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Metallophytes — A Unique Biodiversity and Biotechnological Resource in the Care of the Minerals Industry

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Abstract

Metallophytes – plants that have evolved on metal-enriched soils, and their microbial associates – have key 'values' that must drive research on their unique properties, and ultimately the conservation of the rich biodiversity resource. The ability of metallophytes to tolerate extreme metal concentrations commends them as the optimal choice for ecological restoration of mineral wastes and metal-contaminated sites. Metallophytes have also spawned several novel phytotechnologies, including phytoremediation and phytomining. Action towards conserving the global metallophyte resource base is imperative, because many species are under threat of extinction from mining activities in the underlying metal-rich substrate. The last decade has seen an ever-increasing interest in metal-tolerant and metal-accumulating plants, both from an academic standpoint, and their use in revegetation and phytostabilization, and it is timely to take stock of this important resource that has, largely by default, ended up in the 'trust and care' of the minerals industry.

1 Introduction

Society is making a gradual but progressive transition to a philosophy of sustainable development, and the minerals industry is seeking to maximize its contribution to this change through the charter of the global mining initiative (GMI). Reduced environmental impacts and ecological methods for site restoration are already being realized. Conservation of biodiversity is high on the international agenda, but is enough really known about the plant species indigenous to the metal-rich environments where metalliferous mining occurs? In July 2001, seventeen specialists from around the world joined together in the United Kingdom, at the Rio Tinto plc-sponsored Robert Brooks workshop, hosted by the Royal Botanic Gardens, Kew, to discuss the conservation and exploitation of these plants, and how they can contribute to the ecological restoration of mine sites. Sadly, to date the minerals industry has moved too slowly to recognize and implement the outcomes of this forum.

The demand for minerals continues to rise as populations grow and the expectation of improved living standards brings more countries into a process of industrial development. Minerals and metals have unique properties that underpin many of society's requirements today, and technology is constantly recognizing new applications for those properties. The same technological advancement is also improving resource efficiency, doing more with less. We are encouraged to consume less, to re-use and recycle more, but these factors may only slow the trend of higher demand for minerals, not reverse it.

Individual mineral deposits are finite resources and are not being renewed, except over geological timescales. The discovery of new deposits is therefore required to meet the continuing demand for minerals. All other things being equal, discoveries of minerals are most likely to be made where access to land and the application of new techniques has been difficult or limited by political factors. This suggests that exploration will increasingly be focused on the less well-explored regions of the world. These same regions are frequently those with both the richest biological diversity, and where scientific exploration has been slowest and patchiest. This brings the minerals industry into contact with the issues of the identification and conservation of species and ecosystems in the areas where it seeks to work.

Of particular relevance to the industry are the unique plant and microbial communities, and species they comprise, that thrive on metal-enriched substrates – the metallophytes. Ancient, undisturbed metal-rich substrates often occur where mineral deposits outcrop and may themselves represent mining targets. Even where the economic ore is deep below the surface, the mining process may require the surrounding rocks to be removed and discarded. In so doing, new metal-rich substrates are created, posing a challenge for restoration scientists. This conjunction of factors makes metallophytes a uniquely relevant part of the overall biological diversity for the mining industry. Sustainable development principles lead to an imperative to explore, catalogue and conserve metallophyte species, and to find uses for their unique properties. Furthermore, good economic reasons exist for studying metallophytes. The bad press often associated with mining operations can be closely linked to the loss of biodiversity; the extinction of a rare plant or animal species is much discussed, often causing public outcry. There are also significant potential commercial applications for metallophytes. Metal-tolerant plant species offer an *el dorado* of genetic resources that could be used in the decontamination and ecological restoration of metal-contaminated sites (Baker et al., 2000; Whiting et al., 2004). Unfortunately, metallophytes can be lost in the early stages of mine development, and hence positive actions are required to conserve them. The goal is to raise industry awareness of the value of metallophytes, and to highlight priorities for the minerals industry in relation to metallophyte conservation and exploitation.

2 Evolution of metallophytes

Metal-rich substrates have driven the evolution of some of the world's most remarkable and restricted plants and microbial associations (Antonovics et al., 1971). The weathering of exposed orebodies over a geological timescale has resulted in substrates containing high concentrations of metals. These substrates, however, are rarely totally devoid of vegetation. Their plants must therefore possess biological mechanisms that allow them to tolerate the high concentrations of metals that are toxic to normal plants. The evolution of this high degree of metal tolerance is a result of processes of natural selection. The metals in the soils have exerted a strong selective pressure on the plant colonists whose seeds or propagules have been transported onto the site by the wind, birds or animals. Only those individuals with a degree of innate resistance to metal toxicity have survived and reproduced. Over many generations, this selective pressure has resulted in the development of an assemblage of plants with physiological mechanisms enabling them to tolerate or detoxify the metals.

Metal tolerance in plants is not simply defined, and the mechanisms of tolerance vary considerably according to both the metal and the plant species. In some cases, metal tolerance has evolved in individuals of a common species, which is found growing both on and off mineralized soils; the individuals growing on the metal-rich soil have adapted internal mechanisms to limit uptake of the metals, and/or detoxify them within their tissues. In other cases, metallophytes have diverged genetically and morphologically to form completely new species, not found anywhere else. In the latter case, plants have evolved characteristics that fit that particular ecological niche, and are endemic to the mineralized area. This tends to occur where the outcrop is geographically isolated and has been exposed for very long periods of time.

Metal-hyperaccumulating plants are an extreme example of the extraordinary and complex physiological adaptations of plants to metalliferous environments. Hyperaccumulator plants can amass extremely high concentrations of metals in their tissues without symptoms of toxicity, up to 3% of their dry weight in the case of Ni, Zn, and Mn (Baker and Brooks, 1989). These species are very tolerant to metals. The curiosity value of hyperaccumulator plants has increasingly driven plant scientists to study their ecology and physiology, and in the early 1980s it was recognized that they might be used to 'harvest' toxic metals from polluted sites and allow recovery of valuable metals. This commercial goal is an incentive to find more metal-hyperaccumulating species. In the last few decades, the number of hyperaccumulators identified has risen from tens of species to over 450 (Baker et al., 2000), and the list now is more than 500 taxa. In spite of this, it is reasonable to assume that numerous more hyperaccumulators remain to be discovered, and that many thousands of metal-tolerant species can be added to the patchy existing inventories of metallophytes.

The reasons for the scant information on the numbers of metal-tolerant plants are perhaps two-fold. First, metal tolerance is impossible to test empirically from a field survey. Unlike the hyperaccumulation trait, where foliage can readily be sampled for chemical analysis, the possession of metal tolerance traits is usually a tacit assumption based upon the fact that the plants are surviving on metal-rich substrates. Second, there has been minimal funding available to support large-scale studies, particularly in remote areas that are also major centers of plant diversity in the world. One reason for minimal funding might be that the commercial applications of metal-tolerant, but non-accumulating plants (for example in revegetation) have had lower potential for generating revenue than the recent highly publicized potential for metal extraction using hyperaccumulating plants.

The number of metallophytes identified and studied will no doubt rise sharply in the next few decades, as a result of the recent drive for revegetation of degraded lands using native and local species. The minerals industry is now embracing site restoration using such ecological principles, requiring high native biodiversity rather than monocultures or introduced species (Dobson et al., 1997). This is fuelled by the move toward environmentally-sustainable operations and increasingly strict regulations on mine closure and site decommissioning. Ecological restoration returns a site to a state as close as possible to that existing when the operation commenced. This is a major advance on previous approaches where restoration relied upon natural colonization or manual ‘greening’, often using only a few commercially-available grass cultivars. It is evident that to re-introduce the local metallophyte biodiversity, these plants must be identified, conserved and studied in relation to their metal tolerance and ecological function. Harnessing this natural pre-adaptation of plants to the local conditions provides the additional benefit of preserving global biodiversity.

3 Biodiversity in action

Sustainable development, meeting present-day society’s requirements whilst maintaining an ecosystem in a healthy and viable state, is now a global maxim. One of the primary frameworks for stewardship of the environment is the Convention on Biological Diversity (CBD) adopted at the 1992 Earth Summit in Rio de Janeiro. The CBD has provided the impetus for governments and industry alike to address the key issues of their operations for minimizing impacts on the environment. In the minerals industry, major players committed to responsible operation in both the social and environmental contexts initiated the GMI. The GMI group initiated the Mining, Minerals and Sustainable Development (MMSD) Project, which provided an independent, stakeholder-based analysis of the way in which the minerals industry can contribute to a program of sustainable development. The GMI and MMSD received considerable international acclaim (Anon., 2001). It is through such projects that the importance, conservation and uses of metallophyte biodiversity can best be promoted. For example, the MMSD Report (MMSD Project, 2002) delivered crucial insights for the implementation of a sustainable development model in the minerals industry. Progress in relation to environmental performance and the disposal of wastes are a core part of the Report, and it is hoped that it will provide the agenda for future development under the stewardship of the International Council on Mining and Metals (ICMM, 2006).

4 Immediate conservation action

The minerals industry is generally not aware of the ecological relevance of metallophytes in terms of biodiversity, and the potential value they offer for site restoration. Only recently have concerted efforts been directed at the conservation of biodiversity. Few restoration projects specifically integrate communities of indigenous metal-tolerant plants into the restoration armory. There was a major leap towards the conservation and utilization of metal-tolerant plants seven years ago, when Rio Tinto plc sponsored the Robert Brooks workshop at the Royal Botanic Gardens, Kew. This was a forum on metallophytes, mine waste and ecological reclamation, building upon an existing successful partnership between Rio Tinto plc and RBG Kew. The workshop brought together 17 specialists who research metallophyte floras and their ecology, systematics and physiology at many locations around the world. The aims were to highlight the current state of knowledge on metallophytes, to show how research could be used to address both conservation issues, to enhance future metallophyte use in site restoration, and to establish research priorities to meet the environmental challenges facing the minerals industry in the next decades.

The five major questions addressed by the workshop were:

- What is known about the global status of metallophytes, and what research is required to realize their potential for the reclamation of disturbed land?
- Are metallophytes threatened by the current or likely future activities of the minerals industry, and how can they be conserved?
- What potential do metallophytes offer as a resource for the clean-up of contaminated lands?
- Within the framework of the CBD, what problems exist in gaining prior informed consent to access genetic resources and how can the benefits be shared equitably?

- What are the scientific, practical and ethical issues raised by the prospect of genetically modifying plants to confer metal tolerance for use in site restoration, and what research activities can assist in these issues?

The principal output of the workshop was an agreed list of research priorities. The delegates proposed crucial industry action on biodiversity assessment, and indicated the benefits of partnership between the corporate and non-profit sectors. Seven key issues for formulating an action plan for sustainable metallophyte conservation, research and development work and use were identified. These are listed in Sections 4.1 to 4.7.

4.1 Who should be interested?

The minerals industry must be aware of the importance and potential value of metallophytes. This involves the global-scale dissemination of metallophyte information within the industry. The Robert Brooks workshop was the first industry-led action to publicize the nature of metallophytes and the importance of conserving them, reinforced subsequently by the MMSD Report (MMSD Project 2002). It is important to identify a consortium of industry parties dedicated to the planning, operation and restoration phases of mining ventures in a way that will promote metallophyte biodiversity and ecological sustainability. It is envisioned that many mining companies will become involved at some level because of the increasingly strict legislation on reducing environmental impacts, and the global shift towards sustainable development. The consortium might initially include only the larger players; however, once the vital issues and procedures have been agreed, the industry as a whole will benefit. The consortium must also include scientists involved in metallophyte research. Concern was expressed that many mineral operations in remote areas have not strongly involved local scientists. Local researchers are an indispensable resource in the identification of metallophyte species, and regional knowledge may be a fast-track to recognition of the species most under threat. Involving local researchers is consistent with the basic tenets of sustainable development and the goals of the MMSD Project. The IUCN-ICMM Post-Mining Alliance could also be an appropriate agency to promote this action.

4.2 Development of policies and protocols for metallophyte conservation

A clear statement on the importance of metallophytes in ecological and commercial terms is required. Policies for identifying and preserving metallophytes and their plant communities must be agreed upon within the minerals industry to ensure that conservation of biodiversity is achieved at all sites. These policies must be comprehensive and transparent if they are to be effective. All parties within and outside the consortium should have (equitable) access to metallophyte diversity and share benefits arising from this access in a fair and equitable manner with provider countries. The policies must be consistent with the objectives of the CBD, which came into force in December 1993 (ICMM, 2006). A number of Articles of the Convention are pertinent to metallophyte conservation. A balance must be attained when developing policies for metallophyte conservation. On the one hand, legislation must be sufficiently effective that it prevents large or multinational groups from exploiting indigenous material and information without regard for sustainable development. On the other hand, it must not become so restrictive as to make metallophyte conservation, research and usage impractical or, at worst, impossible. For example, some countries are moving toward more restrictive legislation to control all the initiatives concerning their biological inheritance. The successful strategy for conserving metallophytes must have the advantages of a flexible framework, but be derived from a strong background knowledge of research and case studies. Guided by policy, protocols must be established which guarantee that attempts to conserve biodiversity are effective. Rigorous protocols for identification of metallophyte species will be required when undertaking geobotanical exploration, both in relation to new sites and in planning restoration strategies for decommissioning existing sites. In many cases, the protocols will need to be tailored to the local environmental conditions. Again, utilizing local knowledge under the guidance of a global protocol will improve regional methodologies. It is therefore imperative that objectives and success criteria be clearly established to allow metallophyte conservation to be undertaken systematically. This will ensure that the causes of any failure are evident (through monitoring) and appropriate remedial action (through management) can be taken.

4.3 Identification of metallophyte diversity

Species or assemblages of species must be identified for conservation. The first decision is where geobotanical reconnaissance should focus. The most industrialized areas of the globe, such as Europe and the USA, have been surveyed comprehensively for their botanical diversity, and much is known about the status of their metallophyte flora (Ernst, 1974). Much less information is available on metallophytes from some other regions, particularly in the tropics, which support some of the most diverse plant communities. The information on metallophytes in these ecosystems is typically generated by scientist-initiated expeditions, which continue to produce discoveries of new and unusual metallophyte species. This is exemplified by the rapid expansion in the number of tropical hyperaccumulating plants identified (Baker et al., 2000). In relation to the conservation of biodiversity by the minerals industry, efforts should be focused on surveying any area that is likely to be the target for future minerals extraction. Geobotanical exploration should therefore be directed at areas with sizeable naturally-exposed metal outcrops, for example, mineral ‘hotspot’ areas in Latin America (Ginocchio and Baker, 2004), China and Southeast Asia (Rajakaruna and Baker, 2004), equatorial and southern Africa, and Australia. Priority surveying in zones for development by the minerals industry leads to the second issue: when to survey. The optimal time is clearly prior to development, when the site is undamaged and species have not been lost. This information will provide a benchmark for future restoration. Unfortunately, studies of the vegetation at metal mines are often only implemented towards the end of the operational period in the form of scoping studies for the restoration plan for site closure. At these late stages, a number of the original metallophyte species might have already become extinct (Brooks et al., 1992), and there will be only fragmentary information relating to the original vegetation. The earlier that detailed biological reconnaissance is carried out, the greater the probability of successfully implementing procedures for conserving endemic species. Furthermore, early surveying of a site should not preclude later studies. Anthropogenic metal enrichment of an area during operation can also drive the evolution of metal-tolerant ecotypes, which can occur remarkably rapidly (Antonovics et al., 1971). Plant communities should therefore be monitored before, during and after operation. Third, careful consideration is required when determining how to survey. The procedures for geobotanical exploration must be rigorously designed using ecological techniques, to prevent important species from being overlooked. Before mining commences, knowledge of botanical features of the site must be acquired, including: i) inventory of floral diversity; ii) recognition of vegetation units; and iii) establishment of ecological links between species and/or soils (biogeochemical transects). A detailed knowledge of local taxonomy, coupled with physiological ecology and soil science is essential for successful reconnaissance and a full interpretation of data. Moreover, comprehensive surveying must include species from all major taxonomic groups, including smaller organisms such as metal-tolerant lichens and bryophytes which can exhibit very high levels of endemism to mineralized surfaces (Purvis, 2000). Indeed, the close contact between lichens and rocks suggests that lichen assemblages can be particularly useful as bioindicators of metals for future mineral exploration.

4.4 Development of the metallophyte resource base

Marshalling of metallophyte information and the preservation of germplasm (seeds, spores or other propagules) are critical for metallophyte conservation, for applying them to site restoration, or for exploiting their biological properties for extracting metals (phytoremediation and phytomining (Baker et al., 2000; Chaney et al., 2000, 2005). Collections of metallophytes must be established in herbaria, germplasm banks, and as living collections in situ at mined areas and in botanical gardens. Creating repositories of metallophytes at both the regional and global scale should be a priority. The collections must use an effective methodology to ensure seed viability is maintained, and species must be collected from both exploited and unexploited metalliferous environments. To date, there has been little concerted effort to conserve metallophyte germplasm, with minimal integration at a global level. There is an urgent need to bring together academic interests with those practitioners in the minerals industry striving to reinstate native vegetation on metalliferous soils. Three primary initiatives will advance the conservation of metallophytes:

4.4.1 Database information

Geobotanical data from mineralized areas provides key information on the extent of the metallophyte resource base. Attempts to produce such databases have been few and global coverage is patchy. The most extensive to date are the METALS (metal-accumulating plants) database produced by ECUS at the

University of Sheffield, U.K. originally for Noranda/Falconbridge, and Environment Canada's PHYTOREM database. Significant efforts are required to integrate and expand these metallophyte databases. The development of databases of metallophytes must be well managed, and they should be widely accessible.

4.4.2 Living collections

Living collections of metallophytes can be maintained at botanic gardens and arboreta, allowing both the conservation of the genetic resource and the propagation of materials for further research and development work. Few such collections currently exist, but they should be encouraged. An exceptional example is the collection of some 135 metallophytes endemic to the ultramafic soils of Cuba, growing at the National Botanic Garden in Havana. Even so, only a limited number of species may be preserved in this way (Dobson et al., 2001). Perhaps the solution to conservation of living material lies in setting aside protected areas of land in situ as reserves or gardens, where a large part of the original ecosystem can be retained. Alternative solutions include the establishment of metallophyte nurseries and seed gardens (orchards) on a commercial scale, to generate sufficient material for future restoration schemes. Research efforts should focus on gaining a better knowledge of establishment success, nutritional requirements, growth rate, vegetative multiplication, reproductive biology and seed preservation of native species.

4.4.3 Germplasm and herbarium collections

Collections of germplasm and preserved plant materials are vital for basic research efforts into the conservation of genetic resources, and for large-scale breeding activities. Classically, plant collections are maintained as herbaria, with the intention of cataloguing biodiversity, and as a taxonomic reference library. Larger-scale collections of metallophytes must be made to preserve germplasm as a resource for research, including genetically diverse samples from representative sites. Germplasm repositories should be maintained at both the local and the global scale, and will require a secure base funding. As yet, there are no major germplasm facilities dedicated specifically to metallophytes, although in the last decade a number of small seed collections of metallophytes have been established as 'seed banks'. Underpinning this activity, however, is an urgent need for a much fuller understanding of the storage and viability requirements for seed of metallophytes; this is particularly important for tropical materials that can have very limited viability.

4.5 Access to metallophyte resources

Agreement on information and germplasm sharing is necessary in the conservation of metallophytes, particularly as they might be employed in a commercial environment. Mechanisms to promote access to metallophyte resources must include benefit sharing, focal points for collections, and methods of distribution. The first hurdle will be agreement upon the true value of metallophytes, and the custodianship of the species, ecotypes or cultivars. The CBD already provides a ratified framework within which to operate, ensuring conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of benefits arising from the non-commercial and commercial use of these resources. These three measures govern access by companies and other collectors to genetic resources and traditional knowledge. Parties seeking access must obtain the prior informed consent of the countries of origin and negotiate terms for joint research activities and for the sharing of benefits such as royalties and technology development. The minerals industry could assist in creating a system of facilitated access to metallophytes, including assisting researchers to identify a focal point in each country of origin that deals with access to genetic resources, and working with countries in the development of their national biodiversity conservation plans.

4.6 Commercial and non-commercial uses for metallophytes

Successful commercial applications for metallophytes are particularly important as they ensure that future research and funding are directed toward conservation of metallophyte resources. There has been considerable research into potential applications for metallophytes, which can largely be divided into three fields: i) using metallophytes to delineate metalliferous substrates when prospecting for new orebodies (bioindicators); ii) remedial applications including ecological restoration and phytoremediation of degraded land; iii) metal recovery (phytomining), where metallophytes are used to harvest metals from low grade ores that cannot be processed economically by other means. These have been reviewed comprehensively (Baker et al., 2000; Dobson et al., 1997). The commercial potential of phytoremediation and phytomining has now been demonstrated for a range of metals (Anderson et al., 1999; Van der Lelie et al., 2001; Chaney et al., 2005). The primary non-revenue producing application for metallophytes is site restoration. Restoration of degraded sites is an expensive aspect of mining operations. A stakeholder in commercial metallophyte technologies might produce sufficient revenue to offset the financial commitment to revegetation when decommissioning mines of the future where the environmental policy challenges will be greater than in the past. For ecological restoration, a strong commitment to conservation of metallophyte biodiversity is self-evident. However, conservation of metallophytes will also be important for phytoremediation and phytomining, to provide new materials or genes for future research and application. Rapid development and the full realization of these ‘green’ technologies requires significant support for both applied and ‘blue-skies’ research.

4.7 Assessment and management of environmental risk

The consequences of using metallophytes for phytoremediation must be assessed for their impacts on the environment, food quality and animal/human health. Researchers and practitioners of environmental restoration are already aware of the possible risks associated with the application of non-native species. Three situations are envisaged, with different levels of associated risk: i) revegetation with indigenous species, ii) revegetation, phytoextraction or phytomining with non-indigenous metallophytes, iii) genetically modified (GM) metallophytes or hyperaccumulators. Revegetation of sites with indigenous metallophytes presents minimal risk as the species were originally present at that site. The two latter situations might cause concern, however, related to the potential for non-native species to become weedy or invasive, for mobilization of metals into the food chain, or for hybridization of GM plants with wild relatives. These issues require comprehensive study to assess the associated risk and the ways of preventing or managing it.

5 Conclusions

Metal-tolerant plants and microbial associations are widespread, occurring on almost all metalliferous soils. Many metalliferous areas still support endemic species that have probably evolved in situ; such areas make an important and disproportionate contribution to biological diversity. Furthermore, the floras of these areas often include metal-hyperaccumulator species, which represent a resource that is both scientifically unique and valuable for many applications. However, there is still only fragmentary information on the world's metallophytes, their distribution, rarity and distinctive properties; even less is known of metal-tolerant non-vascular cryptogams and the full diversity of the microbial populations of metal-enriched soils.

The issues identified above should be the primary foci for future research and efforts to conserve metallophytes and more generally the biological diversity of metalliferous substrates. Such research should be strongly supported by the minerals industry, which in many cases is ideally placed both to ensure the conservation of metallophytes and to exploit their unusual properties. That mining companies should recognize this valuable biological resource is therefore implicit in the planning for mine closure before operations commence. Unfortunately, to date this has seldom been the case, and most mine closures occur on sites that have been open for many years. Systematic screening of plants on metalliferous sites, particularly those likely to be the focus of future mining, will identify priority candidates for conservation, for implementing ecological restoration of mine sites, and for the development of future ‘green’ technologies for removing metals from the soil (Whiting et al., 2004).

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