The United States Needs to Innovate New Mineral Production Technologies. Here's One, Phytomining.

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Critical minerals are the basic ingredients for electric vehicles, solar panels, wind turbines, and many advanced climate mitigation technologies. They are also crucial for other technologies (e.g., cell phones) and for the defense sector (e.g., spacecraft power generation and radar missile defense). Of the 50 critical minerals identified in 2022 by the United States Geological Survey (USGS), the United States has a net import reliance greater than 50 percent for 31 commodities, 26 of which are sourced primarily from China.
Innovation that will allow the United States to develop resources sustainably and affordably would also help the nation secure its supply of critical minerals. By leapfrogging the current position of China through innovation, the United States can defend future energy security and provide for economic development. With this in mind, the United States has begun investing in mapping mineral resources, developing novel battery configurations, funding recycling initiatives, and investigating other techniques, such as deep-sea mining.

Another potential innovation is phytomining. Some plants, called hyperaccumulators, have evolved the ability to soak up high concentrations of metals into their leaves, bark, and roots. These plants can accumulate metals up to of dried plant's mass or 16.9 percent by weight in sap and once they are , the metal can then be separated through burning or juicing. Phytomining involves farming these plants above mineral deposits and harvesting them for their metal content. Research into hyperaccumulator metal extraction dates to the 1980s but has gained a resurgence in interest due to skyrocketing commodity prices. Hyperaccumulators have been shown to accumulate nickel, cobalt, selenium, rare earth elements, and more. Hyperaccumulators include flowering plants (e.g., Alyssum bertolinii for nickel; Noccaea caerulescens for nickel, cadmium, and zinc), trees (e.g., Glochidon cf. sericeum for nickel and cobalt), and ferns (Dicranopteris pedata for rare earth elements). Over 700 species hyperaccumulate nickel alone. Commercial phytomining is nascent, but projects are beginning in Albania, using Alyssum murale, and Malaysia, using Phyllanthus securinegioides, to produce nickel. Other research projects have begun in Indonesia, Australia, Tanzania, & many other countries. In 2022, ARPA-E and the U.S. Department of Energy solicited input via a public Request for Information (RFI) on harvesting metal with hyperaccumulators, with particular attention to economic feasibility on nonarable land, achieving commercial scale, and the carbon intensity of production. The Department of Energy's (DOE) Advanced Research Projects Agency-Energy (ARPA-E) RFI highlights several attractive attributes that see phytomining as a key part of an integrated mineral strategy.

First, phytomining can unlock unconventional ores and soils that have never been economically viable to mining companies. The concentration of many metals found across the world in the soil and mineral deposits are not high enough to be mined. As metal demand increases, lower ore grades become economically viable, but extraction of these deposits creates more environmental challenges due to increased waste and tailings. Ore grade decline is a significant challenge in the mining industry, with average global copper ore grade declining over 25 percent in just the past 10 years. Phytomining can provide new opportunities to increase the geographic scope of mining across larger areas despite lower concentrations. This could become very useful on lands where the environmental risk or indigenous sovereignty make traditional mining prohibitive. Assuming low-grade ore deposits become increasingly important for metal production and environmental regulation remains the same, phytomining could reduce the need to open new traditional mines.

Second, phytomining can aid in the cleanup and reclamation of current and legacy mining sites while providing new ore. When mining operations end, waste rock is left near mining sites. Rainwater then creates acid drainage challenges for local water systems. Planting hyperaccumulators could soak up metals in the soil before they leach into groundwater. This could open a new space in the market for reclamation companies to buy up properties and harvest metals from waste. It would also make traditional farming on neighboring land more feasible by reducing contaminants in soil and groundwater and preventing surface erosion.

Third, domestic phytomining could help the United States accomplish its domestic and international climate goals. DOE/ARPA-E's RFI indicates that phytomining could access large enough reserves to satisfy predicted demand for nickel and Rare Earth Elements (REE). The main source of carbon emissions in the production of electric vehicles is in the production of batteries, largely due to emissions from mining and processing battery materials. Phytomining for battery materials could give the United States a double benefit over traditional vehicles. Further, consumers who are especially conscious of their carbon footprint, the labor issues often associated with metals mining, and the potential conflicts with indigenous communities in the United States could have a new, attractive commercial alternative to traditional mining.

Fourth, agriculture-based production could help offset some price volatility related to extractive mining. Political instability and longstanding labor disputes on large mining sites, coupled with the dramatic rise in demand for critical minerals, have made unstable price one of the largest barriers for end-stage users of critical minerals. Non-mined minerals, even if they make up a small share of the overall global production, could serve to offset this. Still, the total impact of phytomining is unclear as of yet. The ARPA-E/DOE RFI has estimated that phytomining could be enough to provide all cobalt for U.S. domestic use (the document states that "these minerals/metals are also found dispersed in U.S. soils and surface rock, and it is estimated that there will be more than enough of this resource to meet the demand for a number of these minerals, including cobalt"). But other studies point to the large demand for arable land this would require, the possibility that metal prices will sink (rendering phytomining less commercially attractive), the relatively low yield per acre of metal (compared with traditional mining operations), and the regulatory overhaul such mass production would require.

Finally, phytomining could be a way to harvest metal in a way that is acceptable to local communities, including indigenous groups across the world. Recent conversations around the artisanal and small-scale mining sectors have highlighted major environmental and social challenges. These operations often extract ore using very inefficient techniques with low productivity leading to unnecessary environmental degradation. Through phytomining, local communities may find new ways to increase their productivity by selling metals, and more people may participate in the energy transition in a sustainable way.

While phytomining is not currently a feasible replacement for large-scale hard rock mining, it opens the possibility for a new group of producers to benefit economically from the increasing demand for critical minerals. A recent study found that roughly 80 kilograms of nickel could be mined in one acre per year, resulting in a gross profit of $3,800 per acre at today's nickel prices. To put it in context, in 2021, Illinois soybean farmers earned a gross revenue of $1,017 per acre, and Illinois corn farmers earned a gross revenue of $1,445 per acre. A project of this size, though, would still only yield enough nickel for about four Tesla Nickel Cobalt Aluminum (NCA) batteries (authors' estimate). In other studies, land reclamation projects have resulted in a double economic benefit: reducing Nickel levels in the soil by farming Streptanthus polygaloides yielded $1,000/hectare in land recovery, plus $410 per hectare in nickel extracted from plants.

Barriers to Phytomining

Challenges to phytomining projects, both in land reclamation and as a freestanding commercial enterprise, have been regulatory in nature. Lack of environmental governance for hard rock mining, both in the United States and abroad have not created the opportunity for innovative technologies and production methods such as phytomining to scale. The general regulation governing hardrock mining in the United States is over 150 years old. The law assigns prospectors' claims to federal public lands without consideration of the impact on soil, water, and air in the surrounding areas. To compensate, piecemeal, confusing, and often overlapping systems of federal and state regulation have been slowly developed since the mining law's enactment to slow or prevent mining activity deemed dangerous. This has left little room for innovative production techniques. Other, more practical and specific issues remain. Little data is available on the impact of introducing nonindigenous hyperaccumulators into the natural environment. In addition, genetically modifying the plants, either with other natural plants or with synthetic plants, may be necessary for hyperaccumulators to be used in certain locations. It may further not be possible for hyperaccumulators to be used in all locations.

Third, startup costs for a new phytomining operation would likely be significant. In addition to the general regulatory issues, both technical and specific regulatory challenges abound. Technically, production techniques and machinery would need to be calibrated to local deposits, requiring a highly skilled mineralogical labor force which the United States currently lacks. From a regulatory perspective, it is unclear how laws around agriculture will map onto the unique needs of phytomining projects for specific soil types. It has historically been prohibitive for farmers to farm on toxic soil: in the case of phytomining, that toxicity is precisely what makes an operation profitable. Operators of phytomining plants would be both farmers and toxic waste handlers and would likely need to bear the regulatory burden of both industries in a way that might be conflicting or even impossible. The regulatory burden on phytomining might stymie any new operation before it was able to scale.

Government Options

So what could the U.S. government do to help break down these barriers and realize the potential of phytomining? There are some immediate options: First, a mend the language of the Inflation Reduction Act to affirm that phytomining and biomining commercial operations, operating under all U.S. law, are entitled to production tax credits similar to recycling enterprises. Second, through the Export–Import Bank of the United States or Development Finance Corporation, fund commercial enterprises in Tanzania, Ecuador, the Democratic Republic of the Congo, and other countries where hyperaccumulator plants are being used to reduce heavy metal toxicity in soil and groundwater close to mining sites. Third, lead efforts to create a system of international standards for the removal, processing, and production of metals derived from hyperaccumulators.

Additionally, the United States would benefit from a research enterprise that can match the potential of phytomining and the urgency of the critical minerals challenge. A study group between the Environmental Protection Agency (EPA), ARPA-E, and the DOE could study the viability of specific uses of hyperaccumulators at former mining sites, and consider developing a framework to balance the costs and benefits of introducing new species at each viable location.
The United States needs a comprehensive and integrative approach to provide multiple ways to mine domestic metals, and not only from large open-pit mines. No method alone will be the silver bullet, but investing in new technologies and nature-based solutions could open exploration in places traditional mining could never occur.

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