Agromining AgroEcology: Crops, Soils, & Metals of Importance

Interdisciplinary Mix of Complex Analysis & Fact-Reporting on Agromining, Phytomining, Phytoremediation, Hyperaccumulating Plants, Metal-Rich Soils, Metals (and other elements of interest) Unusually & Usefully Uptaken by Plants, under an AgroEcological Framework

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1. Introduction:

Plants provide us many goods and services; the former category comes mainly from growing plants or mining the earth, thus a common saying amongst miners is “what you can’t grow, you mine”; while such has been true for millennia, modern knowledge of ecological, agronomic, and edaphic systems can be applied using naturally metal hyperaccumulating plants, which allow us to essentially grow (plants) (and then extract (the desired metals) from) what we can’t mine. Phytomining can be defined as the extraction of metal ore from sub-economical ground with the use of hyperaccumulating plant species (Anderson et al. 1999). It can be thought of simply as **using plants to increases human access to economically profitable metals found in the ground at too low of accumulations to be recovered with traditional mining** techniques. These metals are then extracted, isolated, and concentrated to be used and sold on the market for various manufacturing and production uses (Dinh et al. 2021). Phytomining is also an example of phytoremediation and can be used in a clean-up strategy to help reclaim land that has been anthropogenically polluted or is otherwise ‘naturally damaged’ from edaphic and ecological characteristic associated with high quantities of metals in the soil (Sheoran et al. 2005). Nickel (Ni), gold (Au), and thallium (Tl) are among the metals of highest potential in application and interest in research, and the former will be the most of focus.

We will start first with an exploration of the ecological environments and their abiotic and biotic inhabitants (mainly soil and plants) in order to understand the conditions and organisms involved in the process of phytomining and associated physiology of uptake from soil to plant, and purification from plant to metal. Next will be review of nickel, gold, silver, platinum, and various other metals of interest with an emphasis on their associated characteristics and applications to phytomining. Then areas, geographies, and locations where activities are currently active or possible agromining prospects will be highlighted to wrap up the review / data section of the paper. Tables and figures were created to emphasize critical areas of importance, allow for deeper understanding, and quick information visualization and obtainment.

Next will be discussion of the processes and mechanisms (natural and artificial) involved in the physiology from below ground through uptake into the crop, as well as the post-harvest processing that is involved in isolation and extraction of the metals from the harvested plant materials. Also included is an economic analysis of the metals market to show real-world application potential of phytomining for selected metals. Next will be a discussion from a broader environmental perspective of the role phytomining plays in land reclamation and pollution mitigation. Lastly will be a discussion of the future possibilities and limitations that currently exist in this field of research. Additional supplementary Figures are included to encourage better visualization of the mechanics, physiology, schematics of important elements, systems, and their associated interactions.

Throughout the beginning of this work when talking about specific plants and their general ability to uptake metals term phytomine will be used. For a more systems based agricultural production variation of such a model(s) the term agromining will be used.

It’s important to stay realistic and realize in the ‘bigger picture’ that agromining is not (necessarily) the next big ‘Gold Rush’. Limitations exist and further research of uptake physiology, artificial inducement methods, and post-harvest ore extraction procedures must be continually researched to unlock the full services that phytomining activities offer. It is attracting interest of scientific and commercial parties, diverse academics, and industrial leaders, for good reason however –

it has high potential for benefits, and economic gain over conventional mining techniques for some in demand metals (Anderson et al. 1999 & van der Ent et al. 2021). Agromining is a method of metal extraction that is **economically profitable**, **environmentally beneficial**, **while increasing ecosystems services and agroecosystem multifunctionality**. Many Tropical areas of the World have edaphic and anthropogenic conditions which best warrant the use of these. Common agronomic conditions in these tropical areas include metalrific soil conditions, endemic plants that are known , and need for improved agriculture practices on marginal lands all combined together in the solution of Agroming. While certainly not a relic of the past, research focused in the area will help ensure natural resources are protected in the future and commodities are obtained in a way that maximizes both economic efficiency and ecological quality, benefiting the producer, consumer, surrounding community, and world at large in a way that more traditional metal mining and / or agronomic land use options don't offer.

2. **Plants & Soils of Interest**:

2.1 – Hyperaccumulating of Metals in (Select) Plants

2.1.1 **Introduction**

Certain plants have an inherent natural ability to accumulate metals at large quantitative abundance while others must be induced to do so through artificial chemical supplementation as an additive to the soil for environmental modification. The properties of the metals, their occurrence, and placement in the rhizosphere among multitudes of interacting environmental factors determine the ability of a plant to uptake a particular (combination of) metal(s) of (human) interest. Edaphic properties and associations regarding uptake are discussed in the next section; plants (the hyperaccumulators themselves) will be the objects of focus. Selected hyperaccumulating plants of interest are broken into three large plant families (Asteraceae, Brassicaceae, and Fabaceae), as well as three similar-associating functioning groups (Root & Tuber, Conventional Agronomic, and Outliers & Others). This helps distinguish plants into practical working groups that can be experimentally tried or agronomically applied. It's important to find the correct combination of species (genotype) to correctly match to the particular metal (element) being mined for, as well as the right soil (/location) that is permissible to such. It also important to note that these are not the only hyperaccumulating plants, but just ones selected that are more common, practical, or noteworthy.

Naturally occurring hyperaccumulators are of a practical choice for many land-use reasoning's or operations, one being for a phytoreclamation or ecological restoration goal. They also have situational use when economic gain from ore extraction is the intended means of the operation, but such is typically limited to plants that develop in an environmental situation where occurrence of and resulting exposure to a particular metal was high(er than normal) (Sheorun et al. 2009, Dinh 2021, & van der En et al. 2021). Plants with this naturally ability for hyperaccumulation of metals is often due to the secretion of chelating compounds and siderophores that help lower the pH of the surrounding rhizosphere increasing the availability of the metals to the plant by allowing them to detach from the tight hold of negatively charged clay particles, into free soil solution, and ultimately closer to the plant's roots and availability for uptake (Ma et al. 2001, D'Souza 2005, Sheorun et al. 2009). This is proven to be the case for Ni, Mg, Mn, etc. with certain grass species, among other plants (van der Ent et al. 2021).

Agronomic and more commonly known agricultural crops have a role in phytomining as well as many works have showed that plant performance is an issue when dealing with harsh environmental conditions that decrease the phytomining species to perform their namesake ability (Nkrumah 2016 & van der Ent et al. 2021). Obviosity different families, species, and genotypes of plants have preferential favoritism to and uptake of each of the particular metal elements. However, these same natural hyperaccumulators possess a wide range of diversity that should not only be adequately recognized by anyone involved in these kinds of activities but explored more fully in order to help unlock information and solutions that have yet to have been observed.

Artificial application of chemical additives for phytomining operations modify the environment in a way that helps to make the metal / elements intended to being mined for more readily available. This tends to be done for the more highly valued metals or in situations where a simple change to the rhizosphere could promote better uptake of an otherwise extractable concentration of the wanted metal (van der Ent et al. 2021) . These additives tend to be chelated or acids that help to desorb the wanted metals from the negatively charged clay in the soil. The correct concentration of these chemical compounds must be used in order to ensure chances of not causing an environmental toxicity, from the unnatural addition. It's important to remember as true with all chemical supplementation and patient relationships (in this case the soil and the metals, as the soil to some degrees are the patients being treated) that the poison is (mostly) in the dose, and not the substance; 'everything in moderation' and 'start low and go slow' are good practices to apply in this situation, as taught in pharmacy school and practical to apply in other walks of Life.

Plant families and groups listed within don't comprise the vast array of species over plants with phytomining capabilities. As of present over 700+ plant species have been found and documented (van dern Ent et al. 2015, van der Ent et al, 2021). Ongoing developments make this truly only a partial and working list, but the number is included to highlight the plant species that were not mentioned directly in these writings, associated references are included for those of further interest or specific application.

Phytomining has had a short but diverse history in the past few decades, as it is a relatively novel mining or agriculture practice that pertains to different niches in research trends and practical applications. At the turn of the last millennium initial divulges into phytomining practice were interested primarily in the ever-ongoing earthly pursuit of humans to obtain the highly desired metal that is Gold (through artificially induced hyperaccumulation), as well as on Zinc; focus turned to a more environmental focus in the mid 2000's with the rise of phytoremediation research, steering towards Nickel, trace minerals, and the use Brassicas (as good hyperaccumulators) (in the Temperate) in recent years (Li et al. 2020 & van der Ent et al. 2021). The groundwork has begun to be laid on the research side of the equation but in the 'real World' there is still much time before (increased) large scale phytomining can and or will occur in practical commercial operations due to the gaps in knowledge between research and application. Malaysia, Indonesia, etc. in the Tropics, and Albania, Turkey, Greece, etc. in the Temperate have or / are currently undergoing commercial Agroming operations in pursuit of commercial gain (van der Ent et al. 2021). Work in these areas, and the problems that can be solved form these initial operations will help to translate into more novel success globally as time moves on.

The economic and environmental perspectives in the bigger picture see traditional mining moving towards the wayside both to changes culturally in society and the (realization of) scarcity in abundance of the finite resources stripped from the Earth's crust. Much on the other hand phytomining is seeing a steady rise in popularity and interest due to its dual qualities of environmental remediation and harvest of an economically profitable product (Li et al. 2020). Past research has been focused mostly on elements of interest in phytomining, and traditional mining pursuits in a phytoming perspective such as focus on soils, or geologies of interest. This paper aims to incorporate all that while giving a major focus to the hyperaccumulating plant species that are the 'tool' themselves in this operation.

Plants are defined as metal hyperaccumulators when they have the ability to hold x100 the concentration of a particular metal relative to that of what would be considered a more or less traditional 'normal' plant (Jaffre et al. 1976, Brooks 1998, & Dinh 2021). This ability is what sets them apart from other plant species and is why they are highlighted in this paper. Each plant species is curtailed to uptake of different particular metals due to physiological, environmental, and edaphic associations. Nickel was the first of these metals observed to hyperaccumulate in plants in association with that term, more or less helping to create this field of study (Jaffre et al. 1976). Nickel is also rather abundant compared to other metals in the Earth's crust and is desired heavily by Humans for stainless steel production, amongst other consumer and industrial end uses.

The approach plants take to varying metal concentrations in their edaphic environment is more or less three-fold (Hunt et al 2014 & Harumain 2016). Plants have a response of **hyperaccumulation** (uptake of an amount ≥ x100 greater than normal plants), where metals are higher in the ariel parts of the plant than the surrounding soil. The concentration of the metal in the plant is high (naturally) even when soil accumulation is low. **Metal excluders** have an opposite strategy (partially preventing uptake of the metals). They keep this response of low plant metal concentration relative to high soil metal concentration until exceedingly high metal levels in the soil are present. **Metal indicating** species ((possible) visual symptoms of toxicity seen) have corresponding levels in both the plant and soil; they typically lack a (natural) 'defense' response upon excessive metals in the environment unlike the Metal excluders and hyperaccumulators (Hunt et al. 2014). This fact coupled with their low inherent abilities for metal uptake make this a broad group of species that has been disregarded from further exploration regarding phytomining but are used for **bioprospecting** (van der Ent et al. 2021). Keep in mind however it is always possible the right **soil-plant-metal combination** had just not come to be found yet.

Another key aspect to keep in mind is that the harsher the conditions are the more likely it will be that focus should be on plants that are not natural hyperaccumulating species (Harumain 2016). Many tailings and other anthropogenically created or polluted sites may not have had the length of time for a successful botanical relationship to be established on such through ecological evolution, however that is not to say a combination or relationship could not be created through un-natural introductions and experimentation of different plants in combination with this unnatural anthropogenically created grounds (soils), also more knowledge may be known of these 'traditional' non-hyperaccumulating crops already (Harumain 2016 & van der Ent et al. 2021).

Improving the metal hyperaccumulating plants (genetically) to uptake metals may be an easier broad approach than to improve agronomic presence of naturally phytomining species to withstand the conditions where their growth is needed. Non-metal hyperaccumulating species can become metal accumulating species to some degree, but success is only practical if such can be grown on larger commercial productions scales compared to some of the natural species, however. The fact is that many of the naturally occurring species, or even introduced and adapted species may not ever perform well enough (for positive economic commercial gain) in such a harsh edaphic environment.

A dive into some plants families, genera, and other working groups is in order to showcase the remarkable phytomining capabilities of these hyperaccumulators; a diverse set of plants ranging from member of the Aster Family (Asteraceae) to temperate and tropical root and tuber crops that hold more than just starch, vitamins, and other nutrients in their below ground vegetatively reproductive storage organs (Brooks 1998 & Sheorun 2009). Other hyperaccumulating plants species can be found in the sections below, and throughout the paper.

2.1.2 **Asteraceae**

Asteraceae is the lily, daisy, or sunflower family. Many of these species are natural accumulators of heavy metals such as Nickel (Ni) and can grow in conditions where traditional agriculture crops would not fend agronomically well, or environmentally successful.

The Sunflower (Helianthus anthus) is beautiful plant for viewing but it's uses extend beyond just ornamental components to include uses as animal fodder, cooking / industrial oil, and phytoremediation of damaged lands. That last role emphasizes the importance of Sunflower as a phytomining crop. Experiments from Mexico indicate it's ability serve as a phytomining species for both Gold (Au) and Copper (Cu) (Wilson-Corral et al. 2011). Important to note is the preferential allotment of both of these metals to the stems, and with not that much differing in values when comparing ariel and sub-soil surface plant organs. This work also proved to show the importance that matching the correct chelating chemical to the soil is, as the intended to be acquired metals react and uptake into the plant is affected; accordingly, sodium cyanide working best for gold uptake, ammonium thiosulphate and ammonium thiocyanate producing the highest results for copper (Wilson-Corral et al 2011). There should be continued interest on the idea of pairing between correct soil (chemical), plant (species), and (intended to be acquired) element or metal.

The plant species *Berkheya coddii* is a prolific metal hyperaccumulating species with some of the highest potential in the Asteraceae family. Work in South Africa, among other places, has shown that it can be a substantial (natural) uptaker of the metal nickel; Ni being the most abundant phytomined metal coupled with the fact that this plant can produce much dry matter production under moderate fertility and otherwise low agronomic input can yield high levels of biomass with up to 7 % Nickel (Mesjasz-Przybyłowicz et al. 2020). This powerful combination (**Serpentine Soil -Asteraceae Plants – Nickel**) is what is needed to produce extractable ore with a phytomining crop at an economically practical (and positive) intensity.

Other related species in the aforementioned study included Berkheya zeyheri, Berkheya nivea, Senecio coronatus, & Senecio anomalochrous which are all in the Asteraceae family and natural nickel hyperaccumulators in serpentine soils (Mesjasz-Przybyłowicz et al. 2020). An important feature of these plants such as *Berkheya* is that they have a relationship with mycorrhizal fungi, that help facilitate the survival and thriving of these plants under natural conditions, when grown on artificial soils in greenhouse or laboratory environments they perish without the associated mycorrhizal fungi. Also of note is that biomass production and nickel uptake was always higher in species with colonization by Arbuscular mycorrhiza than without (Mesjasz-Przybyłowicz et al. 2020). Most natural hyperaccumulators of metals are not plants that have associations with arbuscular mycorrhiza, so this not only a relatively novel find by these workers, but also a management tool that can be used to help improve efficiency of Nickel production for phytomining with these crops. On a larger basis, artificial inoculations to promote such a relationship could be applied on an agronomic scale by conventional methods to help improve *Berkheya* (or any plant for phytomining) biomass and thus subsequent nickel uptake to its maximum potential.

Berkheya coddii has also ability for use with more precious and economically valuable metals such as gold (Walton 2002 & Lamb et al. 2016). Other noble metals have also been mined with this plant to include platinum (Pt) and palladium (Pd) (Nemuntandani et al. 2007 & Dinh et al. 2021). This natural ability for metal uptake, coupled with ability to grow in harsh environments is what makes this plant ahead of the rest for phytomining potential. Supplementation of chemicals, such as sodium cyanide helped to make these metals uptake at much larger rates compared to a control of no soil treatment (Walton et al. 2002). A combination of plant genotypes with high natural ability for metal uptake must be combined with correct soil additive for improvement of metal uptake further by *B. coddii*. A turn now to the mustard family and plant species of interest in it that have excellent phytomining abilities.

2.1.3 **Brassicaceae**

The Brassica plant family is also known as the mustard family with familiar favorites such as turnips (*Brassica rapa*) and cabbage (*Brassica oleracea*), as well as its namesake of course common mustard (*Brassica spp*., *Sinapsis spp*.). Indian mustard (*Brassica juncea*) is one of the more popular choices when it comes to metal mining or phytoremediation. Rapeseed (*Brassica napus*) is another common choice, as are Alyssum spp (van dern Ent et al. 2021). Most of these plants can be grown in a somewhat agronomic fashion due to their weedier nature / habit of growth, and somewhat high(er) production of biomass, and are among the more common Agromining crops in temperate operations.

Alyssum murale and Alyssum corsiucum show potential for use in the agromining of nickel (Ni) on ultramafic soils. They are natural hyperaccumulators of Ni and the soils on which they are endemic to tend to have a high abundance of nickel. Agronomic practices have been explored to and these alyssum species show suitability on this end; practices explored that show increases availability or uptake of Nickel include fertilization (N,P,K, & S), pH adjustment, changes in substates, plant growth regulators (PGR) additions, amongst other modifications in agricultural management from propagation through harvest. (Nkrumah et al. 2018). This is **key in developing adequate and successful Agroming operations, good combinations of plants for the particular environments** they are to be used in and metals desired to be extracted must be found, but **such is nothing if traditional agronomic improvements are not made to the plants once found (and in optimization of the operation).** It is these additions of agronomic practices and ecological principles that help establish and difference between agromining (with the aforementioned) from phytomining (without the aforementioned). Time and commitment to the practice will allow for development into a more depended-able segment of the mining industry, an alternative stream of material, but surely not a replacement to traditional mining.

Crops that are hyperaccumulators of metals are of the most obvious and apparent agromining potential when their agronomic qualities are high as well. The best Agroming crops may not have the highest level of metal hyperaccumulators but a high enough level that creates profit through the high level of biomass produced that can harvested. One way to increase the plant's biomass (and thus bio-ore that can be extracted) is fertilization. Additions of common macronutrient fertilizer of nitrogen, phosphorus, potassium, and sulfur have the ability to increase yield of nickel in Alyssum spp. amongst other Brassicas like Nocccea goseingense and Streptanthus polygaloides, in diverse locations (all with ultramafic soils) such as Italy, Spain, and New Zealand (Bennet et al. 1998, Bani et al. 2015, Alverez-Lopez et al. 2016). NPK fertilizers were able to increase biomass of brassicas without diluting the Ni levels in the plant, while some decrease in Ni concentration was shown it was offset greatly by the improved biomass, most explained through phosphorus additions (Nkrumah et al. 2018). This **dilution factor** is critical as some hyperaccumulating plants lose their abilities to do such when much fertilization artificially input; the plants biomass grows but the amount of metal may stay the same, thus decreasing it's overall concertation, and eliminating the hyperaccumulating and metal extraction abilities of the plant (van der Ent et al. 2021). Thus is a critical to evaluate, test, and develop phytomining species to ensure a good-plant-metal-soil combination is of practical use in an agronomic (agromining) situation and not just a natural (phytomining) operation.

The **ultramafic soils** in which the aforementioned plants grow tend to have a pH which favors the unavailability of phosphorus due to its adsorption to the clay and other negatively charged soil particles. Increasing pH (through additions of Lime) as an agronomic practice would be disadvantages to increase P availability as would be recommend in most other tropical climates with similar edaphic properties, due to the decrease in Ni availability that would result from that same action (Nkrumah et al. 2018 & van der Ent et al 2021). Standard (split) applications of macronutrient fertilizers will increase the yield of agromining crops on ultramafic soils, and it can be further increased when coupled with other agronomic practices (Nkrumah et al. 2018). Modification of the soil to increase the availability of metals for uptake should focus on adjustment of the pH.

Agronomic actions such as pH adjustment have shown to improve the agromining potential through increase in biomass production of metal hyperaccumulating plants when grown under agricultural management schemes at the pot level (Li et al. 2003, Kukier et al. 2004). The pH will need to be adjusted based on location specific properties that differ, in order to achieve the (intended) fullest success of the grown plant as an agronomic crop. With ultramafic soils in pots an adjustment of pH to 6.5 shows improvement in Ni yield and biomass production (Chaney et al. 2007 & Nkrumah et al. 2018).

Other **more in-depth agronomic and agricultural practices beyond fertilization addition and pH adjustment should be explored to show how metal yield can be maximized**. Most agronomic practices have been explored on crops that uptake large amounts of Nickel because not only is it the most common metal element to be hyperaccumulated by plants but also due to the high concentration of Nickel in the Earth's crust. Essentially it is the most practical or feasible metal to be extracted from the ground using plants. Other metals however can be hyperaccumulated by brassicas (and other plants) such as gold, silver, and other noble metals, which are of a higher value than nickel and thus require lower yields and biomass produced and metal uptake (Nkrumah et al. 2018 & van der Ent et al. 2021).

Noble metals, not just Nickel (Ni) can also be extracted from the soil beneath us with the use of Brassica plants. Indian mustard has shown to be a hyperaccumulator of gold in both lab or artificial scenarios (natural Au particles added to sand media; induced uptake of synthetic Au ores), as well as with recovery of Au from mine waste ores and tailings that couldn't be (further) economically mined otherwise under traditional measures (Anderson et al. 1998, Lamb et al. 2001, & Anderson et al. 2005).

It's important to note that in these studies and experiments are treatments that had to be added to the substrate unlike with some of the Asteraceae. Although Indian mustard is a natural heavy accumulator of metals, gold and other nobles, their concentration in the soil is not abundant enough to have substantial uptake without (human) modification of the environment (desorbing them from hold by soil particles and released into soil solution), through introduction of chemical compounds like thiosulfate and cyanide (van der Ent et al. 2021). **Most associations between noble metals and plants seemed to be an induced type of accumulation**. This relationship is important because like with the Asteraceae many of these plants have the ability to survive hardily, succeeding well under harsh conditions and little input. The ability to uptake metals among the Brassicaceae is generally higher than the Asteraceae, however the latter tend to have high percentage of leaves (where the most abundant quantities of the mined metals are, even if concentrations are slightly lower than roots, or stems), and overall higher biomass production making them the more a possibly more suitable pick for large-scale or repetitive 'cropping' for extraction of mined metals (van der Ent et al. 2021). Thus, it is more common to see Brassicas specie used for phytoming, theoretical, academic, or laboratory-based approaches and experimentations, while the Asteraceae are more suited for Agroming operations for commercial economic gain. Both are becoming more commonly used for temperate Agroming however (van der Ent et al. 2021). Now to a look at the Fabaceae plants of phytomining significance, with root and tube crops being explored after that, and other outliers (critical 'group' of 'points' in all matters of Life) after that.

2.1.4. **Fabaceae** (1/2)

Legumes or members of the bean or Fabaceae family also have roles in phytomining operations. They have not been as fully explored and implemented for such use however. But such is also true of their role (and potential) in other aspects of tropical agronomy, such as for use in pastures as a forage. Despite such, some legumes have been studied and shown to be natural metal hyperaccumulators. Their role in Agroming seems to be more indirect so far, however. This is a further area however where legumes could be developed for use in tropical areas and knowledge gained from such could be extended to other areas in academia, industry, etc. for assisted benefits sharing of the knowledge gained.

Legumes can be intercropped with grasses or other more conventional agromining crops to help mobilize elements in the soil for uptake by the neighboring (inter)crop 9Wiche et al. 2016 & van der Ent et al. 2021). For example, Lupin (Lupin albus) is a legume that has the ability to secrete chemicals into the rhizosphere lowering the pH and making certain trace elements (Fe, Pb, Th, La and Nd) more available in the soil for uptake by oats (Avena sativa); this (intercropping with legume) treatment resulted in higher tissue concentrations of the aforementioned trace elements (desired metals to be phytoextracted) in the oats tissue as well. (Wiche et al. 2016). The leguminous species Anthyllis vulneraria has been shown to be a leguminous species that can hyperaccumulate Zn (as well as Cd & Pb) on serpentine soils in Italy and showed potential for use in phytoremediation efforts (Grison et al. 2016). The larger problems with implementing legumes into such an agronomic system in largely their finicky nature of growth, difficulty in propagation success at the field level and related establishment, and lack of persistence compared to other endemic plants or agronomic crops with phytomining capabilities (van der Ent et al. 2021). From a phytomining standpoint, legumes seem to be focused more on intercropping efforts to assist in making metals more available in the soil or for small scale phytoremediation efforts when a species is found with such abilities and is adapted well to a particular (small) geographic area, most likely where it evolved such a relationship to the otherwise harsh environment (to other competitors) over a large evolutionary timescale. Legumes are somewhat of a novelty for Agroming operations at this point in time, but further research and experimentation will reveal better plant-metal-soil combinations of this plant family. Root and tube crops can serve a bit more as a specialty than as a novelty as will be explored next.

2.1.5. **Root, Tuber, & Below Ground Crops**

Root and tuber crops have been a staple throughout human history (especially in South America, where most are still widely used, and where many originated). Sweet Potato (Ipomoea batata), Carrot (Daucus carota) & Cassava (Manihot esuclenta) will the crops of focus here, with the first and last being of seemingly greater phytomining importance. These crops are traditionally valued for the high energy content of their roots, but with these characteristic accumulations of metals from the ground, not just starch alone from the above ground retranslocated photoassimilates that is the valued characteristic to be exploited for the extraction of metals from the ground in which the crops are grown. Gold among other precious metals is usually the interest with these root and tuber crops when concerned to phytomining, due to the rarity of the former and the known agronomic knowledge of the latter.

Carrots (Daucus carota) are one of the proven metals phytoaccumulators used for Gold (Au); this is due to their proven ability as an agronomic root crop in temperate environment, high biomass production, and large storage root production and associated uptake through of gold from the soil solution up to the plant (Msuya et al. 1999). Past work in the field has revealed that most metal concentrations, including with gold tend to be higher in the roots versus the shoots (Dinh et al. 2021 & Anderson 1999). This ultimately why root and tuber crops are of so much interest in these pot study type of experiments that concern the more economically high value metals and induced artificial hyperaccumulation. It is beneficial to have such a large natural storage organ, with such minute quantities of desired metals are intended to be extracted, as the capabilities of some plants may be higher for such phytoextraction and hyperaccumulation, but are rather low biomass producers, be that above or below ground biomass.

Carrots tend to be more focused towards phytomining activities in the temperate climates and the tropical tuber crops are more geared to operations in the warmer, near equator latitude. Growing these crops in the environment of high metal abundance needs to be performed at levels of intensity that ensure biomass production and associated metal uptake is viable to the low levels of metals trying to be obtained. Genetic improvement of the hyperaccumulating plants for better physiological mechanisms of metal uptake is one side of the approach but proper agronomic management, especially in such harsh conditions, is needed to help make these types of operations economically practical for commercial operators. These root crops have tended to be more of an experimental success with rare high demand metals rather than more abundant metals like nickel in afield-level setting; advantages exist however in that many of these (below ground crop) crops are already grown agronomically (for food, not for metal) and thus it won’t be as hard to develop an agronomic operation with such, theoretically, as compared to ‘weedier’ hyperaccumulating plant species that are not as ‘developed’, in this way.

Sweet potato is a proven phytominer of gold (Au) in intentional practices of phytoextraction using additives and known to naturally be an accumulator of other (heavy) metals like arsenic, cadmium, & lead and is a heavier accumulator than the other root and tuber crops (Noviardi et al. 2021). It has potential for use in areas that have a minor ore abundance but where economical extraction through traditional mining wouldn't be possible (tailings, reclaimed areas of abandoned sites, currently active mines with diminished productivity due to overharvest of resources, mine sites done with conventional operations and needing agroecological clean-up using phytoremediation qualities of these metal extracting plants). While being a heavy accumulator of (economically) important metals is all good and well, this only works if the plant is alive and working. Sweet potato is a member of Convolvulaceae family and has hardy (even weedy-like at times) growth but abiotic conditions at most sites saw a severe negative effect on performance of plant health and vigor; simply the sweet potato plants couldn't survive (well) and / or thrive on the sites needed to be phytomined due to the acidic pH and inherently low soil fertility (Scott 2020 & Noviardi et al. 2021). Despite this, they are proven Au accumulators and perform best when plant performance and evapotranspiration is high (Scott 2020, van der Ent et al. 2021, & Noviardi et al. 2021).

Cassava is also a root crop known to be a wild and natural hyperaccumulator of gold (Au), among other metals like copper (Cu), lead (Pb), and Zinc (Zn) (Surono et. Al. 2018). Studies have proven it to have much the same abilities as the sweet potato in this feature (Lamb et al. 2001 & Alcantra et al. 2017). The additions of thiosulphate and lime to the soil allowed for mercury tailings to have gold recovered from them using cassava plants (Surono et al. 2018). This is a common addition for the inducement of gold extraction using plants (van der Ent et al. 2021). The limiting problems in these types of scenarios is much like the fate of the sweet potato; the limiting factor is the plant's (lack of ability for) survival in the (harsh) environment. In the situation of the wild-type cassava and accumulation of gold (Au) from mine tailings, biomass of the plant simply wasn't enough to generate an economically feasible return to incorporate such a practice beyond the experimental scale; another major issue being that other heavy metals in the tailings were accumulated at much higher rates relative to the wanted metal, gold (Surono et al. 2018). This was not a practical problem in the agronomics of the operations, but more so in the processing and other post farm-gate activities, as many of these accumulated elements present toxicity problems to the humans handling them, as well as the environment at large (van der Ent et al. 2021). Perhaps research should look into applications of these more 'common' (root) crops with environments high in nickel (Ni), cobalt (Co), Zinc (Zn) or other metals of higher relative abundance in the Earth's crust, as a safer and greener revenue stream than traditional mining.

2.1.6 **Conventional Agronomic Crops**

Tobacco (Nicotiana tabacum) has always been one of humankind's favorite non-food crops and phytomining is just one more use (recreation, medication, pesticide, etc.) that can be added to the (human) uses of this fascinating 'New World' crop. When grown on tailings from precious metals mining it is a proven phytomining species of both Gold (Au) and Silver (Ag); sodium cyanide being used an inducer (Krisnayanti et al. 2016). This work showed more success with silver uptake than for gold or Tobacco. Of these two metal, silver may be the more practical choice of commercial mining focus, especially in combination with conventional agronomic crops like tobacco and other species that can be grown at high vigor and performance across larger areas due to their long history of cultivation, compared to other phytomining species that are lacking in the ability to grow in such agricultural production style systems, and / or without the ability to produce the amount harvestable biomass needed (for an economically feasible operation in a commercial 'real-World' setting). Sunflower is another phytomining crops with these positive agronomic traits that may see it be put to use on larger scale, like Tobacco, as aforementioned at the beginning of these first sections.

Silvergrass (Miscanthus siensis) is a high dry matter producing perennial C4 grass that is typically cultivated for uses such as paper making, biofuel, or heat generation. Experiments in Britain provide prove that non-indued (natural) Palladium (Pd) and Gold (Au) hyperaccumulation with Silvergrass is possible (Harumain 2016). Being more of a natural, rather than artificially induced, metal hyperaccumulating plant species that can uptake a more economically precious metal, the Silvergrass-palladium relationship is important as it's a crop that can be grown on (agricultural or environmentally) marginal lands with high dry matter and biomass productivity without many management inputs needs (compared to many other species), while withstanding abiotic conditions that may limit such positive multifunctional features in other crops. Genetic improvement of the species for better metal mining traits (secretion of chelating or acidifying chemical from root exudates, high transpiration rates, deep root system, etc.) could help improve things further. It is worth noting however, as establishment would be easier and harvest done without much specialized equipment or hand labor, as needed with some more odd or 'weed'-like phytoming species used more traditionally for metal mining.

Hemp (Cannabis sativa) is one of the most multifunctional plants on the Earth, but it isn't just for rope or dope anymore; it's also a phytomining plant with phytoremediation potential. When grown on polluted soils, hemp showed the ability to be a hyperaccumulator of Ni, Cd, and Pb, as well as maintaining its fiber quality and having the ability to accumulate the mined metals at reasonably significant quantities in all plant parts (leaves, seeds, fibers, hurds, etc.,) (Linger et al. 2001). Hemp also has the ability to hyperaccumulate and mine other more rare and profitable metals beyond nickel or lead (Pb). Such would include gold (Au) and palladium (Pd), but an additive of potassium cyanide (KCN) had to be added to the substrate to help induce the availability of these metals for the crop's uptake (Aquan 2015 & Dinh 2021). This same study showed the ability of Hemp to hyperaccumulate copper (Cu) as well (Dinh et al. 2015). While good from the phytomining perspective, the ability of Hemp to uptake and translocate many of these minded metals to all parts of its structure represents a problem, down the line, if the crop were to be used for human (or livestock) consumption, however in a remediation or economic mining perspective this (intended, natural) hyperaccumulator of such (desired) metals would be a (rather) positive trait / quality. The harvested product (fiber) quality has been shown to be not affected by such metal accumulation, and a possibility therefore exists to have a crop that can yield two harvestable products – a metal and a fiber, both of which offer no ill effects on consumers downstream while being of phytoremediation quality for the soil on which they are gown, helping to extend ecosystem services of the land beyond solely the provisioning (van der Ent et al. 2021). The greater point in the bigger picture is that many of these metal mining plants can be treated as crops using agronomic practices for economic gain, as well as treated using ecological principles for environmental (and human) benefits, too extensive and intensive to explore here (last section of paper will cover this topic more).

Conventional agronomic crops have a leg-up against other more 'native' or 'endemic' species that haven't been manipulated by humans, in that we know more about them, and they can be grown as crops in an agronomic systems with higher yields and production. This greatly affects the lower natural ability for metal hyperaccumulation, but obviously such still needs to be present. All this talk about phytomining plants is not completed with a review of the soils in which they grown. This is often overlooked by the average person and specific agronomic attention needs to focus on these soils however to elucidate the plant-metal-soil relationships that could prove to pertinent and potentially profitable for agromining and phytoremediation efforts. The soil is where the metals exist and serves as the substrate in which the plants grow. Understanding more about it will help understand more about the plants and metals they mine from within it.

2.1.7 **Other Plants / Crops of Substantial Interest / Practical Use**

Each metal with have a unique suite of plants that are suitable for its preferential or facultative uptake, and some plants can uptake more than one metal, but for the sake of length the main focus will be on nickel and plants that uptake such, as this is the metal has the most practical and optimistic outlook in terms of Agroming.

Thus, the main phytomining crops of interest are ones that are hypernicklophores (plant hyperaccumulators of Nickel at high levels), but also preferably produce a large (easily harvestable) biomass and are native to a region as to avoid issues with pests and diseases (as well as prevent from introducing these to new areas as well, from outside ‘metal crops’). The main authorities and searchers on the issue have broken the crops of interest down into two majior groups, by plant type and geographic area: tropical / ligneous crops such as *Phyllanthus spp., Rinoera spp.,* and *Geissois spp*., used in the Asia-Pacific region, and the temperate / herbaceous crops such as *Alyssum spp*., *Leptoplax spp*., and *Bornmuellera spp*. (all three are *Brassicaceae*), used in the Mediterranean and Eurasian regions (van der Ent et al. 2015). The list of plants numbers into the 700s of known metal hyperaccumulators.

Table 1: *Agromining Features & Characteristics in Selected (Non-Nickel) Plant-Metal Relationships*

	Asteraceae	**Brassicaceae**	**Root & Tuber**	**Conventional Agronomic**
Associated **Genera** of Proved Phytomining Ability	*Helianthus*[5], *Berkheya*[7],	*Brassica*	*Ipomoea*[1], *Manihot*[2], *Daucus*[3],	*Nicotiana* [4], *Miscanthus*[6]
Model **Species** to be Discussed in the Rows Below	*annus* (Sunflower) [5], *coddii* (Asteraceae)[7],	*juncea* (Indian Mustard) [8]	*batatas* (Sweet Potato)[1], *esuclenta* (Cassava)[2], *carota* (Carrot)[3],	*tabacum* (Tobacco) [4], siensis (Silvergrass) [6],
Metal of Interest Uptaken	Gold (Au)[5] , Copper (Cu)[5], Platinum (Pt) [7], Palladium (Pd) [7]	Gold (Au) [8],	Gold (Au) [1,2,3]	Gold (Au)[4,] , Silver (Ag)[4], Palladium (Pd) [6],
Natural or Induced **Hyperaccumulation**	Induced [5] Natural [7]	Induced [8]	Natural[1], Induced[2,3]	Induced [4, 5, 6]
Uptake Additive	N/A & / or Not Necessary	Ammonium thiocyanate [8] ,	Sodium Thiosulphate & Lime [2] Ammonium thiocyanate & Ammonium thiosulfate [3]	Sodium Cyanide [4,5,6] Ammonium thiocyanate, Ammonium thiosulphate, or Thiourea[5]
Abundance of Metal of Interest in **Soil** (mg / kg)	2.35 / X [5], 0.04 / 0.07 [7]	5 [8],	4.7 [1], 5.1 [2], 48.3 [3,]	1.03 / 18.2 [4], 100 [6]
Concentration of Metal Hyperaccumulation in **Plant** (mg / kg)	21.5 / 141 [5], 0.22 / 0.71 [7]	57 [8],	2.5 – 10.4 [1], ≤ 2.5 [2], 3.8 [3],	1.2 / 54.3 [4], 505 / X [6],
References	Noviardi et al. (2021)[1], Surono et al. (2018)[2], Msuya et al. (1999)[3], Krisnayanti et al. (2016)[4], Wilson-Coral et. al (2011)[5], Harumain (2016)[6], Nemuntandani et al. (2007)[7], Anderson et al. (1998)[8],			

Image Reference(s): (For Pictures on NEXT PAGE)

Phyllanthus rufuschaneyi (Tropical – Malaysia) Alyssum murale (Temperate -Albania)
Salix spp. (Temperate- USA, Europe, Other) (Ag) Pycnandra acuminata (Tropical – New Caledonia) (Ni)
Pteris vittata (Subtropical) (Ar) Viola lutea subsp. Calaminaria (Temperate) (Zn)
Armeria maritima (Temperate) (Cu) Berkheya coddii & Other Berkheya spp. (Temperate) (Ni)

Figure 1: Pictures of Selected Hyperaccumulating Plants & Agroming Crops of Interest

Phyllanthus rufuschaneyi (Tropical – Malaysia) (Ni)

Alyssum murale (Temperate -Albania) (Ni)

Salix spp. (Temperate- USA, Europe, Other) (Ag)

Pycnandra acuminata (Tropical – New Caledonia) (Ni)

Pteris vittata (Subtropical) (Ar)

Viola lutea subsp. Calaminaria (Temperate) (Zn)

Armeria maritima (Temperate) (Cu)

Berkheya coddii & Other *Berkheya spp*. (Temperate) (Ni)

2.2 - 'Metalrific' Soils & Geographies of Interest

2.2.1 – Introduction

Ultramafic rocks are low in silica and have a high concentration of mafic (silicate mineral or igneous rock rich in (over 70%) magnesium (Mg) and iron (Fe)) minerals. These somewhat (rare) soils that originate from the aforementioned types of rock are known as Serpentine soils. Peridotite and serpentinite are two of the most common minerals that break down to form these soils. Such are scattered variously throughout the globe.

Serpentine soils encompass about 1% of terrestrial Earth and have some unique qualities, mostly establishing them as soils that are not suitable for agriculture. They often tend to present challenges both to plants in their germination, propagation, or establishment, or to the mechanization (tractors and like mechanical devices) and or the physical controls (tillage, plowing, cultivation, etc.) needed to implement the growing of such hypermetallophores or any crop for that matter on an agronomic basis (van der Ent et al. 2021).

Ultramafic soils are high in nickel (Ni), Cobalt (Co), and Chromium, (Cr), and they tend to be rocky and shallow, leading to temperatures that can be too high (too quickly) (to sustain substantial plant growth, as compared to other areas with different soils in the same region) and a water holding capacity (WHC) that is too low from the quick drainage of and the lack of ability to hold water adequately (Kidd et al. 2018). These issues obviously present problems to land use, be it development and urbanization (for humans) or agriculture (of plants, for food, feed, fuel, fiber, etc.), thus agromining is a presentable novel land use that helps to circumvent some of these issues while increasing the economic gain (provisioning ecosystem services) in the meantime and helping to restore the land (supporting ecosystem services) to support (more) traditional (conational) agricultural operations in the future.

Other issues of these soils include a high Mg:Ca ratio and low inherent fertility of N, P, & K. While these are correctable with inputs, as what is needed for the establishment of phytoming crops on an agronomic basis, but often these are areas of the World, where socioeconomic and / or infrastructure and market development hinder the use of nutrient inputs due to their high price, lack of availability, lack of transportability, or lack of ability to apply or incorporate easily (or without heavy losses), among other reasons.

All these edaphic and nutrient issues coupled together lead to the inability of these serpentine soils to have much of a practical land use beyond the support of the diverse, rare, unique, natural habitat in which they are. Taking these aforementioned qualities into mind, it can be easy to see why many species do survive under these living conditions, often the ones that do tend to be hyperaccumulators of the metals, which are naturally high in these soils. The species that do survive in these types of environments are mostly endemic adapters that have an ability to live in these soils that are naturally high in the target metal concentration.

It's many of these features and characteristics of the soils that make them poor suitability for plant survivability or productivity. This further creates the rampant endemism of many of the plants growing in these areas as most others can't survive and the ones that do have found their ecological niche and are making the most of it, in the limited specialized areas in which they can. Over time many of these endemic ecotypes and species become noticeably distinct from neighboring plants (outside the areas of ultramafic and serpentine soils) and other areas with not only a different edaphic set of characteristics, but a related and interacting unique botanical composition as well (van der Ent et al. 2021). The relationship between serpentine ecosystems and surrounding ones is everchanging and is often anthropogenically influenced, especially in the modern era of the Anthropocene, as both indirect changes (global warming) and direct changes (land use / development, invasive species introduction) individually and interactively shorten (and change) borders of these habitats constantly. While much in the past serpentine areas were thought to be with marginal or unusable or only to be used for mining of needed metals in certain locales, the mindset nowadays has changed more to the preservation of these lands for the unique set(s) of soils, plants, animals, associations, relationships, etc. that they present to the World; agromining may not be the answer to the (land use) question in some (many) of these cases, but in many other serpentine areas, and other ultramafic and metalrific soils across the globe, agromining is a viable alternative to the current marginal use of the land and helps present a path of forward progression (in land restoration) once undertaken (properly, under the right conditions).

It's these ultramafic and serpentine soil areas that are of the most potential for agromining because of the high concentration of metals (Ni in the case of feasible economic agromining for commercial gain) in the soils that can be uptake by plants. It's many of the plants from within these areas (the native hypernicklophores) that are being used for agromining because of their natural (inherent) ability to hyperaccumulate (desired) metals of (economic, industrial strategic) importance as well as their survivability and resilience in such harsh climatic and edaphic conditions where other plants might not be able to persist and produce as well.

The largest challenge comes in trying to 'convert' these endemic plants with natural metal hyperaccumulating abilities to be (act (more as) like) 'crops' per se, that can be grown on a large (repetitive) scale without more than normal intensity (and hopefully less than so, as to create a more economically profitable, and sustainable agroecosystem) of agronomic management and inputs required relative to more conventional crops. Often these areas can be viewed more like an orchard, as much work, time, labor, capital, etc, has to go into the beginning of the operation, in the establishment of such, than in the continued maintenance, input, and optimization like more intensive annual horticultural crops. Once established the crop will dictate management needs, grasses, and perennial trees that hyperaccumulate metals will be easier to maintain and a lower cost than annuals that need to be created first (intensively in an (often) off-site nursery setting and then reestablished on the metal farm each year (or season) (van der Ent et al. 2021). Temperate areas with ultramafic soils tend to present opportunities for the latter, while tropical areas tend to be more accepting of the former.

Ultramafic soils tend to be extremely high (up to 3600 ppm Ni, compared to 2 -750 PPM normally) in nickel (Ni) compared to more 'normal' soils, and thus these endemic metal hyperaccumulating plants tend to be the only ones that can survive such harsh conditions (or likely to be successful in agronomic establishment), with over 500 of the ~700 known metal hyperaccumulators being Ni phytominers (many endemics to these soils) (Kidd et al. 2018 & van der Ent et al. 2021). It's the physiological adaptation (and thus capabilities) of these plants that allows them not only to survive but to be of interest to agromining, as bio-ore can be extracted from the soil in a way that is less costly than conventional mining and poses less environmental damage in the metal extraction process(es) (van der Ent et al. 2021). This is only the case for Ni in select areas however, more work and research have to go into agromining for other metals to be feasibly extracted from the ground on a metal farming basis and not solely a laboratory or simply experimental one. The barrier with many metals is not only their lower concentrations in soils and less homogenous or large localized hotspots, but also the lack of (known) plants that are hyperaccumulators for such. Accumulators of rare earth elements and other highly desired metals are the next target of interest, as mining anthropogenically polluted areas and or mine tailings would support a phytomining crop to extract these desired resources in a way that current conventional mining techniques don't meet, while creating an agroecological improvement to the local system.

2.2.2 –Bacteria, Fungal, & Other Microbial Relationships

Unique **microbial associations** with plants in theses metal rich soils are present but need further investigation. These inter-kingdom relationships show the ability to naturally (and artificially) assist plants in the metal phytoextraction process, through biological means (that could be additive, as in an agronomic agromining operation, or supportive in amore holistic agroecological approach) (Kidd et al 2018 & van der Ent et al. 2021). These fungal and bacterial interactions with the endemic metal mining plants can help them improve defenses versus pathogen, increase growth productivity, increase stress tolerance, assist in nutrient (and / or metal) uptake, initiate / stimulate growth, and induce changes in plant phenotypic plasticity among other beneficial tasks that help phytomining plants perform their valued work (Kidd et al. 2018). All these are beneficial enhancements that can be manipulated when the outdoor agroecosystem on the field and / or regional scale can be manipulated and controlled (as much as possible), as like in controlled environment agriculture. Using the principles of ecology and the mindset of agroecology, the relationship of interkingdom species can be harnessed for modifying (or enhancing) the environment to support the establishment and feasibility of an agromining crop.

There has been a push as of (more) recent to combine the technology of bioremediation with that of agromining to allow for the beneficial biology of the former to help assist with making metals less persistent / damaging in the edaphic environment (removing them with the use of plants). Metals that have been previously demonstrated to be able to be removed or 'leached' form the soil through biological process of introducing bacteria and fungi, can now be removed purposedly for economic gain using the same technologies.

These bio additives essentially help to make the selected elements in the soil more available, or they serve to improve the growth of the crop (as many of these mined soils are of marginal agricultural use in the first place). The microbial ecology of the soil environment is everchanging, dynamic, and locally unique, however in all cases itself may be limited by the presence of heavy levels of metals in the soils, as the plants are limited in growth by this same aspect of their home soil. By adding certain biologicals, the plants will not only perform better, but the metals in the soil will be more available.

A few examples of broad categories of biological additives in the assistance to the agromining processes would include, but are certainly not limited to mycorrhizal fungi, arbuscular bacteria, rhizosphere microbes and plant exudates, and other endophytic microbes, that have unique, established relationships with the soils and plants in these metal rich environments. Localization of these relationships is key, and often plants may not fend well in a different ultramafic soil without these bio-associations present to assist them in growth and survivability in the harsh environment. Thus, a key to the establishment and conversion of hyperaccumulating plants to new areas where they will (be intended to) be agrominic (metal extracting) crops, is the (artificial) introduction, or enhancement of these fungus and bacteria in the soil to assist the plant in growth.

Microbe associated phytoming can occur under the two frameworks of using the metals to be more available in the soil or the plants to perform better at acquiring the metals; the approach as of recent in determining useful microbe-plant-soil-metal relationships is moving away from that of phenotype evaluation that is cultivation dependent and moving towards a genetic based non-cultivation approach, as technologies for such screening are advancing and the ability to cultivate and test many of these microbes in a field setting is impractical. Thus, being said, an integrative approach of more modern molecular genetics and more traditional agronomic breeding and cultivar trialing and evaluation is needed to be practiced in combinational in order to best support the agronomic and economic feasibility of establishing one of these plants into a crop, for metal-farming.

2.2.3 – Tropical Soils & Geographies of Interest

The area of interest in the **tropical** latitudes most suitable for Agromining is the Asia-Pacific region, predominately New Caledonia, the Philippines, Indonesia, etc.; these are countries with extensive areas of low-grade nickel containing soils that can be mined on a large scale for economic gain, while not posing any competition (and rather providing an otherwise unnoted benefit) to the agricultural or industrial land use choices. Many of the lands to be used for Agromining in Southeast Asia are areas of anthropogenically polluted or extensively modified soils, such as mine tailing, dumping sites, waste soils, soils already through intensive conventional mining, and smelter or industrial contaminated soils; thus so, there is much diversity in these tropical soils, both naturally and artificially.

The main soils of interest are the ultramafic deep laterite, deep montane, and bare serpentine soils, as these are the highest in natural abundance for Nickel, which is the most agronomically set of any of the plant-soil-metal combinations to be used on a large scale for commercial economic gain (van der Ent et al. 2021). Areas with Ni mining prospects may also be suitable for Cr and Mn, but market and botanical conditions don't present a good case for such as compared with Ni. The anthropogenic soils are more favorable to the metal in which they were traditionally mined for, often the precious and noble metals, as well as the rare earth elements, or other metals that are desired more for their preciousness and scarcity, rather than for large scale industrial needs like nickel.

These more precious metals present dual-fold challenge in that soil conditions tend to be harsher to support any plant growth let alone agronomic high performing plants on a repetitive basis, without much need for inputs. Also, the plants that are hyperaccumulators are often needing of assistance through environmentally damaging chemical additives or are only feasible through laboratory, greenhouse, or pot experimentation. Ni, Cr, Mn, and other metals abundant in these tropical soils present a more feasible case for an economically profitable use of the land. It is important to note however that the economic loss may have to be taken on many of these anthropogenic soils for a few years to decades in order to bioremediate and reestablish them as usable for any use beyond the marginal use in which they presently exist. Annually established Legumes, perennial grasses, and even a tree (in Guatemala) are the plants more commonly used in tropical Agroming (van der Ent et al. 2021). More plants will be found as profitable operations in these areas intensify and alternative crops choices will be needed to expand into other areas of the trop for metal farming.

2.2.4 – Temperate Soils & Geographies of Interest

The area of interest in the **temperate** latitudes most suitable for Agroming is the southeastern area of Europe bordering the Mediterranean Sea. There are spotty areas of ultramafic and serpentine soils that are either used for marginal agriculture or little to no economic purpose. The soils of interest would include Vertisols of Albania, Cambisols of Greece, serpentine areas of the Balkans, barren areas of Spain, ultramafic soils of Turkey (van der Ent et al. 2021). Many of these areas are not seen in the same conservation perspective, as serpentine areas are in the USA or Canada, due to their more natural abundance in these European areas, as well as the need for economic probability of the land that can't be met elsewhere due to their higher abundance. The Pindus Mountains of the Balkans are the largest are of ultramafic outcroppings and are highly suitable for agromining using herbaceous alyssum species; the eastern oak-pine forests of Albania will serve Agroming well with their high amount of nickel rich outcrops; peridotite outcrops in Portugal and Spain are also other areas of opportunity for Agroming on the temperate latitudes of Mediterranean Europe (van der Ent et al. 2021).

Many of these areas in the temperate Mediterranean perspective of agromining will have annual crops that established and harvested on yarely basis, and can be undertaken in a more traditional agronomic perspective due to their likeness of traditionally harvested crops, ease of access to inputs, machinery, markets, etc. Elevation and topography (changes) are often (more) of a problem in these temperate areas versus tropical areas, as agromining as any agronomic operations are hindered (and other environmental problems created) when hills are involved.

2.2.5 – Soil Amendments

Part of the appeal to agromining, and the economic feasibility, is the fact that the land that is being used is not being displaced for agriculture or commercial purposes, and thus is seen as otherwise marginal or not in use for producing or productive means. Thus so, the addition of amendments to the soil may be (/ is) necessary in order to create an edaphic environment that is more suitable for plant growth, especially when implementing such on large agronomic scale, to make such a probable endeavor rather than just an exploratory or principle proving application. The most useful addition will vary by geography but in the Tropics for the mining of Nickel this may be Ca and S (Nkrumah et al. 2019). The former is often lacking naturally in these Ni-rich soils, and the latter is often beneficial due to its lacking in natural abundance but also in making the soil slightly more acidic (and thus suitable for the legumes crop growth and making Ni more available to the plant). In the temperate , many of these serpentine areas tend to be toward 7 in pH or even higher in some situations, lowering the pH should help with any agronomic or agromining crop growth.

Organic amendments may help in both tropical and temperate situations, as to build the physical structure, and biological support capabilities of the soil, in order to provide the edaphic framework necessary for the agronomic growth of hyperaccumulator plants on a scale large enough for metal extraction in pursuit of economic gain (van der Ent et al. 2021). With these shallow, rocky soils it's often the physical change and improvement that helps agronomic performance of the crops but implementing such additions on a very large scale and / or repetitive basis is not practical in economic or sustainability sense but can be supported locally when practiced on a more mesoscale, as like with manure additions in eastern Europe to improve growth of Agroming crops for Ni (van der Ent et al.

2021). In a temperate-humid agroecosystem in Albania (where serpentine outcroppings are largely present, but unused otherwise for agriculture, or much else improved use by humans), the addition of N-P-K fertilizers and irrigation were shown to have both cumulative and independent beneficial effects, however what was more positively increasing of the concentration of nickel in aerial plant parts of herbaceous metal crops was the use of the organic amendment manure (which was cheaper in this agroecosystem's context, than irrigation (establishment cost) and fertilization (material cost)) (Bani 2019). The context of improvement of the cropping systems by the use or addition of amendments will be highly localized in context and thus this and the aforementioned tropical examples are just to give a minor glimpse of the implication this aspect has in the greater overall picture of implementing agronomic principle into phytoming to create the more novel concept of agromining.

2.2.6 – Metal Distribution in Soil(s) & Geography

Nickel is most prominent igneous rocks and composes anywhere from 3 to 100 PPM of the soil (Earth's crust) typically; nickel is generally uniform in its distribution but is higher in areas of anthropogenic activity; as for natural occurrence, the abundance is highest in the aforementioned ultramafic serpentine outcrops of temperate Mediterranean Europe and tropical southeast Asia (Iyaka 2011 & van der Ent et al. 2021). Nickel is the metal / element of highest agromining prospects for success, the metal that most plants are known to hyperaccumulate for, and the metal most common in the Earth's crust that has economic desired qualities.

Technosols (or manmade soils) are often found where large amounts of commercial, industrial, and other environmentally modifying (destructive) actives have taken place, such as with areas surrounding conventional mining where tailings and other large amounts of substrates land wastes are dumped on a massive scale. Agromining on these can be to restore their capabilities to be more environmentally beneficial, but also to recover any last bits of metals or rare elements that can't be extracted (or can't be as economically extracted) by conventional means (van der Ent et al. 2021). Cadmium, Zinc, Nickel, Copper, Chromium, and Lead are all targets of phytomining efforts and expeditions on anthropogenically polluted soils have been undertaken for these elements of desired interest (Kanso et al. 2016). The location of these soils varies but are found throughout the globe with a cosmopolitan distribution, the largest of which that have or are currently undergoing agromining pursuits being in China, as mine tailings (van der Ent et al. 2021). The exploration of these soils and related exploitation under the agromining perspective is slightly different and should be thought of an operation undertaken accordingly to these unique characteristics, as compared to agromining with hyperaccumulating plants on naturally (Ni (and other metal)) rich soils, that are of natural occurrence.

Ultramafic sites rich in Ni, tend to be poor for agriculture and are lacking in N, P, K, Ca, and Mo, while they tend to bountiful in Fe, Mn, Cr, and Co; the availability of Ni is dependent largely on the plant, as all plants pull form the same liable and non-liable pools (Centofanti et al. 2012 & van der Ent et al. 2021). Calcium application is usually needed to pursue Agroming on a commercialized scale as the Mg and Mn concentrations of the soil are too high to support good plant growth and additions of calcium with straighten out any issues with the base saturation and CEC due to imbalance of the plant essential cations; 5-7, with 6.5 being the prime, is the goal for pH for most Nickel hyperaccumulators but this varies due to exact agronomic conditions and desires (van der Ent et al. 2021). As with many areas in the tropics, nutrient problems are present for plants (and thus for animals, and humans) due to the conditions that the soils present, due to their weathering and evolution over a large geological timescale. Correcting these (as with low P problems) can often be done through changing the soil conditions (pH, structure, drainage, etc>) rather than dumping in more of the needed chemical; availability is often the problem, not abundance.

USGS publications can provide more in-depth details of where each metal or element is abundant across the globe, how it is mined conventionally, it's end uses, and other necessary facts to provide a more well-rounded look into the metals that make up the conversation of both conventional and agricultural mining. As with all products and goods in the economy, the demand and supply set the price; the more useful and abundant elements like Nickel are practical for phytoming. Gold and Silver are rather wanted and desired, but they are scares metals and have many fewer (if any) natural associations with plants suitable for their uptake. The location of the metals will be the key factor in determining where Agroming takes place, so alike any agronomic crop, such activities and products can't just be practiced wherever the producer desires but rather must be fit into the localized yet globally interconnecting section of the agroecosystem that is suitable for such: spotty areas of marginal (agricultural or development) uses otherwise or anthropogenically disturbed edaphic areas.

2.3 - Non-Nickel 'Metalrific' Soils

Nickel has the most potential for agromining largely because of its abundance in the soil , other metals however show a potential for Agroming beyond nickel. These would include but are not limited to Co and Tl, which have been shown to be able to be mined on an agronomic scale for commercial economic gain (van der Ent et al. 2021).

Thallium is present in the soil at relatively high quantities, as compared to many other metals, which helps to present its case as feasible for agromining. The amount of thallium in the soil varies from 0 to 55 mg /kg, with an average 'background level' around 1; many areas are present broadly at 1-3 mg / kg Tl naturally, and other past mined areas and surrounding polluted areas can have 20 – 50 mg / kg Tl in the soil (van der Ent et al. 2021). These areas with high amounts of thallium in the soil tend to occur around pyrite deposits and areas that are more calcareous, having a higher soil pH and thus are marginal (at best) for current 'agricultural' uses, so agromining presents a novel operation for these lands that produces a product and helps to better the land, for a more traditional crop (or other anthropogenic) land use in the (near) future.

Cobalt also offers much potential for agromining because of its abundance in the soil, as like Nickel and Thallium, as also like these elements it it's a highly human valued resource that has much use in the production of electronic and technological items, all to present and increasing in today's modern society. Cobalt is present at the highest abundance in the Democratic Republic of the Congo, where much of the conventional mining takes place using slavery and child labor; areas high in nickel and associated mining hotspots re other sources of cobalt. Using plants to mine the cobalt would allow for the bettering of the environment of many of these anthropogenically contaminated areas surrounding mining sites, helping to better the land for suture crop growth, while also bettering conditions for the surrounding community inhabitants and workers of the traditional mining industry exposed to such high levels of Co in the soils. The uptake of Co is inhibited by the uptake of Ni (in most plants) and the latter downstream purification is actually harder (not a generation of two metals), causing a slight hinderance to the development of Agroming Thallium on a large scale (van der Ent et al. 2021). Many of the plants that are hyperaccumulators of Ni, are hyperaccumulators of Tl and can be used conversely. Selenium and Manganese present the best potential for agromining of other metals because of their properties on the soil; gold also shows a commercial premise, but this is due to the high value of the metal rather than any unique edaphic quality it possesses that make it suitable for agromining.

Table 2: *Preferential Metals of Abundance in Differing Soils* & Locations

	Tropical	**Temperate**
Working **Definition** [2]	Asia-Pacific Region and other tropical and subtropical Areas with necessary edaphic characteristics	Mediterranean & Eurasian Region and other hotspots of otherwise marginal serpentine soils and ultramafic areas
Elements / **Metals** [2]	**Ni**, Mn, Zn, & Others	**Ni**, Se, Tl. & Others
Concentration in **Crust**[1]	Goal = >1% Ni for Conventional Mining, can be less for Phytomining Many of these areas have up to ~ 3% Ni in the minable soil	Varies largely by area Nickel is the most feasible Se & Tl are feasible as hyperaccumulator plants have been found, however the former is found in vast quantities on the soil (albeit rarely) as compared the absence of such for Tl
Geographic **Locations** of High Natural Abundance [2]	Indonesia, Philippines, New Caledonia, Australia, New Zealand, Puerto Rico, Zimbabwe	Albania, Bosnia, Greece, Russia, Serbia, Turkey,
Plants typically found [2]	*Phyllanthus spp. Rinoera spp., Geissois spp*., etc.	*Alyssum spp., Leptoplax spp., Bornmuellera spp.,* etc.
End Goal [2]	Extraction of metal resources under a novel means that is more economically advantageous than the conventional standard now, and the generation of land that can be used for multi-purpose and biodiverse agriculture	More environmentally sound or agricultural productive land coupled with profitable resource extraction to alternative land use
References: Shacklette et al. (1984)[1], (van der Ent et al. 2015)[2]		

3 Metals - Nickel, Nobles, & Others of Importance

3.1 – Nickel

Nickel is by far the most popular hyperaccumulating metal and generating much research attention and work focus due to the practicality of its importance coupled with its (relatively) moderate abundance in the Earth's crust, compared to many of the other metals, especially the more desired but less abundant Noble Metals. Nickel, along with Cadmium, Zinc, Arsenic, Selenium, & Copper are all heavy metals that can be thought of readily 'bioavailable' in the soil; Cobalt and Manganese are moderately available, while Lead and Chromium are of the least bioavailability in the rhizosphere (Ali et al. 20213 & Muszyńska et al. 2015).

Agromining is much focused on Nickel due to its abundance in the crust and the larger areas of ultramafic soils that are high in nickel. Many of the plants that are endemic to these soils can be crops suitable for growth on these soils with such high abilities for nickel uptake can be further maximized through conventional and innovative agronomic practices (Nkrumah et al. 2018).

3.2 - Noble Metals

The 'Noble Metals' get their namesake for the high economic value they possess. This is to both the physical properties they have, scarcity of their abundance, difficult of obtainment, and to some degree human-imposed value. They include ruthenium (Ru), rhodium (Rh), palladium (Pd), silver (Ag), osmium (Os), iridium (Ir), platinum (Pt), and gold (Au) (Brooks 1992). Mercury (Hg), copper (Cu), & rhenium (Re) are included under this nomenclature sometimes as well (Wells 1860, Ahmed 2006, & Tamoi et al. 2010). Noble comes from the middle English word for 'high born' or 'of high rank' and these metals are certainly that. They have excellent durability, being able to stand up to harsh physical and chemical attack of both natural and artificial environments, as well as the ability to catalyze (increase the rate of) and thus control many chemical reactions with their presence in technology and products we use daily (Sheorah et al. 2009 & Truong et al. 2021). The former ability is largely due to the metals to not react 'negatively' with oxygen, due to their high redox potential; the world being 21% oxygen (yet decreasing currently), that ability to NOT ignite with the air and react creating fire or react with the moisture, humidity, etc. and create tarnish, result, and oxidation is ultimately what help them to resist decay and retain their 'noble' qualities (Bratsch 1989, Douglas et al. 1994, Wolfsburg 2000, & Huger 2005). Positive and beneficial characteristics (high quality) that can be put to use in various electrical products and biochemical applications coupled with natural scarcity (low quantity) of these elements is what makes them truly 'noble'.

3.3 - Other Elements

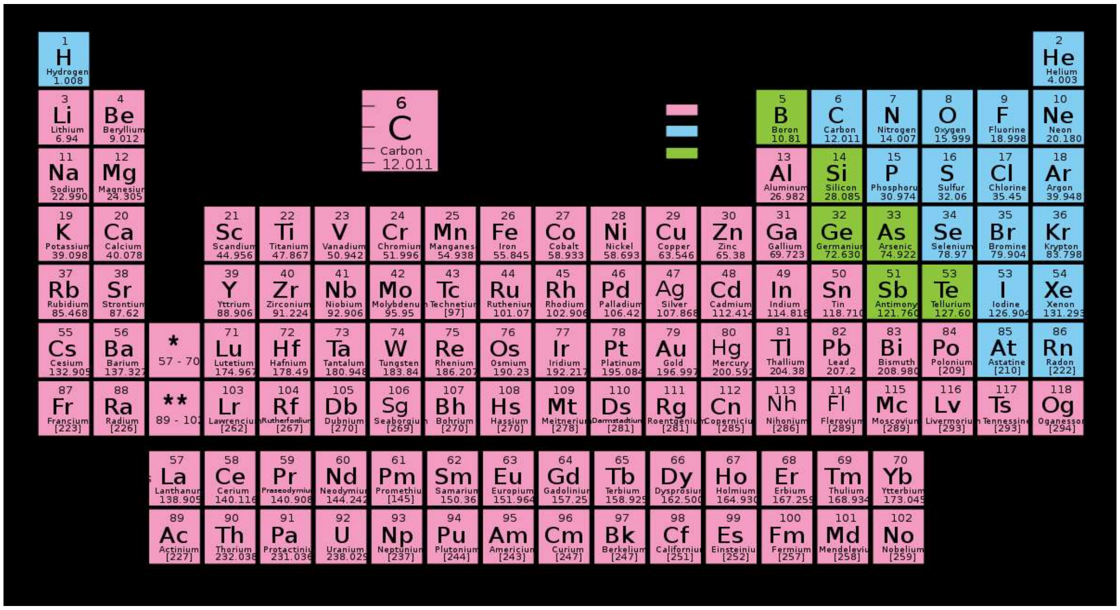
Many elements can be hyperaccumulated by plants, as to include Ni, Co, Cu, Zn, Cd, Pb, Mn, Se, As, Tl, Al, Si, Ba, Sr, Sb, W, and Pd; other elements such as the noble metals and some rare earth elements, amongst other metals and elements, can be selectively accumulated in particular plants in a facultative process using the addition of chemical leachates and or biologicals to the edaphic medium in order to release these for easier access to the plant and uptake into its arboreal parts for human harvest (van der Ent et al. 2021). Cr, V, Mo, and U tend to more available in acidic soils while As and Se tend to be more available in alkaline soils; Ni is the most abundant of the mined metal elements, has the most practical use, and the most plants that are suitable for it' uptake. For this reason, much of this literature review and the future of agromining itself is focused on this useful element.

3.4 – Commercial Interest

As has been presented, nickel shows the best ability to be mined economically effectively with plants. The need for Nickel drives this, but it largely due to be largely present in the soil. Focus on nickel should not preside over that of other metals, as these supplies are dwindling to by the traditional extraction means. Much experimental and laboratory experiments have been completed in the pursuit of advancing knowledge of hyperaccumulating plants and the phytoming of selected elements of interest. It's important to keep in mind however that much of this research however is 'theoretical', showing only a plants' ability to hyperaccumulate a given element under artificial conditions. Many of the times the additive needed to induce such uptake in the plant or make the target (more) available in the soil, as well as the unrealistic amount of the metal target in the artificial substrate, present these studies as being ones of theory only, or establishing a physiological relationship behind the mechanism of the uptake form soil to plant. While this knowledge is extremely helpful in advancing the field, many of these plants can't be grown on agronomic scales for mining of these same metals with the plants for a bevy of reasons. The chief among them is that many metals desired highest by humans (Au and other Noble metals) are those that have a strikingly lack of abundance in the soil by any means, let alone on a quantity high enough to allow for phytomining to be viable.

Other elements such as Cobalt, manganese, and thallium present ana ability to be mined on a large agronomic scale for commercial gain. Thallium is by far the 'best candidate' beside nickel and is being pursued in China currently and could be a viable solution / alternative method for / of (conventional) mining in the DRC (van der Ent et al. 2021). Selenium could also be mined using pants in areas where it is more abundant and used as feed for animals and livestock in areas where such deficiencies occur. These metals present viable cases for agromining. Many of the noble metals can be hyperaccumulated by plants and would be great candidates for phytoming but only in localized areas, usually of much anthropogenic pollution.

Table 3: *Periodic Table with Highlighted Metal Elements*



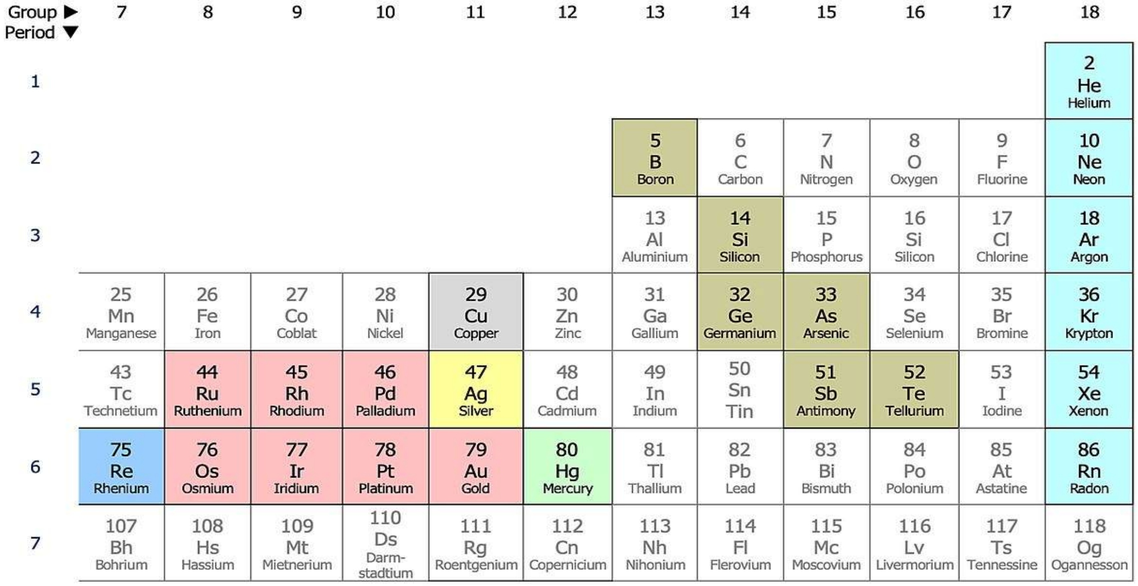
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.94	4 Be Beryllium 9.012					6 C Carbon 12.011						5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesiur 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.085	15 P Phosphoru 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromiun 51.996	25 Mn Manganes 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germaniur 72.630	33 As Arsenic 74.922	34 Se Selenium 78.97	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.468	38 Sr Strontiur 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenu 95.95	43 Tc Technetiur [97]	44 Ru Rutheniur 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	53 Te Tellurium 127.60	53 I Iodine 126.904	54 Xe Xenon 131.293
55 Cs Cesium 132.905	56 Ba Barium 137.327	* 57 - 70	71 Lu Lutetium 174.967	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.997	80 Hg Mercury 200.592	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [210]
87 Fr Francium [223]	88 Ra Radium [226]	** 89 - 10	103 Lr Lawrenciu [262]	104 Rf Rutherfordiur [267]	105 Db Dubnium [270]	106 Sg Seaborgiu [269]	107 Bh Bohrium [270]	108 Hs Hassium [270]	109 Mt Meitneriu [278]	110 Ds Darmstadtiur [281]	111 Rg Roentgeniu [281]	112 Cn Copernicu [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscoviur [289]	116 Lv Livermoriu [293]	117 Ts Tennessine [293]
		57 La Lanthanur 138.905	58 Ce Cerium 140.116	59 Pr Praseodymiu 140.908	60 Nd Neodymiur 144.242	61 Pm Promethiu [145]	62 Sm Samariur 150.36	63 Eu Europium 151.964	64 Gd Gadoliniur 157.25	65 Tb Terbium 158.925	66 Dy Dysprosiur 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.045		
		89 Ac Actinium [227]	90 Th Thorium 232.038	91 Pa Protactiniu 231.036	92 U Uranium 238.029	93 Np Neptuniur [237]	94 Pu Plutonium [244]	95 Am Americiur [243]	96 Cm Curium [247]	97 Bk Berkelium [247]	98 Cf Californiu [251]	99 Es Einsteiniu [252]	100 Fm Fermium [257]	101 Md Mendeleviu [258]	102 No Nobelium [259]		

86 Rn Radon [222]	118 Og Oganessor [294]

Metal elements are highlighted in Pink

Reference: Dmarcus100 (2016)

Table 4: *Periodic Table with Noble Metal, Metalloids, & Noble Gas Elements*



Group ▶ Period ▼	7	8	9	10	11	12	13	14	15	16	17	18
1												2 He Helium
2							5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
3							13 Al Aluminium	14 Si Silicon	15 P Phosphorus	16 Si Silicon	17 Cl Chlorine	18 Ar Argon
4	25 Mn Manganese	26 Fe Iron	27 Co Coblat	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
5	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
6	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
7	107 Bh Bohrium	108 Hs Hassium	109 Mt Mietnerium	110 Ds Darm-stadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson

Noble Metals (**Ru**, **Rh**, **Pd**, Ag, Re, **Os**, **Ir**, **Pt**, **Au**, Hg)

Metalloids are B, Si, Cu Ge, As, Sb, Te; Unrelated Noble Gases on far-right column: He, Ne, Ar, Kr, Xe, Rn

Refence: Sandnh (2020)

Table 5: *Agromining Traits of Noble Metals, Rare Earth Elements & Other Metals*

Element of Interest →	**Au** (Noble Metal)	**Se** (Non-Metal)	**Cu** (Transition Metal)	**Co** (Transition Metal)	**La** (Rare Earth Element)
Atomic Number [1]	79 (Gold)	34 (Selenium)	29 (Copper)	27 (Cobalt)	57 (Lanthanum)
Uses of Metal in Products [1]	Jewelry, Technology, Wealth Storage & Capital Back-Up	Solar Panels, Paint, Pigments, Ink, Plastics, Animal Feed Supplement	Electrical Parts, Motors, Wires, Construction, etc.	Metal Alloys, aircraft and high-Grade engines and mechanical parts	Catalyst, Lighting, Welding, Lighter Flints
Abundance in Earth's Crust (%) 1, 2, 3, 4. 5 10,000 PPM = 1 %	0.003 PPM	0.05 PPM	100 PPM	29 PPM	18 PPM
Plant Species Capable of Uptake 10	**None Naturally** Many have been shown to be able to accumulate at rates higher than standard plants when edaphic chemical additives are used in a facultative process	*Stanleya pinnata* *Astragalus bisulcatus* *Cardamine hupingshanensis*	*Haumaniasstrum katangense*	*Haumaniasstrum robertii*	*Dicranopteris linearis* *Carya spp.* *Asplenium spp.* *Blechum spp.*
Locations of Natural or Anthropogenic Abundant Occurrence 6, 7, 8, 9	Russia, China, South Africa, Australia, USA, Canada	Himalayas, NE Australia, Western USA, Northern Europe	Western Americas, Central Asia, Tropical Asia-Pacific, Central Europe, Middle East	Congo, Madagascar, USA, Canada, Russia, China, Morocco, Australia, New Caledonia, Philippines, South Africa	Russia, Australia, India, China, Canada, USA
Economic Value of Metal @ Fall 2019 ($USD / kg) 11	$ 44,800.00	$21.40	$6.00	$32.80	$4.80

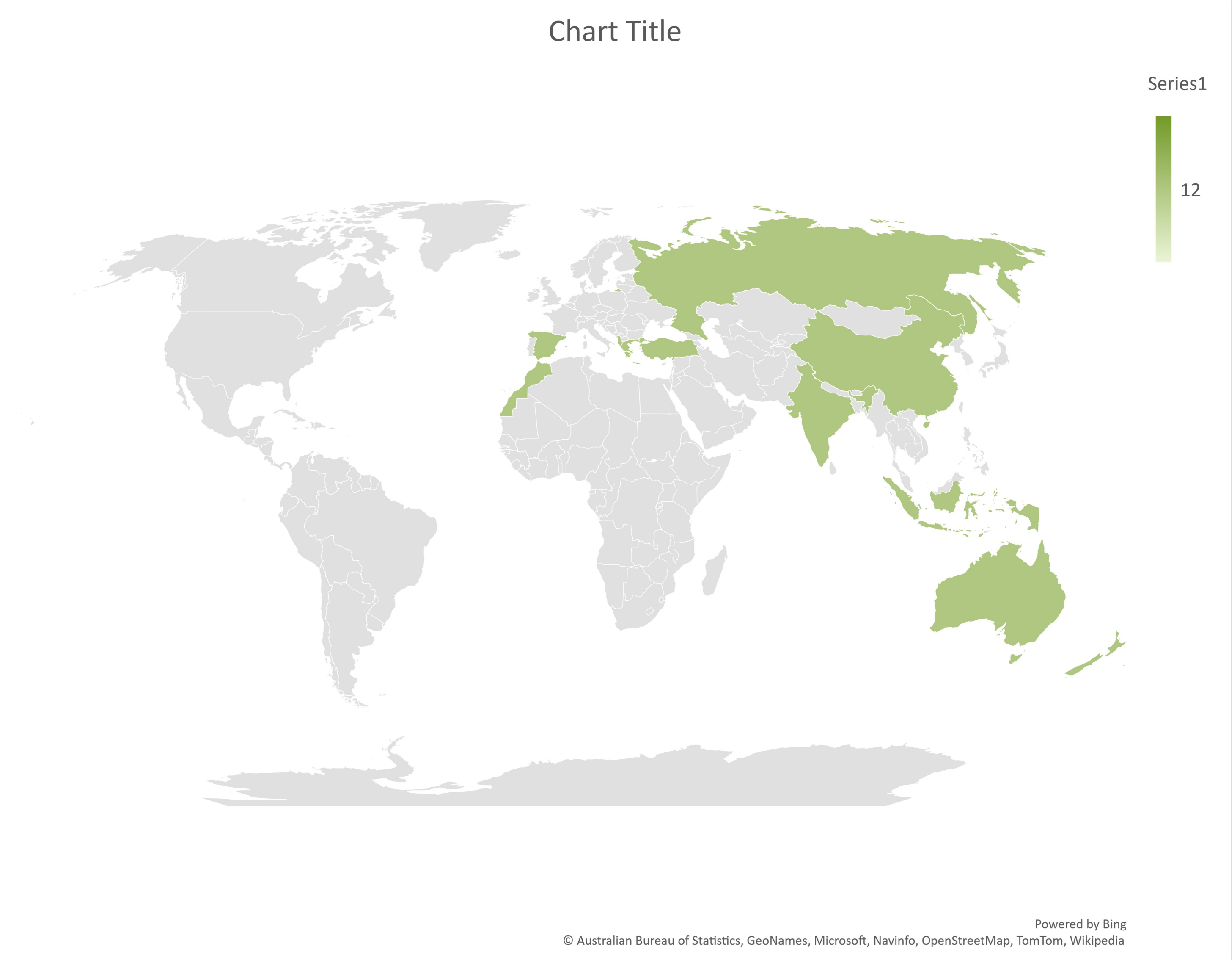
Reference(s):

(NCBI 2022) [1], (Jones 1968) [2], (LibreTexts 2022) [3], (Stillings et al 2017) [4], (Slack et al 2017) [5], (Kirkemo 1991) [6], (Kaur 2014) [7], (Geology.com 2022) [8], (Hache 2020) [9],(van der Ent et al. 2021) [10], (Wikipedia 2022) [11]

Table 6: *Selected Agromining Traits of Elements of Interest*

Element of Interest →	Ni	Mn	As
Atomic Number [1]	28 (Nickel)	25 (Manganese)	33 (Arsenic)
Uses of Metal in Products [1]	Stainless steel, coinage, alloys, electronic components, etc.	Steel, alloys, electronics, fertilizer, textile colorant, paints, etc.	Used to be used for Cattle dipping baths as an insecticide, as to help control exoparasites that degraded livestock perfoamnce. Later found to be toxic and phytomining now used for localized phytoremediation
Abundance in Earth's Crust (%) 1 & 2 10,000 PPM = 1 %	84 PPM	1400 PPM	N/A
Plant Species Capable of Uptake 2	*Alyssum spp.* *Phyllanthus rufuschaneyi* *Blepharidium guatemalense*	*Macadamia neurophylla*	*Pteris vittata*
Locations of Natural or Anthropogenic Abundant Occurrence 2	Tropical Asia-Pacific & Mediterranean Southwest Europe	China, Australia, South Africa, & Mexico	Anthropogenically Polluted Areas (Locations of Previous Cattle Dipping Baths in FL)
Economic Value of Metal @ Fall 2022 ($USD / kg) 3	$ 13.90	$ 1.82	$1.00
Reference(s): (NCBI 2022) [1], (van der Ent et al. 2021) [2], (Wikipedia 2022) [3]			

Figure 2: *Map of Highlighted Areas of Agromining Activity & Potential in World*



References(s): (van der Ent et al. 2021)

NOTE: Other areas show potential, only main countries of interest are highlighted

4 **Phytomining & Agromining- Metal Mining with Plants**:

5.1 – Definitions, Systems, & Applications

Phytomining & agromining are actually two different terms with a bit of a difference in definition and application; the former is a the use of metal hyperaccumulating plants (x100 times more uptake than a 'normal' plant) for the extraction of metal from the soil into harvestable biomass. This could be for commercial gain but is not always the case in laboratory or 'real-World' settings. While the latter is the implementation of this with the principles of agronomy, in a 'integrated agricultural chain' that encompasses a whole system and processes agroecological approach (van der Ent et al. 2015). The use of hyperaccumulators for finishing areas of edaphic interest that may contain large amounts of metals was the first conception of these two practices and is still in use today, being known as 'prospecting'; the conversion of the harvest product by post farm gate industrial processing and metallurgy practices (usually incineration, smelting, hydrometallurgy, or some conversion of the like) will create the usable wanted product: the 'bio-ore' (van der Ent et al. 2015). This is the advantage in Agromining, as with Ni, this ash will contain anywhere from 10 to 25% Ni, while low grade ore that is mined for Ni under conventional practices has less than 1%, thus this bioaccumulation capability of certain plants can be used to produce more economically an otherwise hard to extract and limited resource (the metal Ni) (van der Ent et al. 2015).

4.2 - Soil to Plant (Uptake)

4.2.1 - Mechanisms of uptake from Soil to Plant

Many plants across the globe are known to be hyperaccumulators, and many more are present, but their abilities have just not been discovered yet; by the 2013 definition, a metal hyperaccumulating plant is thus capable of accumulated a selected element at a range of concentration two to three orders of magnitude higher than a comparable plant in the same location (van der Ent 2021). About 700+ plants are known to be hyperaccumulators of naturally occurring elements; this encompasses about 1/5 of a percent of all known vascular plants (Reeves et al. 2018 & van der Ent et al. 2021).

Each group of elements or metals shares a more or less similar path of uptake, as most aren't essential for plant growth, and in fact many are actually damaging to most plant growth at the high abundance found in the soil where hyperaccumulators survive. The uptake of the majior plant essential divalent cations Ca and Mg, influences the uptake of the alkaline earth elements (Ba, Be, Sr, Ra), and they all compete with each other, influencing delivery of the others (van der Ent et al. 2021). The Halogens (F, Br, I) are taken up in high quantities by brown algae and certain types of seaweed; the uptake of F can go along the same pathway as Cl, and while the plants tend to discriminate the former in favor of the latter, it's the former that can hyperaccumulate when levels of the latter in the environment are low (van der Ent et al. 2021). Transition metals (W, V, Mb) are all taken up as a substitute for Molybdenum (MoO_4^{2-}), high levels of accumulation can occur through the use of exclusion and immobilization strategies internal to the plant; another transition metal (Re) can be taken up by the plant (as ReO_4^-) in place of nitrate (NO_3^-) (van der Ent et al. 2021). Toxicity for the transition metal aluminum (Al) is common in many areas across the Tropics due to it's abundance in the soil due to millennium of weathering, etc.; plants that are resistant to such toxicities and thus thrive well in high-Al environments are Al hyperaccumulators are pose a biological advantage in these edaphic niches, as compared to their normal and unresistant counterparts, Tea is the most common plant known to hyperaccumulate AL, but many plants are known to (over 25% according to one study) (van der Ent et al. 2021). Metalloids such as Boron are already plant essential micronutrients, and silicone also a metalloid, is considered more or less a 'quasi' plant nutrient; both of these and the non-essential Sr can be uptake by plants and hyperaccumulated, the latter of which follows the same uptake pathway (and thus influences, is influenced by, and competes) with phosphorus (P) (van der Ent et al. 2021). Many species of fern are known to be uptakers of the light rare earth elements; the platinum group (Pt, Pd, Rh, Ir) and noble elements, along with gold (Au) are inherently high valued because of their precious qualities, rarity, stability, economic value, etc.; most are not naturally hyper accumulated in plants and must be artificially induced through additives to the soil to do so, Pd and Pt however may be uptaken naturally by some tree species, in place of Mn (van der Ent et al. 2021). Radioactive elements (U & Th) should also be noted as being able to be hyperaccumulated in plants. A potential may exist for clean-up of sites contaminated with these elements.

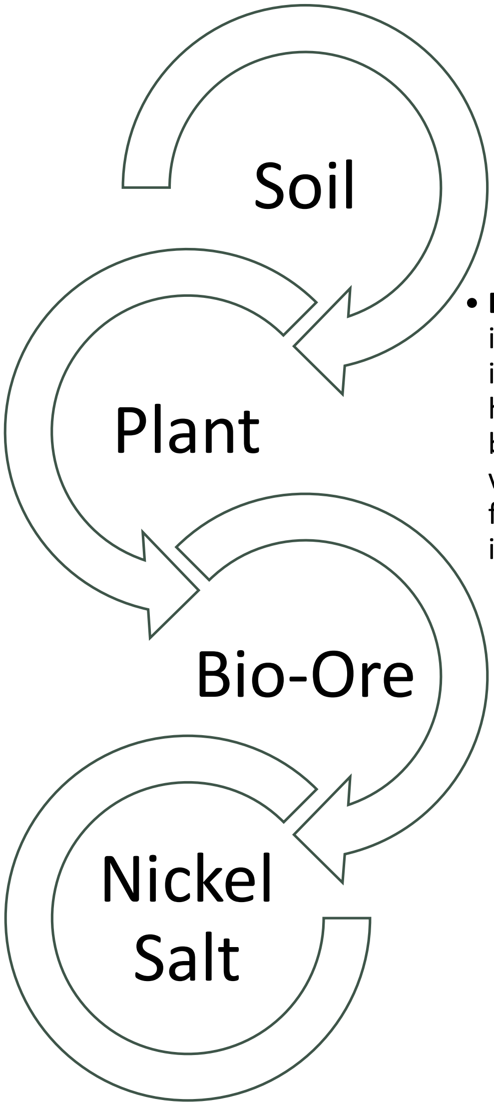
Although variations exist (as in the example of some root crops) most crops used for phytoming are one's that produce a high foliar biomass, as this is what is harvested, to be proceeded into the bio-ore. The temperate herbaceous hyperaccumulator of nickel, *Berkheya coddii*, will be focused on as an example of metal hyperaccumulation uptake from soil to plant. Nickel would be normally toxic to plants at such a high level, thus the plants that do hyperaccumulate such will have to have a strategy for dealing with the excessive amount of this metal that is taken up in the plant, due to being in an environment that is rich in such edaphically. These strategies for detoxification would be complexation or compartmentalization; the latter of which is more common, and the subject of focus in *Berkheya coddii* (van der Ent et al. 2021). As aforementioned, the combination of moderately high Ni hyperaccumulation as well as ease of propagation (for large(er) scale agronomic production), and high biomass generation. The leaves (vacuoles of epidermis) had the most amount of Ni, Ni increased positively with plant age increase and soil Ni level increase; this **hyperaccumulation has been proposed as a defense strategy for ultraviolet light (when occurrence is near the adaxial surface) or for predation defense against herbivorous insects and other animal pests (when metal accumulation is near the abaxial leaf surface**) (Robinson et al. 2003). Ni is taken up in an analogous pathways as other metal divalent cations (K, Mg), however it is still not fully understood why some plants are able to withstand toxic levels other than these prospered defense strategies, just like all adaptive traits in biological organisms, such is a product of evolving in a hostile environment and needing to adapt to survive (van der Ent et al. 2021). Nickel is uptaken via a 'low-affinity' transport system and deters accumulation in the roots from the presence of histidine and is thus translocated (rapidly) in the plant as Ni^{2+} to the storage sink of the leaf, usually the vacuole of outer surface cells in specific; much of this internal movement in the plant is through translocation in the phloem (Deng et al. 2017).

The accumulation of metals in the plant is measured and discussed differently between different searching groups, the term translocation factor (TF), bioconcentration factor (BF or BCF), Enrichment Factor (EF) or BioAccumulation Factor (BAF), and accumulation factor (AF); the most common is the TF which is essentially a measure of the metal concentration in shoot/root; the BF being a like measurement but between root and soil; AF being whole plant: soil, and EF being shoot/soil concentration (van der Ent et al. 2021). Metal hyperaccumulation has been proposed as one part of a multifaceted type of five-fold strategies for plant defense; allelopathy, predator and pathogen defense, drought tolerance, and ‘metal disposal’ are the plants ways or reason for hyperaccumulation of nickel and other metals and or trace element (not necessary for normal plant growth) (van der Ent et al. 2021). Other reasons for hyperaccumulation may exist and will likely be proposed as more research is taken to understand the physiology of metal hyperaccumulation in plants.

4.3 – Isolation of Metal from Plant (Extraction & Purification)

Serpentine and other mined soils high in Nickel will traditionally contain 1% -3.5% Ni and this is the start of the agromining process. Plants that are hyperaccumulators are grown on such soils and will uptake the metals where such will bioaccumulate anywhere from 1% to 25% for Ni in total dry matter composition of the plant. Typically, 1% will be much more common, as these are the plants that can be grown as crops using traditional established agronomic principles and can be harvested for their large amount of foliar biomass. After harvest the plants are crushed and compacted and transported or processed on site into a bio-ore. This bio-ore is the ashes of the plant that were created through ashing or charring techniques and then further refined through selective precipitation or treatment with chemical solvents for more purified extractions (van der Ent et al. 2021). The product most likely for production from the Ni Agroming processes is the Ni salt, known as Nickel sulfate hexahydrate (ANSH); this is created through the addition of water and sulfuric acid to leach the bio-ore, this leachate goes through selective precipitations to create the Ni salt that can be turned into common everyday nickel products through additional processing and manufacturing processes. The large advantage of this creation of the bio-ore -/ ash and the resultant salt is that they are both much higher in Ni that traditionally mined ores and thus can be transported, shipped, etc. with much ease at a lower cost (van der Ent et al. 2021). This downscaling of usable material is a pivotal piece in the scalability of agromining, The bio-ore can even be created on-site to further purify the product before being moved off-site to create further economic gain and producing power of the product; the process of Ni agromining on these marginal lands is much cheaper in both initial set-up and seasonal/yearly cost than a conventional Ni mining on the same land, due to the bioaccumulation factor of the plant and then further refined to a higher metal concentration by the ashing process(es) (van der Ent et al. 2021).

Figure 4: *Processing for Metal Isolation of Nickel from Soil to Plant to Product*



- **Phytoextarcion** of ore material by naturally metal hyperaccumulating plant in areas with high Ni or other Metal conetens

- **Bioaccumulation** in the plant, that is a form of harvestable biomass; Ni values can range from>1% to 25% in these crops

- **Conversion of plants to bio-ore** by drying, washing, leaching, drying, melting, smelting, incineration, roasting, and other associated material recovery and conversion processes. The ash created can be from 10 % to 25 5 Ni, which is extraordinary high, as compared to conventional NI mining, which is a more expensive service in the first place.

References: van der Ent et al. (2015)

5.3 - Economical Market Analysis

As the World population grows, carrying capacity is largely determined by agricultural production capabilities. This is an even more paradoxical situation in the sense of finite resources like metals that are mined from the ground, which also increase in demand, while supply decreases. All (most) products are grown or mined (or from animals, which are sustained with plants and / or mined materials), so with the former you can grow more on the land you have or devote more land to growing crops and for the latter you can traditionally find more metals or minerals through prospecting efforts and then devote land to such, or with the more novel concept of agromining you can use marginal land to increase metal production.

While like with all matters of Life a combinational approach is best to solve the problem, a comparison of the conventional and novel (with plants) mining of metals should be compared as to show the economic viability of the latter in an everchanging World. They should be dual income streams that increase product supply and not compete directly with traditional mining for the same supply. The benefits of Agroming in an economic or financial sense are two-fold: it's an additional stream of the metal to the supply chain, as conventional sources dry up and are contested over, but also it may (in some situations) even prove to be a more economically efficient way of extracting metals from the Earth, as most nickel mining is done on ores containing less than what phytomining bio-ore can produce. It's important to keep in mind that agromining is a lengthy and finite process; it will take long to economically extract resource from the found, and once they are gone agromining will ceases to be an effective agricultural operation for the lands.

Malaysia in the tropics and Turkey in the temperate are the two main geographic areas in which agromining is currently being pursued as metal farming for economic gain, it is important to note however that of both these situations the provisioning ecosystem services (the metals mined) that are not the only goal of the pursuits but also the generation of the land to be able to be used for (conventional) agriculture once the novel mining efforts are undertaken and complete. In the temperate (Albanian) multiple Alyssum species have been showed to be able to generate 100 kilograms per hectare of Ni when experimental metal farming was undertaken; the tropical shrub (when grown agronomically, tree when grown naturally) Phyllanthus rufuschaneyi, showed the most promise, due to its high biomass production and high Ni content of such, which at an average of 2.5 % Ni per (200 g) plant over 5 meters squared, 250 kilograms of Ni could be harvest per harvest cycle (possibly twice a year, probably once due to environmental, agronomic, etc. constraints) (Nkrumah et al. 2019).

The tropical situation is more promising in the sense that vaster amounts of land are available for such metal farming expeditions, as well as the possibility of multiple harvest per year. Nickel is currently (August 2022) selling for $22 / kg (NOTE: only $2 / kg in 1981) so a more intensive tropical system like the one in Malaysia could produce $4,400 / ha in revenue while the less intensive, somewhat more extensive temperate systems could generate $2,200 kg of Ni per year; this is on par (with adjustment for inflation) with estimates derived from previous investigations in the USA, Albanian, and Malaysia (Nkrumah et al, 2015). Cost of production will vary widely by production methodology and location; an extensive temperate system will probably cost less than an intensive tropical system, but the latter has been shown to be economically beneficial, when compared directly on a single seasonal cycle (van der Ent et al. 2021).

Agroming serves as an economic benefit in other ways as well. For one it is not serving to compete with land that is used to produce food, feed, fiber, fuel, etc, (like most of those crops do with each other and other land uses) but uses lands that are marginal (ultramafic soils, serpentine outcrops, Technosols, bioremediation targets), and thus is not taking away spatially from any of these areas, and thus not taking away from that product's entrance into the economic market. Essentially agromining is a 'temporal activity' in 'spatial hotspots' and actually helps to improve the land to grow agricultural crops after the completion of the Agroming life cycle (about ten to thirty years) (Morel et al. 2018). Compared to traditional mining, Agroming can be implemented across more extensive areas while being less intensive (need for inputs), essentially embodying an agroecological approaches that is biologically driven, rather than conventional chemically driven agriculture or physically driven mining. The cost of these latter two is even higher when one factors in the environmental impacts that are created; an Agroming operation on the other hand may serve to generate a 'wide range of ecosystem services' thus being more profitable than just measured by its producing ecosystem service outputs alone (Morel et al. 2018).

Other metals beside nickel are of possible economic feasibility to be mined. These would include gold (Au) and germanium. Germanium is a metalloid and can be used for multiple industrial and technology purposes and has been shown to be able to be hyperaccumulated in ribbon grass when grown on mine tailings and being able to create an x2 economic profit over conventional germanium extraction, with accumulation as little as 10 ppm in arboreal parts (Rentsch et al. 2016). Gold needs to have additives such as cyanide added to the soil to make such plant-extractable and results have been shown that show such can be economically viable but are of varying success widely both in lab and field conditions, mainly due to the concentration of gold in the substrate being tested. Beyond this, rhenium (Re) has also shown to be of economically viable extraction by phytoming, in a greenhouse study that needs to be extended to field conditions but preliminary shows the success possible for this very expensive and rare element (Novo et al. 2015). Thallium and Cobalt also have the ability to be commercially agromined for a positive economic profit, as disused in the soils and metals section.

Most metals beyond this, at this point, have not been shown to present an economic feasibility to being mined with plants, or being metal farmed for commercial economic gain. As more investigations and research is undertaken more metals should show feasibility to be mined, but limitations exist for many in that they are limited in quantity in the soil, while with other limitations are presented in the fact that known species of plant has (yet) shown the ability to hyperaccumulate.

The factor deciding the economics of Agroming is the price of the metal and abundance of such in the soil. Most metals are not present at a high enough rate or are not worth enough to support the efforts of such an agricultural operation. However, when the metal is of high abundance in the soil (like Ni) or is highly valued by humans (like Au) the conditions are set for a commercial agromining operation to take place which will generate the producer a positive economic gain from the metal extracted from the soil by the crops grown.

The crops grown that hyperaccumulate the targeted metals of interest are also the dictators of weather the agromining operations(s) can be economically viable or a wasted experiment. Some of the best phytomining crops are not those that have the highest bioaccumulation of the desired metal, but rather have a relatively high bioaccumulation of the metal coupled with a high production of biomass; it's these two traits in combination that a plant must have to be successful in phytomining (van der Ent et al. 2021). Beyond this however the plant has to be easy to establish in the field and be able to not only survive the harsh environmental and edaphic conditions but thrive in such. The phytoming plants can only be Agroming crops when a successful means of prorogation occurs as to support the operation. In many temperate Agroming operations the brassicas can be annually broadcasted as seed, while in many tropical agromining operation more labor is needed in the establishment of cuttings every (few) seasons from an off-site nursey. The cost of finding and establishing a successful plant, the mining tool, is one of the largest factors in the economic success of an agromining operation, likening it even more to traditional agriculture.

5 Phytoremediation - Land Restoration for Environmental Benefit & AgroMining AgroEcology

5.1 Land Restoration / Reclamation / Phytoremediation

Agroming is an operation for commercial gain from metal farming using the implementation of agronomic principles in the process, as well as the associated post-farm gate activities necessary for production of metal from the plant. Bioremediation however is a different tactic using these same techniques of metal extraction using hyperaccumulating plants and somewhat similar principles but with other ecosystem services targeted for the land in use / production, regulating and supporting ones, not provisioning. Arsenic (Ar) is rather toxic to humans (and wildlife) however in the past was used as a treatment of exoparasites (ticks) on cattle through dipping bath stations that contaminated the soil around them. The use was highly effective against the parasite but left a lasting legacy of environmental damage in the localized spots of past operation. Multiple types of ferns have proved useful in remediation of these contaminated areas (Fayiga et al. 2016). Arsenic is thus not an element that can be profitably agromined but environmentally beneficially phytomined, albeit there is some discussion of such being profitable if used for creation of a biofuel (van der Ent et al. 2021).

5.2 Ecosystem Services & Agroecosystem Multifunctionality

The obvious main benefits of agromining operations are the metal that there a desired is extracted from the soil by the plants, the provisioning service in this agricultural operation, coupled with energy / heat capture from combustion for conversion to bio-ore. This often unthought of benefit of Agroming is the heat that can be generated from the combustion of the plants, necessary during the metallurgical conversion processes from plant to bio-ore; it has even been proposed that such (plant) materials be combined with domestic trash in order to burn in both the creation of heat and the capture (extraction) of (desired precious, economically valuable) metals from (van der Ent et al. 2021). This is critical in helping to increase profiability at the larger (and all) scales, as well as a beneficial 'green' energy source in a more localized or subsistence scale.

Other ecosystem services exist beyond these producing ecosystems services, as well, which supports to the broader appeal of Agroming in the agroecological context. The support of these services also helps to support the economic benefits of agromining, in that land is restored for future high value land uses, that offer other producing ecosystem services beyond what were available spatially before. Thus, the soil quality improvements to the local agroecosystem for later temporal activities is an essential supporting ecosystem service allowed by agromining (Echevarria et al. 2016). These oil quality improvements are included of but not limited to the removal of the excess nutrient / metal that limits plant growth, accumulation of residues and OM allowing soil to develop and stabilize, and the stabilize of soil through run off and sediment decrease since plants are now there to help keep such in place. One can quickly image how this metal faming can help to turn a once barren land to once that is an agroecosystem supportive of more traditional agronomic crops, once the metal extraction from the soil by the hyperaccumulating metal crops has finished.

Beyond this, regulating services are provided in the conservation of these rare hyperaccumulator species, as well as the increase in plants available for pollinators and other beneficial insects helping to 'stimulate and increase [their] populations', while also reducing amount of Nickel and other harmful contaminants metals in the honey of some these pollinators (bees) (Echevarria et al. 2016). Another advantage in terms of ecosystems services provided by metal farming is the sequestration of carbon will most likely be increased in any Agroming operation, as compared to the (low intensity plant presence) land use before, this will be even further increased when traditional agriculture or forestry can take over as the primary land use once the Agroming cycling (~ 30 years) is complete (Echevarria et al. 2016, Zhang et al. 2017, van der Ent et al. 2021).

In terms of cultural ecosystem services, a promising feature of metal farming is the rejuvenation (or essentially repurposing) of the land, in order to have a more valued land use, beyond what it was marginally used for to begin with, and the metals extracted from such; the aesthetic value of both of the temperate and tropical hyperaccumulating plant species should not go without note or notice as well. The process of metal farming is an educational training; work with one metal-plant improves like and unlike operations in similar phytoextractions of metals, contaminants, pollutants, or their desired elements that need to be removed from the soils using plants (van der Ent et al. 2021). All these services should be taken in note for their independent, cumulative, and integrative effects before the true determination of economic and environmental potential of large-scale metal farming is evaluated. Simply put, the metal alone is not the only good or service that agromining can provide and that alone is an essential underpinning in viewing Agroming under the agroecology philosophy.

5.3 – Biodiversity, Biosecurity, & Agricultural Landscape Design

As the nickel agromining operation progresses to it's end point, in certain situations the land could be established for more traditional agronomic purposes, this may even be the case in some anthropogenically created soils (mine tailings, Technosols) as well mined for other metals (van der Ent et al. 2021). The landscape will become more resilient in the long run as once marginal land can be turned into at least somewhat productive land. As with other matters of biology and conservation there are tradeoffs. While you are conserving some (rare plant) species (the metal hyperaccumulator), agromining is essentially the long-term changing of the ecosystem, as this may be appreciated in some ultramafic and serpentine areas but would be seen as complete devastation in others (conservation land, parks, etc.). Biodiversity is both created and destroyed in the purist of agromining and added offs should be taken according to what is valued most to the surrounding communities and producing parties involved, both in the long term and short term.

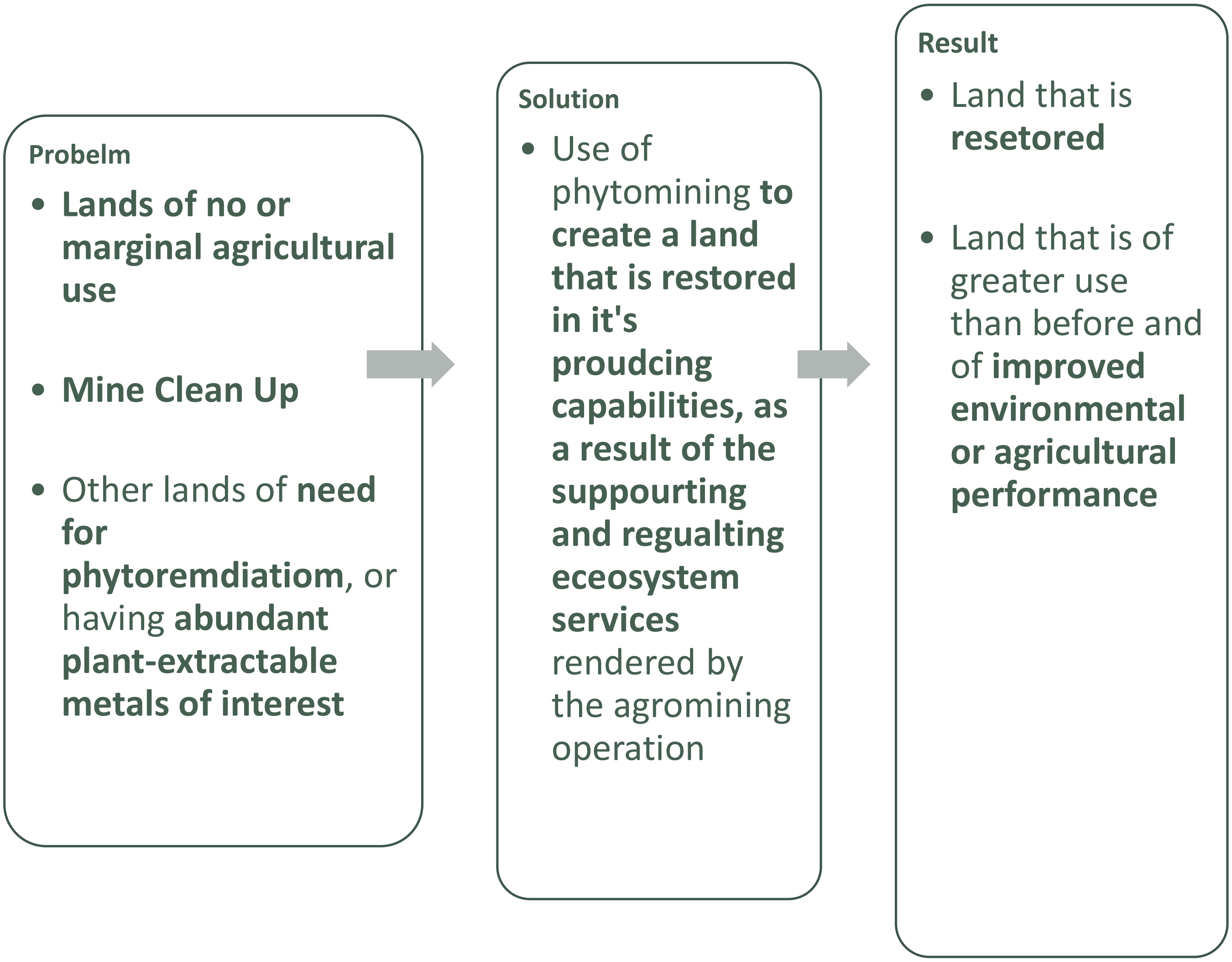
A bigger issuer may be that of **biosecurity**, in that importing plant species (and the pests and pathogens that (may) come with them) is not always a feasible, practical, or scientifically sound solution to a problem. Many of the know metal hyperaccumulators that have been of Agroming success are those that are adapted to the local environment they were already in to begin with, however there are many other traditional agronomic crops and other 'wild' plants species that have shown ability to hyperaccumulate metals; it's this latter category that will be of more worry when transporting across the globe as such have not already been attempted to be established in new areas in the past and / or have not undergone these more rigorous studies as the former.

In the bigger picture, these lands can then be incorporated in the larger agricultural landscape design both during and after the Agroming operations. During the operations traditional agronomic inputs and practices will have to be implemented in order to ensure best propagation, cultivation, survival, success, and harvest of the metal crops, much like as with conventional agronomic crops. Once the operation ceases (plant extractable metals are taken up from the ground).

5.4 – Agroming association to Insects

Much like all biological organisms, insects will find their proper ecological niches to survive, and plants will do the same. A much agreed upon hypothesis for the plant's purpose of Agroming is for defense against herbivores. This is a two-edge sword in that it will deter most insects from feeding, but overtime so will adapt and overcome and be able to feed on such. The highest amount of nickel for most hyperaccumulator in in the phloem (hurting most sucking insects), but high concentrations also arise in the epidermis and cuticle surface of the leaves (Mesjasz-Przybyłowicz et al. 2020). A few insects have been found that specialize on the temperate nickel hyperaccumulator *b. coddii*, these would include certain species of grasshoppers, ladybugs, and leaf beetle that were specialized to feed on high nickel level species without experiencing toxic effects, also found was a parasitic wasp that was predatory to the beetle, all of these relationships being monophagous in their feeding nature, and thus representing the microecology of metal farming itself in a localized temperate perspective (Mesjasz-Przybyłowicz et al. 2020 & van der Ent et al 2021). It's important to note that as like all crops that humans move (and the globe) and improve these will also have pests that attack them and adapt to the plants unique defense characteristics and improvement. The battle against these biotic pests will always be an ongoing one for humankind.

Figure 6: *Functions Involved in Land Reclamation & Restoration in Temperate Agromining*



Probelm

- **Lands of no or marginal agricultural use**
- **Mine Clean Up**
- Other lands of **need for phytoremdiatiom**, or having **abundant plant-extractable metals of interest**

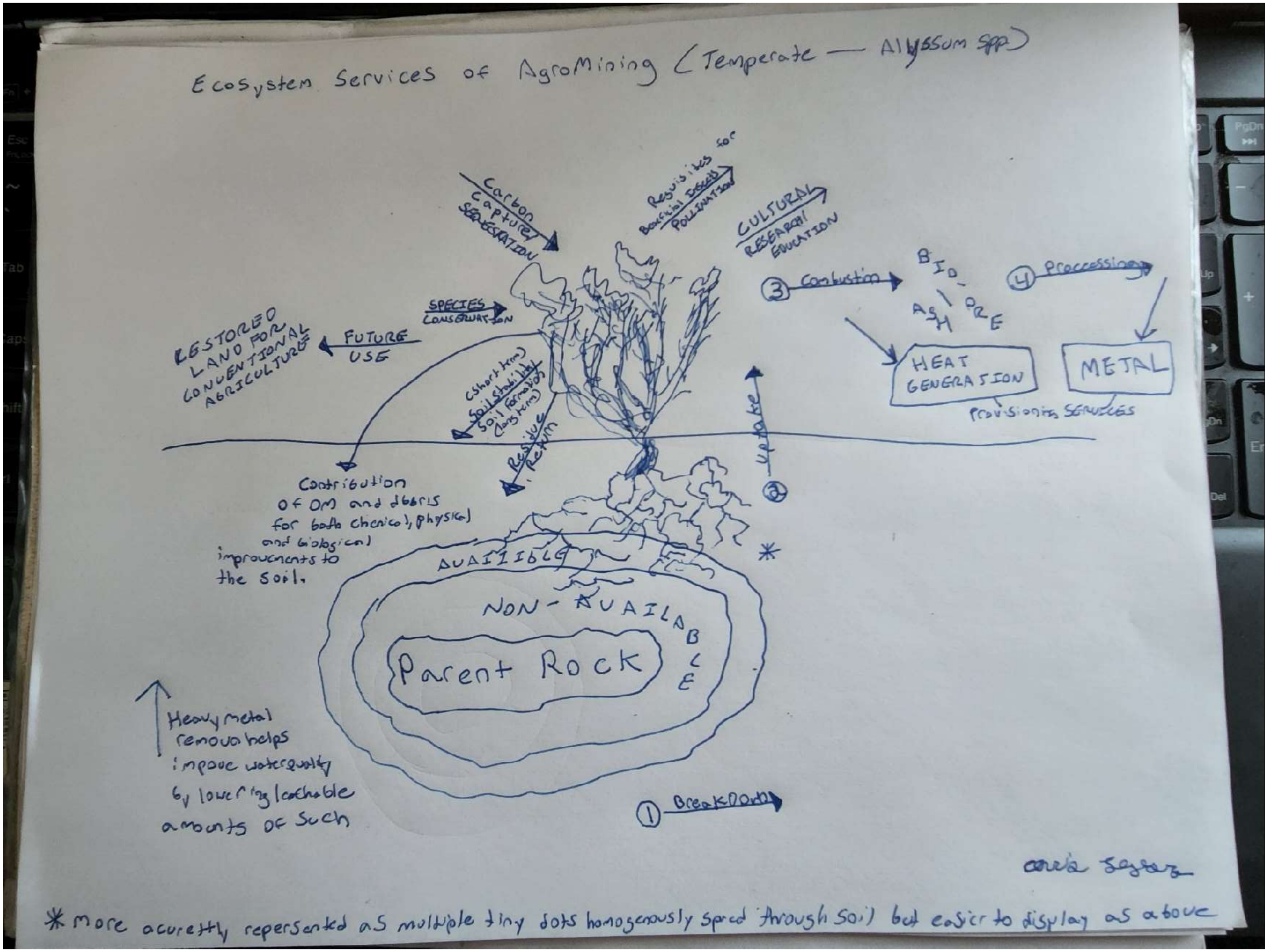
Solution

- Use of phytomining **to create a land that is restored in it's proudcing capabilities, as a result of the suppourting and regualting eceosystem services** rendered by the agromining operation

Result

- Land that is **resetored**
- Land that is of greater use than before and of **improved environmental or agricultural performance**

Figure 7: *Ecosystem Services Drawing*



6 **Future** & **Limitations**:

6.1 - Limitations

Like any new technology, the popularity of such may be a fad or may become the next 'big thing' based on consumer interest or preference leading to worshipping-like behavior for such for a short period of time followed by rejection of this technology to be replaced with another fad or gimmick that will itself by cyclically replaced. The test of time shows worth.

With its relative infancy, observations have already made to show the mistakes, disadvantaged, and negative association related to phytomining and how it is not a holy grail or miracle practice that will help to solve all the problems in the field of mining and agriculture. Problems and limitations exist comprising of issues that deal with biogeochemistry, resiliency, metal mobilization and root access, environmental concerns with artificial metal hyperaccumulation practices, genetic improvement of currently used phytomining plant species, accurate pairing of plants to locations in need, and lack of a large-scale infrastructure for processing of such an industry after the farm gate (Brooks 1998, Anderson 1999, Sheorun 2009, van der ent et al. 2021, & Dinh 2021). Improving on these issues will help improve the phytomining industry to be more efficient and effective in its production and regulating ecosystem services.

6.1.2 – Time/efficiency

The length of the Agroming operation is finite and many of the metals are not in quantities in the soil that present a practical means for an economically profitable agromining venture. This may be that they are of too low concentration and can only be phytoextracted non-economically on a laboratory and theoretical scale. Others like certain Technosols may take a really long time (> ~100 years) to be of efficient means to pursue if such provisioning services provided are not of a means to support such operations over the longer term (van der Ent et al. 2021). With this being said, large expanses of these lands could benefit the State (and the Public) in their restoration, and economic profit from the operation itself hence may / should not be the only way of funding, but perhaps a state funded venture.

The average metal farming operation will be 10-30 years but even this may not be feasibly efficient for many metals beyond Ni (van der Ent et al. 2021). **The appeal of the efficiency of nickel for Agroming is three-fold: there are many known plants that hyperaccumulate such, there are of soils with natural high abundance, and it is material of medium-high economic value**. Many other metals don't share these characteristics and thus won't be of efficient means to be agromined. It's largely this inefficiency factors that makes the economics of the situation unsuitable, as most of the most precious metals are of extremely minute quantities in the soil and as of yet phytoming is not the most economical means of extraction for many of these metals.

6.1.3 – Environmental Concerns

While much of the issue around agromining operations in this review focused on nickel, many of the more precious metals (such as gold or silver) will need to have additives like thiosulfate or cyanide added to the soil in order to make such available for the plants to uptake. Without needing to be said localized and downstream environmental problems surrounding soil and water quality can result if such activities and additives were pursued and applied on a large basis.

6.1.4 – Infrastructure & Logistics

Agroming is all great but like with many academia ideas the results are not practical in the real-World due to many constraints beyond just the operation involved. As with many agricultural productivity issues across the globe, the problem today is not so much lack of knowledge or capital but lack of infrastructure and development. Many of the marginal lands to be agromined are of somewhat near positions to the facilities necessary for processing or could have bio-ore / ash processing on site at smaller scale, however. It's important to note how much development needs to be put into such facilities, roads, infrastructure, etc, that are needed to be co-developed in support of an agromining operation, or any agriculture one in these areas.

The biggest factor however in the logical and infrastructure success of metal farming is the post-farm gate value added processes needed on the original commodity. Having the plants being able to be converted into ashes, turned into bio-ore, onsite helps to reduce the size of materials, helping to raise the concentration of nickel or other metals that is going to be transported off site, making the scale of equipment and capital needed to transport and store such to be of much smaller than it would be otherwise.

6.2 - Future Research & Applications

7.2.1 – Introduction

Research needs to be focused on developing the most economically beneficial practices of extraction of metals from soils , as well as pairing the right species of plants with the metal being extracted in each particular environment.

Although this was an issue of mention in the aforementioned section, there is a need to develop improved extraction methods or genetic improvement of natural hyperaccumulating plants. Improving the additives needed to assist in the accumulation of uptake of some metals (such as Au) could not on the (possibly) harmful environmental toxicities that such can causes hen used incorrectly. Another issue id that of finding the right soil-plant-metal combinations. Focus of phytomining research needs to continue the quest for plant species out there with both natural and induced phytomining capabilities. Much like with other traits (yield, shattering, growth habit, etc.)

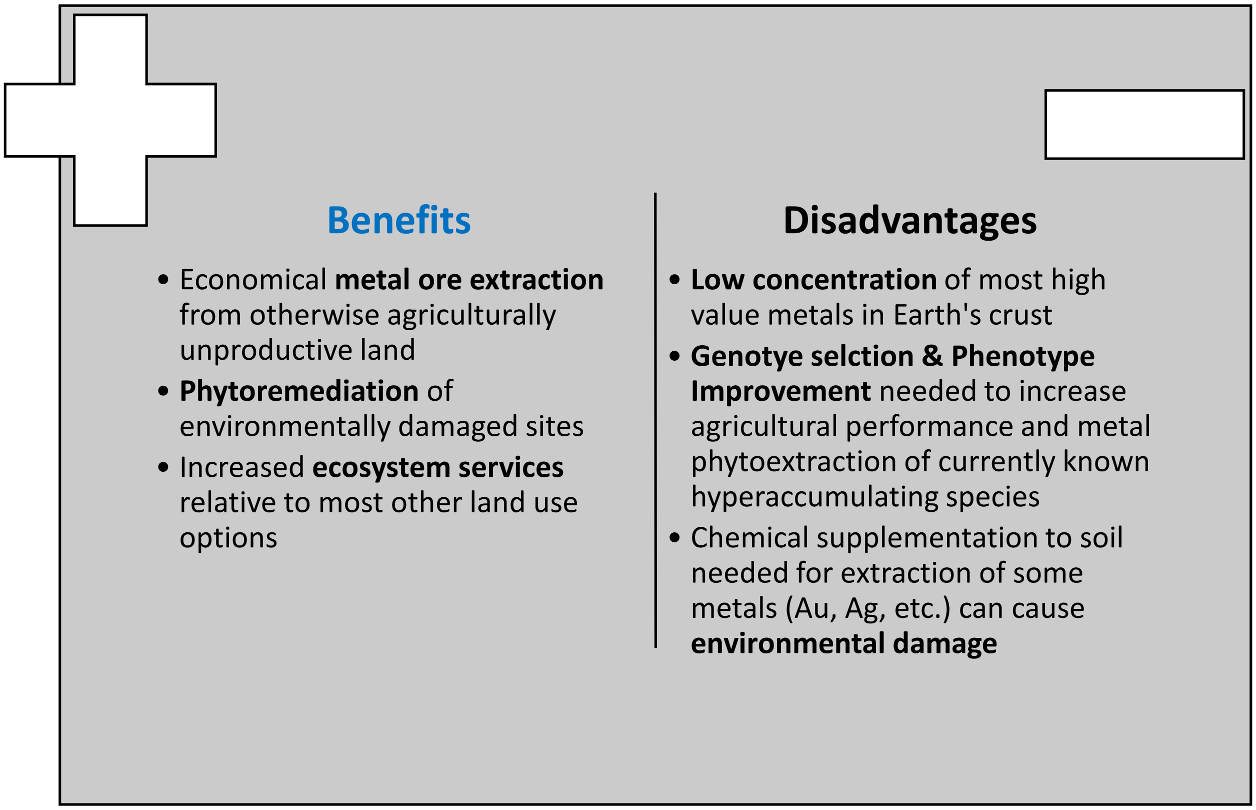
Seed crops are an area of interest that could be explored more fully in that of grain or seed crops used for phytomining in locations deemed marginal for agriculture or traditional mining, while having another (relatively) abundant quantity of (plant) extractable metals in the soil. Seeds would not receive (much) of these (mostly) immobile these immobile metals that tend to follow the route of the xylem once inside the plant heading to areas of highest transpiration, and not entering the phloem and translocating to growing meristems and reproductive organs like fruits and leaves. These 'agrominic' crops would be a dual (or possibly triple or quadruple) purpose harvest that yield producers a seed crop and an extractable metal ore from the same piece of land (as well as financial gain through the combustion of the dry matter during the post-harvest metal isolation and purification processes and possibly from the environmental reclamation services delivered). Only certain locations and applications would be practical for such an idea, but it presents a way to increase possible economic efficiency of otherwise marginal land through increasing and diversifying the producing system services it offers, through just the management tactic of species (and location) selection (or matching).

Native plants are another possible beneficial idea to incorporate into phytomining operations is that should be looked more adequately into is matching indigenous or native plants, as to avoid issues of biosecurity and problems of spread of pests or pathogens when introducing an exotic crop from one geographic area to another. Land-Use Transition for Positive Change cab ne created through metal farming. Traditional mining has seen a decrease in recent years and oppositely phytomining has seen an increase. While the idea of phytoremediation is widely accepted and recognized, hopefully this paper served to highlight more tailored solutions to the diverse problem set at hand as concerning phytomining and the related plants, elements, and soils. Phytomining could be used to help restore land use in old and abandoned mining operations (or ones with negative probability situations or outlook) that are otherwise not presenting economic gain while causing environmental harm. This harm can be reduced through the use of phytomining to restore the landscape over a period of time.

6.3 – Conclusion

No one knows what the future holds but applications for phytomining are going to be more heavily relied on as natural finite reserves of traditionally mined metal sources become scarcer because of their overharvest. Simply phytomining offers ways to extract theses metals from the ground using plants, instead of mechanized equipment. It’s a subtle blend of agriculture and mining that should be explored more to help ensure long term stability of modernly essential products that society and people that lives’ revolve around. The modern image of both the miner and their ‘equipment’ is certainly changing with mineral engineering practices like phytomining compared to that more traditional image of the ‘below-ground miner. This ‘modern image’ not only looks better on the surface but is intrinsically a more environmentally beneficial option of ‘mining’ for metals below ground compared to the traditional mechanized mining. Situations and locations varying in their suitability to this practice as mentioned throughout the paper and the last section. It’s up to the phytomining research, participants, and other stakeholders to decide the future of the industry from here, building on the work that has been established over the last ~50 years.

Figure 8: *Diagram of Benefits and Disadvantages Associated with Agromining*



Benefits

- Economical **metal ore extraction** from otherwise agriculturally unproductive land
- **Phytoremediation** of environmentally damaged sites
- Increased **ecosystem services** relative to most other land use options

Disadvantages

- **Low concentration** of most high value metals in Earth's crust
- **Genotye selction & Phenotype Improvement** needed to increase agricultural performance and metal phytoextraction of currently known hyperaccumulating species
- Chemical supplementation to soil needed for extraction of some metals (Au, Ag, etc.) can cause **environmental damage**

References: van der Ent et al. (2015) & van der Ent et al. (2021)

7 Conclusion

As long as humans inhabited the Earth, they will always find ways to make (the best) use of the abundant natural resources that reside with on and within the planet. Agriculture more or less how we know it today (or before ~70 years ago) is only ~12,000 years old (since Neolithic Revolution or New Stone Age) and mining is ~40,000 as a human practiced activity and ~10,000 as a more industrialized practice (Wiesdorf et al. 2005 & Coulson 2012). **Outlying and foundational experimentation of both must have certainly gone on beforehand, as like with all matters of craft, trade, art, & science.** Agromining is past the experimentation stage and into a more pre-industrial stage, aforementioned in the last section, with much more research needed to break down economic and environmental barriers that would inhibit it's practice as a successful land use option. Nickel seems the most practically minable metal with resiliency in the agronomic perspective but volatility in the economic perspective (Sheoran et al. 2009). Gold (Au), silver (Ag), platinum (Pt) and other high value metals are of extreme interest and importance but lack the high accumulation rates (both edaphically and botanically) necessary for economically feasible extraction, isolation, and concentration.

A two-fold improvement strategy needs to focus on the (sometimes) dualling (but always interacting) agronomic perspectives of management and genetics. Improvements in crop production and management will help to ensure that naturally hyperaccumulating plant species perform at their best to produce high biomass production as well and can survive in unforgiving conditions where phytoremediation or metal ore extraction is needed. Improvements in genetics will help to make non-naturally metal hyperaccumulating plants to unlock their phytomining potential. This way the traits they have that give them advantages beyond metal hyperaccumulation are already there and phytomining is what is added, rather than trying to take a plant that can phytomine and make it a successful agronomic performer.

Findings here showcased the correlation between specific metals and corresponding plants and/or environments of interest . Pertaining information is displayed in both written and graphic formats and can be applied to both help further research or in current field situations to solve complex problems that otherwise wouldn't have a(n) (bevy of) readily available information to effectively apply as adaptable solutions.

The bigger picture to take away from the elements, soils, and plants involved in phytomining is that resources that have been mined traditionally (Ni and other precious metals) are in higher demand as technology develops and population rises. This rise in demand for mineral metals to meet consumer needs and wants can only be met with new technologies both in mining and in agriculture. Agroming allows for the sustainable development of a circular economy while having a crop that yields multiple ecosystems services on otherwise unusable marginal lands while providing an economic profit from the producer. Nickel is the main elements of practical in use for Agroming to work on a commercial scale but such technologies and practices that are used and developed for such can be further implemented for other metals as needed over time. Plants aren't juts for food, feed, or fuel anymore.

At the end of the day, it's crucial to take look at this issue from the economic, environment, and ecological perspectives, as well as other diverse viewpoints. The findings within are limited to my perspective and only shared in hopes of others making good use of the information in pursuit of economic gain of environmental benefit, hopefully the all-to-rare - balanced combination of both.

All in all, it can be safely proven that metal farming is a method of metal extraction that can be economically profitable and environmentally beneficial while increasing ecosystems services delivered and multifunctionality of the agroecosystem in use**.**

8 **Supplementary**: *Table & Figures*

Table 7: *Comparison of Phytomining & Agromining*

Factor / Trait	**Phytomining**	**Agromining**
Use	Bioremediation & extraction of Metal ore for economic Profit	Extraction of metal ore for economic profit
Location	Areas that need to be cleaned up or have phytoremediation services Induced through artificial chemicals for extraction of more highly valued metals on smaller scale and / or in lab / GH studies Old mining sites, toxic waste sites, tailings, brownfields,	Areas with high abundance of metal ore in ground but too low for traditional mining methods Lands with nutrient toxicity to more common agricultural crops
Scale	Small(er)	Large(r)
Common Crop / Plant Species		
Common Metals	Nickel, Arsenic, Fluorine, Gold, Silver	Nickel, Cobalt, Boron, Palladium, Platinum
Production Methodology	Low quantity of endemic plant biomass with a high concentration of extracted metal	High quantity of crop biomass with a low concentration of extracted metal
References	Van der Ent et al. (2015)	

Figure 9: *Role of Metal elements in Plant Functions #1*

Metal Elements Function in Plants

Maganesese (**Mn**)

- Enyme activator
  - Peroxidase (Lignin)
  - PEP Carboxalyze (C4)
  - RNA polymerses (Protein Synetheis)
- Strcutical compent of PSII enxyme inlvoled in water hydrolisis

Magnesium **(Mg)**

- Central atom in chlorophyll molecule
- Ribosome 'bridging' element (Protein synthesis)
- Enzyme promoter

Copper (**Cu**)

- Electron transfer / Redox reactions
  - Chlorophyll (PSI)
- Free radical detoxification
- Respiration
  - Helps make water by transferring electrons to O2

Zinc (**Zn**)

- Carbohydrate, Protein, & Auxin Metabolism
- Pollen Formation

References: Mengel and Kirkby (2001)

Figure 10: *Role of Metal elements in Plant Functions #2*

Metal Elements Function in Plants

Nickel (**Ni**)

- Protein funcition / Enzyme Component
  - Urease, hydrogenase, etc.

Iron (**Fe**)

- Hemi Proteins
  - Cytochromes, Leghemoglobin
- Fe-S Proteins
- Aminolevulinic acid (chlrophyll precursor)

Potasium (**K**)

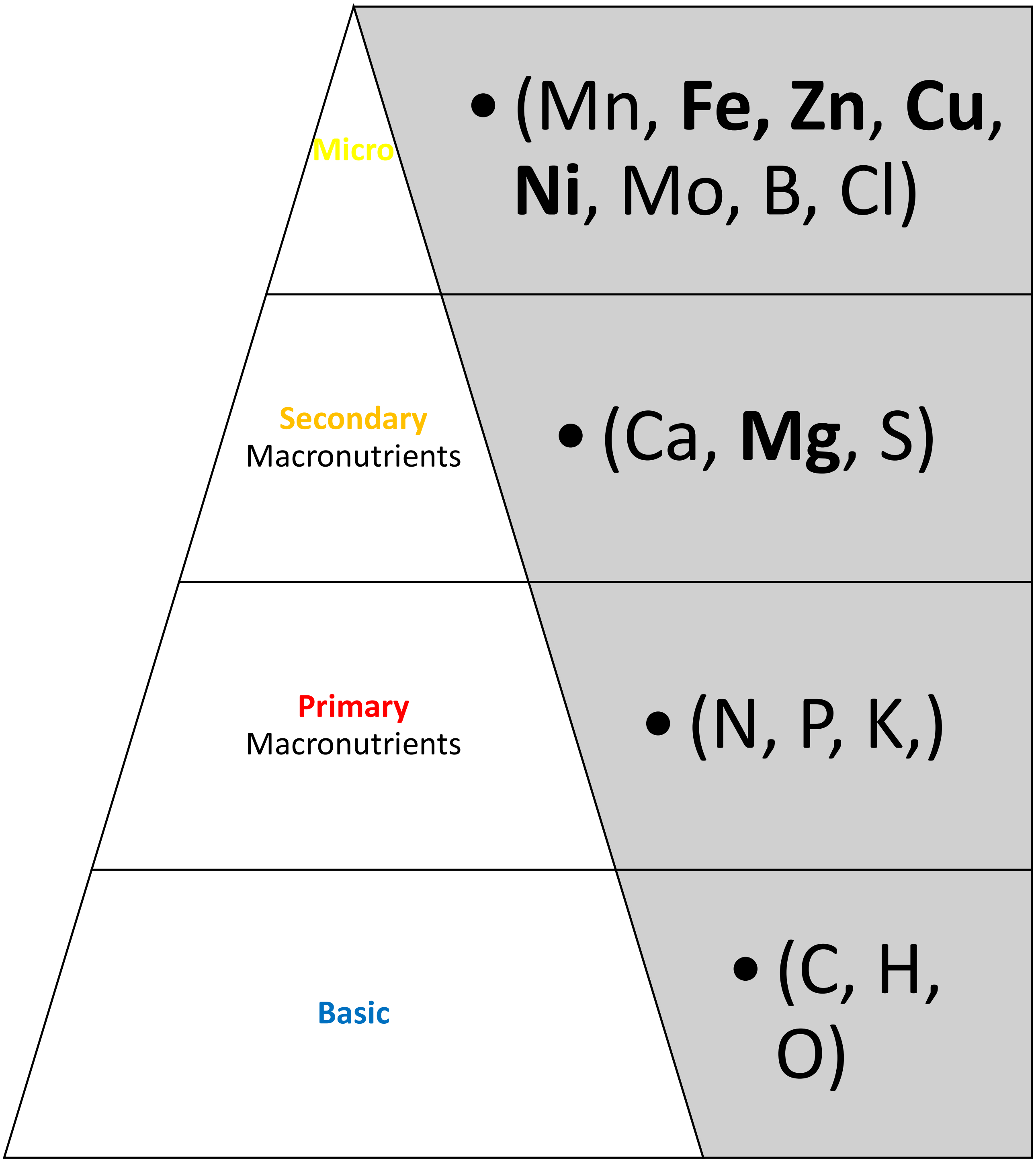
- Osmotic Regulation
- Enzyme activation (ATPase)
- Proetein synthesis & Photosynthesis

Calcium (**Ca**)

- Cell wall & mebrane components
- Secondary Messenger for Stress Respons

References: Mengel & Kirkby 2001

Figure 12: *Plant Nutrition Pyramid*



References: Mengel and Kirkby 2001, Rosen et al. 2005, & Schuman et al. 2018,

Figure 12: *Uses of Metals Common to Phytomining*

Nickel (Ni)

- Coins / Money / Tender
- Foundry Alloy
- Batteries; Stainless Steel
- Agrochemicals Components (Fertilizer & Pesticides)

Gold (Au)

- Jewelry
- Coins / Money / Tender
- Electronics (Circuit boards , wires, etc.)

Silver (Ag)

- Silverware / Jewelry / Musical Instruments
- Coins / Money / Tender
- Electronics: Photography & Solar Panels
- Environmental Modification; Cloud Seeding (Rain)

Platinum (Pt)

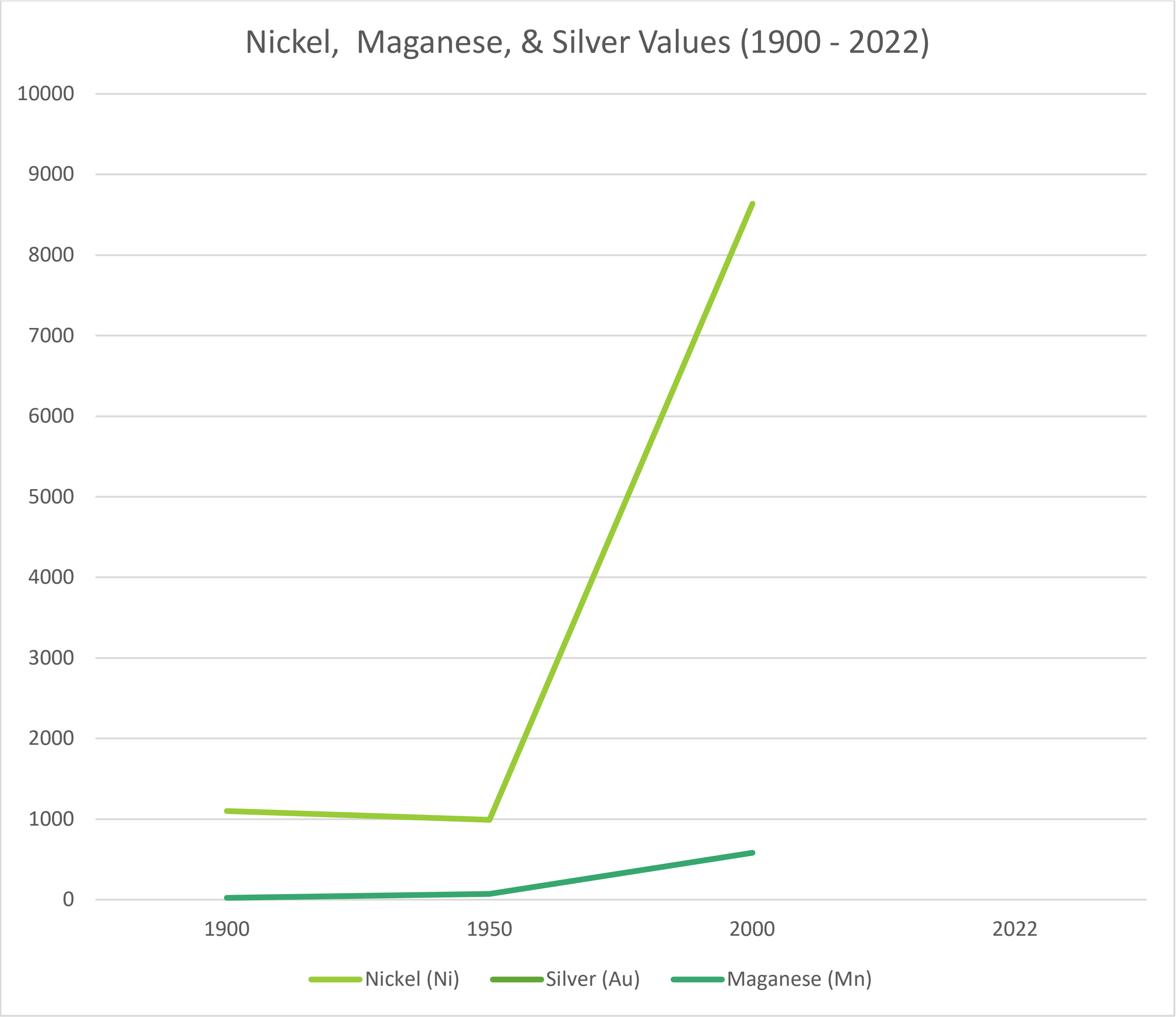
- Medical (Dental, Pacemaker, etc.)
- Jewelry / Investment
- Automotive (Catalytic converter, Spark Plugs)
- Electronics (HD Disks, LCD Screens, etc.)

Cobolt (Co)

- Foundry Alloy
- Magnents; Coatings
- Ceramics / Paints
- Electronics (Batteries, semi-conductors, etc)

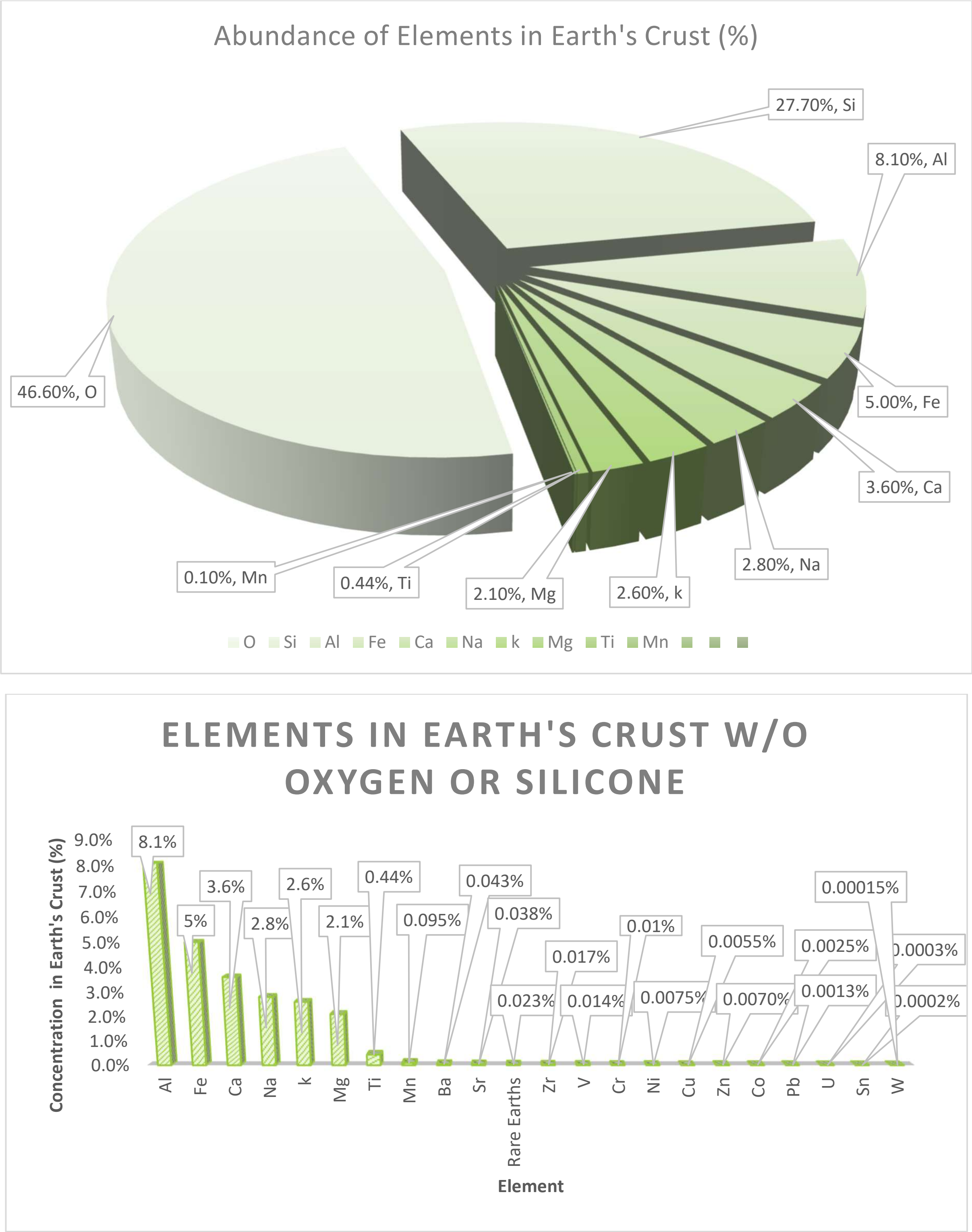
References: Chaterjee (2007)

Figure 14: *Value of Selected Metals over Time*



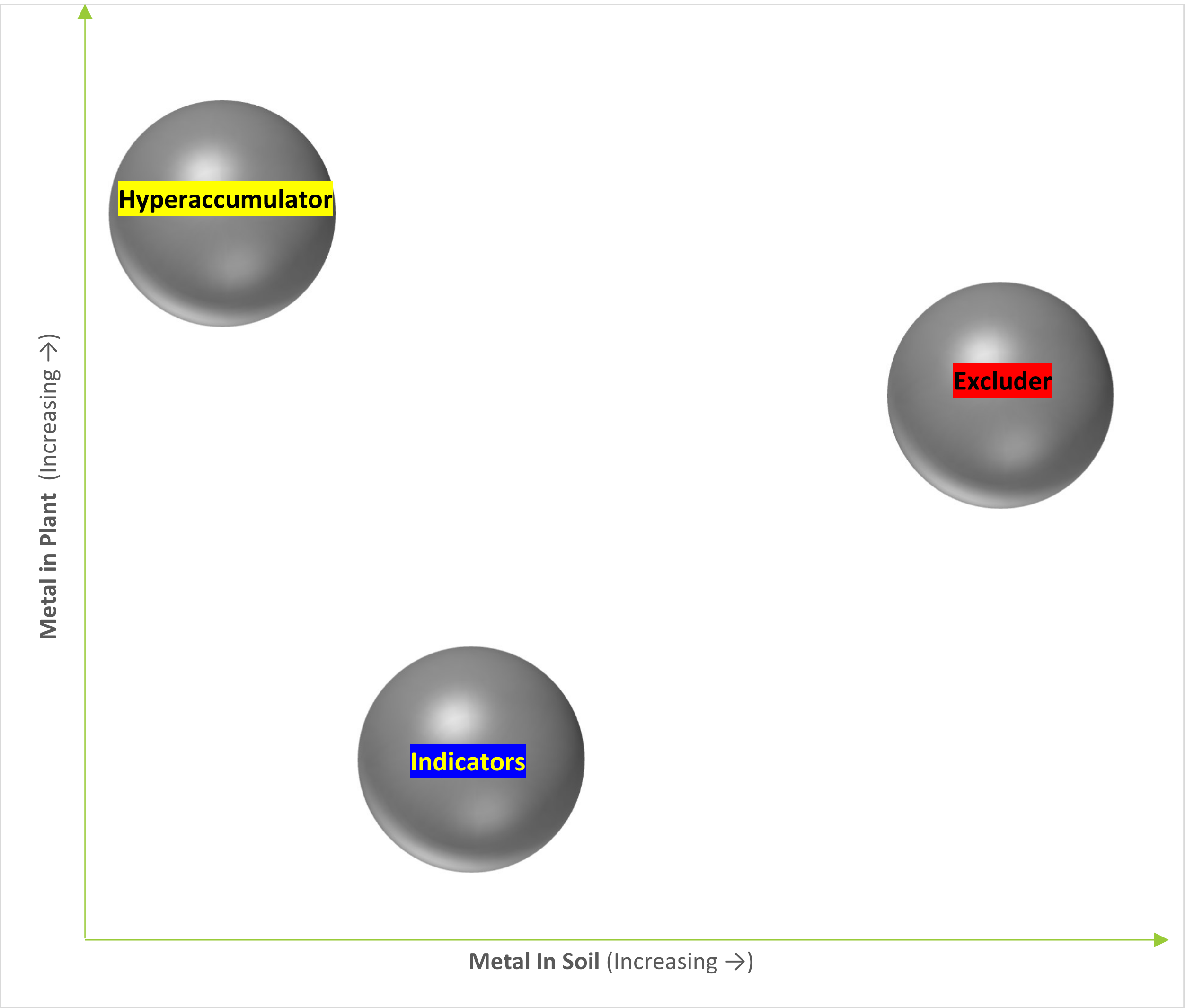
References: Kelly et al (2017),

Figure 15: *Graph(s) of Abundance of Elements in Earth's Crust*



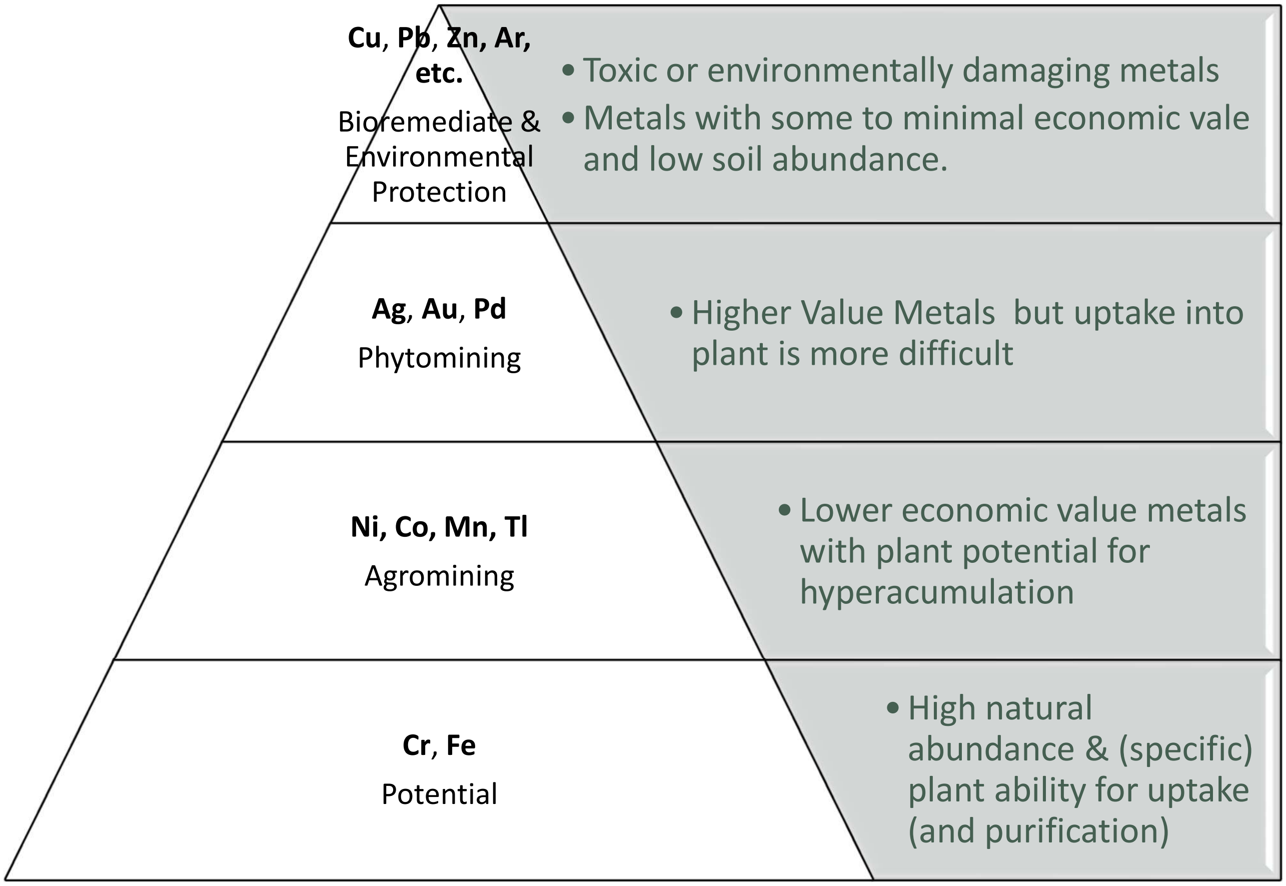
References; Pandy et al. (2012)

Figure 16: *Plant Metal Accumulation Response Strategies*



References: Adaptation of graphics originally composed by - Hunt et al. 2014 & then adapted by Harumain 2016

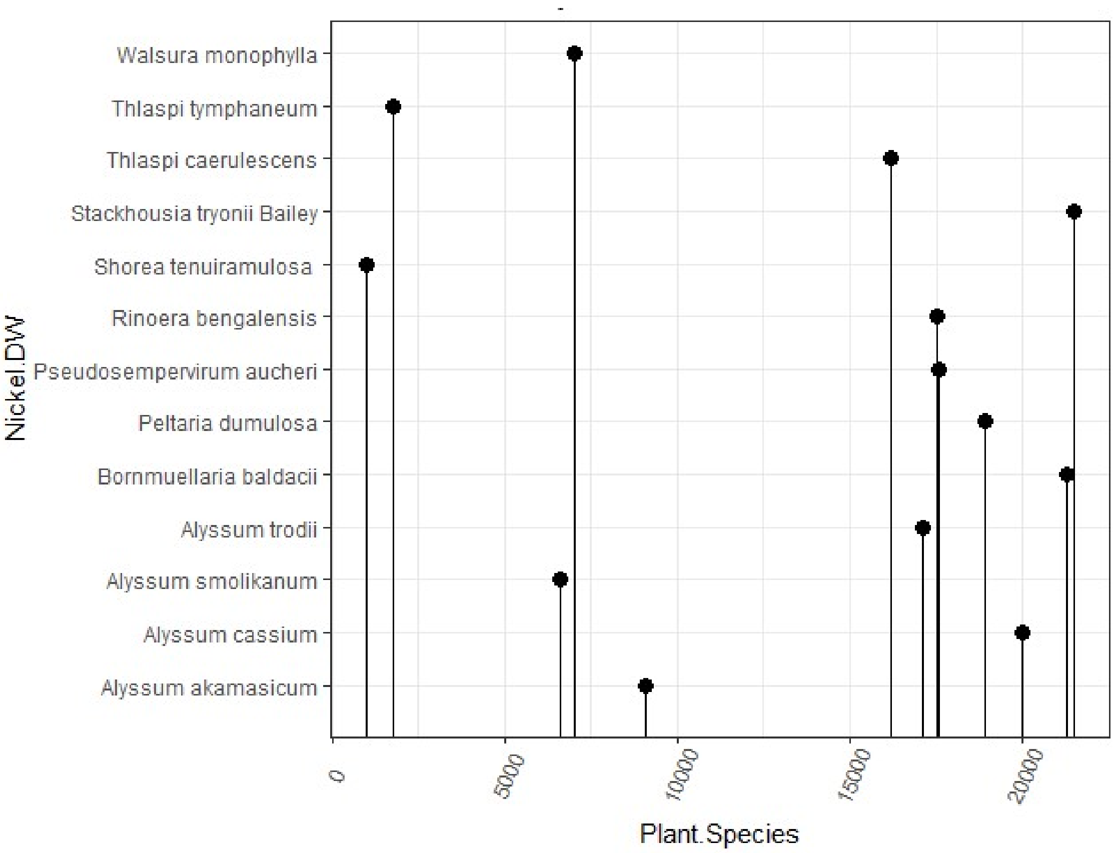
Figure 17: *Agromining Metals of Importance Pyramid*



References: van der Ent et al. (2015)

Figure 18: Visualization With R #1 (Lollipop Chart)

Plant Species ~ Nickel Dry Weight (mg / kg)



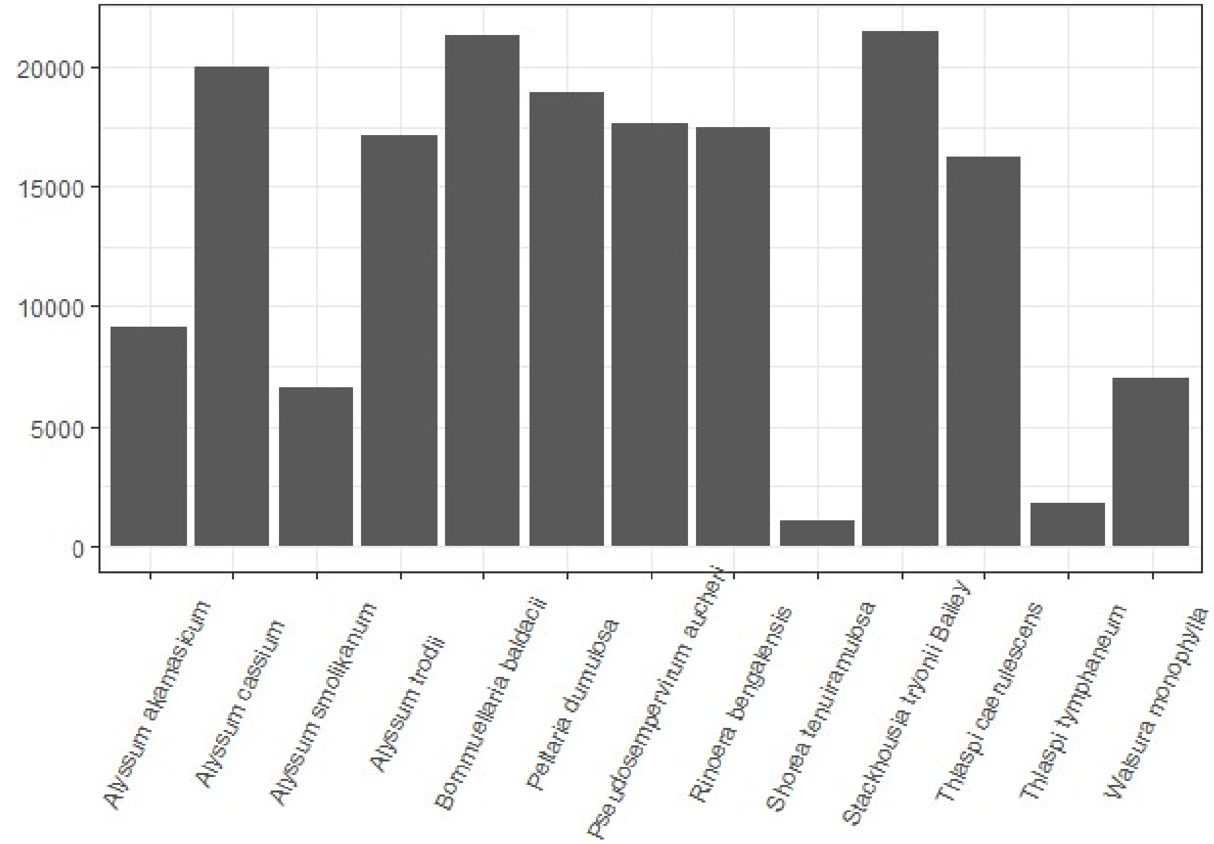
Import

Lollipop Chart

Reference: (van der Ent et al. 2021)

Figure 19: Visualization With R #2 (Bar Plot)

Nickel Dry Weight (mg / kg) ~ Plant Species

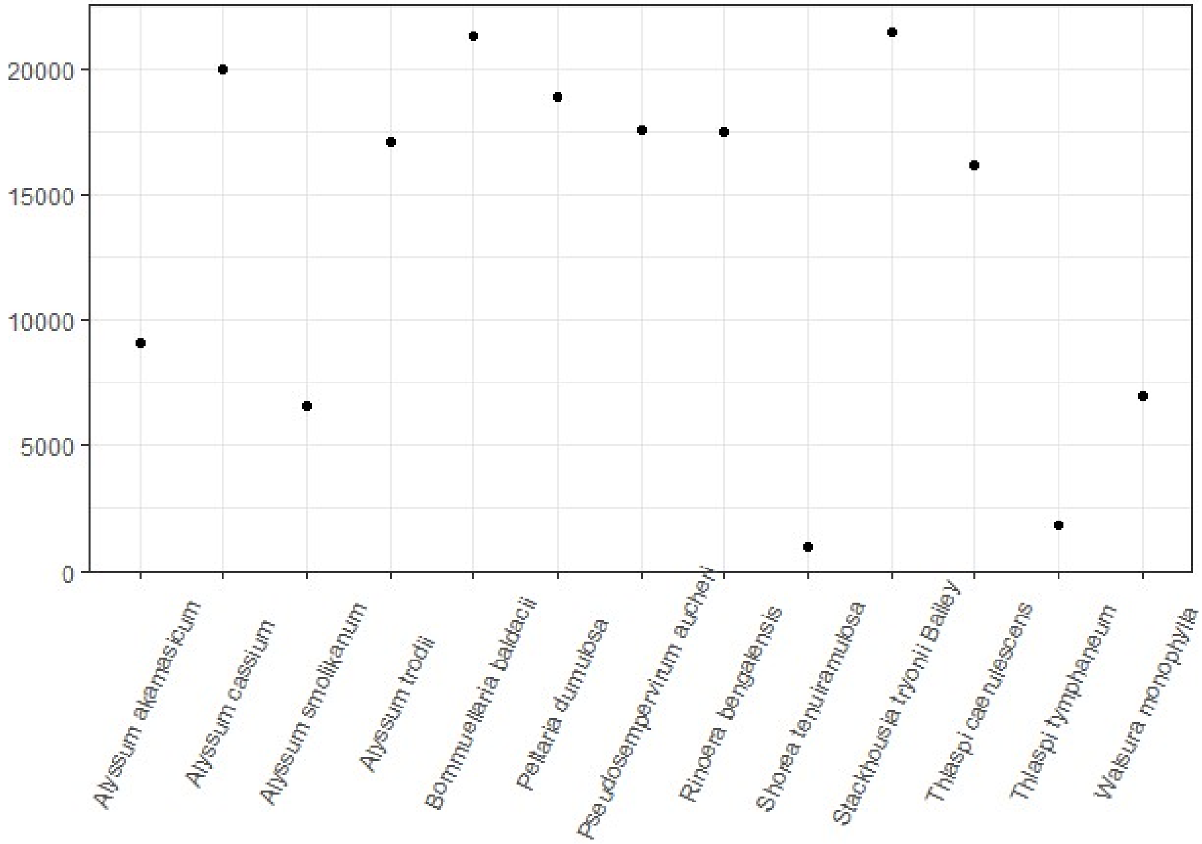


Basic Bar Plot

Reference: van der Ent et al. 2021)

Figure 20: Visualization With R #3 (Scatter Plot)

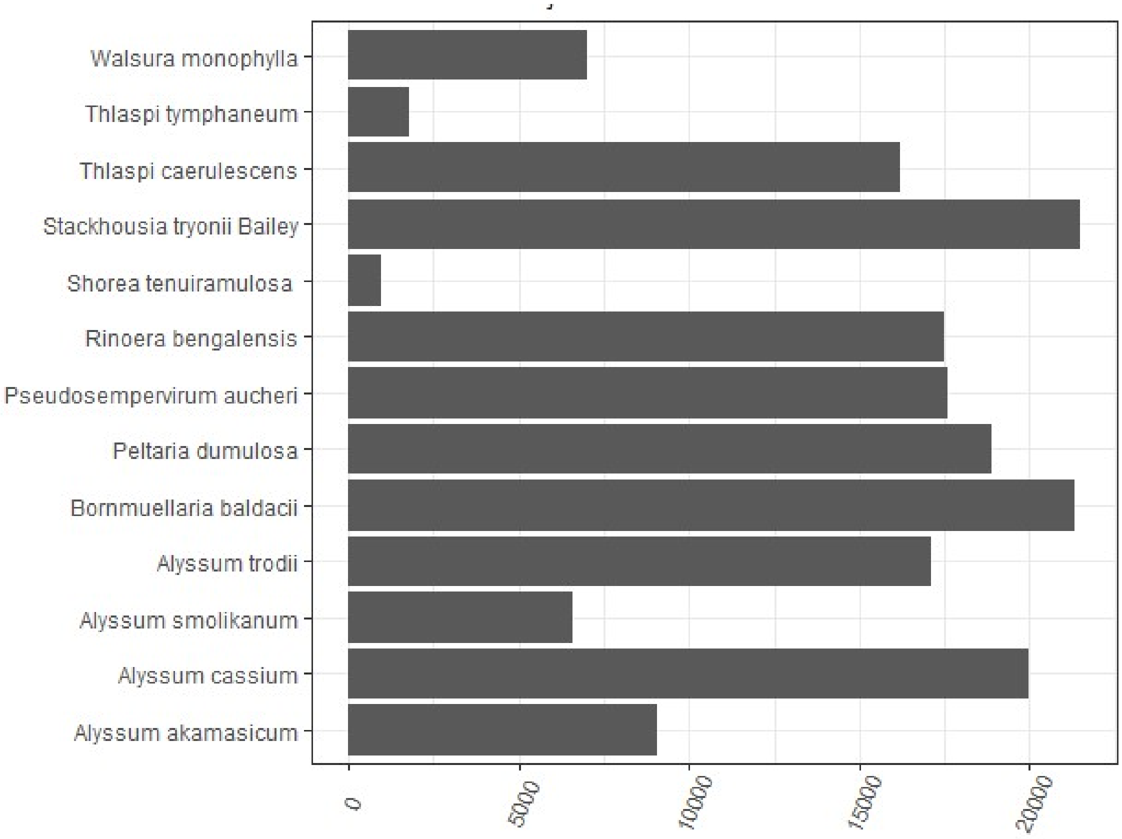
Nickel Dry Weight (mg / kg) ~ Plant Species



Reference: van der Ent et al. 2021

Figure 21: Visualization With R #4 (Horizontal Bar Plot)

Plant Species ~ Nickel Dry Weight (mg /kg)



Reference: van der Ent et al. 2021

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