A PROPOSED FRAMEWORK FOR ASTROAGRONOMY AS A SPACE RESOURCES DISCIPLINE.

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Abstract: A definition of astroagronomy is offered as a distinct discipline within the field of space resources. The provided design framework suggests a methodology for assessing the agronomic potential of any celestial body based on the mineral elements required by food crops, an assessment of the availability of these elements in their *in situ* mineral forms, and determining feasible approaches for making use of these resources. This approach allows for a broader selection of food-crops, leading to greater menu variety—a psychological benefit for exploration missions and likely a prerequisite for a self-sustaining extra-planetary settlement. Scientific data from Mars is applied to demonstrate the feasibility of the framework.

Introduction: The Merriam-Webster dictionary defines agronomy as "a branch of agriculture dealing with field-crop production and soil management." Astroagronomy is an extension of this concept to the production of crops and the management of regolith and other nutritional elements off of Earth. While drawing from complementary scientific disciplines like astrogeology, astrobotany, chemistry, and dietetics, astroagronomy enlarges current conceptions of growing food in space and seeks to grow food on other celestial bodies where available resources may provide some or all of the needs for crop production by harvesting *in situ* resources.

Historical studies of space habitation have tended to take two approaches to food production: (1) beginning with questions about the nutrient requirements of human settlers and deriving possible menu items, e.g., [1], [2], [3], or (2) experimenting with regolith simulants to see how various food crops respond and assessing the merits of the results, e.g., [4], [5]. While practical, these approaches lack situation within a larger theoretical framework to guide prioritization of scientific exploration and future data collection.

Approaching the topic from the perspective of an astroagronomist, however, offers a more holistic theoretical approach. The question may be asked: how would 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? An application of the framework begins with asking what mineral elements are required by the food crops, determining the mineral forms in which they are needed by the plants, assessing the availability of these elements in mineral forms on a celestial body, and determining feasible approaches for making use of these resources (Figure 1). In this way, the analysis enabled by a design framework for astroagronomy links the knowledge of planetary sciences to the practical applications of systems engineering and makes it applicable to analyzing food production on any celestial body. Examples of suggested crops and mineralogical data from Mars are used to illustrate the utility of this framework, which could be employed to prioritize scientific exploration on any celestial body.

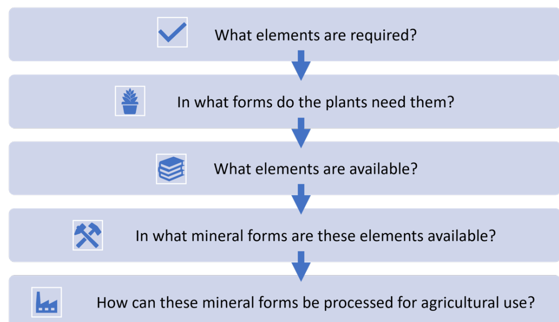

Figure 1: Framework for Astroagronomic Resource Development. *Source*: Author.

Required Elements and Forms: Whether obtained from soil or via nutrified water, and assuming no genetic modifications to significantly alter requirements, photosynthetic plants require a variety of nutritional elements in differing quantities. A comprehensive and useful list bins sixteen nutritional elements into as the mineral elements (carbon, hydrogen, and oxygen), the macronutrients (nitrogen, phosphorous, potassium), the secondary nutrients (calcium, magnesium, sulfur), and the micronutrients (boron, chlorine, copper, iron, manganese, molybdenum, and zinc) [6]. It is noteworthy, however, that this list may vary depending on plant type.

Some of these elements are consumable by plants in their elemental form (e.g., calcium and magnesium), but plants also frequently uptake elements when contained within molecular compounds (e.g., sulfur as contained in sulfuric acid), and in some cases, certain compounds are necessary [5]. Conversely, just because a mineral compound contains an essential element, that compound may be useless for agricultural purposes or even dangerous to plants (e.g., perchlorates) [7]. Thus, a wholistic understanding of the local minerology is required.

If the first two questions in the astroagronomy framework depend upon the types of plants to be grown, the next two questions depend upon the conditions of the celestial body and are site specific. In practical terms, then, there is a very real need for scientific instrumentation that can do more than analyze evolved samples and infer source minerals. Any candidate body for *in-situ* resource utilization (ISRU) would benefit from thorough cataloguing and mapping of its minerals and chemical compounds—especially near settlement locations deemed most suitable for other reasons (e.g., proximity to deposits of water ice or optimal landing locations).

Available Elements: To illustrate the utility of the framework as a way of thinking about agronomic resources, a first-order application of Martian mineralogy to the framework is useful. Since Mars is a terrestrial planet, one may expect the presence of all elements necessary for agriculture, although it has taken until this past decade to verify this supposition.

More specifically, Mars contains abundant sources of carbon, hydrogen, and oxygen in various atmospheric forms and in water ice. Among the macronutrients and secondary nutrients, nitrogen is the most important for plants and is known to exist in the atmosphere as dinitrogen and in the regolith in various forms since its detection by *Curiosity* [8], [9], [10]. Phosphorous, calcium, magnesium, molybdenum, iron, and sulfur, are available in "sufficient quantities" to grow plants [11].

Mineral Forms and Methods: Although an exhaustive list of mineral forms of potential nutrients and methods for extracting them are beyond the scope of this submission, extraction and processing methods will necessarily vary by mineral and likely by location. On Mars, for example, carbon dioxide, oxygen, and nitrogen can likely be made available through compression and/or atmospheric distillation [12]. Phosphorous appears at Gale Crater within apatite ($Ca10(PO_4)6(OH_2)$), and the possibility of obtaining the phosphate radical (PO_4) from this compound is encouraging [13]. Similarly, 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 [13]. 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 [15].

As for micronutrients, chlorine [16] and copper [17] exist in a variety of forms. Iron is abundant as iron oxide and within ilmenite; like magnesium, iron can appear in olivine, pigeonite, and augite [17]. Manganese and zinc also exist in the vicinity of copper on Mars [17]. Discussions of mineral compounds containing molybdenum are noticeably absent from the surveyed literature. Regardless, any potential processing methods should aim to enable uptake of the needed forms (Cl^-, Cu^+ or Cu^{2+}, Zn^{2+}, Mg^{2+}, and MoO_4^-) [18], [19], [20], [21].

Conclusion: 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. Based on this framework, more comprehensive research can be guided to evaluate the suitability of potential settlement locations and mineral processing methods on any celestial body.

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