alyssum* spp. in Indonesia demonstrates (Van der Ent et al., 2013b). Therefore, it is conceivable that *Alyssum* spp. find application in agromining operations in Australia (Queensland), China, Balkans, Iran, Greece, Russia, Turkey, and the Unites States. *Berkheya coddii* might find application in Brazil, South Africa, the United States, and Zimbabwe. Conditional of using introduced species is full compliance with applicable national biosecurity legislation and appropriate crop management. The latter may include harvesting of the crop before flowering to avoid spreading of propagules. Poor management subsequent to the scientific trials with *Alyssum murale* in the United States resulted in the species becoming invasive and eventually being listed as a noxious weed in Oregon (USDA, 2015).

CONCLUSIONS AND OUTLOOK

Although agromining technology has been successfully demonstrated in Mediterranean and temperate climates, to date no trials have been undertaken in tropical regions (– but see Losfeld et al., 2014 for current developments in New Caledonia) until work by our team commenced in Malaysia and Indonesia. The combined efforts are now gaining momentum and significantly further our knowledge on the success factors critical to agromining in the tropical realm. The knowledge critical to advance agromining is both fundamental and applied: (i) a better understanding of the ecophysiology of hyperaccumulator plants may allow for manipulations to stimulate plant nickel uptake; (ii) soil amendments, including nutrition-management, optimizes growth rate and biomass production, while sustaining nickel shoot concentrations, and hence nickel yield (Nkrumah et al., 2016). Ultimately, field-scale demonstrations of agromining are required to evaluate the fundamental parameters (i.e. success of the crop, nickel yield per hectare per year).

Over time, agromining will improve soil fertility and reduce toxicity due to soil nickel; this is a significant service rendered through agromining (Van der Ent et al., 2015a). As such it makes the land suitable for other future, including forestry and some types of traditional agriculture. It is envisaged that agromining could support local livelihoods with income opportunities as an alternative type of agriculture: to farm nickel.

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