Biomineral Fertilizers from Low-Grade Ore and Mine Waste for Remineralizing Soils Damaged by Agricultural Practices and Highly Degraded Farmlands.

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• Introduction

Working with damaged soils can be a huge challenge. In conventional agricultural systems, soil is often considered a lifeless medium with the sole purpose of holding our plants upright. If microorganisms in the soil are considered, they are typically considered a threat to be eradicated. It is up to the plant, and the plant alone, to extract all the elements it needs to grow and stay healthy. So, when the soil is lacking in a particular nutrient, it is applied in the recommended dosages. When the plants don't respond, or only respond marginally, more nutrient is added until the desired result is obtained.

This view neglects a very important and very complex part of the process. By missing this important link in the chain of a nutrient cycling living soil, inputs are increased, creating a treadmill of continual supplementation. Additionally, unintended problems such as erosion, compaction and nutrient leaching occur.

Conventional agriculture alters the microbial communities that deliver or influence the movement of micronutrients from soil to plants. For over a century, and through the lens of germ theory, microbes have been seen as agents of death and disease. Agrichemicals to eradicate pests became embedded in our agricultural practices. Intent upon eradicating microbes seen as detrimental to plant growth, the collateral damage to good microbes that support plant health was never considered. While spraying broad-spectrum biocides on fields may take care of agricultural pests over the short run, the pests return with a vengeance in the long run. We have become addicted to solutions with limited staying power. However, these are no longer the solution for sustained plant growth. While agriculture has successfully kept many pathogens at bay, we're now realizing that practices built upon the foundation of germ theory can harm or destroy the beneficial microbes that reside in our fields.

Changes are on the horizon for the interconnected functions of soil - water management, carbon management, and nutrient management, sparked by the demand for changes to climate and food production. Ultimately, the way in which we directly and indirectly manage our planet's soil will be interwoven within our future success as a species.

- **The Importance of Minerals**

Remineralization is the process of adding ground up rock (Rock Powder) to agricultural land. Rock-forming minerals of igneous and metamorphic rocks contain most of the nutrients required by higher plants for growth and development, and as such, Rock Powder fertilizers provide a source of nutrients to depleted top soil (Harley and Gilkes 2000).

Initially, the potential of Rock Powder as a fertilizer was linked to the chemical view of fertilization and was approached as a geochemical problem where bulk soil solutions not in equilibrium with fresh primary minerals leading to dissolution and nutrient uptake. Most rocks are composed chiefly of silicon and aluminum, both of which are bound tightly to oxygen. Plants don't need much silicon and aluminum. What they require a lot of are three elements—nitrogen, potassium, and phosphorus, to build roots, stems, and leaves. Plants also need other major nutrients, like calcium and magnesium, which are abundant in some types of rock and generally don't limit plant growth. Other elements contained within rocks are considered micronutrients because plants need far less of them. Plants stockpile and concentrate critical micronutrients weathered out of rocks. Among these micronutrients are metals like zinc and iron, which plants fold into complex molecules that serve specialized purposes in their shoots, roots, leaves, seeds, and fruits. Long-term weathering of pulverized silicate minerals has also been proposed for climate change mitigation (Quirk, Andrews et al. 2014; Taylor, Quirk et al. 2015).

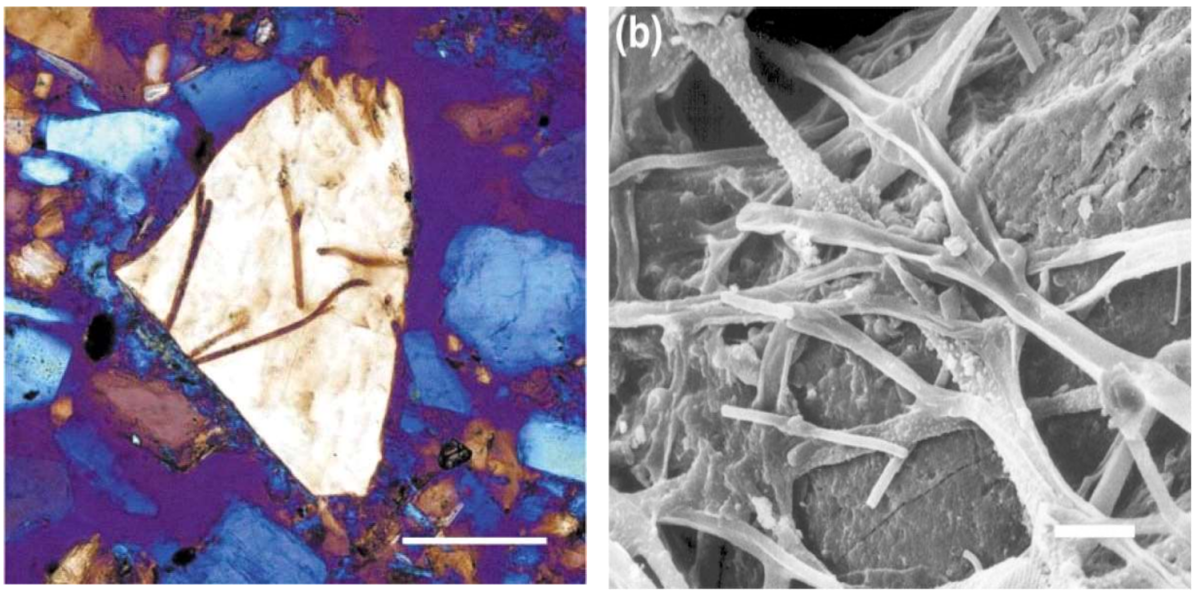
Slow dissolution rates of minerals, however, inhibit the use of Rock Powder in agriculture unless suitable soils are identified and optimum Rock Powder properties developed. In soils, mineral dissolution is enhanced by disequilibrium between soil solution and mineral surfaces through the removal of ions by processes such as leaching and nutrient uptake. Rhizosphere processes and other biological activity further enhance mineral dissolution through the release of complexing organic compounds which react with mineral surfaces (Hinsinger 1998).

What was missing however, was a much easier, and effective, way of getting to the minerals, and it involves a biological, not chemical, approach.

- **The Role of Microorganisms in Extracting Mineral Nutrients from Mineralized Rock Powder**

Plants absorb the metabolic products of soil organisms that feed on and break down organic matter and rocks. When microorganisms decompose dead plants and animals, elemental building blocks are put back into circulation, including nitrogen, potassium and phosphorus as well as the assorted micronutrients important for plant health. Moreover, microbes deliver nutrients right back to where they are needed – a plant's roots.

Micronutrients are generally found in insoluble compounds within the soil, locked and unavailable for plants. Certain microbes help pry these elements loose (Carson, Harley et al. 2012). However, modern agriculture destroys microbes that can make these micronutrients available. Mycorrhizal fungi especially are incredibly valuable, and highly efficient, in enhancing the plant uptake of macronutrients (Dumaresq and Greene 2001) and micronutrients(Burghelea, Zaharescu et al. 2015). Recent research (Landeweert, Hoffland et al. 2001) suggests that mycorrhizal fungi mobilize essential plant nutrients directly from minerals through excretion of organic acids, enabling plants associated with the fungi to utilize essential nutrients from insoluble mineral sources (*Figure 1*).



Scale Bar = 100µm Scale Bar = 10µm

Figure 1: Fungi extracting nutrients from soil minerals (Source: (Landeweert, Hoffland et al. 2001)).

- **The Role of Mineralized Rock Powder on Microorganisms**

Remineralization influences microorganisms because of both composition and particle size. The composition of Rock Powder fertilizers develops microhabitats that differ in mineral composition and size. Different minerals are colonized by distinct microbial communities and preferential colonization of minerals containing nutrients provides "hotspots" of activity. Applying different combinations of mineral rich Rock Powder to soil influences bacterial communities in bulk soil. **The role of minerals is thus two-fold; to provide nutrients for the plant, and to provide opportunities for microbial health within the soil, making them resilient and resistant to attack** (Carson, Harley et al. 2012).

- **The Importance of Biomineral Fertilizers**

The development of a fertilizer that contains both minerals and microbes (a biomineral fertilizer) benefits both the plant and the environment.

Biology is efficient when it comes to plants and animals expending energy because having it and getting it are central to survival. When fertilized, plants don't need to spend as much energy to get nutrients, so they don't grow as extensive a root system or produce as many exudates. This translates into fewer mycorrhizal fungi and beneficial bacteria in the rhizosphere. The net result is a decline in the nutrient exchange, mineral uptake, and phytochemical production vital to plant health and defense against pathogens. Mycorrhizae are known to greatly enhance plant uptake of nutrients. A 2004 comparison of wheat grown under organic and conventional practices in southeastern Australia found that conventional fertilization not only increased crop yields and phosphorus concentrations, it also reduced zinc uptake (Ryan, Derrick et al. 2004). Providing a biomineral fertilizer to the plant provides both the nutrients **and** biology to deliver these nutrients to the plant.

When soil microbes known to deliver micronutrients to plants are added to soil, mineral uptake increases. Additionally, microbial metabolites stimulate plants to produce phytochemicals with antibacterial and antifungal properties to suppress pathogens and promote plant health. It is possible that microbial partnerships hold tremendous potential to reduce, or even replace, pesticides and fertilizers to sustain intensive agriculture.

The increase in root and microbial activity in soil leads to an overall increase in soil organic carbon which has an impact on both soil functions and ecosystem services (*Figure 2*; (Rice, Fabrizzi et al. 2007)). Dead microbes within the soil can account for up to 80% of the organic matter in soil, and this alone has a significant impact.

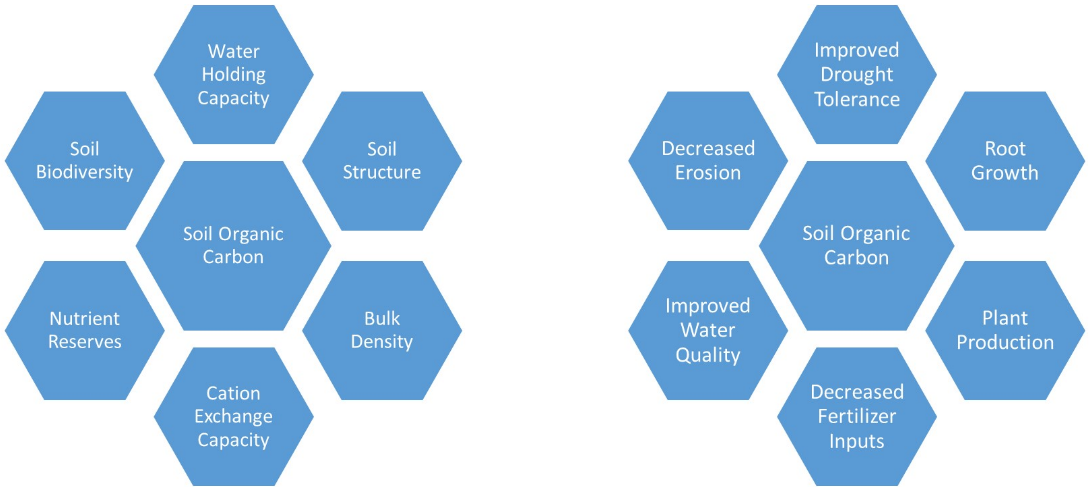


Figure 2: Relationship of Soil Organic Carbon to other Soil Functions (left) and Ecosystem Services (right). Source: (Rice, Fabrizzi et al. 2007)

Key improvements in soil and ecosystem functions include the following (Rice, Fabrizzi et al. 2007):

- Soil organic carbon is largely composed of organic carbon, nitrogen (90-95% of soil N), phosphorus (40% of soil P) and sulfur (90% of soil S). As the nutrients are re-cycled internally over time through plant uptake and residue deposition, microbial decomposition, and SOM formation, effective soil carbon development has the potential to reduce the need for additional N and P fertilization. Rock Powders will supply the potassium (K) fertilization, released by microbial activity to greatly reduce the reliance on, and to eventually replace, chemical fertilizers.

- Increases in soil carbon increases the soil's cation exchange capacity - the capacity to store nutrients in soil. An increase in carbon will reduce the leaching of soluble nutrients out of the root zone and into surface water.

- Plant available soil water also increases between 1-10 gram for every 1 gram of soil organic matter. The ability of organic matter to hold water is due to both its properties and improvement in soil structure. Soil organic carbon enhances soil structure and aggregation, leading to improved infiltration, improved aeration and root growth, and less compaction and crusting, all of which help in reducing erosion. Certain fungi have also been associated with improved drought tolerance (Howieson 2014).

- In addition to managing Earth's soils for food production, there is an increasing need for managing for environmental regulation and Earth system functioning. Building and improving the soil natural capital is an important aim contributing to soil resilience and maintaining balance in the provision of ecosystem services (Abbott and Manning 2015).

- **Biomineral Fertilizers Prepared from Low-grade Ore and Mine Waste**

Ore grades show long-term declining trends over time. As the quality of ore deposits continues to decrease, it is expected that processes which can economically and sustainably extract metals from low grade ores will grow in importance to the minerals industry. Biotechnology and related processes have the potential to transform currently uneconomical ore reserves into a viable resource. Moreover, microorganisms can facilitate the recovery of metals from various metal-containing waste materials.

Abandoned Mine Lands (AMLs) present serious threats to human health and the environment. Addressing AML impacts is becoming increasingly important due to increased exposure to people and risks of accidents, injuries, and claims. According to the Abandoned Mine Lands Portal (http://www.abandonedmines.gov/ep.html) there are estimates of as many as 500,000 abandoned mines in the US, most within the 12 Western states. Mine waste rock is generally difficult to vegetate and may pollute adjacent streams, adversely impacting aquatic life and human health. Elevated levels of metals can cause fish and other aquatic life to die and drinking and agricultural water sources to be contaminated. Mill tailings tend to be fine grained particles susceptible to erosion. Sediment related to mining and milling activities consists of small particles that often contain high concentrations of heavy metals. The mill tailings particles can destroy aquatic habitats by covering the stream bottom and suffocating fish eggs.

Most hardrock AML sites are included and addressed as part of broader agency programs. Each abandoned mine site faces a somewhat unique set of regulatory requirements, depending on federal and state statutes or regulations; whether it is on federal, state, tribal, or private land; local regulations; and site-specific environmental considerations. Although Federal agencies have informally estimated that they expend $80–85 million annually on hardrock AML remediation, the impact of these sites to the environment is still a large problem.

Few private funding options are available to manage the impacts of abandoned mines. However, abandoned hard rock mines provide the source material for preparing biomineral fertilizers. Using a hydrometallurgy stirred reactor, gold and silver (or other resource) can be extracted using a non-toxic leach solution that includes biochemistry beneficial for plant growth. The solid residue is subsequently blended with organic and microbial components to produce biomineral fertilizer.

Income from these sites can be generated from:

- Gold, silver (and other commodities) extracted via a resin-bed ion exchange column;
- Resultant leachate used as a liquid fertilizer;
- Biomineral fertilizer.

This approach will allow for the management of ecosystem degrading mine waste in a manner that provides a net improvement of environmental health while generating income.

- **Conclusion**

By optimizing bioprocesses that allow the extraction of metals from low-grade ores, the processing of which is not economically viable by traditional methods, uneconomic ore resources are transformed into reserves. This approach can make the mining industry more sustainable by prolonging the functional lifespan of mines and decreasing the negative environmental footprint of operations.

More importantly, the growing interest in reducing the need for synthetic nitrogen and phosphorus fertilizers, applying a biotic fertilizer with beneficial microbes offers a new sustainable strategy for soil fertility and intensive agriculture. The growing commercial appeal of biofertilizers reflects the fact that these approaches are cost-competitive with conventional fertilizer, and can produce comparable, if not greater, yields.

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