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Space Crop Considerations for Human Exploration

Ralph Fritsche (retired), Natasha Haveman, Gioia Massa, Matthew Mickens, Trent Smith, and Raymond Wheeler (retired)
Kennedy Space Center, Florida

Bruce Link
Astrion - LASSO II, NASA Kennedy Space Center, Florida

LaShelle Spencer
Noetic Strategies Inc. - LASSO II, Kennedy Space Center, Florida

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Acronyms:

APH	Advanced Plant Habitat
ASC/CSA	Agence Spatiale Canadienne/ Canadian Space Agency
ASI	Agenzia Spaziale Italiana
BPS	Biological and Physical Sciences (NASA)
CCP	Critical Control Point
CFU	Colony Forming Units
CHAPEA	Crew Health and Performance Exploration Analog
CLD	Commercial LEO Destination
DLR	German Aerospace Center
DOD	Department of Defense
DOE	Department of Energy
ECF	Early Career Faculty
ECLSS	Environmental Control and Life Support System
EPA	Environmental Protection Agency
EPSCoR	Established Program to Stimulate Competitive Research
ESA	European Space Agency
ESDMD	Exploration Systems Development Mission Directorate
ESM	Equivalent System Mass
FDA	Food and Drug Agency
GMP	Good Manufacturing Practice
GTD	Ground Test Demonstrator
HACCP	Hazard Analysis and Critical Control Point
HRP	Human Research Program
ISS	International Space Station
JAR	Just About Right
LAM	Lunar Agricultural Module
LEO	Low Earth Orbit
M2M	Moon to Mars
MCO	Mars Campaign Office
MeLISSA	Micro-Ecological Life Support System Alternative
MLE	Mid-deck locker Equivalent (20 X 16 X 11 inches)
MOU	Memorandum of Understanding
NSTGRO	NASA Space Technology Graduate Research Opportunities
OGA	Other Government Agency
SBIR	Small Business Innovative Research
SMD	Science Mission Directorate (NASA)
SOMD	Space Operations Mission Directorate (NASA)
STMD	Space Technology Mission Directorate (NASA)
STRI	Space Technology Research Institutes
STTR	Small Business Technology Transfer
USDA	United States Department of Agriculture

Introduction

Why Plants?

As humanity prepares to extend its presence beyond Earth, an exploration food system that ensures the physical and psychological health and performance of the crews will be required. In 1964, the NASA Associate Administrator of the Office of Advanced Research and Technology, Raymond Bisplinghoff, stated, “We may develop boosters and guidance and control systems and reentry systems of exceptional efficiency, but unless we can at the same time sustain life in space we cannot have a manned space flight program” [1]. This is arguably one of NASA’s first statements that focuses on food systems for astronauts. Experience with the current food system on the International Space Station (ISS) shows that some vitamins degrade and quality declines in the existing prepackaged food over multiple years of storage at 21°C [2] [3]. Additionally, the ISS prepackaged food system contains approximately 46% water. Based on current assumptions, logistics for a Mars mission requires a 5-year or longer shelf life and a significant mass reduction. The Human Research Program (HRP) has been evaluating methods to increase shelf life, which includes a resource impact in the need for cold storage, while the Mars Campaign Office (MCO) is seeking to reduce the water content of prepackaged food to 30%, which may result in a resource savings, but would require evaluation of impacts to variety, choice, and nutritional intake prior to implementation. In light of these issues, HRP and MCO are also investigating supplemental crop systems, which includes evaluation of crop growth within the challenges of spaceflight, resource requirements including mass, volume, power, crew time, cleaning and safety testing, and impacts to other resources, such as water, and how this trades with contributions to human health and performance. In support of these investigations, MCO is investing in the development of a supplemental crop production capability called Ohalo III. On board the ISS, Ohalo III may be used as a testbed for the development of crop growth systems and technologies, as well as implementation of a food safety program for pick-and-eat crops. Ohalo III may also be used to test candidate crops that meet spaceflight resource and safety requirements and provide continuous supplementation of astronaut nutrition, while validating the psychosocial benefits of having plants accompany astronauts on long duration exploration missions.

Alternative Food Systems

Crop production represents an alternative food system component and presents certain challenges that need to be considered. These challenges were delineated by Smith *et al.* [5] [6] and examples are paraphrased or quoted directly below:

Deep Space Exploration Challenges for alternative food systems:

1. **Resource use**: Alternative food systems need to use fewer resources over the life of the mission rather than transporting the necessary foods themselves. This includes storage, power, crew time, spare parts, supplies, ingredients, and anything else required for the food system and food production.

2. **Reliability**: Food systems must be reliable over long periods of time to avoid food scarcity. Space radiation could impact the efficiency of food or nutrient production over the 5 to 7 years that the food system may be needed. This includes time where it is pre-positioned waiting for either crew arrival or for the relevant phase of the mission, e.g., return from Mars.
3. **Acceptability of food, food production, and human factors:** If a system is difficult to use, does not provide familiar or acceptable food, or requires extensive crew time, then it may not be used appropriately, resulting in either inadequate nutritional intake or (with bioregenerative foods) food scarcity. For near-term missions, "food production in space must be something that a person will want to come home and do after a long day of work, an enjoyable activity that efficiently produces a meal."
4. **Food production and preparation equipment:** "Equipment currently available for spaceflight adds only water or heat. New, efficient, and acceptable equipment that produces a variety of nutritious and acceptable food options, while keeping the entire food system within resource requirements, could revolutionize both a Mars exploration food system and food sustainability on Earth. However, additional equipment will factor into resource trades for mass, volume, power, crew time, cleaning and sanitizing, and maintenance resources."
5. **Safety:** "Unlike prepackaged foods where safety is confirmed on Earth, producing food in space will introduce safety challenges. For example, cleaning and sanitizing the equipment could require chemicals that need to be removed from the water system. These chemical sanitizers may also produce volatile compounds that will need to be removed from the air. Furthermore, supplies for microbiological testing will introduce mass and waste, require enrichment steps that are currently not feasible in spaceflight protocols, and mechanical safety, that will have to be addressed, while fitting everything within the resource limitations of the mission."
6. **Cost and schedule feasibility:** Alternative food systems have not progressed to a state where cost and feasibility can be properly evaluated. "Even if a food system is successfully developed with acceptable resource trades, the risks to crew health and performance of any planned food system must be evaluated in realistic mission scenarios—either on Earth or on a Lunar base—before being implemented on a mission to Mars."

Any crop food production system will need to address these challenges. While not currently at a technology readiness level (TRL) to support deep space missions, crop growth systems are attractive because they have potential to:

1. Overcome resource and variety challenges of a prepositioned prepackaged shelf stable food system by producing fresh foods and supplemental nutrition.
2. Address menu fatigue by providing a variety of fresh flavors and nutritious components.
3. Provide countermeasures and psychological benefits for isolation and confinement.
4. Contribute to Environmental Control and Life Support Systems (ECLSS) through air revitalization and water recycling.

To determine crop growth system potential, substantial information and technology gaps need to be filled that address the above challenges. Specific examples include:

1. Determining the full resource trade from growing crops to consumption of crops (crew time, resources, impacts to ECLSS, etc.) to determine at what Mission Concept of Operations they will trade favorably over taking packaging foods. For instance, although a future goal would be to involve crops in air and water revitalization, the resources required to do this such as hardware and spares, mass, volume, crew time, and power have not been fully evaluated in relation to physical and chemical systems. Additionally, to prevent risk to loss of crew, the systems would need to first prove high-fidelity (low risk of crop loss). Even for initial systems that supplement food, air, or water, their impacts to the main chemical and physical system and its resources will be needed by programs to determine the trade against alternatives. Most of the data for these trades do not currently exist, and a full trade has not previously been done, leaving a gap in knowledge as to when, in mission concepts, crop systems may begin to save resources.
2. Developing game changing food safety technologies or methods. On Earth, large amounts of water, harsh cleaning chemicals, and microbiological testing are used to maintain sanitary conditions, and current data do not suggest another technology could replace water and chemical cleaning in these growth environments. The chemicals used in the food and CEA industry are not compatible with current space vehicle water recycling, and approval and up-mass for chemicals is very limited. Water is limited, even when recycled, due to resources used during the recycling process. This is currently a gap that will prevent integration of crops into spaceflight systems if it is not solved.

Moon To Mars (M2M) Overview

Understanding how to produce crops on new worlds is so essential that seven of sixty-three (11%) of NASA's Moon to Mars (M2M) objectives [7] either directly call out the need for plants or are at least partially dependent on the success of crop production. The seven objectives are listed below in the M2M Overview after Figure 1.

The "Moon to Mars" objectives were published by NASA in 2022 [7] to provide vision, constancy, and unity of purpose. This document, along with the M2M Strategy released in 2023 [8], addresses the importance of knowing the goal upfront, and creating an integrated plan to achieve that goal. The M2M documents establish the objective as "creating an objectives-based blueprint for the sustained human exploration of deep space." Long-term plans for sustained human exploration would benefit from explorers, producing their own food and restoring the air they breathe and the water they drink. It is also important to note that plants are emphasized in objective 7 of the Artemis III Science Definition Report for, "…sustaining plant-based products for food and nutrition, as well as plant-based resources for life support systems and materials" [9].

Scientists and theorists have been developing concepts for sustaining crews on long duration missions since before the space age began. The use of biological approaches, or bioregenerative life support, focuses on harnessing photosynthesis to remove carbon dioxide from the air and generate oxygen, while also producing food. This concept was written about in novels and scientific writings in the late 19th and early 20th centuries [10], and expanded rapidly in the 1950s and 1960s [11] [12] [13] [14] [15]. A variety of algae, cyanobacteria, and higher plants (crops) are mentioned repeatedly in early literature [16] [17] [18]. Major challenges remain for algae systems as part of the food system [19] [20]. The concept for growing supplemental, fresh food crops in space has been discussed for over 30 years and was referred to as a ”salad machine” [21] [22] [23]. The feasibility of growing plants in space for crew consumption has been demonstrated over the past decade with the success of NASA’s Veggie and Advanced Plant Habitat (APH) facilities on the ISS. It is important to note that these existing systems were designed for plant science, research, and technology validation, not as crop production systems, so work remains to be done to develop more efficient and reliable crop systems. Over the years, a number of roadmaps and plans have been developed for fresh food production and general life support for space exploration [18] [24] [25] [26], with the most recent development by Douglas *et al.* [19] highlighting food and nutrition from more current spaceflight advances (Figure 1).

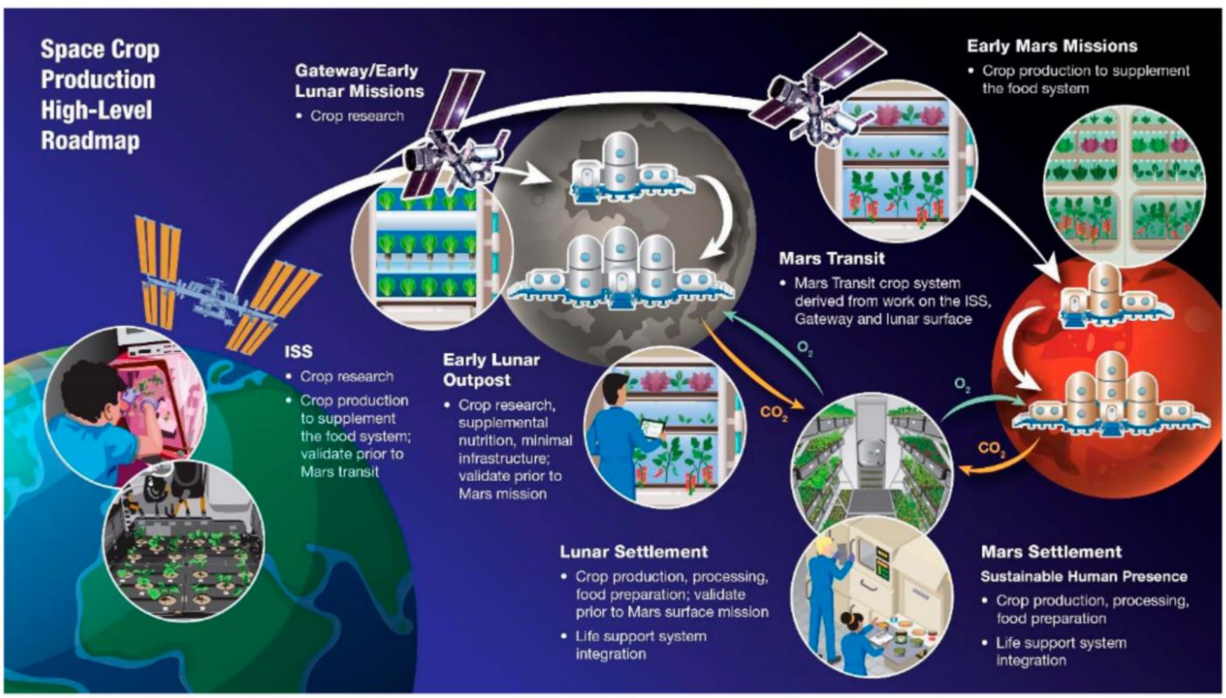

Figure 1 Roadmap for crop research, infrastructure development, and cumulative system integration and validation from ISS to Mars from Sustaining Astronauts: Resource Limitations, Technology Needs, and Parallels between Spaceflight Food Systems and those on Earth [19].

A similar roadmap structure could be applied to any alternative food system, bioregenerative systems, or integration of multiple systems though feasibility may vary, and the timelines could be longer depending on technology readiness level, safety testing, and feasibility studies to provide data sets for mission decision points. The roadmap for space crops shown in Figure 1 aligns well with NASA’s M2M objectives listed below.

NASA's M2M Objectives relating directly to plants and bioregenerative systems are[1]:

- HBS-1LM: Understand the effects of short- and long-term exposures to the Lunar, Martian, and deep space environments on humans, model organisms, systems of human physiology, and plants.
- AS-5LM: Define crop plant species, including methods for their productive growth, and capability to provide sustainable and nutritious food sources for Lunar, Deep Space transit, and Mars habitation.
- AS-4LM: Conduct applied scientific investigations essential for the development of bioregenerative-based ecological life support systems.
- AS-3LM: Characterize accessible Lunar and Martian resources, collect scientific research data, and analyze potential reserves to satisfy science and technology objectives and enable *In-Situ* Resource Utilization (ISRU) on successive missions.
- TH-3L: Develop system(s) to allow crews to explore, operate, and live on the Lunar - surface and in Lunar orbit with scalability up to a continuous presence; conducting scientific and industrial utilization as well as Mars analog activities.
- TH-4LM: Develop in-space and surface habitation system(s) for crew to live in deep space for extended durations, facilitating future missions to Mars.
- SE-6LM: Enable long-term, planet-wide research by delivering science instruments to multiple science-relevant orbits and surface locations at the Moon and Mars.

Plants fulfill key roles in human exploration of deep space (e.g., they can provide whole-food nutrition, menu variety, oxygen, water, and behavioral health benefits). Crop selection should be done to meet the needs of the missions, with the ultimate goal of enabling a sustainable human presence in deep space.

The purposes of this white paper are to: 1) discuss how space crops benefit deep space human exploration, 2) identify the types and numbers of crops required for early Mars exploration missions, 3) establish the processes needed to validate a library of crops for supporting crew health, and 4) review performance and some of the system requirements needed to ensure successful crop production.

Crop Considerations

Resiliency and Robustness

Harry Jones [27] provides useful definitions of robustness and resilience:

> ***Robustness** is the capability of performing without failure under a wide range of possible conditions. Robustness implies strength and toughness under potential off-nominal conditions.*

[1] **Prefix Legend:** HBS = Human and Biological Sciences Goal; AS = Applied Science; TH = Transportation and Habitation; SE = Science-Enabling
Postfix Legend: L = Lunar; M = Mars

Resilience *is the ability to recover from or adjust easily to an unanticipated accident or change.*

Another simple way to think about the difference between the two is that robustness it how hard, or how far off nominal, do conditions need to be to cause a substantial disruption, while resilience is the ability to quickly recover from the off-nominal event.

All space crops are screened for robustness in the sense that they must be able to grow in an ISS atmosphere that is high in CO_2 (roughly 7.5 X Earth normal) with relatively low humidity. Ideally crops should also tolerate excess and insufficient water that can occur in space plant growth systems. Robustness can mean that the crops stop growing under these conditions, then start growing again when over/under water conditions are remedied with little overall impact or damage to the plants. Resilience is about how the crops recover after a damaging event. For example, if the crops wilt from underwatering, do they recover when watered and continue growing or do they drop their leaves (a common drought response)? Do the plants quickly put out new growth when conditions are restored, or do they languish? If a plant pathogen (e.g., fungus) destroys a portion of the crops, are the remaining crops able to quickly take over the space and make up the difference?

Crops for Deep Space Human Exploration

Space crops have the potential to address several human space exploration needs, such as nutrition, menu fatigue, behavioral health, and air/water revitalization.

Plants are a source of many compounds essential to human health, including amino acids, oils, and vitamins. The structures of three important vitamins are shown in Figure 2 to give an idea of vitamin molecular complexity and the difficulty in synthesizing them *de novo* using organic chemistry. Key vitamins, such as vitamin C and B1 may degrade in some foods in the packaged diet under nominal room temperature storage (21°C), and crops offer one method to potentially provide some of these complex nutrients. Plants can use carbon and oxygen from carbon dioxide (CO_2) in the atmosphere along with oxygen and hydrogen from water to produce fresh vitamins. Other elements that make up vitamins are obtained from the atmosphere, fertilizer, or seed. Obtaining vitamins by consuming plants is reported to be more beneficial than taking vitamins in supplement forms [28].

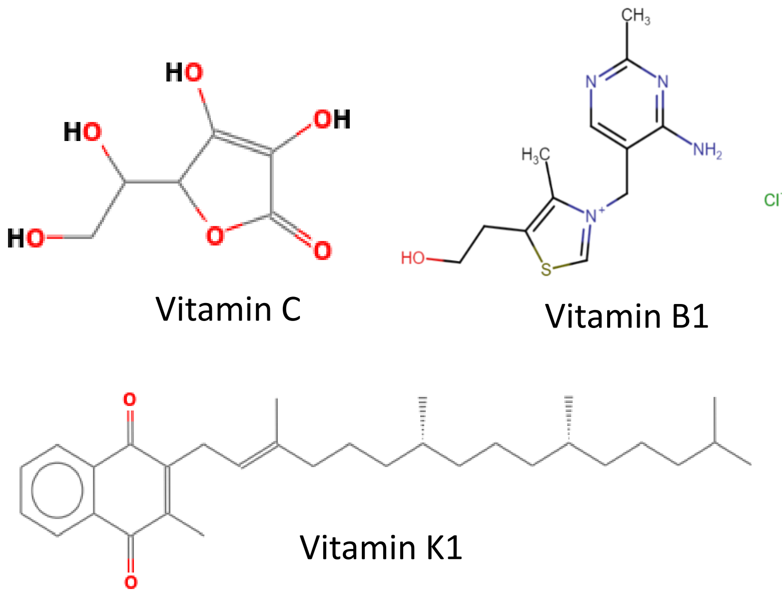

Figure 2 Chemical structures of Vitamin C (L-Ascorbic Acid), Vitamin B1 (thiamine), and Vitamin K1 (phylloquinone).

Crops such as kale and mustard greens can be good sources of freshly made Vitamin C and Vitamin K, while crops, such as peas, beans, buckwheat, and even radish can provide Vitamin B1. Plant production of Vitamin B1 may be best accomplished via microgreen growing techniques. Appendix A describes possible ways to provide vitamins C, K, and B1 using plants as part of the astronaut diet. Appendix A also discusses the numbers of plants, schedules, and consumption amounts necessary to accomplish targeted nutritional outcomes.

The number of plants needed for nutrition, for dietary diversity, and to benefit behavioral health needs to be considered for food security and astronaut health. A diverse selection of crops can improve resiliency to the fresh food system, reduce menu fatigue, and improve aspects of behavioral health. Types of crops considered include leafy greens, fruiting crops, root crops, legumes, herbs, and microgreens. Key nutrients of interest previously mentioned include Vitamins C and B1. Other nutrients of interest include Vitamin K, potassium (K), magnesium (Mg), beneficial phytonutrients and bioactive compounds (e.g., Beta-carotene, Lutein, Zeaxanthin, Lycopene), and essential fatty acids (e.g., Linoleic acid and Alpha-3 linolenic acid), as well as other antioxidants, flavanols, and phenolics [30] [29] [31] [32]. It is key to consider what nutrients the prepackaged system is providing when crops are supplemental, as many nutrients are stable and plentiful in that system. This is also a key consideration for genetic modification, as provision of target amounts of nutrients is the goal but excessive amounts of some, depending on the form, can be toxic.

Due to volume, mass, and power constraints, only small quantities of crops have been produced in space to date. Historically, food crops have added dietary variety, provided vitamins, antioxidants, and other micronutrients and have been considered front-runners in early crop testing. Pick-and-eat crops are easier to implement in missions since they do not require post-harvest processing [23]. These supplemental food crops typically focused on leafy vegetables and small fruits, but research has expanded to evaluate herbs, microgreens, root zone crops, and legumes. Examples of leafy greens include lettuce and kale, while examples of small fruits include peppers, tomatoes, and strawberries, and could also include cucumbers and melons, which are vine crops. Herbs can be added to salads or packaged meals, or used to make tea or tisane, and include crops like basil, mint, cilantro, and chamomile. Microgreens are small, nutrition- and flavor-dense seedlings from a variety of crop species that can be grown in periods of 7-18 days depending on the cultivar. Growing microgreens typically requires many seeds and produces very dense closed canopies when the microgreens are only a few centimeters tall. Root zone crops include radish and carrot. Legumes, such as lentils, peas, and beans, belong to the *Fabaceae* family, are rich in Vitamin B1, and can be consumed as microgreens, mature plant leaves, fruit, or seeds. Substantial work is still needed to collect microbiological safety data and develop protocols and requirements which may dictate the type of crops grown on a space mission.

Follow-ons to nutritional focused pick-and-eat crops are more traditional agronomic crops that provide macronutrients (protein, fat, carbohydrate, dietary fiber), as mission infrastructure and space allow. This would likely begin with crops, such as potato and sweet potato, which are minimally processed, requiring only cooking. These crops could be applicable for early surface missions with long duration (>6 months) stays, after a habitat is in place. It is unlikely that infrastructure will be available for these larger crops including staple crops like wheat, rice, and soybean, until the settlement phase. Staple crops require considerably more processing equipment (e.g., threshing, milling, extruding, etc.) and other resources to make finished food items. While challenging, the need for food processing presents an opportunity to develop robotic and automation systems to meet space exploration goals and help advance the terrestrial agricultural industry. As crop growth expands, plants will have a greater impact on the space habitat environment, helping to reduce the need for air revitalization, for example. Although plants have the potential to contribute significantly to human life support, it will be critical to coordinate with engineering teams to effectively integrate crop production systems in future ECLSS.

Crop Readiness Levels (CRL)

Space crops from seeds and substrates stored at 21°C should support adequate nutrition, especially key vitamins and nutrients that degrade over time in the prepackaged food when stored at 21°C. Crops should expand the variety of the crew diet, have good seed germination and vigor, grow reliably and uniformly, be compact, be tolerant of environmental variances, be able to grow in microgravity, partial gravity, and space radiation, be safe to consume, and take into consideration human factors such as taste, texture, aroma, palatability, desirability, nostalgia and beauty. Appendix B lists examples of selection factors for space crop candidate plants.

NASA has considered measures to select and test for plants and introduced the concept of the Crop Readiness Level (CRL), which is modelled after NASA's Technology Readiness Level (TRL) approach for developing and advancing new technologies for space. This assessment methodology for crops was first suggested by Barry Finger and published by Wheeler and Strayer in 1997 [33]. The concept has been refined over the years and continues to be a living schematic, which can be adapted to different mission architectures and crop types. A similar approach could be developed for other aspects of the exploration food system. Figure 3 and Table A-1 show the current iteration of the crop readiness level approach.

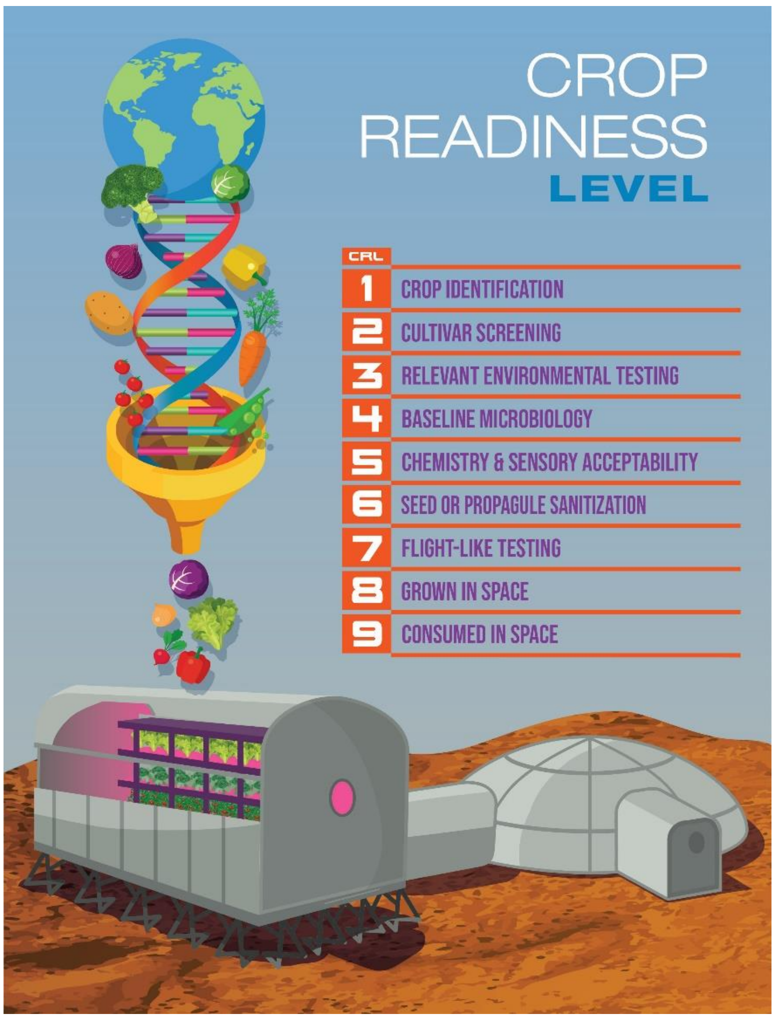

Figure 3 Testing needed to determine crop suitability for space applications.

Table A-1 CRL Version 2.0, modified from Crop Readiness Level (CRL): A Scale to Track Progression of Crop Testing for Space 2019 [34].

CRL Level	Title	Description
1	Crop Identification	Identification of candidate crop at cultivar level. Preliminary assessment of morphology, consumable yield, germination, and mission application. Referrals, database searches, supplier searches, preliminary testing.
2	Cultivar Screening	Detailed assessment of plant dimensions at maximal growth, identification of pollination and germination requirements, quantification of harvest index. (Includes Growing Beyond Earth down-selection).
3	Relevant Environmental Testing	Testing at spaceflight simulated environmental conditions. Currently this is ISS-relevant: ~3000 ppm CO_2, 21-24 °C, 38-44% RH, and LED lighting with no UV. Candidates are screened for robust performance or adverse physiological responses. (flight analog hardware not used)
4	Baseline Microbiology	Baseline microbiological and food safety characterization conducted under flight-like conditions.
5	Chemistry & Sensory Acceptability	Elemental and mission-specific nutritional testing conducted at flight-like conditions. Sensory analysis (taste-testing).
6	Seed or Propagule Sanitization	Identification of acceptable seed surface sterilization or plant propagule sanitization protocols.
7	Flight-like Testing	Testing in flight or flight-analog hardware at flight environmental setpoints.
8	Grown in Space	Crop successfully grown to designated end point in space.
9	Consumed in Space	Good growth in space and consumption by crew with acceptability.

NASA's CRLs are shown as sequential, but they can be run in parallel or out of order when appropriate. For instance, the chemistry, sensory acceptability, and microbial assessments will often be run while crops are being assessed under spaceflight-relevant conditions. As an example of how criteria integrate or change throughout testing, consider if plants grew well in flight (without anomalies), but the crew found the acceptability low. This finding would likely remove that crop from further consideration, and tissue analysis may be conducted to determine reasons for acceptability decline. Currently, crops are evaluated for acceptability attributes both prior to and in-flight. The evaluation uses Just about Right (JAR) metrics, and includes testing of characteristics such as crunchiness, juiciness, freshness, sweetness, spiciness, nuttiness, and bitterness. Other criteria assessed on a 9-point hedonic scale are overall acceptability, appearance, color intensity, aroma, flavor, and texture.

Sensory acceptability is highly important, and lessons from the past should not be re-learned. At the Conference on Nutrition in Space and Related Waste Problems in 1964, Samuel Lepkovsky stated "*In World War II, hashes were common in combat rations because they fitted the filling machines, but the men wanted something they could chew, something into which they could 'sink their teeth.' The rations lacked desirable sensory stimuli and lacked 'belly-filling' properties. The soldiers' evaluation of these rations was, 'We could undoubtedly survive on these rations a lot longer than we'd care to live'*" [35]. While food systems on the ISS are considerably better, menu fatigue and weight loss remain a challenge [6] [19] [36]. For future missions, it is desirable to assess sensory acceptability of crops from crews in flight to confirm acceptability in the relevant microgravity or planetary environment.

Beyond Earth's protective magnetic field, more testing will be needed to assess seed and plant interactions and impacts of the deep space and different vehicle/platform environments. Possible testing to be included as part of augmented deep space CRLs are shown in Table A-2.

Table A-2 Crop readiness testing and considerations for future mission CRLs beyond LEO.

CRL Level	Title	Description
3a	Space Radiation	Viability, genetic stability, and final nutrition and acceptability under space-relevant radiation.
3b	Candidate Nutrient Delivery Systems	Validation of the ability to grow in candidate nutrient delivery systems including selected hydroponic and reusable-substrate approaches.
3c	Atmosphere/ Pressure	Viability of the crop system under exploration atmospheres and pressures
9a	Mars Transit	Microgravity and deep space radiation
9b	Lunar Surface	1/6 gravity and lunar surface radiation
9c	Mars Surface	Enhanced radiation for seeds and propagules during transit and storage on the surface (survivability) at 3/8 gravity

In addition to the items listed in Table A-2, processing considerations, such as ease of harvesting, post-harvest preparation (e.g., shelling or threshing), debris removal, and product preparation are important factors for agronomic crops. Additional factors for space crop selection include the potential uses of inedible biomass, storage/shelf life of seeds, propagules, or crop products, resource and maintenance demands, crop scheduling, and allelopathic (biochemical incompatibility) aspects between plants, as these factors become increasingly important on longer missions.

Driving Factors: How Many Crops Do We Need?

There are four main factors driving the numbers of crops needed: nutrition, menu fatigue, behavioral health, and multiple crops for system resiliency. In addition, there are three important considerations or secondary factors: ECLSS benefits, multiple cultivars for fresh food system resilience, and limitations in crop or hardware compatibility. The primary factors impact the numbers of crops needed, while the secondary considerations impact the specifics of the crops that are ultimately selected.

Primary Factors

Nutrition

To reliably provide bio-available nutrients and improve fresh-food security, we recommend a minimum of 15 crop species/varieties as a starting point. Fifteen crop species would provide at least 3 crops for up to five target nutrients and would ensure the availability of nutrient dense crops. The five targets are determined by the mission food system, however, example vitamin categories are Vitamins B1, C, and B9 and example elements are potassium and magnesium. These crops should be from different plant families when possible, to ensure food system resiliency and reduce risk. Crops can also provide phytonutrients as mentioned in the previous section. Crops may be from the following categories: Microgreens, Leafy Greens, Small Fruits, Legumes, or Root Zone Crops. It is desirable for crops to have overlapping nutritional benefits whenever possible.

Menu Fatigue

Many astronauts lose weight on ISS expeditions, and menu fatigue is a likely contributing factor, with preliminary comments citing breakfast foods and vegetables as the most inadequate in variety and quantity [37]. NASA has increased the variety and quantity since this study, but it is possible that these comments are still valid. Discussions with scientists from EDEN ISS and Amundsen-Scott South Pole Station indicated that menu fatigue is a real concern in constrained diets. Packaged diets will not provide the crunch, juiciness, or aromas that are associated with fresh produce. To counteract menu fatigue, a diversity of crops with different color, texture, flavor, and aroma profiles may be important to maintain body mass, health, and performance. Plant colors can include different leaf shades of green, red, and purple, as well as yellow, orange, and red for fruit, and are contributed by a variety of nutrients [38]. Fresh produce textures might vary from tender to tough, crispy or crunchy, chewy or succulent, juicy, hirsute (fuzzy or hairy), fibrous, and more. Texture may also be modified with preparation (e.g., wilting of leafy crops in a food warmer). Flavors vary along a large spectrum, and crops such as herbs can be added to packaged food to enhance or modify flavor. Appealing aromas can also help stimulate appetite. NASA's Crew Health and Performance Exploration Analog (CHAPEA) study is evaluating the impact of the addition of fresh produce to crew health and performance and will help to inform recommendations for the numbers of crops needed. There is limited data in the scientific literature related to colors, textures, and flavors to mitigate menu fatigue. After internal discussions, the Space Crop Production team at KSC recommends a minimum of 3 colors, 3 textures, and 4 flavors of different types to counteract menu fatigue as a starting point. Aroma is not a driving factor, but it can be a deciding factor in selection. Having different types of crops that can be mixed together are expected to increase both variety and appeal.

The varieties, flavors, and textures provided by pick-and-eat crops are expected to be important factors to prospective crews if they are allowed to select crops for missions. Crew preference crops would be expected to improve consumption as well as drive variety. Crew preference and consumptions habits should be revisited in the future as missions change and in the near-term as tests like CHAPEA show realistic use cases.

Three possible use cases or categories have been initially identified (Figure 4).

1. Supplement or Creative Augmentation to integrate fresh food with the packaged diet, such as adding herbs to packaged meal items to enhance flavor (e.g., fresh basil to pasta dishes), using leafy greens like lettuce, cabbage, or mustard greens to create wraps with packaged meat and other items such as hummus, using microgreens as flavorful toppings for sandwiches, adding space-grown peppers to tacos, or adding leafy crops to packaged bean salads.
2. Crews could create side dishes or healthy snacks, such as wilting pak choi with garlic and soy sauce, or snacking on peppers and/or tomatoes.
3. Salads can be created with a number of fresh grown crop types (with minimum 3-4 categories of crops, e.g., ≥1 leafy green, ≥1 fruit, ≥1 herb, ≥1 root crop).

Use cases can serve as a multiplier to the final number of crops identified to generate hundreds of new menu items – a variety amplifier.

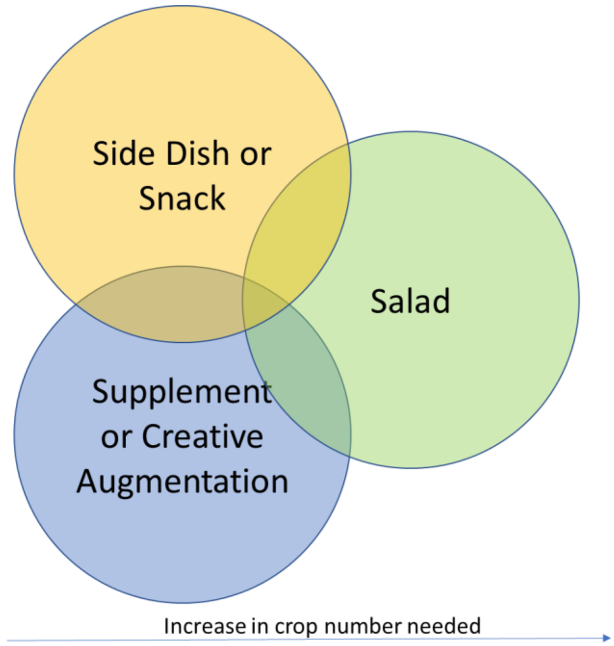

Figure 4 Meal supplement use cases or categories that may reduce dietary fatigue.

Behavioral Health

Behavioral health benefits will focus on non-food related aspects of growing plants and human well-being. Appearance, aroma, and sensory stimulation, as well as activities to care for plants, may enhance crew connection to Earth and provide countermeasures to long duration isolation [39]. Biophilia is the concept that humans have an intrinsic link to other living things [40], and space-grown plants can provide this connection as humans move farther from the Earth's biosphere. Crops that impact behavioral health may be either food or ornamental crops, but food crops can improve behavioral health as a byproduct of their production for food, and so are a focus over ornamentals in the resource limitations of spaceflight. Data are currently being collected, both from ISS astronauts and CHAPEA crew members, to assess the behavioral health benefits of growing and caring for crops. Preliminary ISS data [41] indicate that the amount of interaction and responses to growing crops in Veggie varied widely by individual, with enjoyable tasks like harvesting having higher positive impact than non-enjoyable tasks like cleaning the hardware. Overall, the experience was generally positive. Interacting with Veggie was viewed as engaging and meaningful work, with positive impacts on mood, well-being, and relationships with crew mates, and enhanced connection to Earth. Working with Veggie was a positive source of sensory stimulation. The KSC Crop Production Team recommends crops of <u>at least 3 different growth habits (e.g., leafy, flowering/small fruit, vining, root, upright, small canopy)</u> to provide sensory stimulation, different experiences, and other behavioral health benefits. Crops with undesirable aromas should not be considered.

Multiple Crops for System Resiliency

Resiliency requires multiple crop families to support coverage in case of an entire crop failure. If one crop fails due to poor germination, damage from radiation, or pathogen infection, crews must have other crops that can compensate. Pathogen resistance may evolve and change over the course of a mission. Nonetheless, different crop families (e.g., nightshades like tomatoes, potatoes, and peppers versus cruciferous vegetables such as kale, broccoli, and collards) will generally be unaffected by each other's plant pathogens, providing a degree of resilience, i.e., the impact on a crop family can be overcome by the growth of the other families. Within a crop family, having cultivars with different tolerance bands for environmental factors like temperature, water, light, nutrients, etc., with partial overlap and some outliers will reduce system risk and improve system robustness and resiliency. Having broad resistance to biotic and abiotic stresses, and/or different resistance genes (broad genetic diversity) within a crop type improves both robustness and system resilience. Genetic diversity is a good metric to broadly predict crop resiliency. We recommend at least 3 crop plant families to reduce system risk and increase resiliency.

Secondary Factors

Potential ECLSS Benefits

Plants provide atmospheric revitalization (removing CO_2 and generating O_2) through photosynthesis as a byproduct of their growth. Water from plant transpiration may be captured and recycled within plant growth hardware reducing impacts on vehicle and habitat ECLSS. These benefits may become important for future long-duration surface missions where significant (>10 m^2) growth area is utilized. For reference, 20 m^2 of growing crops under moderate to high light (> ¼ sunlight) can provide all of the oxygen required for an average crew member [14] [42] [43]. ECLSS benefits and challenges are not currently being addressed due to the small volumes currently available or planned on early missions, but these impacts and benefits should be planned for and integrated with other subsystems in advanced mission architectures/designs to allow for seamless integration. ECLSS impacts of crop growth will inform mission design because even small plant systems can impact the larger ECLSS plans. No additional driving recommendations for crop selection are required for this category.

Crops for Robustness

Robustness is defined as the ability to withstand a disturbance and perform without failure, while resiliency is the ability to recover from damage. For example, indifference of individual crops to environmental excursions; insensitivity to water stress and other abiotic stresses, pressure, temperature, and root zone challenges; ability to fend off microbial attacks (pathogen resistance); and insensitivity to chemistry of recycled nutrients are all "robust" characteristics. Germination is a selection factor early on. Seed storage and viability will be critical and must be robust. Seed packaging or encapsulation technologies may be beneficial for helping to maintain long-term viability and robustness. Crops tested on the ISS in the VEG-03I mission showed variability in germination by plant family over 2.5

years of storage, with 3 varieties of crucifers from the Brassica family ('Red Russian' kale, 'Extra Dwarf' Pak choi, and 'Wasabi' mustard) having excellent germination and growth, while two types of lettuce in the daisy family ('Outredgeous' and 'Dragoon') showed slow or no germination under the same storage conditions. Longer term seed viability studies can provide a good reference for assessment, and factors like the oil or protein content of seeds are relevant [44]. Abiotic stress resistance may be selected based on core requirements above. Having broad resistance to abiotic and biotic stresses using multiple or different resistance genes (broad genetic diversity) within a crop type can improve both robustness (crop doesn't fail) and system resilience (only part of the crop fails, or it recovers quickly). Selecting crops for robustness and having at least 3 crop families for system resiliency together improve fresh food security. Robustness does not drive additional crop selection numbers, but can drive the number of crops that need to be evaluated due to crop sensitivities and CRL failures.

Hardware Limitations and Compatibility

Hardware size and configuration will drive the numbers and types of crops that can be grown. We are currently limited by hardware in our ability to advance crop knowledge and validate candidate crops for spaceflight. We also anticipate hardware and volume limitations continuing in future which will impact crop production and the speed at which NASA will gain operational knowledge. Operational knowledge refers to how to grow select crops together, a crop schedule to have crops available to integrate most effectively into meals that crews can create, hardware performance over time, and hardware maintenance as a few examples. A natural question is how many plants are needed to supplement nutrient needs and how much hardware does this require? A 15 g leafy crop salad every day can provide 8% of the necessary Vitamin C and 30% of the Vitamin K but requires 18 plants per astronaut for a continuous production scenario with no storage, as shown in Appendix A. Systems analysis and crop schedule planning will be necessary. Requirements may drive demand for higher nutrient content crops as well as additional hardware. Requirements for crop growth may increase over time, with deployable systems possibly being accessed later in a surface mission or on the return leg of a mission when vehicle volume is available. A combination of unique growing strategies and nutrient-optimized crop production can make a significant contribution to the packaged food. Hardware limitations and compatibility do not drive additional crop selection numbers, but they drive the crops selected.

Estimating the Number of Crops Required

Considering the driving factors detailed above, we recommend a total of more than 30 crops to supplement nutrition, provide dietary variety to reduce menu fatigue, enable crew interactions to positively impact behavioral health, and have different crop types to reduce overall risks. Table A-1 shows the recommended number of plants per factor, and more detail is provided in Appendix C.

Table A-1 Crop numbers and types for early exploration missions.

Driving Factor	Requirement	Minimum Number
Nutrition	3 crop species/varieties for vitamin categories (Vits. B1, C, and B9 as examples) and elements (K and Mg as examples)	15
Menu fatigue	3 colors, 3 textures, and 4 flavors of different types of crops to counteract menu fatigue	10
Behavioral health	At least 3 different growth habits (e.g., leafy, flowering and small fruit, vining, root/stem, small canopy) to provide sensory stimulation and other behavioral health benefits	3
ECLSS	No additional requirements	0
System resiliency	At least 3 crop families per identified nutrient to ensure system resiliency	3
Robustness	Robustness does not drive additional crop selection numbers, but it drives the crops selected	0
Hardware limitations and compatibility	Hardware limitations and compatibility do not drive additional crop selection numbers, but they drive the crops selected	0
	Non-overlapping total	31

The non-overlapping total of 31 crop types given in Table A-1 is the sum of a unique crop for each driving factor, and simply counts the crop families described in System Resiliency as a crop type to add to a number. Crop families can multiply the number of crops significantly, and all categories in driving factors can be a large number when considered in combination. Many crops can fulfill multiple roles, and Appendix C provides possible examples of this situation. The minimum number of crops using existing tested crops which can fulfil multiple driving factor criteria is 22, but in this case ~ 45% of the crops are from a single plant family, the brassicas (Appendix C). Including at least 8 more crops from other non-brassica families is recommended to further reduce risk and bolster crop variety. For crop system resiliency, it is advisable to monitor the overall crop library and to maintain crop family ratios such that one family does not exceed 1/3 of the available crops.

Crop validation on ISS will continue with Ohalo III, but the total number of validated crops, including previously validated crops, may be less than needed by the planned end of ISS (2030), so platforms beyond ISS may be required for validation. Ground testing capabilities may also be limited. The current testing focus is on pick-and-eat crops, but future scenarios will likely require staple crops (e.g., dwarf rice, dwarf wheat), which will expand the list of crops that must be validated in relevant environments. In addition to crop validation, crop optimization should also be performed to obtain reliable outputs with available resources.

There are thousands of crop cultivars and limited resources to test them for spaceflight, so NASA has leveraged middle and high school student citizen scientists across the country through the "Growing Beyond Earth" program [45] to identify hardy varieties for further testing. Additionally, advancements and testing reported in the Controlled Agriculture Environment industry also inform on potential candidate crops.

Overview of Work to Date

Crop Types Currently Validated on Ground and in LEO

Several efforts have been made over the past 30 years to conduct baseline ground-based studies with candidate crops using anticipated spaceflight environment conditions [46]. At that time, flight hardware to further validate these was not available. As NASA has transitioned into the era of ISS utilization, Veggie and Advanced Plant Habitat have allowed a more coordinated progression from ground-based to flight testing. More details on those facilities can be found in Appendix D. This hardware has enabled the growth and consumption of plants in space (CRL 8 & 9). A number of leafy green crops, radishes, and peppers, along with wheat, have been validated on the ISS in NASA's flight hardware. Leafy green crops that have been successfully validated in the Veggie chamber on the ISS include 'Outredgeous' red romaine lettuce, Mizuna mustard, 'Waldmann's Green' leaf lettuce, 'Wasabi' mustard, 'Extra Dwarf' Pak Choi, 'Red Russian' kale, and 'Amara' mustard. 'Tokyo Bekana' Chinese cabbage did not grow well under ISS conditions due to elevated CO_2 [47]. 'Dragoon' lettuce also faced challenges due to watering and seed storage and will need to be retested. 'Red Robin' dwarf tomatoes were recently tested in Veggie, but their growth was unsuccessful due to watering challenges. 'Cherry Belle' radishes, 'Apogee' dwarf wheat, and 'Española Improved' Hatch Chile peppers were successfully grown and tested in the Advanced Plant Habitat, though the wheat was not consumed. Table A-1 shows examples of crops, which have been tested or are undergoing testing, while Table A-2 shows examples of crops which did not pass CRL testing. It is worth mentioning that in 2024 there are no new crops at CRL 7, meaning none are ready for testing on the ISS. 'Red Robin' tomato is the only current CRL 7 crop and it was tested in Veggie on the ISS and warrants re-testing due to the reasons mentioned previously.

Table A-1 Examples of crops that are currently being tested or have recently advanced to CRL 9.

CRL	Crops	Notes
1	'Paris Island' Lettuce	Commercial candidate
2	'Misome' mustard	Growing Beyond Earth candidate
3	'Feisty' Pea	Ready for CRL4 testing
4	'Yellow Snap' pea	Ready for CRL5 testing
5	'Mohamed' Tomato	Ready for CRL 6 testing
6	'Delizz' Strawberry	Variety that grows well from seeds
8	'Red Robin' Tomato	Grown in VEG-05

Table A-2 Examples of crops that did not pass CRL testing.

CRL	Crops	Notes
1	Corn, Sugar cane, Indeterminate tomato	Growth habit not suitable for space
2	NZ Spinach, Greek Oregano, Chinese Sweet Basil	Growing Beyond Earth crops that did not grow well in classrooms
2	'Tyee' and 'Flamingo' spinach	Poor germination and non-uniform growth
3	'Pompeii' Pepper	Severe intumescence
4	Various Microgreen Cultivars	High microbial levels - ongoing development of methods to cultivate cleaner produce in work
5	Radicchio	Poor flavor in informal sensory acceptability assessments
5	Chia and Shiso Microgreens	Failed to pass formal overall sensory acceptability
6	'Bright Lights' Swiss Chard	Sanitization method insufficient and affected germination
7	Shungiku	Experienced severe tip burn attributed to reduced airflow in Veggie analog
7	'Rosette Red' Pepper	Tested in Veggie analog hardware, displayed extreme dwarfing
8	'Tokyo Bekana' Chinese cabbage	Poor growth under elevated CO_2 of ISS

Student citizen scientists in the Growing Beyond Earth program have tested 191 crops, though some crops need to be repeated due to low replication or poor seed quality. KSC, with higher space-fidelity conditions, has tested 37 leafy crops, 10 tomato plant cultivars, 41 pepper plant cultivars, 16 types of herbs, 25 legume cultivars, 67 types of microgreens, 3 strawberry cultivars, 2 cucumber cultivars, and 2 melon cultivars. As of August 2023, NASA has fully validated a total of nine crops through CRL 9 (Table A-3). These include seven leafy greens (two from the Asteraceae family and five Brassicaceae) [48], one radish (Brassicaceae)) [49], and one fruiting pepper crop (Solanaceae). These nine crops have been successfully grown and consumed on the ISS. Crops that were tested but are not fully validated include 'Tokyo Bekana' Chinese Cabbage, which suffered under the elevated CO_2 of the station, 'Dragoon' Lettuce, which was only tested at low sample numbers and struggled due to water stress and seed storage, and 'Red Robin' tomatoes, which performed poorly due to water stress.

Table A-3 Crops which have passed CRL 9.

Type	Crop	Plant Family
Leafy Greens	'Outredgeous' lettuce	Asteraceae
	'Waldmann's Green' lettuce	Asteraceae
	Mizuna mustard	Brassicaceae
	'Wasabi' mustard	Brassicaceae
	'Amara' mustard	Brassicaceae
	'Extra Dwarf' Pak Choi	Brassicaceae
	'Red Russian' kale	Brassicaceae
Small Fruit Crops	Española Improved Pepper	Solanaceae
Root Zone Crops	'Cherry Belle' Radish	Brassicaceae
Herbs	None	
Microgreens	None	
Legumes	None	

Considering that the Growing Beyond Earth program has tested 191 crops and KSC has tested 204 crops listed above and in Appendix E (total 376), but only 9 crops have passed CRL 9, and 10 crops have failed to progress, there remains a non-trivial amount of ground and flight test activities needed to prioritize and progress the remaining crops to provide crews with access to the recommended variety of fresh foods to supplement their diets as shown in Table A-1.

NASA Food Safety Progress for Fresh Produce

NASA was the genesis of the world's modern Hazard Analysis and Critical Control Points (HACCP) food safety system [50] [51], and food safety is still of utmost importance at NASA. Currently, crops have been evaluated individually for consumption in spaceflight and are not validated for nominal use. Current safety methods that have been accepted on a case-by-case basis are described here but are not accepted beyond research and development use. Requirements have not yet been developed due to knowledge gaps for crop safety and hardware cleaning in spaceflight, but requirements are needed before crops can become part of nominal use.

Currently, seed sanitization methods must be successfully demonstrated prior to flight to remove surface microorganisms. However, surface sanitizing of seeds may not be the best option for space crop production, and advancement of knowledge regarding detecting pathogens and biopriming seeds is needed. Sourcing of pathogen-free seeds may also replace the need for sanitizing seeds. At harvest, space-grown leafy green leaves are pressed between food-safe sanitizing wipes in a resealable bag for at least 30 seconds as a precautionary step to reduce potential microbial communities. Peppers and radishes are wiped down thoroughly before consumption. Pressing and wiping produce with food-safe sanitizing wipes is time consuming, requires consumables, is inconsistent in reducing microbes, and may damage the produce, increasing the likelihood of crew non-compliance. Development of easy, rapid, and non-damaging approaches to clean different types of produce could improve food safety and increase the types of crops available for consumption. For example, microgreens have not yet been tested in flight because we don't have working sanitization protocols. However, indoor agriculture currently focuses on cleaning and sanitizing food contact surfaces and hardware, and microbiological testing of crops rather than sanitizing harvested produce. Growing microgreens and other crops for consumption may require developing hardware cleaning and testing comparable to Earth indoor agriculture which includes the challenges of using water to flush systems and need for harsh sanitizers, as well as rapid microbial testing methods with minimal resource requirements. Alternatively, a game changing technology yet to be identified is needed for space produce safety.

HACCP plans are in development for Ohalo III, and critical areas where control is warranted have been identified with initial assessment for mitigation of risks. Table A-1 shows the current Veggie analysis and the key steps that are currently followed to maintain crew safety.

Table A-1 Food Safety Plan for ISS Veggie, and initial step to development of Hazard Analysis and Critical Control Point (HACCP) showing a Critical Control Point (CCP) or Good Agricultural Practice (GAP) or a Good Manufacturing Practice (GMP)

Process Step/ Control Point CCP/GAP/GMP	**Food Safety Hazard**	**Methods to Reduce Hazard**
Ground processing- Plant pillows	Introduction of microbes via handling and materials	Sterilize components, aseptic technique used while assembling
Ground Processing- Seed	Introduction of microbes via handling, indigenous microbes present on seeds	Disinfection. Certification of pathogen free seed. Use of sanitary handling practices
Packing	Introduction of microbes via handling and materials	Sterilize components, aseptic technique used while packing
Transport	Introduction of microbes via handling and materials	Packed materials are heat sealed in polymer bags during packing
Integrate with Veggie Hardware	Introduction of microbes via handling	Use of sanitary handling
Watering	Introduction of microbes via water supply or unsanitary handling	Water is potable quality and treated with biocide
Grow	Potential contamination from air and human presence, increase in indigenous flora due to availability of nutrients	Use of sanitary handling. Minimize handling of plants before harvest
Harvest	Introduction of microbes due to harvest procedures/human handling	Use of sanitized instruments and gloves
Post-harvest	Microbial presence established during plant growth or introduction via handling	Crops cleaned and sanitized with wipes before consumption following procedures. Veggie facility thoroughly cleaned and sanitized with wipes

Implementing timely routines for hardware cleaning and sanitization and hazard mitigation strategies during the crop production process can help ensure food-safe growing environments that could reduce the current burden and inconsistency of sanitizing produce at the end of production [52]. Identifying all food safety hazards and requirements are challenges that NASA is in the process of understanding and resolving. Identifying food grade materials for food contact surfaces that also meet spaceflight requirements is a challenge for materials engineers. Higher microbial loads such as aerobic colony counts that are naturally high on fresh produce, may not necessarily be indicative of food safety concerns, but a more comprehensive understanding of incident human and plant pathogens in the space environment is in progress. Technologies to rapidly and easily identify potentially harmful microbes in food have yet to reach maturity, but chip technologies that can detect hundreds, if not thousands, of potential pathogens without amplification or sequencing are advancing rapidly [53]. There are handheld fluorescence-based imaging technologies available that may have future potential to be used as monitoring and verification tools for cleanliness of food contact surfaces and growth chambers before and after routine disinfection events [54]. There is no *in situ* food safety screening approach that can be implemented within resource restrictions of spaceflight and compare to Controlled Environment Agriculture (CEA) industry approaches. NASA can leverage the food industry's investment in food safety acceptance levels based off sequencing technology, if it advances to a level where food pathogens detected in sequencing compares to other more established methods.

Crop Production Performance and System Requirements Considerations

Plants have fundamental needs to survive and thrive. Plants need an appropriate temperature range, water availability in the rootzone, fertilizer composition/concentration, light spectrum, atmosphere (O_2/CO_2) and gas exchange. Systems designed to grow crops need to provide appropriate volume for the shoots and roots to grow and maintain crop health and food safety. Plant growth systems need to provide an appropriate atmospheric composition and pressure for plants to grow. Gas exchange has been a major issue in microgravity where there is no natural convection. Forced convection may be necessary to maintain adequate gas exchange and prevent pathogen growth. The atmosphere should include CO_2 for photosynthesis and O_2 for root and plant respiration. Exploration vehicle pressures are expected to range between 101 kPa (14.7 psi) and 56.5 kPa (8.2 psi). Most plants prefer humidity to be between 60% to 80% relative humidity (RH), but transpiration increases at lower pressures, and at very low pressures RH and O_2 percentage should be increased to reduce the higher transpiration/evaporation rates and maintain sufficient pO_2 to support plant respiration. [55] [56] [57]

Crop production systems should provide temperature ranges that enable selected crops to grow. If more than one crop growth system is available, thermal variation could enable a cool temperature crop system and a warm temperature crop system. A versatile crop system that can grow both cool and warm temperature crops should be able to maintain temperatures ranging between 16°C and 28°C.

Crops require light to grow. The amount of light, duration, and spectrum of light (quality) are all important for crop production. Crop growth systems should provide at least 300 µmol m^{-1} s^{-1}. NASA's Advanced Plant Habitat can provide up to 1000 µmol m^{-1} s^{-1}. Plants use light both for photosynthesis and as environmental cues. Since different plants prefer different environments and have different evolutionary strategies, they may also have different spectral or "light quality" optimums. Light sources should at a minimum provide tunable red and blue light for basic plant functions. Adding green or broad-spectrum (white) options to the red and blue are recommended for improved crop health and visual assessment of plant health status. Far red and near IR may provide additional growth benefits for some crops. Additions of UV can help with intumescence for certain crops, or trigger vitamin D production in mushrooms. Spectral quality can also alter other aspects of plant growth like the shape and color of leaves [58].

Crop growth systems must provide adequate quantities of water to the plant rootzone to enable germination and growth. Water delivery to the root zone should not flood seedlings and small plants, but it must be able to keep mature plants from wilting and experiencing drought stress. Healthy leafy greens can use more than 100 mL of water per day and larger plants can utilize even more water. A crop growth system should size the water reservoir, pump, and associated systems to account for the crop types and numbers planned. A crop growth system should provide adequate nutrient solution to the rootzone. APH and Veggie have used controlled release fertilizer for research in crop production. Sierra Space tested a system called XRoots which utilized a liquid nutrient delivery system. Controlled release fertilizer has been helpful to NASA to research crop growth and food safety, but it is heavy and a one-time use system. Nutrient solutions are expected to use fewer resources to grow crops. As recycling systems of spaceflight wastes advance it may be possible to recover resources from those systems to replenish nutrient solutions for use in crop growth facilities. Extraction of nutrients from *in situ* resources like regolith may also be possible in future surface systems.

Food safety is a major concern, so crop growth systems should also allow for cleaning and sanitizing/disinfecting growth volumes, rootzone subsystems, and water/nutrient subsystems as well as any other system that can impact food safety at a level at least equivalent to those provided by water and chemical agents used by the food industry. Crop production will require spare parts and consumable items. Appendix F discusses power, mass, volume, and crew time data points that crop systems need to capture to empower mission planners and vehicle designers to account for regenerative food systems for missions and vehicles. This appendix should be updated as new data points/vehicle impacts are identified.

Open Work and Opportunities

Gaps remain with respect to the science of crop production, as well as technology gaps to reliably produce crops in space. Questions remain on which crops grow well with each other, cropping schedules, optimizing food or nutrient production, understanding the impact and benefits of the microbiome for crop health and food safety, optimizing lighting and atmospheric compositions for a broad range of crops, crop modeling for planning and forecasting harvests, and best practices for recovering from hardware anomalies.

Research and testing are needed to add more leafy greens, fruiting crops, herbs, microgreens, legumes, and root crops of existing, commercially available cultivars to reduce menu fatigue, improve behavioral health, and provide whole food nutrition. NASA has a near-term need to identify and test existing cultivars to CRL 9 to have an existing library of space exploration crops.

Advances in microgreen cultivation and technology can provide astronauts with dietary variety, nutritious fresh food, and good production quantities in a compact volume. Microgreens have not yet been grown in microgravity, and food safety aspects require further investigation.

Methods for harvesting and handling have been tested in parabolic flight [59] but need to be further refined, while relevant growth techniques remain to be developed.

Plant scientists and horticulturalists can improve crops for space by optimizing fertilizer composition and timing as well as different light recipes to improve crop yield, impact color, change flavor, and alter nutrient content. Manipulation of light quality can enhance vitamin production. Crop breeders can develop or identify new cultivars that may be better suited for space production. Some of these varieties, or custom breeds, have been tested after breeders contacted the NASA Space Crop Production team with potential candidates for assessment (e.g., University of Minnesota dwarf tomatoes, Pureline seeds). There are direct overlaps in NASA's needs for Space Crops and the Vertical Farming and Controlled Environmental Agriculture (CEA) industries that are already working on optimizing crop production by manipulating light, fertilizer, temperature, pCO_2, humidity, and stress. These industries are also working on producing more and better crops with fewer inputs and improving food safety. For example, crops have been bred for higher productivity under lower light conditions to save energy. In cases where desired crop requirements cannot be met through traditional breeding, crop engineering may be useful to achieve these goals.

Genetic engineering of crops specifically for space environments faces regulatory and public perception challenges but offers key advantages. One example is the USDA engineered dwarf plum tree, which has no dormancy requirement and can progress from seed to fruit formation in 12-18 months. The agricultural industry is continuously developing new crops with valuable traits, such as fruiting without pollination (parthenocarpy) [60] or tomatoes rich in lycopene and other antioxidants for use on Earth that may be relevant to space [31].

In addition to food, crops may have medicinal or therapeutic uses. Plants naturally produce many medicines, including caffeine, salicylic acid, morphine, quinine, digoxin, vincristine, and paclitaxel. Plants can also be engineered to produce specific medicines. For example, the NASA-funded Center for the Utilization of Bioengineering for Space (CUBES) has developed lettuce that has a parathyroid protein that can act as a countermeasure for bone loss [61]. The newly funded Australian Centre for Excellence in Plants for Space (P4S) is planning to develop several plants and plant-based products specifically for the space environment and pursue regulatory approvals for their use in controlled environment agriculture (CEA) on Earth as well. NASA recognizes the challenges of including genetically engineered crops in the food system, as well as the power of the tool set to do science and improve the food system. Regulations exist regarding food safety and consumption of genetically engineered crops as outlined by the United States Government, with the Environmental Protection Agency (EPA), United States Department of Agriculture (USDA), and Food and Drug Administration (FDA) all being responsible for various regulatory aspects. Since space crops are only intended to be farmed "off Earth" and not in farmer's fields, FDA approval is most relevant and is an important consideration for engineered crops. A number of selection factors for space plants relevant to both traditionally bred and genetically engineered crops have been developed by our team and are shared in Appendix B. Given the challenges that genetic engineering can introduce (e.g., flavor or safety), for the best efficiency, genetic engineering should only be used for specific spaceflight crops when a true gap in available commercial options is identified. NASA is working with the U.S. Food and Drug Administration (FDA), U.S. Environmental Protection Agency (EPA), and U.S. Department of Agriculture (USDA) to understand genetically engineered crop risks and required testing for crew consumption of engineered crops. Engineered crops should have no reasonable commercial option available and align with the food system needs (e.g., no risk of nutrient toxicity).

Seed sourcing is an important consideration for space crop selection, and research remains to be done on seed sourcing, processing, testing, and storage. For instance, a small seed company might have a desirable space crop that tests well and completes CRL 9, but the company may then go out of business, or a large seed company might remove a good candidate seed line due to market demands. There are commercial seed processes and materials used for germination, production, and plant health that NASA needs to understand and consider for space crop production, but there is limited capacity to do this. Currently, seeds that have been used are commercially available varieties selected for dwarf growth and other relevant characteristics. Seed quality for many of these can be variable, as they are marketed to home gardeners. While preliminary testing has helped to identify the types of plants that are desired, moving forward, working with seed sourcing companies that specifically develop seeds for agricultural production has numerous advantages. Working with these seed producers and seed associations (e.g., American Seed Trade Association) to develop/identify high quality, pathogen-free seeds that have increased reliability makes sense for future space crop growth. Creating these collaborations is also beneficial if these groups are willing to maintain desired cultivars in perpetuity; we have seen desired cultivars disappear from commercial seed catalogs and thereafter lose their availability. Near-term follow-on activities will include exploring these potential collaborations with seed vendors through implementation of a formal Approved Suppliers Program (ASP), which is currently underway at NASA. An ASP mitigates risk to seed quality and availability through routine interviews with suppliers (no less than annually) to obtain certificate of analyses (COAs) representative of purchased seed lots. Moreover, ASP interviews review changes to supplier site storage and handling practices, and inquire into product stock and potential discontinuance during the year, enabling opportunity to promptly switch to alternate suppliers when necessary. A maintained list of approved vendors ensures seeds are always sourced from reputable suppliers. Typically, vendors who demonstrate adherence to standards (e.g., ISO certification) are more likely to have better systems of control. The ASP is just one component of a systems-based approach that involves ‘stacking’ multiple interventions to improve food safety and reduce security risk to acceptable thresholds [52], while subsequent hazard mitigations such as seed pathogen testing would follow.

The crop microbiome should be investigated to better understand beneficial plant-microbe interactions, as well as ways to mitigate negative impacts on crops and growth hardware. A better understanding of space crop microbiomes and the growth system microbiome should enable strategies to maintain crop health and improve food safety while improving the serviceability, and longevity of the growth systems. Advances in scientific knowledge of interactions, transport mechanisms, and community evolution will be important, as well as technologies to quickly and accurately measure and identify microbial populations. .

Organizational Challenges for Space Crops

Space crop production at NASA currently has a complex funding arrangement, and we expect this to continue. NASA's Division of Biological and Physical Sciences (BPS) in the Science Mission Directorate (SMD) has interests in "Thriving in Deep Space," and focuses on fundamental biological and physical research, but the recently released Decadal survey [62] drives more focus on crop science and applications. Examples of areas of BPS research might include plant-human-microbiome studies using crops, genetic investigations of engineering new crops for spaceflight, and advanced plant health and food safety technology research. BPS funds research primarily through a competitive, peer-review process, with a small amount of directed collaborative work (e.g., with USDA). SMD has also recently funded the Lunar Effects on Agricultural Flora (LEAF) payload as one of the Artemis III deployed instruments. LEAF will test plant and crop growth on the lunar surface with species *Arabidopsis thaliana*, *Brassica rapa*, and *Wolfia* sp., an aquatic crop plant and is expected to begin to address science questions and objectives listed in the Artemis report [9].

The Space Technology Mission Directorate (STMD) currently funds specific topics, such as food production technology concepts via the Deep Space Food Challenge (a NASA Centennial Challenge), and programs like CUBES, which completes both food and medicinal investigations, through the Space Technology Research Institutes (STRI). STMD also funds graduate technology research fellows through the NASA Space Technology Graduate Research Opportunities (NSTGRO) fellowship program, as well as early career faculty. The Small Business Innovative Research (SBIR)/Small Business Technology Transfer Research (STTR) program is also a source for the development of innovative topics or technologies. Recent SBIR/STTR awards in the area of space crop production include the development of growth systems (Microgravity Lilypond, Mars Oasis) and needed technologies (imaging systems, ethylene sensors, produce sanitizing approaches). STMD approaches are generally competed.

Current initiatives in the Space Operations Mission Directorate's (SOMD) Human Research Program (HRP) include competed, peer-reviewed grants (e.g., ILSRA-HERO work which, jointly funded by BPS, led to the VEG-04/VEG-05 flight experiments) as well as directed work on specific topics. HRP historically has funded plant nutritional, microbiological food safety, and sensory acceptability analysis; food safety standards and risk assessment research and discussions; and crop identification and selection process development. In several cases, HRP has funded analyses related to human research from experiments funded by other stakeholders, for example they leveraged the HRF-VEG studies on human sensory acceptability and behavioral assessments of crops grown with funding from BPS Space Biology.

Exploration Systems Development Mission Directorate (ESDMD) Mars Campaign Office (MCO) is funding plant growth technologies like the OHALO III crop production system for the ISS, and the water and nutrient delivery and volume optimization work that will interface with this through the ROSBio-2018 solicitation [63]. In addition, MCO, formerly Exploration Capabilities, has funded collaborative work with the German Space Agency, DLR, at the EDEN-ISS facility in

Antarctica looking at long-duration crop production in isolated environments, as well as behavioral health and performance metrics involving plants. NASA's CHAPEA study at Johnson Space Center completed the first of three year-long crewed Mars analogs, which have a crop growth component for portions of the study as part of each mission. This study will assess aspects of crop inclusion in a Mars mission including impacts on behavioral health and performance, menu fatigue and dietary assessment, and other human health and performance measures.

Other programs like NASA's Established Program to Stimulate Competitive Research (EPSCOR), or work with capstone engineering design teams (e.g., eXploration HABitation [X-HAB]), may also develop needed technologies or generate data to support space crop production. NASA outreach and engagement activities come from various sources, including the state Space Grant consortia (e.g., Plant the Moon Challenge, funding for NASA interns) and SMD's Science Activation and Citizen Science Programs (Growing Beyond Earth Program). Other activities have been funded through NASA Stem Engagement (e.g., MUREP fellowships, Growing Beyond Earth Maker Challenge, internships).

Going forward, NASA's Space Crop Production team would like to be able to leverage contributions from international partners and commercial stakeholders in identifying, selecting, and validating space food crops. The value proposition of developing and testing these crops also has incredible potential for benefiting terrestrial CEA. There can be common stresses that crops experience both in space and terrestrially, but other unique stresses occur only in the space environment. Discovering and quantifying plant responses to extreme environments advances knowledge for both space and ground applications. Other space agencies and countries recognize the challenge and expected rewards of developing technologies for space crop production and advances in knowledge centered around space crop science. The Australian Centre of Plants for Space (P4S) represents a sizeable investment in this sector by the Australian government. The Canadian Space Agency (CSA/ASC) has a long history in robotics, and if they choose to leverage their space resources and expertise in crop production technologies, they could greatly benefit space and terrestrial populations. The German Aerospace Center has indicated interest in continuing their research on development of greenhouse systems for the Moon and Mars and are designing a Lunar Agricultural Module Ground Test Demonstrator (LAM-GTD) with CSA/ASC and the Italian Space Agency (ASI). The International Space Life Sciences Working Group (ISLSWG) may provide mechanisms for discussions between space agencies on space biology. Table A-1 lists examples of organizations which support space crop production or have activities to advance various aspects associated with it.

Table A-1 Examples of space crop-related organizations.

	Organization	Type of Work (Current and Future)
NASA Core Stakeholders	SMD BPS	Grants, directed work, internships, fellowships
	STMD	Centennial Challenges, STRI, NSTRGO, ECF, SBIR, STTR
	SOMD HRP	Directed, competed
	ESDMD MCO	Technology development (OHALO III), analog studies (EDEN-ISS, CHAPEA)
	EPSCOR	Competed science and technology grants
	NASA Engagement	SMD science activation, NASA STEM engagement, OSTEM interns, Space Grant projects
OGA Related Activities	USDA	Collaborative directed work, joint workshops, Internal ARS Grand Challenge in Systems for the Production of Agricultural Crops in Extraterrestrial Settings (SPACES); MOUs for Microgreen Research, Environmental Test Chamber Development, and Spectral Sensing of Crops
	DOE	Joint workshops
	DOD	Natick labs, food safety research
Space Act Agreements	US Universities	Winston Salem State University, Florida Institute of Technology, University of Florida
International	Australia	Centre of Plants for Space (P4S) (led by the University of Adelaide)
	CSA	EDEN-ISS, LAM-GTD
	DLR	EDEN-ISS, Bioregenerative Life Support Testbed, LAM-GTD
	ESA	Micro-Ecological Life Support System Alternative (MELiSSA) Project

<u>Other initiatives the authors are not involved with but are aware of include:</u>

- USDA: AFRI research proposals, SCRI proposals (especially in Controlled Environment Agriculture)
- DOE work: Lawrence Berkley Labs closed chamber research, Precision Urban Agriculture Initiative
- University of North Dakota: Collaborative Aerospace and Research
- Japan: Proposed Research Center for Space Agriculture and Horticulture (Chiba University)
- China: Lunar Palace

In addition to the more near-term goals of validating pick-and-eat crops for human exploration, research on intermediate staple crops like potato and sweet potato, and traditional staple crops (e.g. wheat, rice, beans) for long-term surface missions should not be ignored. Plant growth in regolith simulants is an example of advancing knowledge for long-term surface missions, as is testing dwarf, genetically engineered fruit trees. Off-planet seed production is yet another example of a long-term research need.

The landscape of funding organizations, international partners, and interested technical teams, coupled with the many open challenges and gaps in space crop production, require integration, close cooperation, effective communications, and leadership.

Conclusion

As humans expanded across the continents and the oceans, they always took their crops with them to sustain their presence in new worlds. The long-term exploration of space will be no different and will be even more challenging. NASA recognizes the strategic importance of plants to crew health and long-term missions, as illustrated by incorporating them into the Moon to Mars objectives and strategies. NASA's Space Crop Production team has identified both primary and secondary driving factors impacting how many crops might be needed to achieve the M2M objectives and has assessed that about 30 crops will be needed in the near-term for whole food nutrition, to reduce dietary fatigue, and to provide a resilient crop production system. In addition, the authors have revised the CRL system that is being used to validate crops for early crop systems. These crops will first focus on providing variety in the diet, positively impacting behavioral health, providing whole food nutritional benefits, and later expand to provide calories, augment the ECLSS, and provide valuable biomaterials.

Science investments in acceptable, nutritionally dense crops will enable deep space human exploration and improve terrestrial agriculture. There are several concepts of operations regarding utilizing a crop growth system on deep space missions. One possible operational consideration is to rely more heavily on crop production in the latter half of the mission as vehicle volume becomes available. Shifting to fresh food production may create opportunities to maximize use of vehicle volume and consumables while supplementing nutrients, reducing menu fatigue, and improving behavioral health. Communication and integration between NASA programs can enable substantial progress, which can be augmented by significant contributions from international partners. Plants are an important component for deep space human exploration and have the potential to eventually contribute to crew food security. They can be a key component to provide deep space crews access to sufficient, safe, and nutritious fresh food, which meets both their dietary needs and food preferences to maintain health and performance. Prepackaged foods are a reliable and easy to use option that will likely remain a staple of exploration missions, and regenerative foods are expected to contribute to more Earth independence and help enable missions that are longer and further from Earth.

References

[1] R. L. Bisplinghoff, "Conference Introduction," in *Conference on Nutrition in Space and Related Waste Problems*, Tampa, 1964.

[2] M. Cooper, M. Perchonok and G. L. Douglas, "Initial assessment of the nutritional quality of the space food," *npj Microgravity ,* vol. 3, no. 17, 2017.

[3] P. M. Catauro and M. H. Perchonok, "Assessment of the Long-Term Stability of Retort Pouch Foods to Support Extended Duration Spaceflight," *Journal of Food Science,* vol. 77, no. 1, pp. S23-S39, 2012.

[4] G. L. Douglas, G. D. Massa, M. E. Hummerick and P. E. Hintze, "Cold plasma to disinfect spaceflight grown produce," in *Advances in cold plasma applications for food safety and preservation*, D. Bermudez-Aguirre, Ed., London, Elsevier, Academic Press, 2020, pp. 333 - 340.

[5] G. L. Douglas, S. R. Swart and S. M. Smith, "Douglas, Space food for thought: challenges and considerations for food and nutrition on exploration missions," *The Journal of Nutrition,* vol. 150, no. 9, pp. 2242-2244, 2020.

[6] S. Smith, S. Zwart, G. Douglas and M. Heer, Human Adaptation to Spaceflight: The Role of Food and Nutrition, 2nd ed, Houston, Texas: National Aeronautics and Space Administration Lyndon B. Johnson Space Center, 2021.

[7] NASA, "Moon to Mars Objectives," 2022. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/m2m-objectives-exec-summary.pdf. [Accessed 20 07 2023].

[8] NASA, "NASA’S Moon to Mars Strategy and Objectives Development," National Aeronautics and Space Administration, Washington, DC, 2023.

[9] NASA, "Artemis III Science Definition Team Report," [Online]. Available: https://www.nasa.gov/wp-content/uploads/2015/01/artemis-iii-science-definition-report-12042020c.pdf. [Accessed 24 07 2024].

[10] K. Tsiolkovsky, Issledovaniyye mirovykh prostranstv reaktivnymi proborami (Exploration of world space with rockets), Kaluga Press, 1926.

[11] J. Myers, "Basic remarks on the use of plants as biological gas exchangers in a closed system," *Medicine, Journal of Aviation,* vol. 25, no. 4, pp. 407-411, 1954.

[12] J. Myers, "Use of algae for support of the human in space," *Life Science Space Research,* vol. 2, pp. 323-326, 1964.

[13] A. Krall and B. Kok, "Studies on algal gas exchangers with reference to space flight," in *Developments in Industrial Microbiology*, State College, 1960.

[14] F. Salisbury, J. Gitelson and G. Lisovsky, "Bios-3: Siberian experiments in bioregenerative life support," *Bioscience,* vol. 47, no. 9, pp. 575-585, 1997.

[15] R. M. Wheeler, "Agriculture for Space: People and Places Paving the Way," *Open Agriculture,* vol. 2, no. 1, pp. 14-32, 2017.

[16] C. Ward and R. Miller, "Algal Systems for Biological Food Synthesis," in *The Closed Life-Support System* , Ames Research Center, 1966.

[17] J. Hoff, J. Howe and C. Mitchell, "Development of selection criteria and their application in evaluation of CELSS candidate species," in *Controlled Ecological Life Support System: First Principal Investigators*, Washington DC, 1982.

[18] F. Salisbury and M. Clark, "Choosing plants to be grown in a Controlled Environment Life Support System (CELSS) based upon attractive vegetarian diets," *Life Support and Biosphere Science,* vol. 2, no. 3-4, pp. 169-179, 1996.

[19] G. L. Douglas, R. M. Wheeler and R. F. Fritsche, "Sustaining Astronauts: Resource Limitations, Technology Needs, and Parallels between Spaceflight Food Systems and those on Earth," *Sustainability,* vol. 13, no. 16, p. 9424, 2021.

[20] M. Averner, M. Karel and R. Radmer, "Problems associated with the use of algae in bioregenerative life support systems," NASA - Ames Research Center, Moffett Field, 1984.

[21] M. Kliss and R. MacElroy, "Salad machine: A vegetable production unit for long duration space missions," in *International Conference On Environmental Systems*, Williamsburg, VA, 1990.

[22] M. Kliss, A. Heyenga, A. Hoehn and L. Stodieck, "Recent advances in technologies required for a “Salad Machine”," *Advances in Space Research,* vol. 26, no. 2, pp. 263-269, 2000.

[23] R. MacElroy, M. Kliss and C. Straight, "Life support systems for Mars transit," *Advances in Space Research,* vol. 12, no. 5, pp. 159-166, 1992.

[24] J. Hoff, J. Howe and C. Mitchel, "Nutritional and cultural aspects of plant species selection for a controlled ecological life support system," NASA, 1982.

[25] R. M. Wheeler, "Roadmaps and strategies for crop research for bioregenerative life support systems," NASA, 2009.

[26] R. Wheeler, "Plants for Human Life Support in Space: From Myers to Mars," *Gravitional and Space Biology,* vol. 23, no. 2, pp. 25-35, 2010.

[27] H. W. Jones, "Going Beyond Reliability to Robustness and Resilience in Space Life Support Systems," Vols. ICES-2021-140, 2021.

[28] S. M. Smith, S. R. Swart, G. L. Douglas and M. Heer, "Human Adaptation to Spaceflight: The Role of Food and Nutrition," NASA, 2021.

[29] A. Basu and V. Imrhan, "Tomatoes versus lycopene in oxidative stress and carcinogenesis: conclusions from clinical trials," *European Journal of Clincal Nutrition,* vol. 61, pp. 295-303, 2007.

[30] R. H. Liu, "Health benefits of fruit and vegetables are from additive and synergistic combinations of phytochemicals," *The American Journal of Clincal Nutrition,* vol. 78, no. 3, pp. 517S-520S, 2003.

[31] L. H. Campestrini, M. P. S, L. E. Peres, R. C. Calhelha, F. I. CFR and A. S. M, "A new variety of purple tomato as a rich source of bioactive carotenoids and its potential health benefits," *Heliyon,* vol. 5, no. 11, p. e02831, 14 Nov 2019.

[32] N. Pathare, F. Fayet-Moore, J. Fogarty, F. Jacka, P. Strandwitz, G. Strangman and D. Donoviel, "Nourishing the brain on deep space missions: nutritional psychiatry in promoting resilience," *Frontiers in Neural Circuits,* vol. 17, pp. 1-9, 2023.

[33] R. Wheeler and R. Strayer, "Use of Bioregenerative Technologies for Advanced Life Support: Some Considerations for BIO-Plex and Related Testbeds," NASA, 1997.

[34] M. Romeyn, L. Spencer, G. Massa and R. Wheeler, "Crop Readiness Level (CRL): A Scale to Track Progression of Crop Testing for Space," in *International Conference on Environmental Systems*, Boston, 2019.

[35] S. Lepkovsky, "The Appetite Factor," in *Conference on Nutrition in Space and Related Waste Problems*, Tampa, 1964.

[36] T. A. Sirmons, P. G. Roma, A. M. Whitmire, S. M. Smith, S. R. Zwart, M. Young and G. L. Douglas, "Meal replacement in isolated and confined mission environments: Consumption, acceptability, and implications for physical and behavioral health," *Physiol Behav.,* vol. 15, no. 219, p. 112829, May 2020.

[37] G. L. Douglas, P. G. Roma and M. Young, "Food Acceptability, Menu Fatigue, and Aversion on ISS Missions," in *NASA Human Research Program Investigator Workshop*, Galveston, 2020.

[38] D. M. Minich, "A Review of the Science of Colorful, Plant-Based Food and Practical Strategies for “Eating the Rainbow”," *Journal of Nutrition and Metabolism,* p. 19, 2019.

[39] R. Odeh and C. L. Guy, "Gardening for Therapeutic People-Plant Interactions during Long-Duration Space Missions," *Open Agriculture,* vol. 2, no. 1, pp. 1-13, 2017.

[40] E. O. Wilson, Biophilia, Harvard University Press, 1984, p. 157.

[41] G. Massa, D. Arias, J. Bunchek, G. Douglas, J. Gooden, M. Hummerick, C. Mitchell, R. Morrow, P. Roma, M. Romeyn, L. Sirianni, L. Spencer, R. Wheeler and M. Young, "VEG-04 Pick-and-Eat Crop Production and Human Research on the International Space Station," in *HRP Investigators Workshop*, Galveston, 2021.

[42] R. Wheeler, C. Mackowiak, G. Stutte, N. Yorio, L. Ruffe, J. Sager, R. Prince and W. Knott, "Crop productivities and radiation use efficiencies for bioregenerative life suppor," *Advances in Space Research,* vol. 41, no. 5, pp. 706-713, 2008.

[43] Y. Fu, Z. Yi, Y. Dua, H. Liua, B. Xie and H. Liua, "Establishment of a closed artificial ecosystem to ensure human long-term survival on the moon," *bioRxiv,* p. 23, 2021.

[44] C. Walters, L. M. Wheeler and J. M. Grotenhuis, "Longevity of seeds stored in a genebank: species characteristics," *Seed Science Research,* vol. 15, no. 1, pp. 1-20, 2005.

[45] Fairchild Tropical Botanic Garden, "Growing Beyond Earth®," 2023. [Online]. Available: https://fairchildgarden.org/gbe/. [Accessed 27 10 2023].

[46] NASA, "Life Support Baseline Values and Assumptions Document," 2022.

[47] S. Burgner, C. Mitchell, G. Massa, M. Romeyn, R. Wheeler and R. Morrow, "Troubleshooting Performance Failures of Chinese Cabbage for Veggie on the ISS," in *ICES-2019*, 2019.

[48] "NASA Facts - Veggie (FS-2020-01-007-KSC)," 2020.

[49] K. H. Hasenstein, S. P. John and J. P. Vandenbrink, "Assessing Radish Health during Space Cultivation by Gene Transcription," *Plants,* vol. 12, no. 19, p. 3458, 2023.

[50] N. D. Hedielbaugh, "Space flight feeding systems: characteristics, concepts for improvement, and public health implications," *Journal of the American Veterinary Medical Association,* vol. 149, no. 12, pp. 1662-1671, 1966.

[51] NASA, "How the Moon Landing Led to Safer Food for Everyone," 23 11 2020. [Online]. Available: https://spinoff.nasa.gov/moon-landing-food-safety. [Accessed 24 07 2023].

[52] C. E. A. Alliance, "Commodity Specific Food Safety Guidelines for Controlled Environment Agriculture focused on leafy greens and herbs," Controlled Environment Agriculture Alliance , 2023.

[53] J. Hu, F. Safir, K. Chang, S. Dagli, H. B. Balch, J. M. Abendroth, J. Dixon, P. Moradifar, V. Dolia, M. K. Sahoo, P. B. A, S. S. Jeffrey, M. Lawrence and J. A. Dionne, "Rapid genetic screening with high quality factor metasurfaces," *Nature Communications,* no. 14, p. 4486, 2023.

[54] M. Sueker, K. Stromsodt, H. Taheri Gorji, F. Vasefi, N. Khan, T. Schmit, R. Varma, N. Mackinnon, S. Sokolov, A. Akhbardeh, B. Liang, J. Qin, D. E. Chan, I. Baek, M. Kim and K. Tavakolian, "Handheld Multispectral Fluorescence Imaging System to Detect and Disinfect Surface Contamination," *Sensors,* vol. 21, no. 21, 2021.

[55] K. A. Corey, M. E. Bates and S. L. Adams, "Carbon dioxide exchange of lettuce plants under hypobaric conditions," *Adv Space Res,* vol. 18, no. 4-5, pp. 265-72, 1996.

[56] K. A. Corey, P. A. Fowler and R. M. Wheeler, "Plant Responses To Rarified Atmospheres," in *Mars Greenhouses: Concepts and Challenges. Proceedings from a 1999 Workshop*, Kennedy Space Center, 2000.

[57] C. He, F. T. D. Jr and R. E. Lacey, "Separating the effects of hypobaria and hypoxia on lettuce: growth and gas exchange," *Physiologia Plantarum,* vol. 131, no. 2, pp. 226-40, October 2007.

[58] S. D. Carvalho and K. Fota, "Environmentally modified organisms - Expanding genetic potential with light," *CRC. Crit. Rev. Plant Sci.,* vol. 33, pp. 486-508, 2014.

[59] H. Boles, L. Poulet, C. Johnson, J. Torres, L. Koss, L. Spencer and G. Massa, "Design, Build and Testing of Hardware to Safely Harvest Microgreens in Microgravity," *Gravitational and Space Research,* vol. 11, pp. 1-14, 2023.

[60] E. Vignati, M. Lipska, J. M. Dunwell, M. Caccamo and A. J. Simkin, "Options for the generation of seedless cherry, the ultimate snacking product," *Planta,* vol. 256, no. 5, p. 90, 28 Sep 2022.

[61] Y. Xiong, H. Hirano, N. E. Lane, S. Nandi and K. A. McDonald, "Plant-Based Production and Characterization of a Promising FC-Fusion Protein Against Bone Mass Density Loss," *bioRxiv,* 2022.

[62] National Academies of Sciences, Engineering, and Medicine, "Thriving in Space: Ensuring the Future of Biological and Physical Sciences Research: A Decadal Survey for 2023-2032," The National Academies Press, Washington, DC, 2023.

[63] C. Webb, "Sustaining Astronauts in Space: NASA Selects Five Research Projects Designed to Improve Crop Habitats," NASA, 20 02 2020. [Online]. Available: https://www.nasa.gov/feature/nasa-selects-five-research-projects-designed-to-improve-crop-habitats. [Accessed 19 08 2023].

[64] K. Corey and R. Wheeler, "Gas exchange in NASA's biomass production chamber: a preprototype closed human life support system," *Bioscience,* Vols. Jul-Aug;42, no. 7, pp. 503-9, 1992.

[65] B. Yandell, A. Najar, R. Wheeler and T. Tibbitts, "Modeling the effects of light, carbon dioxide, and temperature on the growth of potato," *Crop Sci.,* vol. 28, no. 5, pp. 811-8, Sept-Oct 1988.

[66] "Vitamin C," NIST Chemistry WebBook, [Online]. Available: https://webbook.nist.gov/cgi/cbook.cgi?Name=50-81-7&Units=SI.

[67] "3-(4-Amino-2-methyl-pyrimidin-5-ylmethyl)-5-(2-hydroxy-ethyl)-4-methyl-thiazol-3-ium," PubChem, [Online]. Available: https://pubchem.ncbi.nlm.nih.gov/compound/thiamine#section=2D-Structure&fullscreen=true.

[68] "Phytonadione," NIST Chemistry WebBook, [Online]. Available: https://webbook.nist.gov/cgi/cbook.cgi?Name=phylloquinone&Units=SI.

[69] L. Carotti, A. Pistillo, I. Zauli, D. Meneghello, M. Martin, G. Pennisi, G. Gianquinto, Orsini and Francesco, "Improving water use efficiency in vertical farming: Effects of growing systems, far-red

radiation and planting density on lettuce cultivation," *Agriculture Water Management,* vol. 285, p. 10, 2023.

Appendix A Space Crop Production—Hypothetical Scenarios

The intent of this appendix is to calculate the approximate number of plants and determine planting schedules needed to supply crew members with a portion of their daily vitamin allowance and establish the hypothetical assumptions that enable the calculations. Plant nutrition data from the USDA are the basis for these estimates. We start with the Recommended Dietary Allowance (RDA) as a guide for astronaut diets with respect to Vitamins K, C, and B1. Table A-1 lists the RDA for Exploration Mission crews[1].

Table A-1 NASA Exploration Crew Recommended Dietary Allowance for Vitamin B1 (Thiamine), Vitamin C, and Vitamin K.

Vitamin/Mineral of Interest	RDA for Men (mg)	RDA for Women (mg)
Vitamin B1 (Thiamine)	1.20	1.10
Vitamin K	0.120	0.090
Vitamin C	125	110

If space crops are at least as nutritious as ground crops, then nutritional data for select plants from the USDA Food Data Central website allow for consumption calculations. For instance, NASA has grown leafy greens on the ISS, including Red Russian Kale, Extra Dwarf Pak Choi, Amara and Wasabi Mustard Greens. The USDA site lists nutritional data for Kale, Mustard greens, and Cabbage Chinese (pak-choi), as shown in Table A-2. These leafy greens are high in Vitamins C and K, but provide little B1.

Table A-2 Vitamin data for select leafy greens.

Plant	USDA Plant	Vitamin	Quantity (mg/100g portion)	USDA Web Address Data Source
Red Russian Kale	Kale, Raw	K	0.390	https://fdc.nal.usda.gov/fdc-app.html#/food-details/323505/nutrients
		C	93.4	
Wasabi Mustard, Amara Mustard	Mustard greens, Raw	K	0.258	https://fdc.nal.usda.gov/fdc-app.html#/food-details/169256/nutrients
		C	70	
Extra Dwarf Pak Choi	Cabbage, Chinese (pak-choi), Raw	K	0.0455	https://fdc.nal.usda.gov/fdc-app.html#/food-details/170390/nutrients
		C	45	

[1] Smith, Scott M.; Zwart Sara, R, "Nutritional Requirements for Exploration Missions up to 365 days", NASA, JSC-67378 Rev1, 2020. https://ntrs.nasa.gov/citations/20205008306

Vitamins C and K

Estimating how much of Vitamins C and K select leafy greens can provide per day allows further estimations on crop numbers and schedules. Assuming that leafy greens will provide approximately 10% of the RDA of Vitamin C for men, then enough greens to provide 12.5 mg of Vitamin C per day would be needed. If one then assumes that a salad is comprised of roughly 1/3 kale, 1/3 mustard greens, and 1/3 pak-choi, then the amount of each vitamin can be estimated using data from Table A-2 and the calculations are shown in Table A-3.

Table A-3 Vitamins in a 15g Kale, Mustard Green, and Pak-choi salad.

Vitamin	Amount in 5 g Kale	Amount in 5 g Mustard Green	Amount in 5 g Pak-choi	Total Amount in 15 g Salad
C	$5\ g\ x \left(\frac{93\ mg}{100g}\right) = 4.65\ mg$	$5\ g\ x \left(\frac{70\ mg}{100g}\right) = 3.50\ mg$	$5\ g\ x \left(\frac{45\ mg}{100g}\right) = 2.25\ mg$	**10.4 mg**
K	$5\ g\ x \left(\frac{390\ \mu g}{100g}\right) = 19.5\ \mu g$	$5\ g\ x \left(\frac{258\ \mu g}{100g}\right) = 12.9\ \mu g$	$5\ g\ x \left(\frac{45\ \mu g}{100g}\right) = 2.25\ \mu g$	**34.65 µg**

A small salad of 15 g provides a total of 10.4 mg Vitamin C, comprising 8% of the daily need. The same small salad also provides 34.7 µg of Vitamin K, or 29% of the daily need. A single serving salad is typically listed on package labels as 85 g, and so a 15 g salad is about the serving size that many Americans would consider to be a side salad.

To grow the plants needed to provide 5 g of kale, 5 g of mustard greens, and 5 g of pak-choi per day per crew member, one can make assumptions regarding growth duration, harvest amount, and harvest techniques. Harvest techniques include a single terminal harvest (e.g. 28 days after planting) or repetitive cut-and-come-again harvesting from the same plant with regrowth (e.g. for an additional 2 weeks or longer after maturity). Assuming these leafy greens grow for 28 days prior to harvest, and that the harvest technique is cut-and-come-again for a duration of 14 days, then based on typical harvest data at KSC, the total harvest per plant over the 14-day period can be estimated to be 50 g. Each plant provides 3.6 g of edible mass per day, so two plants are needed per cultivar to provide 5 g of fresh mass per day.

Over two weeks, two kale, two mustard greens, and two pak-choi are harvested per crewmember for food, providing more than 15 g salad options. To continuously produce salads, a crop schedule needs to be considered where six plants are required per crew member, and crops are produced in three groups. The grouping of crops into three groups allows for continuous harvesting of one group of plants while the other two groups grow for future harvests, as shown in Figure A- 1.

Figure A- 1 Leafy green crop schedule showing a 14-day continuous harvest technique.

Accounting for the crop schedule, each crew member would require 18 plants to provide a continuous supply of small salads, or 72 plants for a crew of four.

A leafy green plant needs a space of about 15 x 15 cm to grow or 0.0225 m^2 per plant. Multiplying 0.0225 m^2 by 72 plants then means that 1.62 m^2 of growth area is required for a crew of four to have a continuous supply of 15 g salads per day. If plants are only harvested once, then they could possibly be grown in similar densities to those grown in the Controlled Environment Agriculture (CEA) industry. CEA leafy green densities can be 192 plants/m^2, so 72 plants would only require 0.375 m^2 or 23.2 % of the area of cut-and-come-again. Tightly packing in plants in microgravity would require careful monitoring of the air flow to ensure adequate ventilation above and below the canopy. It should be noted that plant densities reported for CEA vary between 30 plants/m^2 and 270 plants/m^2 [2,3]for leafy greens. Production technique, growth habit, crop type and mix, and food safety all need to be carefully considered when determining plant densities.

Vitamin B1

The most expedient means to provide crews with fresh, nutritious food rich in B1 is likely by growing microgreens. A microgreen plant is simply a young plant typically harvested when the first true leaf appears. They are grown at high seed densities and quickly close their canopy, giving the impression of a lawn. They are often more nutritious than the same variety as a mature plant, and they provide a variety of flavors and textures. Typical microgreens are harvested between 7 and 18 days after planting, reducing growth durations and resource inputs, and increasing growth cycles.

Table A-1 shows that the RDA of Vitamin B1 for men is 1.20 mg/day. A recent paper reported Vitamin B1 amounts in microgreens[4], with Buckwheat Groats, Dun Pea, Dwarf Grey Sugar Pea, and Daikon Radish having some of the highest totals. These data compare well with raw, leafy Cowpea plant tips and raw, sprouted Lentils reported by the USDA to be high in vitamin B1 having 0.354 mg of B1/100g edible mass[5] and 0.228 mg of B1/100g edible mass[6] respectively.

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[2] Answering key questions about indoor crops, 11/09/2022, https://www.canr.msu.edu/floriculture/uploads/files/Answering%20key%20questions.pdf, accessed 10/27/2023

[3] L. Carotti, A. Pistillo, I. Zauli, D. Meneghello, M. Martin, G. Pennisi, G. Gianquinto, Orsini and Francesco, "Improving water use efficiency in vertical farming: Effects of growing systems, far-red radiation and planting density on lettuce cultivation," Agriculture Water Management, vol. 285, 2023.

[4] "Novel Microgreen Crop Testing for Space", 52nd International Conference on Environmental Systems 2023.

[5] https://fdc.nal.usda.gov/fdc-app.html#/food-details/169224/nutrients accessed 07/19/2023.

[6] https://fdc.nal.usda.gov/fdc-app.html#/food-details/168427/nutrients accessed 07/19/2023.

Table A-4 Vitamins in a 25 g Serving of Legume Microgreens (% RDA)[4].

Microgreen	Vitamin B1 /25g	Vitamin C /25g	Vitamin K /25g
Dwarf Grey Sugar Pea	75 µg (6.3% men) (6.8% women)	495 µg (0.4% men) (0.5% women)	15 µg (12.5% men) (16.7% women)
Buckwheat Groats	34.5µg (2.9% men) (3.1% women)	938 µg (0.8% men) (0.9% women)	5 µg (4.2% men) (5.6% women)

Table A-4 shows that eating one 25 g serving of Dwarf Grey Sugar Pea microgreens with lunch and one serving of Buckwheat microgreens with dinner would provide 9.2% of men's and 9.9% of women's RDA for Vitamin B1. While legume microgreens are not a good source of vitamin C, they can be a source of vitamin K in addition to vitamin B1 and could provide more than 16% of the RDA for men and 22.2% for women in the proposed two daily servings.

A small, dedicated area of about 0.030 m^2, which is the size of a small tray (17.32 cm X 17.32 cm), is required to grow 25 g of harvest mass of microgreens. Microgreens would need to be harvested and replanted daily for a continuous daily supply. Microgreens take approximately 14 days to grow, and thus each crew member would need two small trays per day for 14 days, which is 28 trays per crew member. Therefore, a total area of 0.84 m^2 would be needed per crew member or 3.36 m^2 for a four-person crew. Microgreens do not require much canopy volume and can be stacked more tightly than mature crops for growing. If microgreen storage is available in cold stowage, then harvest/re-planting could be consolidated to save setup/break-down crew time associated with the activity, or technology advancements could automate harvest and re-planting.

Growth and Volume Considerations

To calculate the volume required to grow fresh produce, one needs to know the required heights for the plants and the headspace. Experience from KSC indicates that 0.30 m for leafy greens and 0.20 m for microgreens are reasonable estimates for crop height and distance to lights.

Table A-5 Volume Requirements by cropping technique.

Crop *Technique*	**Area For Crew of four (m^2)**	**Height Required (m)**	**Volume for crew of four (m^3)**
Leafy Green *Cut-and-come-again*	1.62	0.30	0.486
Leafy Green *CEA/ single harvest*	0.375	0.30	0.113
Microgreens	3.36	0.20	0.672

The calculated volumes in table A-5 demonstrate how the production technique and growth habit can change the volume and hardware design. Based on the assumptions 0.486 m^3 can grow 72 leafy greens with 24 plants being harvested at any given time for the four-person crew. As assumed before, each plant produces up to 3.6 g of fresh harvest per day which would be 177 g m^{-3} day^{-1}. Based on 50 g of fresh microgreens per crew member grown in a volume of 0.672m^3 that calculates to 298 g day^{-1} m^{-3} which is nearly double that of mature leafy greens. While microgreens can produce more fresh harvest in comparison to mature leafy greens, they also require further work for food safety and automation due to the touch activities required to plant and clean the microgreen growth system. Pick-and-eat space crops can provide nutrition, flavor variety, texture variety, and can positively impact crew behavioral health and more study is needed to better understand production techniques.

Appendix B Examples of Selection Factors for Space Plant Breeding

Traits for space crops typically focus on compactness, harvest index, productivity, and germination but other factors are just as important. For instance, acceptability is just as important since it is expected that crews will under consume crops they prefer not to eat. The types of crops chosen, how they are grown, and for what purposes, impacts the areas and volumes required to meet fresh food nutritional goals as well as the selection factors for the crops themselves. Selection factors for several different categories are listed below.

Plant Growth and Development

- Compact size (low height and volume)
- High yield
- High edible/inedible biomass ratio (harvest index)
- Rapid growth to first yield
- Reliable germination
- Rapid germination
- Uniform growth and development between individuals
- Sustained production capability over long duration (e.g, repetitive fruiting, or cut-and-come again repetitive harvesting)
- Low debris formation (leaves, flowers, pollen, seeds, etc. remain attached)
- Glabrous ("hairless") plants to reduce debris generated from trichomes
- Reduced crew time for cultivation, harvesting, and cleanup

Plant Physiology

- Stress tolerance
- Ability to grow well under conditions of:
    - Elevated CO_2
    - Low RH
    - Uniform temperature of 20-23°C
    - Electric lights
- Reduced light (energy) requirements
- Shade tolerance
- Tolerance of broad environment range
- Drought tolerance
- No dormancy requirements
- Low or pleasing aroma
- Low levels of volatile organic compounds (VOC) released
- High sodium tolerance (e.g., urine recycling)
- Preference for ammonia nitrogen sources (e.g., urine recycling)

Sensory Acceptability

- Excellent flavor
- Intense flavors
- Good texture
- Good appearance, color

Nutrition

- High normal levels of antioxidants
- High normal levels of beneficial phytonutrients (e.g., lutein, zeaxanthin, lycopene, phenolics, anthocyanins)
- For fresh produce to supplement a packaged diet:
    - High normal levels of potassium and magnesium
    - Low normal levels of iron
    - High normal levels of Vitamin C, Vitamin K, and Vitamin B1
    - Low levels of antinutrients

Postharvest

- Good produce storage capabilities
- Reduced processing (e.g., seeds easily removed from seed coats)
- Easy composting/digestion of inedible plant waste for nutrient reclamation
- Reduced structural materials (e.g., lignin and other cell wall components)
- Use of inedible waste for other food sources (e.g., fish food stocks or edible fungus production)
- Other useful materials produced from inedible wastes (e.g. medicines, bioplastics)

Appendix C Examples of Driving Factors and Space Crop Selections

Primary and near-term factors for selecting and growing space crops are the ability to supplement astronaut nutrition with fresh, acceptable, and nutritious food, reduce menu fatigue, positively impact astronaut behavioral health, and successfully test multiple cultivars for food system resiliency. These factors directly impact the number and types of crops needed. Secondary factors for crop selections include plant integration into Environmental Control and Life Support Systems (ECLSS), tolerant crop types for robustness, and factors centered around hardware limitations and compatibility. Secondary factors do not increase the numbers of crops needed but add selection parameters. All factors are described in Table A-1.

The tables below break down each factor into crops which have been tested and passed CRL 9, as well as candidate crops and placeholders to be tested in the future. Nutrition is called out with the recommendation that three crop species be selected for each vitamin category, and lists Vitamins C, K, and B1 as examples and also lists potassium and magnesium as minerals of interest. Table C-1 identifies candidate crops which are high in the target vitamins/minerals. The "Crop" column lists crops which have passed CRL 9 and placeholders not yet tested in flight. The table also shows candidate crops in blue font which have not been flight tested but are reportedly rich in the target nutrient. Herb-01 is the placeholder for a candidate herb, and Micro-01 is a placeholder for a candidate microgreen. Examples of candidates that could fill those placeholders are given in the "Candidate Crop" column. Legume crops such as peas, beans and lentils are high in Vitamin B1. Other crops that are high in vitamin B1 include asparagus, Brussel sprouts, buckwheat microgreens, Daikon radish microgreens, and many seed crops. Due to growth time and yield considerations, microgreens look to be the most effective way to provide Vitamin B1. Candidate B1 microgreen crops have been ground tested, and results were reported in a recent publication[1].

[1] "Novel Microgreen Crop Testing for Space", 52nd International Conference on Environmental Systems 2023.

Table C-1 Crop examples for vitamin and mineral driving factors for human space exploration. All named crops in the "Crop" column are at CRL 9. All "Candidate crops" are at CRL 1-6 (shown in blue).

Nutrient	Crop	Candidate Crop	Family
Vitamin C	Red Russian Kale		Brassicaceae
	Extra Dwarf Pak Choi		Brassicaceae
	Wasabi Mustard		Brassicaceae
Vitamin K	Red Russian Kale		Brassicaceae
	Wasabi or Amara Mustard		Brassicaceae
	Herb-01	Parsley, fresh	Apiaceae
Vitamin B1	Micro-01	Buckwheat, micro	Polygonaceae
	Micro-02	Dwarf Grey Sugar Pea, micro	Fabaceae
	Micro-03	Daikon Radish, micro	Brassicaceae
K	Red Russian Kale		Brassicaceae
	Extra Dwarf Pak Choi		Brassicaceae
	Red Romaine Lettuce		Asteraceae
Mg	Extra Dwarf Pak Choi		Brassicaceae
	Red Russian Kale		Brassicaceae
	Micro-04	Broccoli, micro	Brassicaceae

Some crops such as kale, mustard greens, and pak choi are high in many of the example target nutrients and can fulfill multiple roles. The maximum number of crops needed would use three unique crops for each example nutrient, and thus be fifteen, while the minimum number of crops would use just three crops for all nutrients. The five crops and four placeholders listed in Table C-1 represent the lowest realistic number of crops rich in the example target nutrients, and do not consider other factors. Visual characteristics, texture, flavor, simple descriptions of leafy green, fruiting, and microgreen crop characteristics are listed below in Table C-2 - Table C-4.

Table C-2 Leafy green crop characteristics in consideration of menu fatigue.

Crop	Crop Family	Candidate	Characteristic	Description
Red Russian Kale	Brassicaceae		Color	Green and red
			Visual/Texture	Large, frilly, hairy
			Flavor	Earthy, bitter
Extra Dwarf Pak Choi	Brassicaceae		Color	Green and white
			Visual/Texture	Small, smooth, rounded
			Flavor	Crisp, mild
Wasabi Mustard	Brassicaceae		Color	Green
			Visual/Texture	Large, semi-smooth, rounded
			Flavor	Crisp, spicy
Amara Mustard	Brassicaceae		Color	Green
			Visual/Texture	Large, semi-smooth, rounded
			Flavor	Crisp, umami

Table C-3 Fruiting crop characteristics in consideration of menu fatigue.

Crop	Crop Family	Candidate	Characteristic	Description
Micro-Tom Tomato	Solanaceae		Color	Red
			Visual/Texture	Small, sphere, smooth
			Flavor	Juicy, mild
Española Improved Pepper	Solanaceae		Color	Green to Red
			Visual/Texture	Large, cone-shaped, smooth
			Flavor	Crisp, slow onset pungency
Fruit-01	Solanaceae	Bulgarian carrot pepper	Color	Orange
			Visual/Texture	Small, cone-shaped, smooth
			Flavor	Crisp, citrus, fast onset pungency

Fruit-02	Cucurbitaceae	Dwarf melon	Color	Green
			Visual/Texture	Smooth, round, thin skinned fruit
			Flavor	Juicy, mild, sweet

Table C-4 Microgreen crop characteristics in consideration of menu fatigue.

Crop	Crop Family	Candidate	Characteristic	Description
Micro-01	Polygonaceae	Buckwheat groat	Color	Green
			Visual/Texture	Round leaves
			Flavor	Nutty
Micro-05	Brassicaceae	Wasabi Mustard	Color	Green
			Visual/Texture	Round
			Flavor	Pungent
Micro-06	Brassicaceae	Garnet Giant	Color	Purple
			Visual/Texture	Red-green
			Flavor	Pungent
Micro-07	Brassicaceae	Red Russian Kale	Color	Red
			Visual/Texture	Frilly
			Flavor	Mild
Micro-08	Amaryllidaceae	Green Onion	Color	Green
			Visual/Texture	Vertical
			Flavor	Mild onion flavor to sweet
Micro-09	Brassicaceae	Tokyo Bekana	Color	Green
			Visual/Texture	Round
			Flavor	Crisp and Mild

It is outside the scope of this paper to consider fully the impact of each crop and candidate crop on how crew might incorporate the fresh produce into menu items and consume them. Another paper focused on consumption of crops would be beneficial. For instance, it is not realistic to expect crew to grow and eat parsley and microgreen green onions in great quantities for Vitamin K. While parsley and green onion microgreens are nutritionally dense and likely acceptable crops, they have limitations in how they can be incorporated in the crew diet and be routinely eaten in significant quantities though they could be beneficial to the packaged diet.

The lists of crops thus far have not focused on biodiversity, which is important because it improves resiliency. In consideration of risk and resiliency, our recommendation is to have

three crops from separate families for each example nutrient of interest. Taking Table C-1 into account and considering three crops from different families changes the list.
Table C-5 lists crops, with candidate crops in parenthesis, and placeholders to account for biodiversity from three different families.

Table C-5 Crops, candidate crops, and placeholders that are rich in the target nutrient and provide three distinct family taxonomy for resiliency.

Nutrient	Crop	Family
Vitamin C	Red Russian Kale	Brassicaceae
	Española Improved Pepper	Solanaceae
	Fruit-03 (Strawberry)	Rosaceae
Vitamin K	Red Russian Kale	Brassicaceae
	Herb-01 (Parsley)	Apiaceae
	Herb-02 (Green Onion)	Amaryllidaceae
Vitamin B1	Micro-01 (Buckwheat – micro green)	Polygonaceae
	Micro-02 (Dwarf Grey Sugar Pea – micro green)	Fabaceae
	Micro-03 (Daikon Radish – micro green)	Brassicaceae
K	Extra Dwarf Pak Choi	Brassicaceae
	Red Romaine Lettuce	Asteraceae
	Micro-10 (Carrot – micro green)	Apiaceae
Mg	Extra Dwarf Pak Choi	Brassicaceae
	Fruit-02 (Dwarf melon)	Cucurbitaceae
	Micro-10 (Carrot – micro green)	Apiaceae

Taking all aspects into consideration, a minimum number of crops required can be as low as 22, with many crops serving multiple roles. Nonetheless, we recommend 30 crops to improve the resiliency of the system. Table C-6 lists crops and candidate crops which meet or could meet several requirements.

Table C-6 Example of minimum number of crops to satisfy several driving factors.

Number	Crop	Family
1	Red Russian Kale	Brassicaceae
2	Extra Dwarf Pak Choi	Brassicaceae
3	Wasabi Mustard	Brassicaceae
4	Herb-01 (Parsley)	Apiaceae

Number	Crop	Family
5	Micro-01 (Buckwheat)	Polygonaceae
6	Micro-02 (Dwarf Grey Sugar Pea)	Fabaceae
7	Micro-03 (Daikon Radish)	Brassicaceae
8	Red Romaine Lettuce	Asteraceae
9	Micro-04 (Broccoli)	Brassicaceae
10	Amara Mustard	Brassicaceae
11	Micro-Tom Tomato	Solanaceae
12	Española Improved Pepper	Solanaceae
13	Fruit-01 (Bulgarian Carrot Pepper)	Solanaceae
14	Fruit-02 (Dwarf Melon)	Cucurbitaceae
15	Micro-05 (Wasabi Mustard)	Brassicaceae
16	Micro-06 (Garnet Giant)	Brassicaceae
17	Micro-07 (Red Russian Kale)	Brassicaceae
18	Micro-08 (Green Onion)	Amaryllidaceae
19	Micro-09 (Tokyo Bekana)	Brassicaceae
20	Fruit-03 (Strawberry)	Rosaceae
21	Herb-02 (Green Onion)	Amaryllidaceae
22	Micro-10 (Carrot)	Apiaceae

Many of the leafy greens listed can also be grown as microgreens, which could increase the utility of the packed seeds. For instance, if there were an issue with leafy green Red Russian Kale seeds, the microgreen Red Russian Kale seeds could be used to grow the plants to maturity as a leafy green with a bit of crew work. Microgreens are anticipated to be packed in high density sheets, and thus crews would need to separate seeds from the microgreen pack to plant as leafy greens. The amount of crew time required to process microgreen seeds for leafy greens would be short. The reverse, however, would be quite time intensive. Microgreens provide a variety of flavors and textures and increasing the number of available crops above 22 enables more variety and biodiversity. The rationale to have more than a minimum number of crops is, if for example, an opportunistic pathogen presented itself which effected plants in the Brassicaceae, then more than 40% of the crop list might be impacted. This would affect timing and crop schedules for fresh food production of whole food nutrients as well as reduce variety and impact menu fatigue. The candidate crops listed are those which have been assessed and tested which may meet the crop needs of deep space crews, although other crops may be better selections. They are simply candidates to enable discussion and advance knowledge. Finally, this list of crops is a starting point to identify the minimum set to fulfill the multiple roles that plants can fill for deep space exploration. More crops for crews to select from will enable more creative menu items, more options for nutritious combinations, and reduce risk of opportunistic pathogens by broadening the diversity of crops. Relying on a few crops to provide the bulk of whole food nutrition for deep space crews is the reason to broaden the load to at least three families, but production rates differ for those crops. Brassica leafy greens and microgreens are anticipated to be the most effective means of producing pick-and-eat crops in large consumable quantities because they germinate reliably, they grow fast, they are nutritious, and they taste good. Nonetheless, spreading more of the fresh production capability across more crop families can be considered as a good practice, and a crop number greater than 22 is expected once production rates and consumption habits are considered.

Appendix D Plant Growth Hardware

The concept of producing fresh, supplemental foods for space missions was suggested as early as 1990 and referred to as a, "salad machine"[1,2,3]. NASA currently has two systems to test crop-type plants in microgravity that are essential in progressing plants through CRL 8 and 9: Veggie and APH. A third system, Ohalo III, is under development for deployment on the ISS.

Veggie

Veggie is a 0.13 m^2 growing facility with red, blue, and green LED lights with transparent bellows[4,5,6]. It is a simple system, with the only powered components being red, blue, and green LED lights and fans to move ISS-cabin atmosphere through the plant canopy. The bellows provide partial humidity containment and a way for the crew to interact with the plants. They are attached via magnets, and crew members can easily detach these to interact with the plants. Plants are grown in a variety of growth subsystems inside Veggie depending on the research goal. Currently, crop plants that have been grown and eaten by the crew are grown using small plant pillows, essentially "space grow bags" that contain a porous ceramic substrate, a controlled release fertilizer, wicks secured by a foam gasket, and seeds which are glued in the wicks[7]. The plant pillows have an external irrigation tube which connects to an interior water distribution ring that is embedded in the substrate. Pillows are constructed from a Teflon™ coated Kevlar™ fabric with a gusset that allows expansion as they fill with roots. The bottom surface is Nomex™, which allows wicking from a root mat reservoir. The root mat is a polymer bag with a Nomex™ upper surface that can be filled with water and passively wick the water to the plant pillows. Pillows are attached to the root mat with elastic bands. Generally, Veggie requires low power and only Avionics Air Assembly (AAA) cooling from ISS, but considerable crew time is required to grow crops, especially for watering[8]. Development of a

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[1] M. Kliss and R.D. MacElroy. 1990. Salad machine: A vegetable production unit for long duration space missions. SAE Tech. Paper 901280. Williamsburg, VA, USA. July 1990.

[2] R.D. MacElroy, M. Kliss and C. Straight. 1992. Life support systems for Mars transit. Adv. Space Res. Vol. 12 (5): 159-166.

[3] M. Kliss, A.G. Heyenga, A. Hoehn, L.S. Stodieck. 2000. Recent advances in technologies required for a "Salad Machine". Adv. Space Res. Vol. 26 (2): 263-269

[4] R. Morrow, R. Remiker, M. Mischnick, L. Tuominen, M. Lee and T. Crabb, "A low equivalent system mass plant growth unit for space exploration," in International Conference On Environmental Systems, 2005

[5] R. Morrow and R. Remiker, "A deployable salad crop production system for lunar habitats," in International Conference On Environmental Systems, 2009.

[6] G. Massa, R. Wheeler, R. Morrow and H. Levine, "Growth chambers on the International Space Station for large plants," Acta Hortic., no. 1134, pp. 215-222, 2016.

[7] G. Massa, G. Newsham, M. Hummerick, R. Morrow and R. Wheeler, "Plant Pillow Preparation for the Veggie Plant Growth System on the International Space Station," Gravitational and Space Research, vol. 5, no. 1, pp. 24-34, 2017.

[8] L. Poulet, C. Zeidler, J. Bunchek, P. Zabel, V. Vrakking, D. Shubert, G. Massa and R. Wheeler, "Crew time in a space greenhouse using data from analog missions and Veggie," Life Sciences in Space Research, vol. 31, pp. 101-112, 2021.

powered watering system for Veggie has the capability to significantly reduce this labor requirement. There are currently two Veggie units on the ISS, and there are typically six Veggie units at Kennedy Space Center.

Advanced Plant Habitat (APH)

The Advanced Plant Habitat (APH) provides 0.2 m^2 of growth area with extensive autonomy and capability to control from Earth[6,9]. APH has over 180 sensors and controls almost every aspect of the crop growth environment. It provides independent control of red, green, blue, white, and far-red LED lights, and controls temperature, relative humidity, airflow, and CO_2 inside the chamber. Volatile organics are removed from the atmosphere using scrubbers. Overhead and side cameras allow for plant imaging. Other sensors include light sensing and infrared leaf temperature sensing in the shoot zone. The root zone of APH consists of a rigid science carrier tray with four independent quadrants, each with porous ceramic water distribution tubes and sensors for substrate moisture, temperature, and root zone oxygen. The science carrier is filled with tightly packed porous ceramic substrate and a controlled release fertilizer (or substrate preloaded with fertilizer), and wicks with seeds attached are secured in an open cell foam sheet that holds the substrate beneath the lid. The lid has holes for gas exchange. Irrigation in APH begins with flooding of the science carrier, and then water is maintained at desired levels via negative pressure on the porous tubes, or water can be maintained by manual water addition. APH requires considerable power, data, and ISS cooling resources, such as an Avionics Air Assembly high speed fan that provides cooling air to the rear of the locker and Moderate Temperature Loop water to cool components. APH requires less crew time in comparison to Veggie since plant irrigation, photography, environmental changes, and monitoring can all be done remotely by operators on the ground. One APH unit is installed on ISS, with a second flight unit and an Engineering Development Unit located at Kennedy Space Center.

Both Veggie and APH traditionally use calcined montmorillonite clay for a rooting medium, and this has been successful as a scientific soil substitute. Soils are not used due to the safety concerns over small particle sizes and challenges with consistency. Calcined clay is heavy, and APH uses about 4 kg in its root module[10]. Going forward, the goal is to have either a very light weight, reusable rooting medium, or no medium at all (e.g., hydroponics or aeroponics). The hydroponic nutrient film technique (NFT) used by Wheeler reports crop yields exceeding typical field-grown records on Earth[11], however, traditional NFT relies on gravity to draw the nutrient stream into a film, making it difficult to use in space, though it may be suitable for partial

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[9] R. Morrow, R. Richter, G. Tellez, O. Monje, R. Wheeler, G. Massa, N. Dufour and B. Onate, "A New Plant Habitat Facility for the ISS," in International Conference on Environmental Systems, 2016.

[10] O. Monje, J. T. Richards, J. A. Carver, D. I. Dimapilis, H. G. Levine, N. F. Dufour and B. G. Onate, "Hardware Validation of the Advanced Plant Habitat on ISS: Canopy Photosynthesis in Reduced Gravity," Front. Plant Sci., vol. 11, no. 673, 18 June 2020 .

[11] R. M. Wheeler, "Potato and Human Exploration of Space: Some Observations from NASA-Sponsored Controlled Environment Studies," Potato Research, vol. 49, pp. 67-90, 2006.

gravity destinations. Recently, XROOTS has demonstrated aeroponics and ebb/flow hydroponics in the space environment, but these technologies remain at a relatively low TRL[12].

Ohalo III

The Ohalo III facility[13] is currently being designed and developed by engineers and scientists at KSC and will be an environmentally-closed plant growth system to be deployed on the ISS and located within an EXpedite the PRocessing of Experiments to the Space Station (EXPRESS) rack. One flight unit and one Engineering Development Unit are planned. Unlike Veggie or APH, which were designed as plant research facilities to conduct a range of fundamental plant science experiments, Ohalo is being designed to address two specific objectives: 1) To explore novel water/nutrient delivery and volume optimization concepts, and 2) to be the first operational space crop production system. In this role, Ohalo will serve as both a system and technology demonstrator for a future Mars transit system and as a platform to select and validate crops for their potential incorporation as part of an exploration food system.

Beyond ISS/Commercial Low-Earth Orbit Destinations (CLD)

NASA is engaged with several companies regarding commercial space stations to continue NASA research in Low-Earth Orbit (LEO)[14]. Discussions with CLD providers regarding plant growth hardware and potential collaborations with international partners are happening at the time of writing this paper. Recently, industry provided feedback to NASA on a Request for Information for future Commercial LEO Destinations - Concept of Operations and Utilization[15]. NASA expects to continue to study space plant biology on commercial platforms, and it is unknown what types of crop growth systems commercial companies are considering for their customers, if any.

Regolith for Plant Growth

Regolith plant growth research may be important for long-term exploration, but in the near-term, low mass, low consumable use systems are needed that can be operated either in space or on a planetary surface. There are significant safety and operational concerns about lunar

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[12] J. Wetzel, R. Morrow, G. Tellez and D. Wyman, "XROOTS ISS tech demo of aeroponics and hydroponics nutrient delivery in microgravity," in International Conference on Environmental Systems, Calgary, 2023.
[13] Ohalo III in Techport, https://techport.nasa.gov/projects/97036.
[14] NASA, "Commercial Destinations in Low Earth Orbit," 18 05 2023. [Online]. Available: https://www.nasa.gov/leo-economy/commercial-destinations-in-low-earth-orbit. [Accessed 26 07 2023].
[15] GSA, "Request for Information for future Commercial LEO Destinations - Concept of Operations and Utilization," 30 05 2023. [Online]. Available: https://sam.gov/opp/33aeaf2871124821a7788acb038d602f/view#attachments-links. [Accessed 26 07 2023].

regolith[16]. As stated by Gene Cernan, “I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust.”[17]. Using regolith as a rooting medium on the Moon and Mars will require careful safety analyses and operational reviews. Other approaches, such as extracting nutrients from regolith or using leftover materials from ISRU, may be better alternatives for crops in surface systems. Versions of hydroponics or aeroponics remain more attractive in the near term for crop production.

[16] D. Ming and D. Henninger, Lunar Base Agriculture: Soils for Plant Growth, Madison, WI: Amer. Soc. Agronomy, 1989, p. 255.
[17] "Apollo 17 Technical Crew Debriefing, pg. 20-12" NASA, Houston, 1973 https://www.nasa.gov/wp-content/uploads/static/history/alsj/a17/AS17Tech4.pdf.

Appendix E Crop Readiness Levels for NASA Crops

Plant testing at Kennedy Space Center has a long history. From the 1960's to around 2000 most experiments used plants selected by principal investigators for scientific purposes and included mosses, pepper plants, roses, wheat, and Arabidopsis. Experiments became increasingly more complex during the shuttle and MIR era, but science was considered more important than producing edible crops. Since 2001, with the assembly of the International Space Station, KSC has screened more than 200 crops on the ground, NASA has screened 11 crops on the ISS, and the tables listed below provide a simple pass/fail data point for crops that have been tested in the past decade. A failure in any category does not necessarily mean a plant is out forever, but rather that more work may be required to have the crop pass that level. However, unique characteristics or specific crop performance criteria would likely be needed to justify spending extra resources to advance a plant that has failed at a certain point. Some tests may involve a risk analysis to justify advancing a crop if criteria cannot be met.

- CRL 1 is an assessment of crop growth descriptions and performance in seed catalogs, the scientific literature, or via other means, and considering how it might align with criteria discussed in Appendix B.
- CRL 2 is a general observation of plant health and performance that align with criteria discussed in Appendix B.
- CRL 3 is a similar assessment as CRL 2, except the plants are grown under ISS-like environmental conditions (≈22°C, ≈40% RH, ≈3000ppm CO_2, flight-like LED lighting).
- CRL 4 is microbiology testing. The testing identifies pathogens and measures yeast, mold, and bacteria. A crop can fail by having high bacterial, yeast, or mold counts above those of non-thermostabilized food standards. Having aerobic bacteria CFU/g fresh produce greater than 2×10^4 on a single sample or greater than 1×10^4 on two of five samples would fail. Yeasts and molds should not exceed 1000 CFU/g for any single sample. Testing also screens for potential food borne pathogens, such as *E. coli* and coliforms, *Salmonella* sp., and *S. aureus*, on the produce.
- CRL 5 combines chemistry analysis and acceptability testing into one pass/fail category. Chemistry assessment measures and tests for elements such as K, Mg, Fe, and Ca. Other elements like P, N, S, Na, and Zn are sometimes measured. Antioxidants, anthocyanins, and phenolics are also often analyzed in addition to Vitamins C, B1, and K. Chemistry is typically used to rank crops but not pass/fail crops. In the future as gene edited crops become more widely available, antinutritional chemicals and potential allergens might be assessed and could be a pass/fail criteria. Sensory acceptability testing can only be passed by testing at the JSC Food Laboratory. Crops must score average acceptability of at least 6 on a nine-point hedonic rating scale. Crops can fail informal tastings at KSC, which screen out crops that would have a low probability of passing at JSC. Radicchio is an example crop that failed at KSC due to a strong bitter flavor.
- CRL 6 involves various techniques to reduce microbial counts on the surface of seeds and maintain a high germination rate (e.g., >60%) or a low reduction in the starting germination rate (<30% reduction). Seed surface morphology and chemistry can impact chemical methods to reduce microbial counts. Passing or failing CRL 6 is normally based on a percentage of sanitized seeds that lack microbial/fungal growth after being placed on an agar plate, with the goal being no culturable microbial on an agar plate and maintaining germination.
- CRL 7 is similar to CRL 3, but the candidate crop is grown in ISS flight-like hardware such as Veggie or APH to assess crop performance in those hardware configurations.

- CRL 8 is similar to CRL 7, but crops are grown on the ISS or another space platform.
- CRL 9 involves growing the crop in space and then successfully consuming it.

KSC has tested more than 204 crops in the past ten years, and the lists below, separated by crop types, capture nearly all the crops tested in the past 10 years with the CRL's obtained by each. In addition to KSC testing high school and middle school citizen student scientists have performed plant testing for NASA as part of Growing Beyond Earth (GBE) challenge led by Fairchild Tropical Botanic Garden and funded by NASA OSTEM and SMD. More than 200 crops have been tested from 2015-2023. GBE crops that are chosen pass CRL 1 and crops are assessed based on aggregated data to determine if they pass CRL 2. Some GBE crops were first tested at KSC and re-tested by student citizen scientists, but most were new cultivars identified by Fairchild staff along with KSC personnel to expand the crop library. Out of more than 400 crops, there are 153 crops at CRL 3 awaiting testing and GBE has at least 47 crops at CRL 2 awaiting further screening at KSC. In total, there are 10 crops that have passed CRL 9 and so it is important to continue testing to find the starter set of crops for deep space human exploration.

Table E-1. Shows leafy green crops tested at Kennedy Space Center since about 2010.

	KSC Leafy Greens	Crop ID	Screening	Env Test	Micro	Chem/ Acceptability	Seed Sanitization	Flight-like test	Grown in Space	Eaten in Space	
Count	**Cultivar**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Family**
1	'Vit' Mache	P	P	P							Caprifoliaceae
2	Arugula	P	P								Brassicaceae
3	'Fiero' Radicchio	P	P	P		F					Asteraceae
4	Mizuna	P	P	P	P	P	P	P	P	P	Brassicaceae
5	'Outredgeous' Lettuce	P	P	P	P	P	P	P	P	P	Asteraceae
6	'Extra Dwarf' Pak Choi	P	P	P	P	P	P	P	P	P	Brassicaceae
7	'Bel' Radicchio	P	P	P		F					Asteraceae
8	'Dragoon' Lettuce	P	P	P	P	P	P	P	P	P	Asteraceae
9	'Eros' Escarole	P	P	P							Asteraceae
10	Sorrel, Green	P	P	P							Polygonaceae
11	'Amara' Mustard	P	P	P	P	P	P	P	P	P	Brassicaceae
12	Shungiku	P	P	P		P		F			Asteraceae
13	'Red Russian' Kale	P	P	P	P	P	P	P	P	P	Brassicaceae
14	Rubarb Chard	P	P			P	F				Chenopodiacea
15	Wasabi Mustard	P	P	P	P	P	P	P	P	P	Brassicaceae
16	'Toscano' Kale	P	P	P		P					Brassicaceae

Count	KSC Leafy Greens Cultivar	Crop ID 1	Screening 2	Env Test 3	Micro 4	Chem/ Acceptability 5	Seed Sanitization 6	Flight-like test 7	Grown in Space 8	Eaten in Space 9	Family
17	'Giant Red' Mustard	P	P	P		F					Brassicaceae
18	'Barese Swiss' Chard	P	P	P		P	F				Amaranthaceae
19	'Wasabina' Mustard	P	P	P							Brassicaceae
20	Wasabi Arugula	P	P	P							Brassicaceae
21	'Perseo' Radicchio	P	P	P		F					Asteraceae
22	'Indigo' Radicchio	P	P	P		F					Asteraceae
23	'Dwarf Grey' Sugar Pea	P	P								Fabaceae
24	'Bright Lights' Swiss Chard	P	P	P			F				Amaranthaceae
25	'Miz America' Kale	P	P	P		P					Brassicaceae
26	'Redbor' Kale	P	P	P		P					Brassicaceae
27	'Rainbow Candy Crush' Kale	P	P	P		P					Brassicaceae
28	'Red Tatsoi'	P	P	P		P					Brassicaceae
29	Dandelion	P	P								Asteraceae
30	Purslane, Golden	P	P	P		P					Portulacaceae
31	Garlic Mustard	P	F								Brassicaceae
32	Malabar Spinach	P									Basellaceae
33	Tokyo Bekana	P	P	P	P	P	P	...	F	P	Brassicaceae
34	Waldmann's Green Lettuce	P	P	P	P		P	P	P	P	Asteraceae
35	Bull's Blood Beet	P	P	F							Amaranthaceae
36	Tyee Spinach	P	F								Amaranthaceae
37	Flamingo Spinach	P	P	F							Amaranthaceae
38	Kudzu	P	P	P		P					Fabaceae

Table E-2. Shows pepper plant crops tested at Kennedy Space Center since about 2010.

	KSC Peppers	Crop ID	Screening	Env Test	Micro	Chem/Acceptability	Seed Sanitization	Flight-like test	Grown in Space	Eaten in Space	
Count	**Cultivar**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Family**
1	Rosette Red	P	P	P		P		F			Solanaceae
2	Mimi Red	P	P	P		P		F			Solanaceae
3	Compact Red	P	P	F							Solanaceae
4	Sweet Orange	P	P	P							Solanaceae
5	Red Skin	P	P	P		P					Solanaceae
6	Hot Fajita	P	P	P		P					Solanaceae
7	Joker	P	P	P							Solanaceae
8	Golden Pepper Yum Yum	P	P	F							Solanaceae
9	NuMex Espanola Improved	P	P	P	P	P	P	P	P	P	Solanaceae
10	Numex Heritage 6-4	P	P	F							Solanaceae
11	Bulgarian Carrot	P	P	P		P					Solanaceae
12	Big Jim Heritage	P	F								Solanaceae
13	Slovenia Hybrid	P	P								Solanaceae
14	Feher Ozon Paprika	P	F								Solanaceae
15	Ace F1 Bell	P	P								Solanaceae
16	Numex Piñata	P	P								Solanaceae
17	Tangerine Dream	P	P								Solanaceae
18	Garden Sunshine	P	P	F							Solanaceae
19	Italico	P	F								Solanaceae
20	Fruit Basket	P	P	P		P					Solanaceae
21	Chablis	P	P	F							Solanaceae
22	Pompeii	P	P	F		P					Solanaceae
23	Mohawk	P	P	P							Solanaceae
24	Cajun Belle	P	P	F							Solanaceae
25	Numex Halloween	P	F								Solanaceae
26	Numex Lemon Spice	P	F								Solanaceae
27	Cueno dwarf red	P	F								Solanaceae

Count	KSC Peppers Cultivar	Crop ID 1	Screening 2	Env Test 3	Micro 4	Chem/Acceptability 5	Seed Sanitization 6	Flight-like test 7	Grown in Space 8	Eaten in Space 9	Family
28	Cueno Dwarf Yellow	P	F								Solanaceae
29	Martinez Chimayo	P	P	P		P					Solanaceae
30	Chimayo	P	P								Solanaceae
31	"Altiplano F1" Serrano	P	P								Solanaceae
32	Big Dipper	P	P								Solanaceae
33	Golden Baby Bell Hybrid	P	P								Solanaceae
34	Hot Italian Pepperoncini	P	P								Solanaceae
35	Sweet Heat Pepper	P	P								Solanaceae
36	Hot Burrito Pepper	P	P								Solanaceae
37	Hot Joker	P	P								Solanaceae
38	Tamale	P	P								Solanaceae
39	Taquito	P	P								Solanaceae
40	Sweet Pickle Pepper	P	F								Solanaceae
41	Scorpion Pepper	P	F								Solanaceae

Table E-3. Shows tomato varieties tested at Kennedy Space Center since about 2010.

Count	KSC Tomato Cultivar	Crop ID 1	Screening 2	Env Test 3	Micro 4	Chem/ Acceptability 5	Seed Sanitization 6	Flight-like test 7	Grown in Space 8	Eaten in Space 9	Family
1	Ground Jewel-97	P	P	P		P					Solanaceae
2	Ground Dew-104	P	P	P		P					Solanaceae
3	Dwarf High Yielding 851	P	P	P		P					Solanaceae
4	Golden Harvest Cherry	P	P	P		P					Solanaceae
5	Sweet N' Neat	P	P	P		P					Solanaceae

Count	KSC Tomato Cultivar	Crop ID 1	Screening 2	Env Test 3	Micro 4	Chem/ Acceptability 5	Seed Sanitization 6	Flight-like test 7	Grown in Space 8	Eaten in Space 9	Family
6	Red Robin	P	P	P	P	P	P	P	F		Solanaceae
7	Mohamed	P	P	P	P	P					Solanaceae
8	Patio Princess	P	P	F							Solanaceae
9	Tumbler	P	P	F							Solanaceae
10	Tiny Tim	P	P	F							Solanaceae

Table E-4. Shows legume crops tested at Kennedy Space Center since about 2010.

Count	KSC Legumes Cultivar	Crop ID 1	Screening 2	Env Test 3	Micro 4	Chem/ Acceptability 5	Seed Sanitization 6	Flight-like test 7	Grown in Space 8	Eaten in Space 9	Family
1	PLS 0120	P	P	P							Fabaceae
2	PLS 0122	P	P	P							Fabaceae
3	Antigua	P	P	P		P					Fabaceae
4	4921	P	P	P		P					Fabaceae
5	Very Early Snap Pea/351-6-1	P	P	P							Fabaceae
6	Early Snap Pea Thick Pod/404-35-1-2-1	P	P	P							Fabaceae
7	Early Snap Pea, Dark Green/412-1-1	P	P	P							Fabaceae
8	Honey Snap (yellow)/274-1-2-1	P	P	P							
9	Acacia Leaf (snow pea)/299	P	P	P							Fabaceae
10	Multi Leaf (snow pea)/220-1-2	P	P	P							Fabaceae
11	Royal Snow (purple snow)/99-7-1-1	P	P	P							Fabaceae

	KSC Legumes	Crop ID	Screening	Env Test	Micro	Chem/ Acceptability	Seed Sanitization	Flight-like test	Grown in Space	Eaten in Space	
Count	**Cultivar**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Family**
12	Feisty pea	P	P	P							Fabaceae
13	Early Snap Pea/91E	P	P	P							Fabaceae
14	Early Snap Pea Thick Pod/404-51-2	P	P	P		P					Fabaceae
15	Early Snap Pea Thick Pod/404-52-2-1	P	P	P		P					Fabaceae
16	Early Snap Pea/430-1-4-1-2	P	P	P							Fabaceae
17	Royal Snap (purple snap)/337-1-1-3	P	P	P		P					Fabaceae
18	Yellow Snap/485-2	P	P	P		P					Fabaceae
19	'Tom Thumb'	P	P	P		F					Fabaceae
20	'Earligreen'	P	P	P							Fabaceae
21	Blue Bantam Dwarf	P	P	P							Fabaceae
22	Little SnapPea Crunch	P	P	P							Fabaceae
23	Little Marvel	P	P	P							Fabaceae
24	Velour Purple	P	P	P		F					Fabaceae
25	Russian peas	P	P	P		F					Fabaceae

Table E-5. Shows microgreen crops tested at Kennedy Space Center since about 2010.

	KSC Microgreens	Crop ID	Screening	Env Test	Micro	Chem/ Acceptability	Seed Sanitization	Flight-like test	Grown in Space	Eaten in Space	
Count	**Cultivar**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Family**
1	Alfalfa	P	P	P	F						Fabaceae
2	Arugula	P	P	P	F						Brassicaceae
3	Arugula, Wasabi	P	P	P		F					Brassicaceae
4	Basil, 'Dark Opal'	P	P	P							Lamiaceae
5	Basil, Lemon	P	P	P							Lamiaceae

Count	KSC Microgreens Cultivar	Crop ID 1	Screening 2	Env Test 3	Micro 4	Chem/ Acceptability 5	Seed Sanitization 6	Flight-like test 7	Grown in Space 8	Eaten in Space 9	Family
6	Beet, 'Bulls Blood'	P	P	P							Amaranthaceae
7	Broccoli	P	P	P	F						Brassicaceae
8	Brussel Sprouts	P	P	P							Brassicaceae
9	Borage	P	P	P							Boraginaceae
10	Buckwheat, Groats	P	P	P	F	P					Polygonaceae
11	Buckwheat, OG	P	P	F	F						Polygonaceae
12	Buckwheat, Shoot	P	P	F	F						Polygonaceae
13	Cabbage, 'Mammoth Red Rock'	P	P	P	F						Brassicaceae
14	Cabbage, Red	P	P	P	F						Brassicaceae
15	Cantaloupe	P	P	F		P					Cucurbitaceae
16	Cauliflower, 'Y Improved'	P	P	P	F						Brassicaceae
17	Chia	P	P	P		F					Lamiaceae
18	Cilantro	P	P	P		P					Apiaceae
19	Chinese Cabbage 'Tokyo Bekana'	P	P	P	F		P				Brassicaceae
20	Chives, Garlic	P	P	P							Amaryllidaceae
21	Collards, 'Vates'	P	P	P		P					Brassicaceae
22	Cress, Cressida	P	P	P		F					Brassicaceae
23	Cress, Persian	P	P	P		P					Brassicaceae
24	Cress, 'Upland'	P	P	P							Brassicaceae
25	Dandelion, Red	P	P	P	F						Asteraceae
26	Dill	P	P	P							Apiaceae
27	Fennel	P	P	P							Apiaceae
28	Fenugreek	P	P	P							Fabaceae
29	Mustard 'Golden Frills'	P	P	P	F						Brassicaceae
30	Kale, 'Dwarf Siberian'	P	P	P	F						Brassicaceae

Count	KSC Microgreens Cultivar	Crop ID 1	Screening 2	Env Test 3	Micro 4	Chem/ Acceptability 5	Seed Sanitization 6	Flight-like test 7	Grown in Space 8	Eaten in Space 9	Family
31	Kale, 'Red Russian'	P	P	P	F		P				Brassicaceae
32	Kale, Toscano	P	P	P	F						Brassicaceae
33	Kale, 'Vates Blue Scotch Curled'	P	P	P	F						Brassicaceae
34	Kohlrabi, Purple	P	P	P							Brassicaceae
35	Kohlrabi, White	P	P	P		P					Brassicaceae
36	Komatsuna	P	P	P	F						Brassicaceae
37	Lentils	P	P	P							Fabacea
38	Lettuce Mix, Mucelum	P	P	P							Asteraceae
39	Marjaram	P	P	P							Lamiaceae
40	Mizuna	P	P	P	F		P				Brassicaceae
41	Mizuna, 'Red Kingdom'	P	P	P	F						Brassicaceae
42	Mung Beans	P	P	P		P					Fabacea
43	Mustard, 'Garnet Giant'	P	P	P	F						Brassicaceae
44	Mustard, 'Scarlet Frills'	P	P	P	F						Brassicaceae
45	Mustard, 'Wasabi'	P	P	P	F	P	P				Brassicaceae
46	Orach	P	P	F							Amaranthaceae
47	Pac Choi, Red	P	P	P	F						Brassicaceae
48	Pac Choi, 'Rosi'	P	P	P	F						Brassicaceae
49	Pac Choi, White Stem	P	P	P	F	P					Brassicaceae
50	Pac Choi, White Stem Extra Dwarf	P	P	P	F		P				Brassicaceae
51	Parsley	P	P	P							Apiaceae
52	Pea, Dun	P	P	P		P					Fabaceae
53	Pea, 'Dwarf Grey Sugar'	P	P	P		P					Fabaceae
54	Pea, Mammoth Melting Sugar'	P	P	P		P					Fabaceae
55	Quinoa	P	P	P							Amaranthaceae

Count	KSC Microgreens Cultivar	Crop ID 1	Screening 2	Env Test 3	Micro 4	Chem/ Acceptability 5	Seed Sanitization 6	Flight-like test 7	Grown in Space 8	Eaten in Space 9	Family
56	Radish, Daikon	P	P	P	F	P					Brassicaceae
57	Radish, Daikon (white)	P	P	P	F						Brassicaceae
58	Radish, 'Red Rambo'	P	P	P	F						Brassicaceae
59	Rutabaga	P	P	P	F	P					Brassicaceae
60	Shiso	P	P	P		F					Lamiaceae
61	Shungiku	P	P	F	F						Asteraceae
62	Shungiku, Broadleaf	P	P	F	F						Asteraceae
63	Sunflower, 'Black Oil'	P	P	P	F	P					Asteraceae
64	Sunflower, 'Grey Striped'	P	P	P	F	P					Asteraceae
65	Swiss Chard, Yellow	P	P	P							Amaranthaceae
66	Tatsoi	P	P	P							Brassicaceae
67	Turnip, 'Purple Top White Globe'	P	P	P	F						Brassicaceae

Table E-6. Shows various herbs tested at Kennedy Space Center since about 2010.

Count	KSC Herbs Cultivar	Crop ID 1	Screening 2	Env Test 3	Micro 4	Chem/ Acceptability 5	Seed Sanitization 6	Flight-like test 7	Grown in Space 8	Eaten in Space 9	Family
1	Lemon Basil	P	P	P							Lamiaceae
2	Parsley	P	P	P							Apiaceae
3	Fernleaf Dill	P	P	P							Apiaceae
4	Peppermint	P	P	F							Lamiaceae
5	Basil Prospera Compact	P	P	P							Lamiaceae
6	Oregano, 'Greek'	P	P	P							Lamiaceae
7	Cilantro	P	P	P							Apiaceae
8	Emily Basil	P	P	P							Lamiaceae
9	Lemon Balm	P	P	P							Lamiaceae

	KSC Herbs	Crop ID	Screening	Env Test	Micro	Chem/ Acceptability	Seed Sanitization	Flight-like test	Grown in Space	Eaten in Space	
Count	**Cultivar**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Family**
10	Chives	P	P	F							Amaryllidaceae
11	Amythyst Basil	P	P	P							Lamiaceae
12	Teddy dill	P	P	P							Apiaceae
13	Fenugreek	P	P	P							Fabaceae
14	Spearmint	P	P	P							Lamiaceae
15	Mountain Mint	P	P	P							Lamiaceae
16	Fennel	P	P	F							Apiaceae

Table E-7. Shows various crops tested at Kennedy Space Center since about 2010. The Cherry Belle Radish was tested at KSC and on ISS as part of PH-02.

	KSC Misc.	Crop ID	Screening	Env Test	Micro	Chem/ Acceptability	Seed Sanitization	Flight-like test	Grown in Space	Eaten in Space	
Count	**Cultivar**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Family**
1	H-10 Cucumber	P	P	P							Cucurbitaceae
2	Iznick Hybrid Cucumber	P	P	P							Cucurbitaceae
3	Minnesota Midget Melon	P	P	P		F					Cucurbitaceae
4	Early Silverline Melon	P	P	P		F					Cucurbitaceae
5	Cherry Belle Radish[1]	P	P	P	P	…	P	P	P	P	Brassicaceae
6	Delizz Strawberry	P	P	P	P	P					Rosaceae
7	Temptation Strawberry	P	P	P	P	F					Rosaceae
8	Pineberry Strawberry	P	P	F							Rosaceae

[1] Hasenstein, K.H.; John, S.P.; Vandenbrink, J.P. Assessing Radish Health during Space Cultivation by Gene Transcription. *Plants* **2023**, *12*, 3458. https://doi.org/10.3390/plants12193458

Table E-8. NASA funded and Fairchild Tropical Botanic Garden led, Growing Beyond Earth leafy green crops tested between 2015 and 2023.

Count	Growing Beyond Earth Leafy Green Cultivars	1	2	Family
1	Outredgeous (GBE1)	P	P	Asteraceae
2	Tokyo Bekana (GBE2)	P	P	Brassicaceae
3	Redleaf amaranth (GBE3)	P	P	Amaranthaceae
4	Red Orach (GBE4)	P	F	Amaranthaceae
5	Bright Lights Swiss Chard (GBE5)	P	P	Amaranthaceae
6	Babybeat (GBE6)	P	P	Amaranthaceae
7	Strawberry spinach (GBE7)	P	F	Amaranthaceae
8	Saltwort (GBE8)	P	F	Amaranthaceae
9	Red Kitten Spinach (GBE9)	P	F	Amaranthaceae
10	Koidzumi Ashitaba (GBE11)	P	F	Apiaceae
11	Natacha Escarole (GBE14)	P	P	Asteraceae
12	Shungiku (GBE15)	P	P	Asteraceae
13	Starfighter Lettuce (GBE16)	P	P	Asteraceae
14	Rubra red malabar spinach (GBE17)	P	P	Basellaceae
15	Upland cress (GBE18)	P	P	Brassicaceae
16	Misome (GBE19)	P	P	Brassicaceae
17	Toscano Kale (GBE20)	P	P	Brassicaceae
18	Starbor Kale (GBE21)	P	P	Brassicaceae
19	Quickstar Kohlrabi (GBE22)	P	F	Brassicaceae
20	Komatsuna (GBE23)	P	P	Brassicaceae
21	Mizuna (GBE24)	P	P	Brassicaceae
22	Tatsoi (GBE25)	P	P	Brassicaceae
23	Minuet Chinese cabbage (GBE26)	P	P	Brassicaceae
24	White wall rocket (GBE27)	P	F	Brassicaceae
25	Sylvetta (GBE28)	P	P	Brassicaceae
26	Arugula (GBE29)	P	P	Brassicaceae
27	Persian cress (GBE30)	P	P	Brassicaceae
28	Molokhia (GBE33)	P	F	Malvaceae
29	Minutina (GBE34)	P	P	Plantaginaceae
30	Sorrel (GBE35)	P	P	Polygonaceae
31	Goldberg golden purslane (GBE36)	P	P	Portulacaceae
32	Watercress (GBE37)	P	F	Brassicaceae
33	New Zealand Spinach (GBE38)	P	F	Aizoaceae
34	Good King Henry (GBE39)	P	F	Amaranthaceae
35	Spring Tower celtuce (GBE41)	P	P	Asteraceae
36	Papalo (GBE42)	P	F	Asteraceae
37	Collard (GBE43)	P	F	Brassicaceae
38	Win-win Choi (GBE45)	P	P	Brassicaceae
39	Cressida (GBE46)	P	P	Brassicaceae

Count	Growing Beyond Earth Leafy Green Cultivars	1	2	Family
40	Mache (GBE47)	P	F	Caprifoliaceae
41	Red Shiso (GBE48)	P	P	Lamiaceae
42	Green Shiso (GBE49)	P	P	Lamiaceae
43	Roselle (GBE50)	P	F	Malvaceae
44	Miner's lettuce (GBE51)	P	F	Montiaceae
45	Pepper elder (GBE52)	P	F	Piperaceae
46	Water pepper (GBE53)	P	F	Polygonaceae
47	Salad burnet (GBE54)	P	P	Rosaceae
48	Empress of India nasturtium (GBE55)	P	P	Tropaeolaceae
49	Extra dwarf Pak Choi (GBE56)	P	P	Brassicaceae
50	Cicoria spadena da taglia (chicory) (GBE57)	P	F	Asteraceae
51	Emperor Chinese Kale (GBE58)	P	F	Brassicaceae
52	Pak Choi (Purple magic) (GBE59)	P	P	Brassicaceae
53	Yhod Fah Chinese Kale (GBE60)	P	F	Brassicaceae
54	Garland round leaved shungiku (GBE61)	P	P	Asteraceae
55	Large leaf tong ho shungiku (GBE68)	P	P	Asteraceae
	Dragon’s tongue (GBE78)	P	P	Brassicaceae
56	Yellow velvetleaf (GBE81)	P	F	Alismataceae
57	Maquarie Island Cabbage (GBE82)	P	F	Araliaceae
58	Dragoon Lettuce (GBE83)	P	P	Asteraceae
59	Koji F1 (GBE90)	P	F	Brassicaceae
60	Lime Streak mizuna (GBE95)	P	P	Brassicaceae
61	Yukina Savoy/chijimina chinese cabbage (GBE96)	P	P	Brassicaceae
62	Early Mizuna (E) (GBE97)	P	P	Brassicaceae
63	Red Tatsoi Pac Choi (GBE98)	P	P	Brassicaceae
64	Toy Choi/shakushina (GBE99)	P	P	Brassicaceae
65	Beka Santoh Chinese Cabbage (BS) (GBE100)	P	P	Brassicaceae
66	Mibuna, Early (GBE101)	P	P	Brassicaceae
67	Mizuna (GBE102)	P	P	Brassicaceae
68	Mizuna (Seeds of Change) (GBE103)	P	P	Brassicaceae
69	Li Ren Pac Choi (GBE104)	P	P	Brassicaceae
70	Prizm Kale (GBE105)	P	P	Brassicaceae
71	Wasabi Arugula (GBE107)	P	P	Brassicaceae
72	Waldmann’s dark green MT0 OG lettuce (GBE108)	P	P	Asteracea
73	Wasabina Mustard (JS) (GBE109)	P	P	Brassicacea
74	Choho (GBE110)	P	P	Brassicaceae
75	Karashina Wasabina (GBE111)	P	P	Brassicaceae
76	Micro greens Borage (GBE112)	P	F	Boraginaceae
77	Amara Mustard (GBE113)	P	P	Brassicaceae

Count	Growing Beyond Earth Leafy Green Cultivars	1	2	Family
78	Wasabi Mustard (MV) (GBE114)	P	P	Brassicaceae
79	Red Pac F1 Pac Choi (GBE115)	P	P	Brassicaceae
80	Black summer F1 Pac Choi (GBE116)	P	P	Brassicaceae
81	Mei Quing Choi F1 Pac Choi (GBE117)	P	P	Brassicaceae
82	Shiro F1 Pac Choi (GBE118)	P	P	Brassicaceae
83	Truchas OG MT0 Romaine Lettuce (GBE119)	P	P	Asteraceae
84	Rosie F1 Hybrid Pac Choi (GBE120)	P	P	Brassicaceae
85	Salanova Red incised MT0 OG-Pelleted (GBE121)	P	P	Asteraceae
86	Red Russian kale (GBE122)	P	P	Brassicaceae
87	Puerto Rican Lettuce (GBE123)	P	P	Asteraceae
88	Purslane (GBE132)	P	P	Portulacaceae
89	Lovage (GBE133)	P	F	Apiaceae
90	Delight Pak Choi (GBE135)	P	P	Brassicaceae
91	Butterhead Flandria (pelleted) lettuce (GBE136)	P	P	Asteraceae
92	Flashy Trout's Back lettuce (GBE137)	P	P	Asteraceae
93	Yuushou F1 Pac Choi (GBE138)	P	P	Brassicaceae
94	Bopak F1 Pac Choi (GBE139)	P	P	Brassicaceae
95	Alkindus (pelleted) lettuce (GBE140)	P	P	Asteraceae
96	Buttercrunch lettuce (GBE141)	P	P	Asteraceae
97	Red Spike amaranth (GBE192)	P	F	Amaranthaceae
98	Red Leaf Specialty amaranth (GBE193)	P	P	Amaranthaceae
99	Garnet Red (microgreen) amaranth (GBE200)	P	P	Amaranthaceae
100	Narinosa misome (GBE201)	P	P	Brassicaceae
101	Pekinensis chinese cabbage (GBE202)	P	P	Brassicaceae
102	Seaside F1 smooth leaf spinach (GBE203)	P	P	Amaranthaceae

Table E-9. NASA funded and Fairchild Tropical Botanic Garden led, Growing Beyond Earth herb crops tested between 2015 and 2023.

Count	Growing Beyond Earth Herb Cultivars	1	2	Family
1	Parade Bunching Onions (GBE10)	P	F	Amaryllidaceae
2	Samphire (GBE12)	P	F	Apiaceae
3	Pluto fine leaf basil (GBE32)	P	P	Lamiaceae
4	Calypso cilantro (GBE40)	P	F	Apiaceae
5	Kinh gioi (GBE63)	P	F	Lamiaceae
6	Mitsuba (GBE64)	P	F	Apiaceae
7	Korean minari flamingo (GBE65)	P	F	Apiaceae
8	Fenugreek (GBE66)	P	F	Fabaceae

Count	Growing Beyond Earth Herb Cultivars	1	2	Family
9	Toothache plant (GBE67)	P	P	Asteraceae
10	Ice plant (GBE69)	P	P	Aizoaceae
11	Stevia (GBE70)	P	F	Asteraceae
12	Cook's scurvy grass (GBE71)	P	P	Brassicaceae
13	Lemon Balm (GBE72)	P	P	Lamiaceae
14	Lisette (GBE73)	P	P	Apiaceae
15	Dill (GBE74)	P	P	Apiaceae
16	Rosemary (GBE79)	P	P	Lamiaceae
17	Dwarf Moringa (GBE80)	P	P	Moringaceae
18	"red gem" marigold (GBE85)	P	F	Asteraceae
19	"tangerine" marigold (GBE86)	P	F	Asteraceae
20	Borage (GBE87)	P	P	Boraginaceae
21	Cilantro (GBE91)	P	F	Apiaceae
22	Savory (GBE92)	P	F	Lamiaceae
23	Thai Basil (GBE93)	P	P	Lamiaceae
24	Greek Oregano (GBE94)	P	F	Lamiaceae
25	Wega parsley (GBE147)	P	P	Apiaceae
26	Oregano (GBE148)	P	F	Lamiaceae
27	Holy Green (GBE149)	P	F	Lamiaceae
28	Sweet basil (GBE150)	P	P	Lamiaceae
29	Finocchio fennel (GBE159)	P	P	Apiaceae
30	Broadleaf sage (GBE160)	P	P	Lamiaceae
31	Santo cilantro (GBE161)	P	P	Apiaceae
32	Fernleaf dill (GBE162)	P	P	Apiaceae
33	Confetti cilantro (GBE163)	P	P	Apiaceae
34	Persian basil (GBE164)	P	P	Lamiaceae
35	Cinnamon basil (GBE165)	P	P	Lamiaceae
36	Chinese Sweet basil (GBE166)	P	P	Lamiaceae
37	Purple ball basil (GBE167)	P	P	Lamiaceae
38	Genovese "prosepera compact" (pelleted) basil (GBE168)	P	P	Lamiaceae
39	Genovese "prospera compact" (non-pelleted) basil (GBE169)	P	P	Lamiaceae
40	Tarragon, French (GBE170)	P	F	Asteraceae
41	Vertissimo chevril (GBE171)	P	F	Apiaceae
42	Grossfruchtiger fennel (GBE172)	P	P	Apiaceae
43	Darki parsley (GBE173)	P	F	Apiaceae
44	Lettuce Leaf basil (GBE174)	P	P	Lamiaceae
45	Dark Purple Opal basil (GBE175)	P	P	Lamiaceae
46	Mountain Mint (GBE176)	P	F	Lamiaceae
47	Peppermint (GBE178)	P	F	Lamiaceae

Count	Growing Beyond Earth Herb Cultivars	1	2	Family
48	Mammolo basil (GBE179)	P	P	Lamiaceae
49	Blue Spice basil (GBE180)	P	P	Lamiaceae
50	Emily basil (GBE181)	P	P	Lamiaceae
51	Lime basil (GBE182)	P	P	Lamiaceae
52	Thai Sweet basil (GBE183)	P	P	Lamiaceae
53	Thai Hily "Kaprao" basil (GBE184)	P	P	Lamiaceae
54	African Nunum basil (GBE185)	P	F	Lamiaceae
55	Lemon basil (GBE186)	P	P	Lamiaceae
56	Ghana Akokomesa basil (GBE187)	P	F	Lamiaceae
57	Dolce Fresca basil (GBE188)	P	P	Lamiaceae
58	Newton basil (GBE189)	P	P	Lamiaceae
59	Everleaf Emerald Tower basil (GBE190)	P	P	Lamiaceae
60	Geisha garlic chives (GBE191)	P	P	Amaryllidaceae
61	Pink Dandelion (GBE196)	P	F	Asteraceae
62	Sativa purslane (GBE199)	P	F	Portulacaceae
63	Red Ruben basil (GBE204)	P	F	Lamiaceae
64	Nebechan bunching onions (GBE205)	P	P	Amaryllidaceae
65	Common chamomile (GBE206)	P	F	Asteraceae
66	Roman chamomile (GBE207)	P	F	Asteraceae
67	Officinalis sage (GBE208)	P	P	Lamiaceae
68	Pilosum mountain mint (GBE209)	P	F	Lamiaceae
69	Scardica mountain mint (GBE210)	P	P	Lamiaceae
70	Patula durango outback mix (GBE211)	P	P	Asteraceae
71	Angustifolia lavendar (GBE212)	P	F	Lamiaceae
72	Mandarina lemon balm (GBE213)	P	F	Lamiaceae

Table E-10. NASA funded and Fairchild Tropical Botanic Garden led, Growing Beyond Earth pepper plant crops tested between 2015 and 2023.

Count	Growing Beyond Earth Pepper Cultivars	1	2	Family
1	Pepper sweet pickle (GBE77)	P	P	Solanaceae
2	Sweet Chocolate pepper (GBE88)	P	P	Solanaceae
3	Hungarian Stuffing Pepper (GBE106)	P	F	Solanaceae
4	Martinez Farm pepper (GBE142)	P	P	Solanaceae
5	Pepper chablis hybrid (GBE76)	P	P	Solanaceae

Table E-11. NASA funded and Fairchild Tropical Botanic Garden led, Growing Beyond Earth tomato plant crops tested between 2015 and 2023.

Count	Growing Beyond Earth Tomato Cultivars	1	2	Family
1	Tomato Red Robin (GBE75)	P	P	Solanaceae

Table E-12. NASA funded and Fairchild Tropical Botanic Garden led, Growing Beyond Earth legume crops tested between 2015 and 2023.

Count	Growing Beyond Earth Legumes Cultivars	1	2	Family
1	Dwarf grey sugar peas (GBE84)	P	P	Fabacaea
2	Petite snap-greens peas (GBE89)	P	P	Fabaceae
3	Feisty pea (GBE129)	P	P	Fabaceae
4	Royal Snow pea (GBE130)	P	P	Fabaceae
5	Golden Sweet pea (GBE131)	P	P	Fabaceae
6	Little snowpea white pea (GBE145)	P	P	Fabaceae
7	Little snowpea purple pea (GBE146)	P	P	Fabaceae
8	California Blackeye Pea cowpea (GBE197)	P	P	Fabaceae
9	Ozark Razorback cowpea (GBE198)	P	P	Fabaceae

Table E-13. NASA funded and Fairchild Tropical Botanic Garden led, Growing Beyond Earth miscellaneous crops tested between 2015 and 2023.

Count	Growing Beyond Earth Misc. Cultivars	1	2	Family
1	Atlantis mini broccoli (GBE44)	P	F	Brassicaceae
2	Dark green cutting celery (GBE62)	P	F	Apiaceae
3	Baby Hybrid cauliflower (GBE143)	P	P	Brassicaceae
4	Green Stem Song TJS-65 (F1) cauliflower (GBE144)	P	P	Brassicaceae
5	Apollo brocolli (GBE230)	P	P	Brassicaceae
6	Hybrid Mini Broccoli (GBE233)	P	P	Brassicaceae
7	Mokum Carrot (GBE13)	P	P	Apiaceae
8	Cherriett radish (GBE31)	P	P	Brassicaceae
9	Mini Mak F1 radish (GBE124)	P	P	Brassicaceae
10	Sora radish (GBE125)	P	P	Brassicaceae
11	Easter Egg II radish (GBE126)	P	P	Brassicaceae
12	Pink Beauty radish (GBE127)	P	P	Brassicaceae

Count	Growing Beyond Earth Misc. Cultivars	1	2	Family
13	Bacchus F1 radish (GBE128)	P	P	Brassicaceae
14	Cherry Belle radish (GBE151)	P	P	Brassicaceae
15	Crunchy Crimson radish (GBE152)	P	P	Brassicaceae
16	Karami Green radish (GBE153)	P	F	Brassicaceae
17	French Breakfast radish (GBE154)	P	P	Brassicaceae
18	Roxanne F1 Radish (GBE155)	P	P	Brassicaceae
19	Celesta F1 Radish (GBE156)	P	P	Brassicaceae
20	Dragon F1 Radish (GBE157)	P	P	Brassicaceae
21	Red Head Radish (GBE158)	P	P	Brassicaceae
22	Fresh Pak F1 beet (GBE194)	P	P	Amaranthaceae
23	Early Wonder Tall Top beet (GBE195)	P	P	Amaranthaceae
24	Donato F1 radish (GBE218)	P	P	Brassicaceae (Cruciferae)
25	Longipinnatus radish (GBE219)	P	P	Brassicaceae (Cruciferae)

Appendix F Space Crop Systems Data for Vehicles and Missions

Long term, sustainable living off-Earth will require systems that produce foods, renew air and water, and recycle waste. This is because of the logistical challenges of space transportation. "*Thriving in Space: Ensuring the Future of Biological and Physical Sciences Research: A Decadal Survey for 2023-2032"* [1] devoted a major campaign to improving the technology readiness level (TRL) of a biological life support system (BLiSS). A complete BLiSS needs to produce food from available resources, renew the air and water, and pull essential nutrients (for the BLiSS) out of waste streams. Each of these functions can be its own module or subsystem and designing a BLiSS requires understanding the performance of each of these functions at different scales.

The Kennedy Space Center focuses on space crop production, so for the purposes of this appendix will define the inputs and outputs of crop production systems to provide more details and examples of items that should be measured for designers and analysts considering how to calculate Equivalent System Mass (ESM) for crop systems. Several publications on ESM and life support systems have been published [2,3,4,5] and we do not intend to review them but rather provide details to consider for crop systems. Estimating mass, power, and volume is difficult due to large uncertainties in the design of the systems. For example, whether a cropping system is open or closed and the pressures and atmospheres that they are designed to operate under will have significant implications on power usage, and potentially crop productivity.

It helps to understand what may or may not be part of a cropping system. Elements of a space crop production system include the volume for growing the crop, lighting, watering systems, nutrient systems for providing essential nutrients to the crop, a "rooting" zone for anchoring the crop and delivering water and nutrients, humidity control systems, atmospheric control systems for gas mixing, ventilation, and thermal control, avionics systems for automating and commanding. In addition, there are sub systems to utilize power, move fluids, exchange heat, take photographs, make measurements (environmental and engineering), etc. Automated planting and harvesting will not be considered here, but these may play an important role in future systems as crop production scales up. Depending on the design of the crop system, some functions may be shared with space craft or habitat systems. For example, the two state of the art (SOA) growth systems on ISS, Veggie and Advanced Plant Habitat (APH), are very different in their designs. APH is complex and self-contained, hosting all functions internally including a CO_2 cylinder to replace CO_2 used by the plants. APH typically does not require significant crew time except at harvest or resetting with a new root tray, but it uses considerable amounts of power, with a large portion going to recondensing the plant transpiration stream. On the

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[1] National Academies of Sciences, Engineering, and Medicine, "Thriving in Space: Ensuring the Future of Biological and Physical Sciences Research: A Decadal Survey for 2023-2032," The National Academies Press, Washington, DC, 2023.

[2] Levri, J.A.; Fisher, J.W.; Jones, H.W.; Drysdale, A.E.; Ewert, M.K.; Hanford, A.J.; Hogan, J.A.; Joshi, J.A.; Vaccari, D.A.; Advanced Life Support Equivalent System Mass Guidelines Document, NASA/TM-2003-212278, 2003.

[3] Drysdale, A., "Life Support Trade Studies Involving Plants," SAE Technical Paper 2001-01-2362, 2001.

[4] Lucie Poulet, Conrad Zeidler, Jess Bunchek, Paul Zabel, Vincent Vrakking, Daniel Schubert, Gioia Massa, Raymond Wheeler, Crew time in a space greenhouse using data from analog missions and Veggie, Life Sciences in Space Research, 31, 2021, pp 101-112.

[5] Ewert, M.K.; Chen, T.T.; Powell, C.D.; Life Support Baseline Values and Assumptions Document, NASA/TP-2015-218570/REV2, 2022.

other hand, Veggie's design off loads most of its environmental control functions to the ISS and the crew. It does not have humidity, temperature, or CO_2 control, or an automated watering system. Temperature and atmosphere composition are determined by the station. Humidity is enhanced in the growth area by the adjustable bellows around the growth space trapping some of the transpiration stream around the plants which may elevate humidity levels above cabin ambient. The atmosphere (cabin air) is pulled through Veggie by an internal fan. Watering is currently done by hand, leading to many over or under watering challenges as described by Scott Kelly in his memoir "Endurance" where he describes rescuing the famous space zinnias and bringing some of them to flowering. While Veggie is energy and system "light" compared to APH, those burdens are transferred directly to the spacecraft ECLSS system and the crew.

The current SOA systems are small (2-4 Middeck Locker Equivalents (MLEs)) and are not sufficient for generating significant amounts of food or oxygen, or removing appreciable amounts of CO_2. It is easy to imagine that in future Lunar or Martian habitats the astronauts and the plants would be sharing large living spaces, particularly if the plants are providing all of the necessary food and oxygen for the astronauts. Under moderate lighting ~50 m^2 of crop growth to provide sufficient food calories for each crew member while ~20 m^2 of crops would provide all of the oxygen[6,7]. Under these conditions many of the ECLSS functions would either be shared or shifted entirely to the BLiSS system. For example, Veggie currently off loads the entire plant transpiration stream to the ECLSS while creating a minute reduction in the ECLSS CO_2 load because it directly takes CO_2 from cabin air and converts it to biomass. In a fully scaled BLiSS the majority of the humidity removal would need to be handled by the BLiSS because 50 m^2 of plants in a hydroponic system will transpire 250 - 500 L of water per day[8]. Most of this can be water simply recondensed and fed back to the plants. Some could be cleanly captured and stored and provided as potable water to the crew. At that scale, all of the CO_2 removal and oxygen generation would be performed by the plants in the BLiSS, but a backup system might be required for redundancy. A true BLiSS remains a tantalizing goal because by regenerating all of the fresh and nutritious foods that a crew would need, while simultaneously providing them with water and oxygen, the resupply up mass is nearly or completely eliminated. The resupply would be reduced to essential parts that can't be made or regenerated locally.

NASA has long used the metric Equivalent System Mass (ESM) in trade studies to compare technologies and operational concepts for specified missions, especially in Advanced Life Support or Bioregenerative Projects. ESM is a rollup metric that captures mass, power, cooling power, volume, and crew time as a function of mission duration. ESM is only as good as the data and assumptions used to calculate the metric, and thus the inputs and outputs are critical aspects of understanding the overall system. Capturing and accounting for the systems, sub-systems, spare parts, and consumable items enables a clearer understanding of how a crop production facility will operate and provides vehicle and habitat designers a better understanding of the system requirements. The tables below are intended to allow vehicle and habitat designers to ask questions and for space crop production system engineers to better

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[6] K. Corey and R. Wheeler, "Gas exchange in NASA's biomass production chamber: a preprototype closed human life support system," Bioscience, Vols. Jul-Aug;42, no. 7, pp. 503-9, 1992.
[7] B. Yandell, A. Najar, R. Wheeler and T. Tibbitts, "Modeling the effects of light, carbon dioxide, and temperature on the growth of potato," Crop Sci., vol. 28, no. 5, pp. 811-8, Sept-Oct 1988.
[8] R. Wheeler, C. Mackowiak, G. Stutte, N. Yorio, L. Ruffe, J. Sager, R. Prince and W. Knott, "Crop productivities and radiation use efficiencies for bioregenerative life suppor," Advances in Space Research, vol. 41, no. 5, pp. 706-713, 2008.

understand how systems impact vehicles and habitats. Ultimately, these are the questions that will need to be answered for any system that may be considered for space crop production.

The tables listed below are a starting point to enable discussions and trades. They capture major inputs and outputs of crop systems. Some outputs such as meals augmented do not cleanly fall within ESM but have value and warrant highlighting and discussion.

Inputs	Crew Time (hrs)	Notes
Initiate crop growth		Sum total of all activities and account for crew members to initiate crops per system. The number and types of crops grown in the system should be listed to calculate crew time per crop to initiate. The hours should be summed over the mission.
Crop care		Sum total of all activities accounting for crew to care for crops through harvest. The crew time should be per system and the number and type of crop should be listed to calculate crew time per crop to grow. The hours should be summed over the mission.
Harvest		Sum total of all activities to successfully complete a harvest including post-harvest activities needed to safe crops for consumption or storage. The crew time should be per system and the number of crops should be listed, the type of crops should be listed, and the type of harvest should be listed to calculate crew time per crop for harvest and harvest type. The hours should be summed over the mission.
System Maintenance		Sum total of all activities needed to operate and maintain the crop growth system over the mission accounting for the crops grown, crop schedule, expected maintenance, expected cleaning, expected parts replacements per unit over the mission.

Inputs	Mass (kg)	Volume (m3)	Power (W)	Notes
Crop Growth System				Mass, volume, and power of the crop growth system(s) to complete the mission. If more than one unit, then it should be indicated.

Inputs	Mass (kg)	Volume (m3)	Power (W)	Notes
Crop Growth System Spares (all)				Spares needed to complete mission (mission definition).
Crop Growth System Tools (all)				Tool examples harvest tools, cleaning tools, water transfer bags, microbial safety tools. All tools needed to complete mission (mission definition).
Crop Growth System Consumable items (all)				Consumable item examples, wipes, cleaning fluids, acid/base for pH control, adapters, swabs, cartridges, syringes, gloves. All consumables needed to complete the mission (mission definition).
Crop Growth System Post Processing Consumable items (all)				Consumable item examples storage bags, gloves, etc. All post-harvest consumables needed to complete the mission (mission definition).
Seeds/propagules (all)				All seeds/propagules needed to complete the mission stored at room temperature (mission definition).
Fertilizer (all)				Fertilizer in undiluted form needed for all crop growth. Can be controlled release fertilizer, encapsulated salts, concentrated fluids. All fertilizers needed to complete the mission (mission definition).
Water				Quantity of water needed to prime the system, grow plants, clean the system, rinse the system, and other water uses. All water needed to complete the mission (mission definition).
Carbon Dioxide				Quantity of CO_2 needed to grow the plants. Total CO_2 needed to grow the plants for the mission and expected CO_2 consumption rate for the mission.
Oxygen				Starting quantity of oxygen required for germination. This is small, but required during germination when plants respire heavily and photosynthesize very little.

Inputs	Mass (kg)	Volume (m3)	Power (W)	Notes
Systems Associated with Crop Growth				Systems required to grow crops and safely eat them that are not tightly coupled or connected to the Crop Growth System (unaccounted mass/volume/power). An example could be an external plasma production system to create plasma activated water or an in-situ H_2O_2 production system as possible examples, and any consumables required to ensure safety of these devices in the closed spaceflight environment.
Data				Data rates and amounts needed to monitor and control plant growth system(s). Mbps and total per data per day per system.

Outputs	Mass (kg)	Volume (m3)	Power (W)	Notes
Edible biomass				Mass of crops harvested noting crop type and number of crops.
Inedible plant matter				Mass of inedible plant parts and associated materials for a harvest noting crop type and number of crops.
Water vapor				Quantity of water expelled into the cabin from plant contribution. This can be calculated based on water usage. For instance, if there are 10 leafy greens going through 100mL of water per day then the crop growth system emits 1kg per day, unless the system captures and reuses.
Waste nutrient solution				Quantity and frequency of nutrient solution change out or waste water production.
Volatile Organic Compounds				Quantity and composition of expected VOCs from plant growth. Considers type of crop and number of crops grown with respect to time.
Oxygen				Oxygen production of plants over time. Considers the type and number of crops grown with the respect to time.

Outputs	Mass (kg)	Volume (m3)	Power (W)	Notes
Waste plant growth consumable items				Consumable item examples wipes, cleaning fluids, acid/base, adapters, swabs, cartridges, syringes, gloves. Consumable items used per system considering the number and types of crops over time.
Spare parts				Spare part waste over time. Considers number of units, types of crops grown, and number of crops grown.
Cooling power				Crop growth systems generate heat and this is the outflow of heat from vehicle/habitat cooling systems and/or into the cabin environment in Watts.
Data				Data rates and amounts needed to monitor and control plant growth system(s). Mbps and total per data per day per system.
Meals augmented				Number of meals and/or meal items augmented per harvest. Provides some insight into variety and nutritional supplementation.
Non-required crew visits to the crop growth system				Number of non-required crew visits per unit time when crops are grown. Provides some insight into crew interest.
Photos with crops and crop growth system or mentions of fresh crops in media scenarios.				Number of unique, non-required photos crew take with crops, harvested crops, and crop system to provide some insight into crew interest.