AN EVALUATION OF CI CARBONACEOUS ASTEROID REGOLITH AS A PLANT GROWTH MEDIUM FOR SPACE CROP PRODUCTION.

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Introduction: C-type asteroids have been postulated as analogous to a variety of meteorite types including the CI, CM, CV, CO subclasses [1]. The CI carbonaceous meteorites are of particular interest to researchers because of their organic compositions, and because they have experienced varying degrees of aqueous alteration since their formation, as well as the fact that they have retained a majority of elements from the formation epoch of the solar system [2,3]. As such, the asteroid-meteorite link between the C-type asteroids and the carbonaceous meteorites is important because the regolith of these asteroids may contain organic soluble elemental nutrients that plants can utilize for growth and development. In particular, nitrogen, phosphorus and potassium and the trace nutrients of magnesium, iron, and calcium are vital for plant growth [4,5,6].

With a concerted effort to establish long-term inhabitants on the Moon and Mars, as stated by NASA with the Artemis program, crewed missions to asteroids should not be ignored—asteroid mining has been seriously considered as a future endeavor for human spaceflight [7,8]. A critical aspect of human missions is self-sustainability and *in-situ* resource utilization. Part of this self-sustainability is food production via edible crops. As such, the surface minerals of the carbonaceous asteroids could be used as fertilizer that could help feed large populations, space based or here on Earth [9]. Our study focuses on the ability of CI carbonaceous asteroid regolith simulant, produced by CLASS Exolith Lab, to sustain plant growth and produce edible biomass.

We are investigating three methods in which asteroid regolith could be used to grow edible crops:

- As a fertilizer.
- As a stand-alone soil (*in-situ* resource).
- As a stand-alone soil in microgravity (using simulators).

Methods and Materials:

To assess Earth soil fertilization, we selected three crops (lettuce, radish and pepper) to grow in the CI asteroid regolith simulant, along with peat moss and increasing combinations thereof (e.g. 25% peat moss 75% simulant, 50% peat moss 50% simulant, etc.). We are also growing crops in a standard topsoil with added vermiculite as a standard control. We have five seed per pot set up in randomized treatment blocks (Fig. 1A) and we are repeating this 3 times. We chose Canadian sphagnum peat moss due to it's high acidity and lack of essential nutrients. However, the high magnesium oxide and some calcium oxide content of the simulant will likely cause the peat moss to induce a neutralizing effect similar to that of dolomitic lime, a common soil neutralizer [10]. Regolith, mixture, and peat moss soil analysis will be conducted at the Kansas State University Soil Testing Laboratory.

Water is a necessary factor of our experiment. For example, when water is added to 100% simulant, it clumps into a solid mass. This effect is likely due to the phyllosilicate minerals in the simulant, which does not allow air or water to reach the seed. Also, it should be noted, peat moss is an excellent seed starting material.

Our second experiment aims to address these issues by increasing drainage and aeration in the simulant and determining if the simulant itself can support germination and growth. Pots again contain five seeds per pot in randomized blocks with the treatments of a mixture of simulant and perlite, pure perlite, and topsoil with 25% vermiculite/perlite mixture (Fig 1B).

Since asteroids are small bodies, experiments conducted in space near asteroids will be exposed to microgravity. To study this, we have a separate experiment with radishes planted in a simulant/perlite mixture and placed into two 2D clinostats (Fig. 1C). Clinostats simulate microgravity by rotating plants parallel to gravity at a constant rate so that they do not experience the full effect of gravity at any given time.

In each case, germination percentage, number of leaves, plant height, above-ground biomass, below-ground biomass, and total biomass data were collected at 55 days after planting. The incidence of germination and leaf production were modeled as a function of simulant concentration (or microgravity) with a generalized linear mixed model using PROC GLIMMIX in SAS (SAS Institute, Cary, NC), assuming each response variable is a binary/Bernoulli distribution. The effect simulant concentration (or microgravity) on plant height, above, below, and total biomass was tested by ANOVA using the lm() function in R (R Core Team, 2020).

In each instance, experiments were conducted in a controlled environment using a Percival AR-66L2 plant growth chamber provided by the University of North Dakota Department of Biology. Controlled parameters include humidity (50%-60%), temperature (18˚C-24˚C), light, and photoperiod (16hrs day, 8hrs night).

Crop Selection: We chose crops based on variety, growth mechanism, and applicability to human missions to the ISS and the Moon. A summary of each crop can be found in Table 1. Lettuce and radish seeds were purchased commercially online from Johnny's Selected Seeds (Johnny's Selected Seeds Co., Winslow, ME, USA), and pepper seeds were purchased commercially online from the Sandia Seed Company (Sandia Seed Co., Albuquerque, NM, USA).

Table 1
Crop Species

Scientific Name	Common Name	Cultivar (cv)	Growth Mechanism
Lactuca sativa	Lettuce	'Outredgeous'	Leafy Green
Raphanus sativus	Radish	'Pink Celebration'	Root Crop
Capsicum annuum	Pepper	'Chimayo'	Fruit Crop

Plant Mediums: CI asteroid regolith simulant was supplied by the CLASS Exolith Lab at the University of Central Florida (UCF, Orlando, FL., USA). The minerology and bulk chemistry composition of the simulant is based on the Orgueil meteorite [11]. The simulant is considered 'high-fidelity', possessing accurate qualities of suspected carbonaceous asteroid regolith and is to be used for scientific investigations. Creekside topsoil and Sungro Sunshine Canadian sphagnum peat moss were purchased from a local gardening store. Vermiculite and Perlite were soil amendments used in this study.

Microgravity Simulators: Two Eisco Labs 2D Clinostats were used in this study.

Results: Our research is currently in the collection/analysis phase. However, our initial results will be complete in February 2021. As such, our results will be further discussed at that time.

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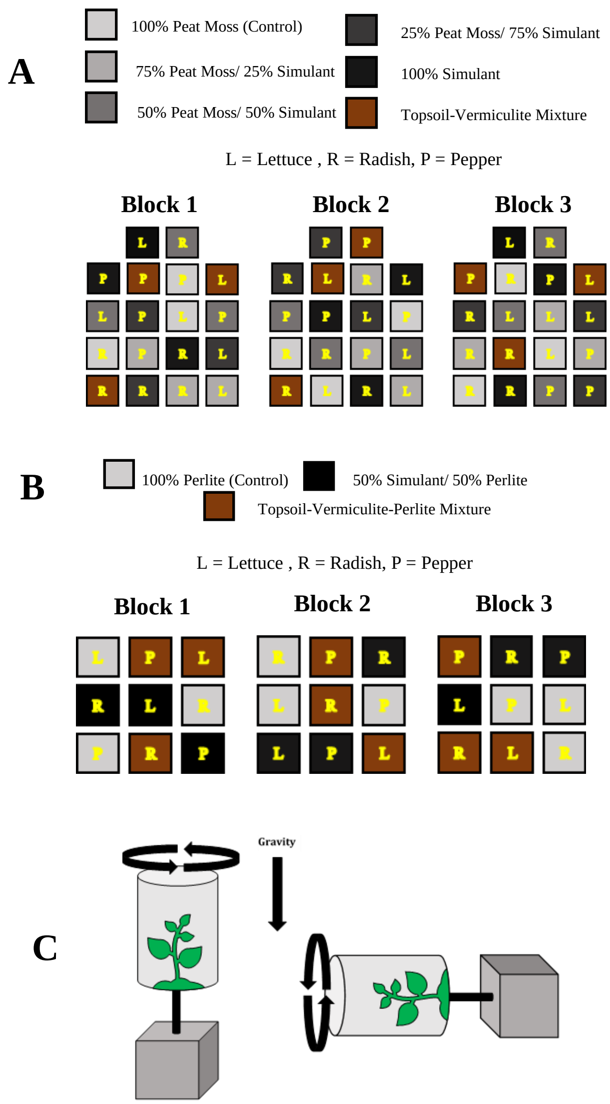

Figure 1. Experimental designs. Three randomized blocks of 18 pots, 5 seeds per crop per pot with increasing amounts of regolith simulant added to peat moss(A). Randomized blocks of 9 pots, 5 seeds per crop per pot with perlite, regolith and topsoil (B). 2D Clinorotation of a plant. Normal gravity conditions rotate perpendicular to the surface, experiencing the force of gravity (left). Microgravity conditions rotate parallel (90o) to the surface, mimicking the state of free-fall, or microgravity (right). Radishes will be tested under these conditions where the control is normal gravity (left) and treatment is microgravity (right) both with simulant/perlite mixture (C).