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Ultramafic nickel laterites in Indonesia (Sulawesi, Halmahera): Mining, nickel hyperaccumulators and opportunities for phytomining

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ABSTRACT

Indonesia (Sulawesi and Halmahera Islands) has some of the largest surface exposures of ultramafic bedrock in the world, and these are the sites of productive lateritic nickel mining operations. The proven and potential use of native plant species of ultramafic outcrops in mine rehabilitation can help drive conservation efforts, and nickel hyperaccumulators in particular can potentially be used in phytomining. The phytomining operation uses hyperaccumulators to extract residual nickel from stripped land. As such, in the foreseeable future, implementation of this technology is likely to be seen as a part of a progressive rehabilitation strategy of lateritic nickel mining in Indonesia. This approach ensures effective erosion control (e.g. 're-greening') while at the same time generating income by gaining residual nickel.

1. Introduction

Ultramafic rocks are derived from ferromagnesian-rich mantle and composed mainly of mafic minerals (magnesium, iron and siderophile elements such as nickel) (Brooks, 1987; Proctor et al., 2000) that weather in tropical humid climates to form thick lateritic red soils (Baillie et al., 2000). Ultramafic bedrock is widespread and extensive in Indonesia, such as in Sulawesi where with about 15,400 km^2 it is probably the world's largest of such outcrops, and another approximately 8000 km^2 of ultramafic outcrops in Halmahera (Hall, 2012). Soils derived from ultramafic bedrock have a number of extreme chemical properties that challenge plants to survive, which include a deficiency in the macronutrients phosphorus, potassium, calcium, and nitrogen, and unusually high concentrations of magnesium and nickel which may act as toxins (Baillie et al., 2000; O'Dell and Rajakaruna, 2011). Nickel hyperaccumulators represent a rare group of plants, which have the ability to concentrate nickel in their living shoots (by definition a plant is designated a 'hyperaccumulator' when it accumulates at least 1000 μg/g dry weight of nickel in its dried leaves) (Reeves and Brooks, 1983; Van der Ent et al., 2012). Where they occur, ultramafic ecosystems are renowned for high levels of endemism (e.g. plant species restricted to a limited geographic area) in plant species occurring on this substrate (Rajakaruna and Baker, 2006). At the same time, ultramafic outcrops holding nickel-rich laterites are prime nickel mining targets in the Indonesian region. That brings the minerals industry capitalizing on nickel resources in direct conflict with biodiversity. That situation is especially dire because species adapted to thrive on ultramafic outcrops offer rich genetic resources for mine site rehabilitation after strip-mining, which are likely to be destroyed during mining operations. The resource of native plant species occurring on ultramafic outcrops is therefore an asset for the mineral resource industry, waiting to be utilized and incentives for utilization in mined site rehabilitation, and ultimately conservation, is therefore a responsibility of the nickel mining industry and regulation by the local government.

Virtually no studies relating to nickel hyperaccumulators have been undertaken in Indonesia to date, and few publications have addressed the need for conservation of the native plant diversity resource on mining targets in the region. The objectives of this work are to synthesize existing information, to highlight the importance of using native plant resources in mined land rehabilitation, and to outline the potential for nickel phytomining (e.g. cultivating hyperaccumulator plants at an agricultural scale to extract nickel metal from the soil) in the region.

2. Ultramafic nickel laterites

Ultramafic bedrock are parts of the upper mantle (made of peridotite) obducted in continental margins (Searle and Stevens, 1984). Peridotite consists of the magnesium-iron-silicates in the form of the minerals olivine and pyroxene (Coleman, 1971). In the metamorphic

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process of 'serpentinization' of peridotite, the mineral composition is completely altered to metamorphic equivalents (Alexander, 2009). The original ultramafic rock contains 0.16–0.4% nickel (Butt, 2007), but this is strongly enriched as a result of lateritization during surface weathering in tropical settings, resulting in nickel laterites. Nickel laterites occur as regolith material in layers from <1 to over 40 m thick over ultramafic bedrock. The typical soil profile consists of an iron concretion or 'iron cap' (magnetite) on the surface, iron/chromic oxides (limonite) underneath, followed by chemically weathered bedrock (saprolite) and finally ultramafic bedrock (peridotite). In tropical conditions, the surface weathering takes place in two stages: (1) dissolution of olivine and pyroxenes in the peridotite, migration of magnesium and silica and accumulation of residual iron oxyhydroxides, (2) recombination of silica and magnesium to for smectite clays at the base of slopes (Latham, 1975; Trescases, 1975). The first stage takes place in humid tropical conditions and forms laterite (ferralitic) soils, and the second stage takes place under drier conditions and leads to the formation of hypermagnesian soils (Proctor, 2003). In tropical humid climates, nickel laterite deposits are generally found in two distinct types: (1) limonite type, formed by the removal of magnesium and silica, consisting mainly of iron oxyhydroxides (goethite) with 1–1.6% nickel, and (2) saprolite type, found deeper in the profile under the limonite zone, consisting mainly of magnesium hydrous silicates with 1.8–2.5% nickel, sometimes with phyllosilicate minerals such as garnierite with 20–40% nickel (Butt, 2007; Freyssinet et al., 2005; Gleeson et al., 2003). The different types are often part of separate layers of the same soil profile e.g. most laterite deposits contain both limonite and saprolite type of ores (Brand et al., 1998).

Ultramafic laterite soils are deep and well drained, and characterized by very high total iron, chromium, manganese and nickel concentrations, low CEC dominated by magnesium, extremely low concentrations of the plant available nutrients potassium, phosphorus and calcium (Read et al., 2006), and increasing concentration of magnesium and nickel with depth (Proctor, 2003). The topsoil pH is typically acidic around 5–5.5, but increases to about 7 or higher with depth (Table 1). Low pH (<6) increases nickel phytoavailability (e.g. the relative amount of soil nickel available for uptake to plants) and exacerbates phytotoxicity. Compared with other ultramafic soils in Southeast Asia the ultramafics from Soroako are relatively benign for plant growth, having low magnesium/calcium ratios and intermediate nutrient levels, but having high total nickel concentrations (Table 1).

Laterite nickel deposits account for about 70% of the known nickel resources globally while currently producing 40% of the global supply (Mudd, 2009; Sudol, 2005). The most economically important nickel laterite occurrences are in equatorial regions (Berger et al., 2011), especially in tectonically active plate collision zones (Gleeson et al., 2003). Globally, the largest nickel laterite resources are in New Caledonia (21%), Australia (20%), the Philippines (17%), and Indonesia (12%) (Dalvi et al., 2004). Nickel sulfide deposits are depleting, and as a result, a higher proportion of future nickel production is expected to come from laterite deposits (Dalvi et al., 2004). Generally, nickel laterite deposits are very high in bulk (1000 + Mt) but low grade (0.5–2% contained nickel). Because of the surface expression of the laterite deposits, nickel laterite mining operations commonly work as either opencast or strip mining using excavators and trucks. The nickel (and cobalt) is extracted from the limonite or saprolite by either pyrometallurgical smelting to produce ferronickel (matte), the Caron process (ammoniacal ammonium carbonate leach solution after reduction roasting), high-pressure acid leaching (HPAL) or 'atmospheric' leaching (Butt, 2007).

3. Nickel mining operations in Indonesia

Nickel mining has a long history in Indonesia, which started with the Dutch government in the early 1900s. At present, there are two major nickel mining companies in Sulawesi, the state-owned but publicly listed PT Aneka Tambang Tbk (known as PT Antam) and PT International Nickel Indonesia Tbk (known as PT Vale Indonesia, subsidiary of minerals giant Vale Group). The main lateritic nickel mining takes place at Soroako, Pomalaa (Sulawesi) and Teluk Weda (Halmahera). Smaller operations are at Gee, Tanjung Buli and Mornopo. Matte nickel smelting operations are situated in Soroako and Pomalaa (Sulawesi). In Sulawesi, nickel concession areas of PT Vale Indonesia are located in three out of six of the Sulawesian provinces: South Sulawesi (54.17%), Central Sulawesi (16.76%), and Southeast Sulawesi (29.06%), with total area of about 218.000 ha (Coumans, 2003), whereas PT Antam has sites in Pomalaa, Southeast Sulawesi. In 1996 an estimated 108 Mt of lateritic nickel ore was contained inside the Soroako mining area of PT Vale Indonesia. Another large nickel reserve is in the Bahodopi Block (Central Sulawesi Province) with 180 Mt of lateritic nickel ore, and more in the Pomalaa Block (South Sulawesi Province). PT Vale Indonesia began exploration for nickel laterite in South Sulawesi in 1968 and by 1978 had

Table 1
Soil chemistry of ultramafic soils from Soroako, Indonesia.

Parameters	Closed forest		Grassland	Saprolitic Laterite	Limonitic Laterite
	0–3 cm	0–15 cm	0–15 cm		
pH[1]	5.77	5.75	6.05	7.01	6.52
P total[2]	14.40	237.00	95.00	83.10	110.00
P extractable[3]	3.48	3.87	1.67	0.32	0.23
K total[2]	3281	5164	6260	4138	4018
K exch.[4]	0.03	0.03	0.10	0.02	0.01
CEC[4]	69.60	42.50	67.90	19.90	35.10
Mg exch.[4]	0.99	0.52	1.18	4.64	0.61
Ca exch.[4]	1.58	0.81	0.57	0.45	0.24
Mg/Ca	0.63	0.64	2.08	10.40	2.59
Ni total[2]	7273	7051	3730	10,524	7884
Ni extractable[3]	5.52	7.54	6.00	30.20	2.07
Fe total[2]	417,911	131,668	292,550	240,068	436,372
Co total[2]	75	57	337	536	294
Mn total[2]	844	1076	3500	4926	3053
Al total[2]	84,362	154,849	110,124	35,029	73,984
Cr total[2]	3477	17,216	9531	8595	11,263

Notes: Values are average of two samples. Analyzed by laboratory of STORMA (Analytical laboratory of the Stability Rain Forest Margin Project), Tadulako University, with ICP-OES.
[1] pH in H_2O extract.
[2] Hot block HNO_3–HCl soil digestion elemental concentrations in μg/g d.w.
[3] Bray-1 extractant P in μg/g dry weight soil.
[4] Extracted with 1 M ammonium acetate at pH 7, concentrations in meq/100 g dry weight soil.

commenced commercial production at its Soroako facility, which is now one of the largest nickel laterite operations in the world with 4 electric smelting lines. The majority of the nickel product is exported to Japan. In 2009, PT Vale Indonesia published the proven and probably nickel reserves as 153 Mt of ore at 1.77% nickel at Sorowako saprolitic resources (PT Inco, 2009). PT Vale Indonesia produced 72 kt/year of nickel matte in 2008 (PT Inco, 2009) for which 57 Mt/year of material was excavated (Golder Associates, 2010). Historically, Antam extracts around 3.5 Mt of Ni laterite ore annually. Since 2006, Antam's annual production has increased substantially due to strong demand. Some portion of the production by Antam is used as feedstock to produce ferronickel, however, the majority is exported to Japan and to Eastern Europe, and since 2007 also to China.

Rio Tinto reported a 162 Mt lateritic Ni deposit at 1.62% nickel (one of the largest undeveloped nickel deposits in the world), and has a mining lease of about 84 km^2 near Soroako within two main clusters, approximately 30 km apart, and estimates a base case production of 46 kt/year, planned to commence by 2015, with potential to support future expansion beyond 100 kt/year (Rio Tinto, 2008). In December 2010, Sherritt announced to buy 57.5% from Rio Tinto and take over as the operator of the project. Another substantial nickel mining project currently in development is the Weda Bay project in Halmahera (with a contract area of 54,874 ha) and a resource of 5.1 Mt of nickel and targeted annual capacity of 65 kt/year in nickel. The project is operated by PT Weda Bay Nickel constituting for 90% by Strand Minerals (majority owned by Eramet and Mitsubishi) and 10% by Indonesian State owned PT Aneka Tambang (Eramet, 2009). The Gag Island nickel project from BHP Billiton was effectively terminated from mining due to an Indonesian Constitutional Court decision in 2008.

4. Vegetation on ultramafic soils and challenges for rehabilitation

The typical soil chemical conditions of ultramafic bedrock pose significant challenges to rehabilitation efforts after strip-mining. The implementation of 'green' technologies in nickel mining in the Indonesia has been hindered by a lack of knowledge and awareness of ultramafic ecosystems, which has led to widespread biodiversity loss and missing out on the value of native plants in rehabilitation. The re-vegetation of strip-mined land should aim to mimic that of natural regeneration and succession. In areas that have been strip-mined and where topsoil is left, 'belukar' vegetation (dense growth on disturbed land) with native species originally confined to open areas, starts the successional series. It is important to avoid complete stripping to the bedrock, as re-vegetation is then nearly impossible within reasonable time scales. The subsoil below about 30 cm is devoid of most plant nutrients (Ca, P, K, and N), which have been accumulated in the topsoil through the development of vegetation. As such, disturbance of the topsoil inevitably induces severe nutrient deficiencies. Topsoil scraped off at the commencement of strip-mining could be used to cover bare rock, and this soil will most likely also contain germplasm to initiate regeneration of vegetation. Plants native to ultramafic substrates have different strategies for colonizing new habitats, which requires different conservation strategies. It is much more effective to conserve (parts of) native ecosystems in situ than it is to attempt to recreate native ecosystems after land clearance. As such, to improve the efficacy of land rehabilitation after strip-mining, leaving sufficiently large patches of vegetation in the mining lease intact preserves local germplasm and promotes the establishment of native species on cleared land after mining. Utilizing the capabilities of native plants might assist to accelerate natural succession, but strip-mined lands present a range of environmental challenges for plant establishment which include low water retention capacity of the bare soil, erosion exposure and lack in major nutrient supply.

Table 2
Known nickel hyperaccumulators from Indonesia.

Plant species	μg/g nickel in dried foliage	Distribution	Reference
Rinorea bengalensis	17,350	Throughout SE Asia	Wither and Brooks (1977); Reeves (2003)
Rinorea javanica	2170	Kalimantan	Brooks (1987)
Rinorea sp.	2170	Karakelong, Talaud Islands	Proctor et al. (1994)
Brackenridgea palustris ssp. *kjellbergii*	1440	Sulawesi	Reeves (2003)
Dichapetalum gelonioides ssp. *andamanicum*	3160	Andaman Islands	Brooks (1987)
Trichospermum kjelbergii	3770	Sulawesi	Wither and Brooks (1977)
Planchonella oxyhedra	19,600	Obi Islands	Wither and Brooks (1977)
Myristica laurifolia var. *bifurcata*	1100	Obi Islands	Wither and Brooks (1977)
Phyllanthus insulae-japen	34,330–38,720	Japen Island	Reeves (2003)
Glochidion aff. *acustylum*	6060	Sulawesi	Reeves (2003)
Psychotria sp.	938–1820	Sulawesi	Reeves (2003)
Sarcotheca celebica	700–1000	Sulawesi	unpublished data A. Tjoa
Knema matanensis	2500–5000	Sulawesi	unpublished data A. Tjoa

5. Nickel hyperaccumulators in Indonesia

Globally, around 400 nickel hyperaccumulators have been described as of 2012 (Van der Ent et al., 2012). Nickel hyperaccumulators are widely distributed among plant families with a great variety of growth forms and physiologies (Pollard et al., 2002), although most tropical nickel hyperaccumulators are small trees or shrubs, particularly in the families, Phyllanthaceae, Rubiaceae and Salicaceae (Reeves, 2003). Nickel hyperaccumulation in higher plants is a relatively rare phenomenon with perhaps 0.5–1% of plant species native to ultramafic soils exhibiting nickel hyperaccumulation. Nickel hyperaccumulators can be qualitatively identified in the field with paper impregnated with the chemical dimethylglyoxime (Baker et al., 1992), or semi-quantitatively with a hand-held XRF-instrument and subsequent elemental analysis of dried plant material with ICP-AES/MS in the laboratory. By screening herbarium species, Brooks and Wither (1977) discovered the widespread species *Rinorea bengalensis* and *Rinorea javanica* to be nickel hyperaccumulators. The same procedure was repeated and *Trichospermum kjelbergii*, *Planchonella oxyhedra* and *Myristica laurifolia* var. *bifurcata* were also determined to be hyperaccumulators from herbarium specimens by Wither and Brooks (1977) without ever actually visiting Indonesia. Reeves (2003) used the same method and added *Brackenridgea palustris* ssp. *kjellbergii* (Ochnaceae), *Psychotria* sp. (Rubiaceae), *Phyllanthus insulae-japen* and *Glochidion* aff. *acustylum* (Phyllanthaceae) to the growing list. Most recently, new nickel hyperaccumulators were discovered working with field material in Sulawesi, including *Sarcotheca celebica* (Oxalidaceae), a small tree near Soroako, Sulawesi (local name "Sengilu"), and *Knema matanensis* (Myristicaceae), a large tree, also near Soroako, to be a moderate and strong nickel hyperaccumulators respectively (Pitopang et al., 2009; Tjoa, 2010), see Table 2.

Compared with Cuba (130 nickel hyperaccumulators; Reeves et al., 1999), Brazil (40 nickel hyperaccumulators; Reeves et al., 2007) and New Caledonia (56 nickel hyperaccumulators; Amir et al., 2007; Boyd and Jaffré, 2009), it is remarkable that so few nickel hyperaccumulators have been recorded from Indonesia, especially given the high overall plant diversity and very large ultramafic exposures in the region. This can be explained by the lack of research effort to identify nickel hyperaccumulators in this region.

6. Phytomining technology

The concept of phytomining technology is based on hyperaccumulator plants taking up nickel from the (ultramafic) soil into their living biomass, which are then harvested on a large scale, and nickel in their biomass retrieved (Chaney, 1983; Chaney et al., 1998). Normal agricultural crops are generally difficult to cultivate on ultramafic soils because they lack the necessary edaphic tolerances found in native plants of ultramafic soils. However, hyperaccumulators are found in Indonesia and it is conceivable that using agricultural practices selected hyperaccumulators will be grown here, including several more species that complement each other in growth habits and ecological requirements. The soil metal level required by hyperaccumulators in order to be able to produce significant levels of metal accumulation in biomass is much lower than necessary for conventional mining technology. Currently only soil/substrate with minimal 1% of nickel will be worked to produce nickel, but hyperaccumulators can achieve high levels of nickel accumulation in soils with nickel concentrations of just 0.1%.

Using plants to recover metals from sub-economic ores (low-grade ultramafic soils) on a commercial scale may have many benefits because the costs of growing and harvesting hyperaccumulator crops are minimal compared to traditional mining operations (Chaney et al., 1997), particularly given the high costs involved in recovery of nickel from lateritic soils. Phytomining offers an in situ, potentially economic method to 'mine' nickel metal. Nickel is undoubtedly the best candidate metal for phytomining above all other metals (Chaney et al., 2007) with a number of known hyperaccumulators that accumulate 1–3% nickel in dry matter, providing 12% to >20% in the ash (Dickinson et al., 2009). The bio-ore produced from the phytomining operation can be a feed-stock supplied to existing conventional smelters (Chaney et al., 2007). Alternatively, the hyperaccumulator biomass can potentially be used to produce nickel catalysts for the organic chemistry industry (Losfeld et al., 2012) or turned into high value nickel chemicals, such as for the electroplating industry. Initial experiments in temperate regions using hyperaccumulator herbs (Nicks and Chambers, 1995, 1998) made 100 kg/ha nickel from ultramafic soils (with 0.35% total nickel). Further experiments in temperate regions yielded 72–100 kg/ha (Robinson et al., 1997a,b). The actual amount of nickel gained per hectare per annum in a phytomining operation depends essentially on the proportional relationship between nickel concentration in the phytomining crop and its harvestable biomass yield, thus:

$$Y_{Ni} = F_{Ni} \cdot Y_{bio}$$

F_{Ni} Average fraction of nickel in hyperaccumulator biomass
Y_{bio} Biomass yield of hyperaccumulator (kg/(ha·year))
Y_{Ni} Total nickel gain (kg/(ha·year))

Selected candidate species should ideally have high accumulation and high biomass, or moderate accumulation and very high biomass, or vice versa. Note that some woody nickel hyperaccumulators have very high biomass, but a slow growth rate; hence, their biomass production per annum should be considered. In the Indonesian context, realistic values for Y_{Ni} range from 40 to 300 (F_{Ni} 0.005–0.02 and Y_{bio} 8000–15,000 kg). The economical aspects of phytomining (and phytoextraction) have been the subject of detailed calculations and modeling by Robinson et al., 2003. In its simplest form, in a steady-state, the net gain of a phytomining operation, can be represented as:

$$G = \{V_{Ni} \cdot Y_{Ni}\} - C$$

G Net economic gain (US$/(ha·year))
C Operating costs e.g. labor, fertilizers and amendments (US$/(ha·year))
V_{Ni} Current nickel metal value (US$/kg)
Y_{Ni} Total nickel gain (kg/(ha·year))

This formula represents the running operation, after establishment. However, the accumulation yield in the hyperaccumulator crop decreases over time with successive harvests as phytoavailable nickel pools diminish and re-supply and exchange from other soil nickel pools slow down. It follows that the relatively low operating costs and land acquisition costs in Indonesia make phytomining more economically attractive. Assuming a crop with a moderate Y_{Ni} 150, operating costs of US$ 500 and a November 2012 nickel price of US$ 16, then the net economic gain will be US$ 1900 per hectare per year. This estimate excludes costs for nickel processing and refining, but given the high purity of hyperaccumulator biomass, the end-product can also be nickel chloride or nickel sulfate salts for the plating industry that have significantly more commercial value than the raw metal.

Phytomining depends on the co-distribution of the target metal and plant roots within the soil profile, as well as the phytoavailability of the target metal (nickel). Total substrate concentrations of metals such as nickel do not generally indicate phytoavailable concentrations (Ernst, 1996). In soils, the total metal pool is distributed among phytoavailable, potentially phytoavailable and non-phytoavailable pools. Robinson et al. (1999) showed that in many nickel-rich ultramafic soils between 13 and 80% of the total nickel in the soil potentially available to plants. However, it is unknown what the phytoavailable nickel pool is in ultramafic laterite soils in Indonesia and how this might be measured in relation to uptake in native hyperaccumulators. The rate and level of addition of phytoavailable metal from the non-phytoavailable and potentially phytoavailable pools due to extraction of metals by plants in phytomining are an important factor to consider in feasibility studies. This might be assessed with the isotopic exchange kinetics (IEK) method (Chardot et al., 2005; Echevarria et al., 1998, 2006). Another important factor is the level of accumulation that will be achieved when the immediately phytoavailable soil metal concentration drops as a result of phytomining. However once the initial metal content of the topsoil has been depleted, the topsoil can be plowed to bring fresh material to the surface (Anderson et al., 1999b). Alternatively, the topsoil could be removed after years of phytomining to bring high-nickel soil to the surface for continued phytomining while using the considerably improved topsoil for re-vegetation elsewhere in the mine lease. Ultimately phytomining is finite as the target metal is removed, as opposed to conventional agriculture that can theoretically continue indefinitely (Anderson et al., 1999a).

7. Previous experiments in Soroako, Sulawesi

The Indonesian Phytomining Viability Study took place in Soroako between 2004 and 2007. This was a collaborative project between Inco Ltd (Canada)/PT Vale Indonesia and Viridian Resources LLC (US). Unfortunately, the well-known temperate nickel hyperaccumulator *Alyssum* spp. used for these trials accumulated significantly less nickel when grown on ultramafics in Sulawesi. This could be a result of the relatively low soil pH locally and issues with managing soil fertility. In addition, the biomass production was also low, probably caused by lack of adaptation to local climatic conditions. Such adaptation to the local environment and the edaphic conditions (e.g. soil chemistry) of the overburden soil includes the physiological capacity to cope with low soil fertility, heavy soil texture, poor water holding capacity and soil dust/erosion (impact on photosynthesis). Small plants (such as *Alyssum* spp.) also suffered from strong winds, and therefore a windbreak is needed if the plants are annuals or small shrubs. Finally, candidate

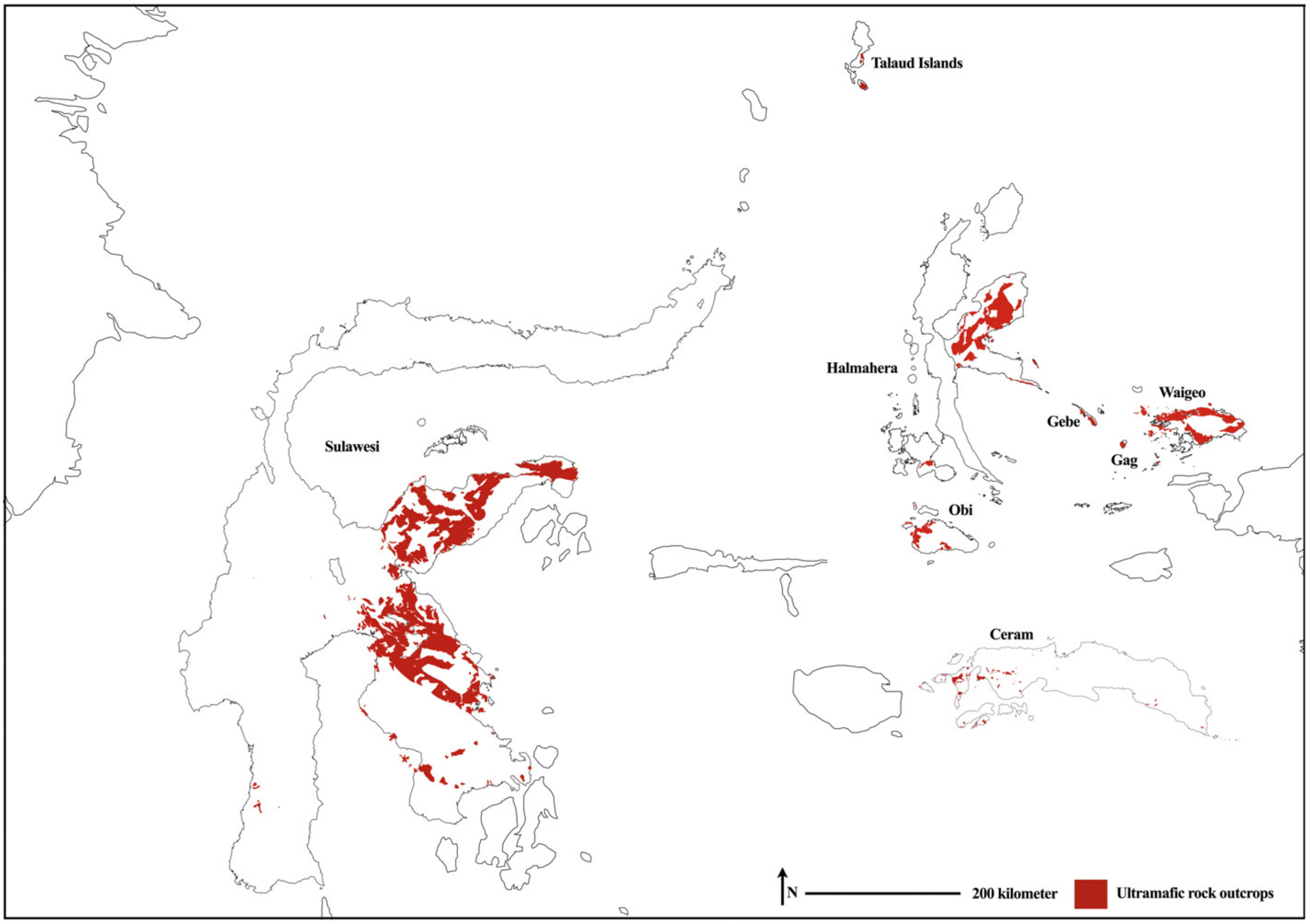

Fig. 1. Distribution of ultramafic outcrops in Sulawesi, Halmahera and surrounding islands. This map is based on database files created by the SE Asia Research Group, Department of Geology, Royal Holloway University of London (Hall, 2012), except the section of the Talaud Islands, which is based on Moore et al., 1981.

hyperaccumulator species need to have a good root system, which enables such plants to access nutrients and nickel throughout the soil profile, while at the same stabilizing the substrate. The lessons learnt from these trials using non-native species, has led to future reconnaissance to find nickel hyperaccumulators native to the site. New research efforts have attempted to relocate the nickel hyperaccumulator *R. bengalensis* from Soroako, Sulawesi that was identified in herbarium specimens by Reeves (2003), from material collected in 1979. The species is rare, if not extinct, at the site, due to strip-mining and to date it has not been found. Samples of *Psychotria* sp. and *Glochidion* sp. previously identified as strong accumulators (Reeves, 2003) were however found but with much lower nickel accumulations. The old herbarium vouchers were probably contaminated by soil dust, as herbarium collection normally does not include any rinsing of the leaves. In further surveys, nearly a thousand samples were collected of which 500 samples, representing about 100 genera were analyzed for nickel, resulting in several species that contained >200 μg/g nickel (Table 2).

8. Implementation of phytomining in Indonesia

Potentially, the most promising area of immediate implementation is in the residual wastes of lateritic nickel mining. The stripped land there is relatively benign for plant growth (at least to native plants) and phytomining can be used as remediation strategy while gaining residual metal. As such, phytomining offers to reduce the impact of strip-mining for nickel, enhance biodiversity on the mined areas and facilitates carbon-storage. Currently rehabilitation is undertaken by planting large amounts of 'normal' plants. Phytomining means merely replacing those plants with hyperaccumulator species. As such, phytomining will not only have economic impacts but can also positively impact soil fertility status, which can lower the constraints of re-greening programs and promote the return of natural vegetation when phytomining is completed.

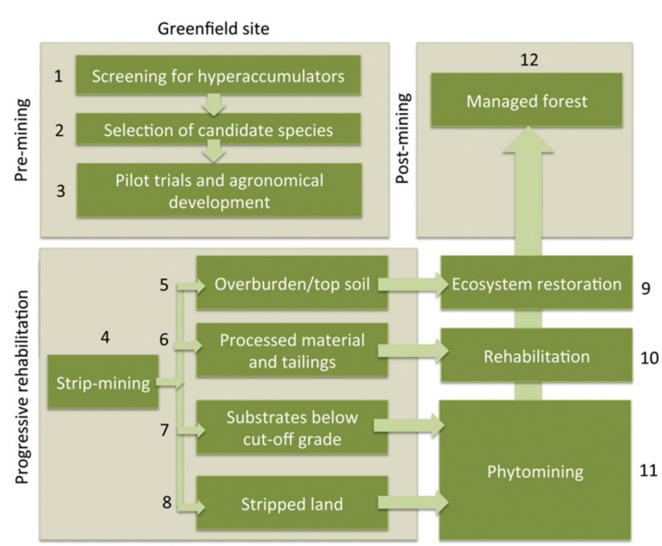

Fig. 2. The 'phytomining cycle' depicting the role of phytomining in progressive rehabilitation. this is further explained in the text.

Fig. 3. The strong nickel hyperaccumulator *Phyllanthus balgooyi* from ultramafic areas Sabah (Malaysia) and the Philippines.

A range of native hyperaccumulators can potentially be used; of the species known today *Phyllanthus*-species, such as *P. balgooyi* (Phyllanthaceae), which originates from Malaysia (Sabah) and the Philippines, but does not occur natively in Indonesia, seems most promising (Fig. 3). This plant grows fast and prefers open, disturbed habitats where it can dominate. This species accumulates between 0.5 and 1.2%% of nickel on average in its dried biomass (leaves, twigs, and stems), and can produce an estimated 10 t/ha/year, which could thus produce up to 120 kg nickel per ha/year. *Phyllanthus*-species also have the benefit of being able to withstand pruning, and therefore re-sprouted biomass can periodically be harvested while leaving the stem and root system intact. Field trials using this species are currently underway in Sabah, Malaysia and the Philippines. Effective nickel phytomining depends on the identification of high-biomass and fast-growing hyperaccumulator species (Shah and Nongkynrih, 2007) and further screening of the ultramafic flora in Indonesia will undoubtedly result in a range of candidate species. Ultimately, the success of phytomining depends upon: (1) the concentration of nickel in the soil/substrate; (2) nickel phytoavailability (chemical, biological and physical aspects), (3) the bioconcentration and hyperaccumulation factors of the species employed, and (4) the harvestable biomass produced annually. However, progress in the real-life implementation of phytomining is hindered by a lack of understanding of the complex interactions in the root-soil interactive and the ecophysiological mechanisms of nickel translocation, and accumulation in plants (Baker et al., 1994; Lasat, 2002). Since nickel phytomining is in essence agriculture, albeit not for food crops, but to farm nickel metal (Chaney, 1983), agricultural practice has to be employed effectively. This means that management and plant genetics (selection and breeding) need to be optimized to develop commercially viable phytomining on a large scale (Chaney et al., 2007). Agricultural practice also includes increasing the soil fertility with NPK-fertilizer, liming to increase soil calcium and buffer pH and applying organic matter to improve water-holding capacity and to combat the heavy texture of the soil substrate. Fig. 2 provides an overview of the role of phytomining as part of the progressive rehabilitation strategy of strip-mining. In the pre-mining phase, screening for locally adapted nickel hyperaccumulators takes place (1), followed by selection of potential candidate species (2) and pilot trials and agronomical development at the site of eventual implementation (3). During strip-mining (4) phytomining is best suited to be developed on the strip-mined land left over after resource extraction (8 and 11) and on substrates in the mining lease that are below the cut-off grade (7 and 11). The overburden inclusive of topsoil (5 and 9) is best utilized for direct ecosystem restoration. Tailings (chemically processed substrates from which nickel was extracted) present a unique challenge to rehabilitation because of the very low soil fertility (low total and extractable phosphorus and potassium) and high magnesium to calcium ratio's present. Hence, these are very difficult materials for re-vegetation and most suited for rehabilitation efforts (6 and 10). In the post-mining phase, restored ecosystems, rehabilitated land, and land previously used for phytomining (after reaching resource exhaustion) can be successively transformed into managed forests (Fig. 2).

9. Conclusions

Because ultramafic outcrops are specifically targeted for nickel mining, action towards conserving biodiversity on ultramafic outcrops is imperative. Strip-mining necessarily removes all vegetation and large-scale operations in the Soroako area for several decades have thus unquestionably resulted in loss of forest and biodiversity. These concerns are further exacerbated because large sections of the Contract of Work (CoW) area of PT Vale Indonesia are classified as forest reserves under the Forestry Act of 1999 (Coumans, 2003). The true extent of biodiversity loss as a result of nickel mining is however unknown as to date only limited research has been undertaken in Indonesia. Several authors have stressed the importance of conservation in this region (Baker et al., 1992; Proctor, 2003; Van Balgooy and Tantra, 1986), but so far systematic screening and cataloging of plant species at the onset of mining has not taken place. The international minerals industry in the MMSD Project of the Global Mining Initiative (2002) set high-level aspirations to "*exercise prudence where impacts are unknown or uncertain*" and to "*operate within ecological limits and protect critical natural capital*". Given that Indonesia is the area in the world where the lack of scientific knowledge on plant diversity on ultramafic outcrops is greatest, precaution and due diligence should be taken, particularly in Sulawesi. Baker et al. (1992) made that point: "*The ultramafics of Soroako … could reveal other new hyperaccumulators of nickel…in view of extensive mining… urgent investigation is suggested before there has been serious loss of habitat*". The nickel mining industry in Indonesia should develop appropriate biodiversity management plans (e.g. 'intact mosaics in the mining lease') and use offsite offsetting (regulatory protection of ultramafic reserves representative to the area impacted by mining). For the minerals industry, stewardship and adequate strategies for biodiversity conservation before mining commences ensure that these valuable resources are not lost 'in the process' and to capitalize on the unique properties of specialized plant species in mine site rehabilitation. As part of the progressive rehabilitation strategy, phytomining offers the opportunity to re-vegetate large tracts of stripped land after lateritic nickel mining, while at the same time creating revenue (by 'harvesting' nickel metal). As such, phytomining bridges the transition to the establishment of biodiverse ecosystems or managed forests.

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