A Proposed Framework for Astroagronomy as a Space Resources Discipline

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Agronomy: "a branch of agriculture dealing with field-crop production and soil management" (Merriam-Webster, 2024)

The Framework

Plants need certain elements to grow; those elements are often available from the regolith and/or the atmosphere.

Just as agronomy on Earth concerns itself with the study of crop production and soil management, astroagronomy seeks to do the same given the constraints of extraterrestrial environments. This paper proposes a systematic way of assessing what is known about the key requirements for crop production and soil management and what remains to be discovered. It acknowledges the importance of oxygen and water to life as we know it and offers a schema for prioritizing development of other space resources based on their relative importance to photosynthetic plants. To that end, the astroagronomy framework suggests six questions that must be answered for any food production system in space.

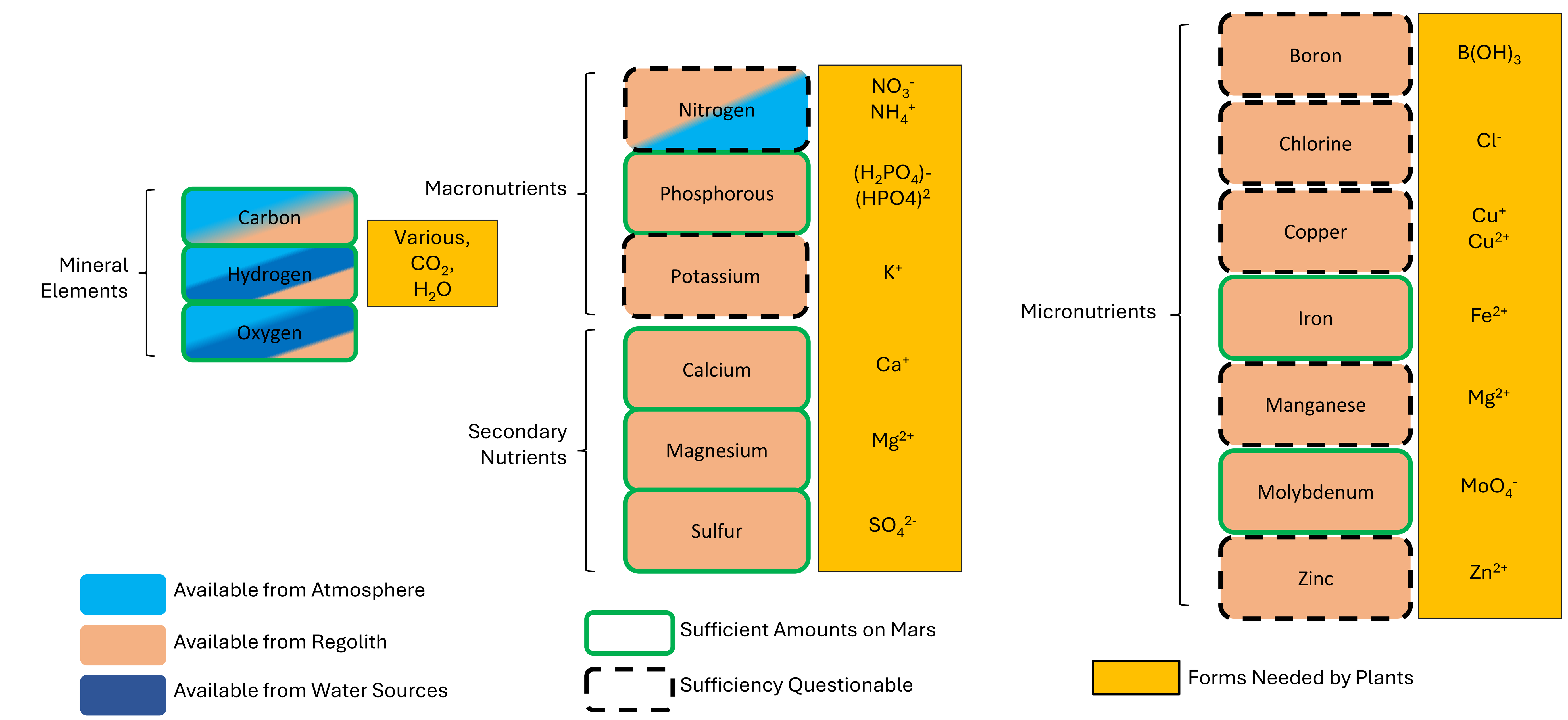
Astroagronomy: Defining the Problem

How might an extra-terrestrial settlement harvest—to the greatest extent possible—the nutrient elements necessary for crop growth *in situ,* reducing their dependence on Earth-bound supply chains and increasing the probability of a successful settlement over the long term?

1. What elements are required?
2. In what forms do the plants need them?
3. What elements are available?
4. In what mineral forms are these elements available?
5. How can these mineral forms be processed for agricultural use?

1 2 3 Required Elements, Needed Forms, & Availability

*As applied to a Mars scenario. Variations in plant requirements may occur.



3 4 Available Minerals

Resource development should proceed from mineral elements to micronutrients in descending order. We continue with examples from the Mars use-case scenario.

- **Mineral Elements:** Mars contains abundant sources of carbon, hydrogen, and oxygen in various forms including atmospheric carbon dioxide and water ice.
- **Macronutrients:** Nitrogen exists in the atmosphere (primarily as dinitrogen) and in the regolith as a variety of species (Ming et al., 2014). Phosphorous appears at Gale Crater within apatite (Blake et al., 2013). Potassium appears on Mars within sanidine and orthoclase (Blake et al., 2013).
- **Secondary Nutrients:** Calcium appears in numerous compounds, including within apatite, anhydrite, and possibly in variants of pigeonite and augite; pigeonite and augite, however, can form around magnesium also, as can olivine (Blake et al., 2013). *Odyssey* measured substantial amounts of sulfur, possibly as bioavailable PO_4 (Payre et al., 2019).
- **Micronutrients:** Chlorine exists in a variety of forms (Fernanders et al., 2022). The Martian supply of iron is vast, much of it in the form of ferric oxide (Fe_2O_3) (Herndon, 2009). Manganese, once only known from meteorites, and boron, once thought to be entirely absent from regolith (Yazawa, Mikouchi, & Takeda, 2009) have both been located on Mars (Payre et al., 2019; Gasda et al., 2017).Eichler et al. point out that, copper, boron, and zinc are all currently estimated to be "deficient" on "much of the surface of Mars," but they do allow for the possibility of its use for plant growth (2021). Molybdenum is known to exist on Mars, but discussion of its Martian forms is noticeably absent from the surveyed literature.

5 Processing Options

Extraction and processing methods will necessarily vary by mineral and likely by location.

On Mars, for example, carbon dioxide, oxygen, and nitrogen can be made available through compression (Zubrin, Baker, & Gwynn) and/or atmospheric distillation. The Mars Oxygen-generating Experiment (MOXIE) has already demonstrated the ability of a system to isolate atmospheric oxygen (Hoffman et al., 2022). Projects like RedWater are working to develop the technologies necessary to extract and process glacial water (Zacny, 2022).

Cannon and Britt (2019) assess that nitrate (NO_3^-) can be obtained from regolith leachate via a "moderate" degree of processing. Similarly, forms of phosphorous can become available over time through weathering, dissolution, or desorption (Prasad & Chakraborth, 2019). PO_4 in a readily useful form—possibly from apatite—would be a crucial agricultural resource.

As for sulfur, plants primarily uptake that element in anionic form (SO_4^{2-}) (Narayan et al., 2022), and it is this form—along with ions K^+, Ca^{2+}, Mg^{2+}—that could potentially be made available from Martian regolith via leaching (Cannon and Britt, 2019). Iron can be chemically separated to enable plant uptake (Morrissey & Guerinot, 2009).

As for the micronutrients, plants uptake boron primarily as boric acid (B(OH)3), making it "the only element which is not taken up from the soil as an ion" (Brdar-Jokanović, 2021). The useful ion forms of the other micronutrients are Cu^+ or Cu^{2+} (Mir, Pichtel, & Hayat, 2021), Zn^{2+} (Gupta, Ram, & Kumar, 2016), Mg^{2+} (Chaudhry et al., 2021), and molybdenum as MoO_4. (Kaiser et al., 2005), so any potential processing of minerals for agricultural purposes should aim to enable uptake of these forms.

Significance

- Required elements and needed elements (Steps 1 & 2) are unlikely to vary significantly.
- Additional research and exploration are needed to more comprehensively catalog available elements (Step 3), available mineral forms (Step 4), and potential methods for making those forms agronomically useful (Step 5).
- While the use-case in this paper focused on a Mars scenario, the framework is applicable to any space environment, including the Moon, asteroids, and interplanetary space itself.

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