Systems Level Solutions and Analysis for Phytomining Viability in the US

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I support ARPA-E's interest in exploring phytomining as a potential avenue to meet the growing need for critical minerals and provide the following responses to DE-FOA-0002751.

A rapid deployment of clean energy technologies will require, among many other factors, a substantial investment in new mining supply for various minerals, including lithium, cobalt, and nickel for energy storage both at the grid-level and for electric vehicles[2]. Numerous technoeconomic analyses have shown that the scale and speed required to reach net-zero by 2050 will require a substantial increase in mining capacity in the next decade of these minerals[3]. Figure 1 compares predicted nickel demand from electric vehicle batteries with existing nickel mining supply and shows a shortage will emerge around 2025 and grow to ~150 kt by 2030 if no further action is taken.

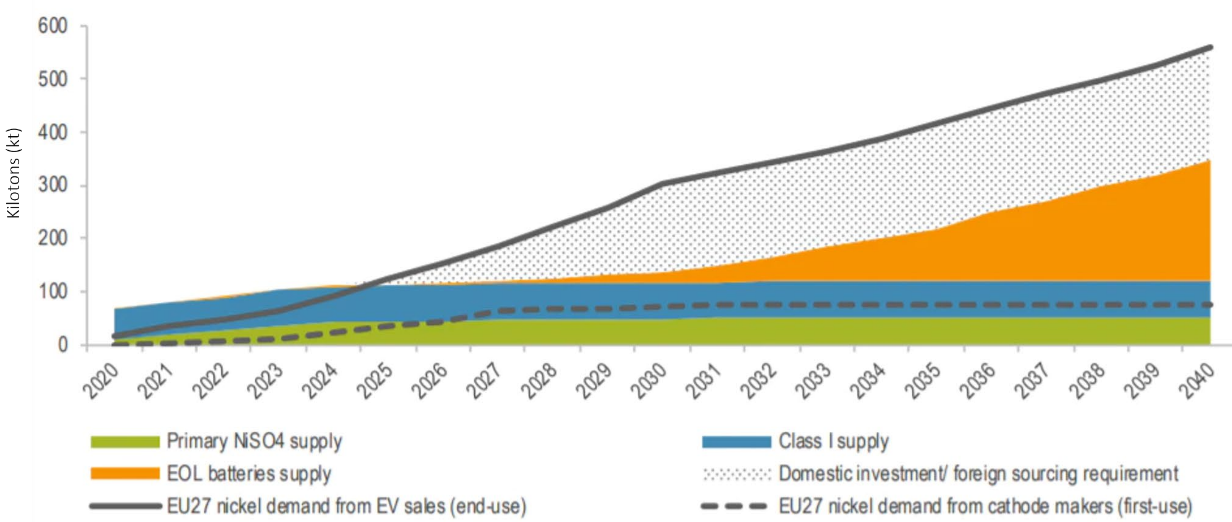

Figure 1. Nickel demand from EV's is predicted to outpace current primary mining supplies by 2025[4]

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[1] All views here are my own and do not necessarily represent the view of my employers
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[2] "The Role of Critical Minerals in Clean Energy Transitions," International Energy Agency (IEA). 2021

[3] "Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-based Growth," 100-Day Reviews under Exec. Order No. 14017. 2021

[4] Jake Fraser *et. al.,* "Study on future demand and supply security of nickel for electric vehicle Batteries," Publications Office of the European Union, 2021.

However, opening new mines and operating them sustainably is a challenge, both in terms of the environment and with respect to human rights. Maintaining ethical supply chains is a challenge for many producers who source minerals from mines across the world[5]. While many mines in developing nations lack strong regulatory safeguards, the strong protections in the US can lead to higher costs, increased uncertainty, and multi-year lead times for opening new mines[6]. Despite these challenges, US investment in developing its own sources of critical clean energy materials would help ensure consistent and reliable supply of these critical materials both domestically and globally.

Phytomining is a potential technology for extracting critical materials that addresses both human rights and environmental issues. It is less intrusive than traditional mining, involves less toxic processes, and can offer environmental remediation benefits to degraded lands, which minimizes the challenges that traditional mines face in the regulatory and permitting process. Despite this, phytomining as a research field is one of the few areas where the US is critically underrepresented. A metasurvey of phytomining found only 1 of the top 10 authors in this field are based in the US.[7] The unique system-level advantages offered by phytomining against the backdrop of the required increase in mining supply combined with a deficit in the US research ecosystem around this technology all provide strong support for ARPA-E setting up a program in phytomining. In our response to this RFI, we outline the need for mapping optimal locations for phytomining and technoeconomic analysis, the concurrent importance of pilot-scale real-world first-of-a-kind (FOAK) demonstration projects, and finally the opportunity to co-produce biomass-based carbon removal sequestration in conjunction with phytomining farms.

Mapping out the Optimal Locations for Phytomining and Scoping out a Technoeconomic Analysis

The profitability of a potential phytomining farm depends on a variety of factors, ranging from technical to market-based. We believe ARPA-E can fill a missing information gap by mapping out the phytomining opportunity in the US. Such a resource is a public good: an output that private sources are not incentivized to publicly share and public groups currently lack the resources to create. Mapping out the phytomining opportunity will be important for future technoeconomic analysis and for identifying ideal locations for demonstration projects. In particular, it can also help guide investors and financing towards commercialization and demonstration projects by clearly outlining the expected returns and technical merits required for commercialization.

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[5] Cornelia Lichner, "Ethical strategies for cobalt supply," *PV Magazine*, 2020.
[6] Jael Holzman and Hannah Northey, "Biden mining order won't change biggest hurdle: Permits", *E&E News*, 2022.
[7] Chen Li *et. al.*, "Visualizing Hotspots and Future Trends in Phytomining Research Through Scientometrics," *MDPI Sustainability*, 2020.

Part of a technoeconomic analysis will require mapping out the available opportunity in the US. Understanding the availability of ultramafic and serpentine rocks and the number of brownfields and EPA superfunds with relevant waste material that could be phytomined will give a better understanding of the commercialization potential and estimate of the scale phytomining can play in supplying US mineral demand for clean energy materials. As shown in Figure 2a,b, there exists an abundance of data spread across the federal government that can help identify locations that have high concentrations of metals ideal for phytomining. Such a data mining and synthesizing project could also be combined with real-world soil samples of identified promising sites for FOAK demonstration plots.

Once this soil and geological data is collated, different technical parameters for phytomining performance can be included, alongside market information around land and labor cost, mining revenue, capital expenditure. A compiled technoeconomic review can quantify phytomining's potential to scale to actual climate impact and identify minimum technical performance criteria for profitability.

The need for real-world demonstration projects

In the phytomining literature, we have found few examples of recent phytomining field studies and none that have been done in the US in the past decade. While identifying novel hyperaccumulators, particularly for under-studied high-value metals besides nickel, is important and should be funded as well, we believe there is sufficient scientific literature regarding best practices for cultivating phytomining that one of the unknown frontiers for phytomining is its performance at acre-scale plots. In particular, some critical data points that will determine phytomining's profitability is real-world metal uptake in the presence of non-target metals, biomass yield per acre, and soil depletion rate, none of which can be conclusively answered in a lab pot. Providing trial-based estimates for these parameters in US-based experiments will be important for investors and funders, whose support will be critical for commercializing such technology. In building a program portfolio of research for an ARPA-E phytomining program, we strongly recommend including a robust set of performers who have outlined clear pathways towards real-world demonstrations. The results and performance of real-world demonstration plots can also be used in informing the parameters for technoeconomic analysis. Combining a TEA with real-world results can highlight the "innovation gap" between where current best practices and technologies are compared with where they need to be to be profitable.

Diverse and innovative phytomining demonstration projects can also co-develop alongside other land-uses. Opportunities include agrivoltaics[8] or solar on brownfield redevelopment projects. In particular, using phytomining for environmental remediation for brownfield sites may provide a profitable exit strategy for phytomining after metal soil depletion and provides a continued stream of jobs and income for local communities affected by such sites.

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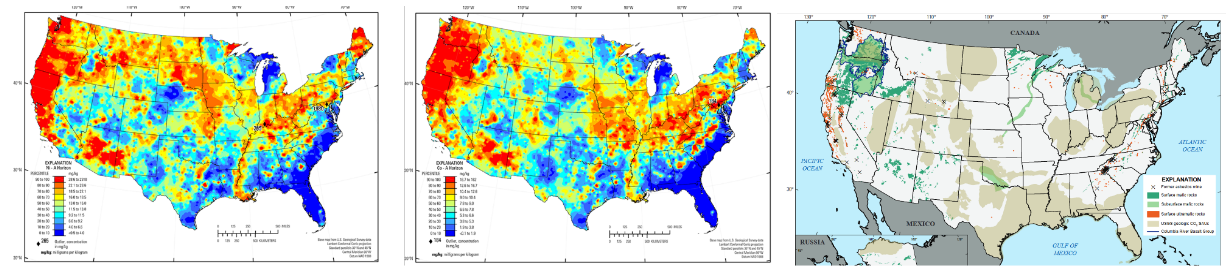
[8] See this DOE EERE FOA: https://www.energy.gov/eere/solar/articles/funding-notice-foundational-agrivoltaic-research-megawatt-scale-farms

In summary, combining phytomining with existing redevelopment projects can be a way for researchers to minimize costs for experiments and explore innovative solutions for minimizing costs and improving project revenue projections.

Outlining the Opportunity for Phytomining and Carbon Sequestration



a) b) c)

Figure 2. USGS maps of metal availability in topsoil and carbon sequestration capabilities. a) shows nickel, b) shows cobalt, and c) shows geological carbon sequestration reservoirs[9]

One important co-development technology that we believe pairs well with phytomining is carbon sequestration of the associated biomass from phytomining. Firstly, the process of extracting metals from phytomining biomass is remarkably similar to biomass carbon sequestration, namely the use of thermal decomposition. This should significantly lower the CapEx required to add carbon sequestration as an additional product, as the pyrolysis is already included in the phytomining extraction process. Secondly, adding in carbon sequestration provides revenue diversification for phytomining operations, protecting against metal price instability and improving revenue generation intensity. In Table 1, we outline some back-of-the-envelope calculations that show how phytomining farms can be cost-competitive and how carbon sequestration can complement revenue from phytomining.

The phytomining results in Table 1 are based on a recent field trial in Austria[10]. Therefore, the phytomining results should be taken as a picture of where phytomining practices are today, not an upper-bound of where they could be. For context, we provide our estimate of corn farm revenues normalized to a per-acre basis. However, it is worth noting that corn farms have different cost structures around land, labor, and equipment and capital and land scaling considerations compared to phytomining, so a per-acre comparison basis is not a strict apple-to-apple comparison. In particular, ideal phytomining conditions, namely high metal concentration

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[9] a) and b) are from David Smith *et. al.,* "Geochemical and Mineralogical Maps for Soils of the Conterminous United States" *US Geological Survey*, 2014. c) is from U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team, "National assessment of geologic carbon dioxide storage resources—Results (ver. 1.1, September 2013)" *U.S. Geological Survey Circular*, 2013. https://pubs.usgs.gov/circ/1386

[10] Theresa Rosenkranz *et. al.,* "A nickel phytomining field trial using *Odontarrhena chalcidica* and *Noccaea goesingensis* on an Austrian serpentine soil," *Journal of Environmental Management*, 2019.

in soil, are usually mutually exclusive to arable farming conditions. Further TEA as described above can offer a finer picture of cost/revenue for phytomining, particularly on the role of land value in profitability of a phytomining farm.

In Figure 2, we can see that the pacific northwest, northern california, and the midwest offer a combination of high nickel and cobalt concentrations in soils colocated alongside geological sequestration. In addition to geological carbon sequestration, biochar[11] and enhanced weathering of ultramafic soil are other carbon sequestration products that could be co-produced with phytomining farms. We strongly recommend ARPA-E solicit proposals from performers that consider and include co-optimizing carbon sequestration and hydrogen production alongside investigating downstream phytomining extraction processes e.g. hydrometallurgy, pyrolysis. Carbon sequestration capacity and associated cost/revenue can also be another resource included in a mapping and TEA project.

	Value	Notes
Nickel price ($/kg)	25	
Biomass yield (ton/acre/year)	2	US corn farms yield 4.2t/acre[12]
Nickel yield from biomass (wt%)	1%	
Biomass(dry ton) to CO2(ton) ratio	0.8	Given biomass generally produces 1.6tCO2/1t dry biomass, this is a conservative estimate assuming a 50% loss rate during pyrolysis and capture
Price of CO2 ($/tCO2)	50	
Phytomining Revenue ($/year)	500	US corn farms yield $1300/acre[13]
CO2 Revenue ($/year)	160	

Table 1. Back-of-the-envelope calculations for phytomining combined with CO2 sequestration revenue on a per-acre basis.

[11] Rachel A. Smoak and Jerald L. Schnoor, “Nickel Hyperaccumulator Biochar as a Ni-Adsorbent and Enhanced Bio-ore,” *ACS Environmental*, 2022.

[12] Calculations based off of bushel per acre yield from USDA: https://www.nass.usda.gov/Newsroom/2022/01-12-2022.php

[13] Based off of 2020 corn prices https://crsreports.congress.gov/product/pdf/R/R46676

Conclusion

Phytomining is an underresourced technology that could help tackle a fundamental looming challenge for clean energy costs and productions. Concurrently, phytomining surpasses current environmental regulations as a potent step-change technology that could completely change the field of mining. In this response to RFI, I have argued that there is a clear need for synthesizing government data to identify ideal FOAK demonstration plots; that ARPA-E should support performers who conduct real-world field studies of phytomining performance; and outlined how phytomining and biomass based carbon sequestration share similar technology pathways and can mutually support a commercial enterprise by providing diverse revenue streams with minimal additional CapEx.