Key Gaps for Enabling Plant Growth in Future Missions

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Growing plants to provide food or psychological benefits to crewmembers is a common vision for the future of human spaceflight, often represented both in media and in serious concept studies. The complexity of controlled environment agriculture and of plant growth in microgravity have and continue to be the subject of dedicated scientific research. However, actually implementing these systems in a way that will be cost effective, efficient, and sustainable for future space missions is a complex, multi-disciplinary problem. Key questions exist in many areas: human research in nutrition and psychology, horticulture, plant physiology and microbiology, multi-phase microgravity fluid physics, hardware design and technology development, and system design, operations and mission planning. The criticality of the research, and the ideal solution, will vary depending on the mission and type of system implementation being considered.

Nomenclature

ECLSS	=	Environmental Control and Life Support System
EXPRESS	=	EXpedite the PRocessing of Experiments for Space Station
HRP	=	Human Research Program
ISS	=	International Space Station
NASA	=	National Aeronautics and Space Administration
SWEG	=	Spacecraft Water Exposure Guideline

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I. Introduction

THIS paper describes key plant growth knowledge gaps in the growing of plant and the production of food in the Space Exploration environments. Development of closed ecological systems that utilize waste, such as CO_2, and which provide resources, such as food and oxygen, are necessary to support truly Earth-independent human spaceflight, space exploration and colonization. Introduction of edible crop plants is central to a closed ecological system, and may have benefits when integrated in small quantities into physico-chemical life support and food systems. However, many technological and knowledge gaps need to be addressed before even crop plants can be integrated into spaceflight infrastructure and food systems. The gaps and questions described here were identified by a multi-disciplinary working group within the National Aeronautics and Space Administration (NASA). Where possible, it also begins to identify research pathways and solutions to questions identified by the group based on work initiated in 2017.

The intention of this paper is to organize discussion and highlight key questions for future research. The questions identified were relevant to a range of fields, including microbiology, horticulture, food science, physics and engineering.

A. Implementation Architectures

Discussing plant growth in spaceflight systems invites images of a wide range of systems and possibilities. A closed ecological system can be interpreted to mean anything from a glass jar with an equilibrium of heterotrophs and autotrophs[1] to the planet Earth. An engineered life support system could be anything from a space suit to a deliberately terraformed planet. But not every problem in biological life support systems has to be solved for every implementation case. Thus it helps to have a frame of reference to define relevant scenarios as examples in discussion.

The near term goal identified by NASA for plant growth systems is a "Pick-and-Eat" system. This phrasing has been used by the NASA Human Research Program (HRP) roadmaps[2], but terms like "salad machine" and "vegetable production unit" are refer to similar system concepts. The intent is that the salad or fruit crops grown in the system will grow robustly with minimal resources, require minimal processing (e.g. disinfection), and can be consumed raw. Based on the type of crops in this category (e.g. leafy greens, tomatoes), even in continuous weekly or daily harvest cycle, it's assumed that this type of food production system does not provide a significant contribution to daily caloric intake for the crew. In early implementation where the systems are still considered a capability demonstration and considered high risk, there cannot be any risk to food scarcity if the crops do not grow. Ideally the crops would provide a nutrition benefit of some sort, perhaps to supplement vitamins that are degrading within the processed, stored food system on long duration missions[3], but at this scale it may not be a measurable impact. Even at small scale, the systems could provide variety and interest in the diet, and a potential countermeasure to psychological or behavioral conditions for the crew on very long missions

Food production systems are initially evaluated on the ground, and but these systems must be designed for microgravity and consider a deep space radiation environment. This system concept should also be somewhat modular and scalable so that one or multiple copies could be provided to a vehicle or habitat depending on available vehicle resources and desired food production. ISS provides an accessible platform for near-term microgravity evaluations, and follow-on evaluations in cislunar space can assess the impacts of deep space radiation in a "Gateway Garden"[4] . The first human missions to cislunar space since the Apollo program are planned to begin in the 2020s and are intended to be a proving ground for enabling technologies for future exploration. Proving reliable operation of the plant growth system would be required before the technology can have any impact on logistics supply or habitat design for future missions. Demonstrating successful performance of the plant growth system technologies, integration with spacecraft systems and crew food systems, and impacts of the system on mission resources will provide valuable data for future planning. Small-scale systems must be developed to validate crop growth potential and procedures before they can be dependably integrated into near term vehicle designs and food systems. Growth systems could then be augmented as reliability is proven and mission length and distance from Earth requires greater resource autonomy. A variant of this system design could easily be considered for initial missions to Mars surface or to the Moon's surface for "Pick-and-Eat" crops. Since these systems would be tested on Earth before being flown in space, the addition of gravity shouldn't add new challenges.

An "Intermediate Plant Growth System" would add new functions and complexity to the spacecraft or habitat system. While concept studies are occasionally conducted for intergenerational starships or solar system exploration, NASA's current focus on longer exploration missions away from Earth include destinations where gravity can be utilized in system design, like Mars or Earth's moon. Planetary missions as described in references like NASA's Mars Design Reference Mission 5[5] and most of the missions considered by the Evolvable Mars Campaign[6] team

show architectures based on conjunction class missions with surface stays on the order of 500 days. While a "Pick-and-Eat" system will still be useful, these missions provide an opportunity to increase the variety and the amount of food provided from locally grown plants in the crew diet, since gravity makes many necessary systems (food processing and preparation, waste management) easier to design. Many staple crops (wheat, soy) require significant processing before the crew can eat them, and create much more waste biomass that needs to be managed. Plants like potatoes or others that have significant volume changes in the root area may be too hard to manage in microgravity, but become much easier for surface missions. Selection of these crops for integration into a crew diet would be very complex, and would require balancing macro- and micro-nutrients to meet nutritional requirements over the mission duration, potentially with changing nutritional content of the stored food over time for long duration missions. The impact on carbon dioxide and oxygen control in the habitat would be significant, since analysis has shown that all of the crew's oxygen needs are met when approximately 50% of the crew's calories come from plants[7]. Thus these systems should be considered to be bounded by approximately 50% calorie contribution to the diet. Prior to dependence on crop systems, reliable production and surpluses must be available to prevent the risk of food scarcity in the case of crop failure. Additionally, the mission goals must be considered. Growing, processing, and preparing meals would require significant crew time during a mission in which there should be many exploration and science related activities. The resource requirements of a processed system compared to a crop system, and the extent of automation will also be factors.

Truly independent settlements beyond the Earth would require systems that can provide the complete food source for the crew. The challenge of designing a nutritionally complete diet, that will be acceptable for the crew to eat is substantial. For a complete food system, protein sources are often the key gap. Systems with aquaculture[8] or livestock[9] could be considered. Concepts are beginning to emerge on Earth for biotech enabled sources like cultured cells[10], although these would add significant additional challenges in spaceflight, such as additional resource requirements, microbiological concerns, and psychological factors. For a truly independent system, recycling solid waste effectively would also be an critical part of system design. If these systems provide the full crew diet, they will also produce more oxygen than the crew needs and require more carbon dioxide than the crew produces. This will require integration with new kinds of oxygen and carbon dioxide control system, waste management, and possibly in-situ resource utilization systems to interface with resources and venting options on Mars or Earth's moon.

Long duration microgravity missions should not necessarily be forgotten just because they are not in NASA's current exploration mission architecture. Permanent space stations feature in commercial space architectures and even call out farming applications[11]. Concepts for ultra-long duration microgravity missions across the solar system, imagined interstellar missions, and permanent space stations could also require microgravity solutions and ultra-stable, closed-loop systems. These missions will have the maximum combination of questions from microgravity systems and fully closed systems.

B. Existing Systems

Another useful point of reference for discussin future questions is understanding the known state of the art, and what they represent. Spaceflight systems exist that are both sources of useful models for the "Pick and Eat" system. The VEGGIE system on ISS has been used to grow leafy greens and flowers, and has been very well received by crew. Even though it doesn't provide significant nutritional impact, it has added novelty and interest in the crew diet and they have found many ways to integrate the edible lettuce with the stored food system. The enjoyment provided to the crew members is demonstrated by their willingness to use their discretionary free time on the system. It is a relatively simple system, with LED lighting, plastic bellow walls that partially isolate but do not control the plant growth environment, and a passive watering system using disposable soil media "pillows". In contrast, the Advanced Plant Habitat design will have a wide variety of controllable LED lights, a fully enclosed growing volume with CO2, humidity, and ethylene control, and an active watering system using porous tubes that dispense water to a media system (or other special growth system installed as part of the experiment.) The APH will host scientific experiments on model organisms such as Arabidopsis, but it can also be used for scientific evaluations of relevant food crops. Russian systems have also performed important in-space experiments in plant growth. Experiments have been conducted on ISS with LADA and were conducted on Mir with the SVET system. Plant growth data and system design information can also be gathered from relevant, high fidelity ground tests. The Lunar Greenhouse is an existing system, while NASA has also conducted critical tests in the BPH or the Lunar Mars Life Support Test Project (LMLSTP) in the late 1990s. Japanese experiments in the Closed Environment Ecological Facility (CEEF) have examined very closed biological systems with humans as part of the system.

Despite all these open research questions, plants have successfully been grown in space in multiple systems. Many of these have been research tools, but the crews have also been able to eat plants in space from Russian and US systems. The most recent NASA activities have utilized the VEGGIE unit on ISS. But there is a substantial difference between demonstrating that plants can survive in space, and demonstrating that they can be a reliable component of a food and life support system. Using the VEGGIE system for food production for the crew required new levels of integration with the crewmembers. This emphasized additional challenges, like food safety, that will have system impacts. Additionally, the experience re-emphasized the challenges of microgravity fluid management. But it has successfully produced food for crew consumption multiple times, and thus is a proven model showing the basic feasibility of food production that NASA intends to reuse over the life of ISS. However, it was never intended as the model for large scale food production, and new designs could provide substantial improvements.

C. Multi-disciplinary Problems

A diverse range of disciplines is required to successfully develop and integrate a plant growth system in future space exploration missions. The concepts developed in this paper came from a group of experts in human health and nutrition, plant physiology and biology, microgravity physical sciences, technology development, and system architecture. Each field is already engaged in relevant work. Each field also has critical expertise to provide necessary answers to the other teams that would not necessarily have appeared in discipline-centric development plans. Many of the questions really are tied to the realistic environment. The space environment provides microgravity and radiation exposure. The spacecraft environment creates constraints and unique interfaces in lighting, water quality, and atmosphere that may not be part of classical scientific investigations. The spacecraft also has a biological environment, including the microbiome of the habitat. The microbiome of the plant growth system, in the root zone or on the plant itself, is an important consideration for crew health as well, and may behave differently in space or with spacecraft system water than it does on Earth in more traditional agricultural settings. The key risks or open questions identified have been sorted based on the type of expertise needed to carry out the investigations.

II. Human Research Questions

The purpose of all spacecraft environmental control and life support systems (ECLSS) and spaceflight food systems is to protect and provide for the human crewmembers. Human-centric questions are a critical part of successful design and integration of any of those systems, and plant growth systems are no exception.

Two questions are critical for trade studies exploring the use of plant growth systems for food in near term microgravity vehicles. The first is: *what nutrition gaps are present in the current spaceflight food system*? Nutrition has been successfully provided for crew missions to date through processed, shelf-stable foods, but it is expected that 1000-day class Mars missions will have new gaps. HRP already recognizes this "Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System"[12]. Food for a three-year crewed mission to Mars will likely require a five-year shelf life due to the logistics of processing, delivering, and potential prepositioning of food prior to crew arrival. Previous studies indicate that the quality of many shelf-stable foods will become unacceptable, and several critical nutrients degrade to unacceptable levels within three years[3,14]. Food that is not acceptable may not be eaten in adequate quantities to maintain nutritional adequacy, which can impact body mass, performance, cognition, and overall health; detailed information related to previous human exploration and spaceflight missions is available in a previous review. Studies are ongoing to determine technologies and methods that may increase the shelf-life of prepackaged foods, such as the implementation of novel processing strategies, and the inclusion of cold storage, which is not currently available on space vehicles due to resource constraints. Although prepackaged food research solutions have the potential to adequately provide nutrition and quality for near term Mars missions, crops may supplement several nutrients that have been identified to be deficient or to degrade over time in the shelf-stable food system, including potassium, vitamin K, and vitamin C. Additionally, the ability to extend exploration missions, begin colonization, and become Earth-independent will require continuous development and increasing reliability of bioregenerative plant growth technologies.

The acceptability of food becomes more important as the length of a mission increases and environmental conditions become more isolated and unfamiliar. ISS crewmembers often identify a variety of enjoyable food as one of the most important factors to crew morale during their mission. The importance attributed to the psychological aspects of food, in addition to the nutritional aspects, make crops ideal candidates for integration into crew diets on future missions. Fresh produce may also promote psychological health by providing highly acceptable textures, colors, and flavors that may be missing from the processed diet. Similarly with prepackaged foods, it is likely that

variety will be important and that individual crewmembers will have preferences for what is available to be grown, especially over longer missions.

Understanding this perspective is important, because many system developers would like to have a "unit of usefulness" to define how large of a plant growth system they need to create. But a generic definition of a salad does is not a useful way to address nutrition gaps. Identifying plants that are cost effective and robust to grow while addressing key nutrient deficits will be more important than matching a pre-defined meal. The initial selection of crops for VEGGIE did evaluate these factors as well as palatability when selecting the varietals to be tested. The crew on the ISS has found multiple ways to integrate the initial leafy greens grown in VEGGIE into their diet, from eating it with a light dressing, to putting it on tortilla wraps, to inventing lettuce wraps using stored food fillings.

In addition to nutrition and acceptability, safety is a critical food factor in relation to human health. The shelf stable food that makes up the bulk of the food system on ISS is required to meet rigorous microbiological safety standards through testing on Earth prior to launch. The evaluation methods for food safety are not yet sufficiently rapid and resource efficient for spaceflight. When the VEGGIE system was delivered to the ISS, the initial lettuce grown was not consumed by the crew. Samples from the initial crop of lettuce was returned to Earth for evaluation. After several safety reviews were conducted and a suitable cleaning technique using sanitizing wipes was identified, the crew was allowed to eat the next leafy green crop. However, fresh produce standards, appropriate food safety protocols for produce grown in flight, and microbiological testing methods are all current gaps for bioregenerative food safety in spaceflight. Questions on achieving and confirming food safety are sorted as technology questions. But human medical research does have a role in determining what is the definition of food that is safe to eat for in-situ grown foods? Standards applied to stored food, such as those treated with heating and drying processes, are not appropriate for fresh foods. Data from plant growth studies over time will also develop a database of the organisms that are found on fresh crops in space.

Plant growth has the potential to provide psychological benefits to crewmembers even during growth phases. If plant growth systems are to be justified based on behavioral countermeasures, research needs to be conducted to confirm and quantify the effectiveness of various plant growth scenarios during the isolation and confinement of a long duration space mission. Astronauts on the ISS have chosen to spend free time on the VEGGIE experiment, which reinforces that it is a desirable activity. One study is planned to begin investigating the benefits of plant growth to crewmembers on ISS. NASA vehicle developers need to know not only that a proposed counter measure provides benefit, but that the cost of providing this countermeasure provides more benefit than the cost of providing another countermeasure. Vehicle developers also need to know the extent of plant growth interaction that would be beneficial to crewmembers in relation to the crew time available on exploration missions. Virtual reality has also been pursued as a behavioral countermeasure[18], including natural scenes, and would likely be less costly to the vehicle infrastructure. However, virtual reality will not benefit the development and testing of technology advancements that will be needed for future food production systems if humans are to advance to Earth-independent space exploration.

As the scale of plant growth systems increases, the tasks required to operate the food system, and needed crew time, will also increase tremendously. Varying degrees of mechanized systems, automation, and autonomous systems have been proposed to reduce this burden. But a key question is what tasks required for operating a plant growth system provide the most positive crew experience, and which tasks create the most negative stress? These crew experiences can be measured by scaling up a "Pick-and-Eat" system in ground analogs and through ISS experience. Analysis of the time required for tasks beyond the "Pick-and-Eat" scale, including processing the crops and food preparation is important to determine whether it is even feasible for crewmembers to manage an intermediate or fully closed food system.

It is important to note that spaceflight crew will be a part of every aspect of growing, processing, and preparing food. While concepts such as food produced by cell culture or bioreactors are utilized to produce food ingredients on Earth, the modern consumer is not a part of the whole process, of which several parts will produce unappealing odors, appearances, or texture. Negative aspects of biotechnology techniques in a closed source food system must be considered, as detriments to psychological health may be exacerbated in an enclosed space vehicle, where food familiarity is known to increase in importance.

III. Biological Science Questions

Questions requiring insight from biological scientists seem to mostly fall into two categories: questions about the plants, and questions about microbial life related to the plants.

The basic question to answer is *what are the best plants to grow for each type of food system*? But the definition of best requires rigorous examination of many different parameters. Nutrition and palatability, growth system

requirements, robustness to stresses, and ease of operations to grow each type of plant are all important. Other biological performance parameters are also important in selecting crops for reliable and efficient plant growth sytems, including reliable germination (including either long term seed storage or multiple generations from seeds or cuttings), rapid growth, and low native microbial levels[19]. In most of the discussions below, references are provided that illustrate the topic or issue from previous research. However, this does not mean that the issue is solved for future spaceflight. These studies have been conducted for a very limited number of crops. A complete data set across the range of proposed crops is necessary to plan a future spaceflight system. Additionally, because the time scale of many of the experiments is long, they tend to be conducted at a limited number of points. These may or may not be the ideal design point, and they do a limited mapping of plant responses and performance which would eventually be necessary to predict system behavior in a spacecraft or habitat.

Nutrition and palatability studies are necessary to meet the needs of the HRP risk roadmap, but require growth studies of many different potential crops to perform assays of nutrient content. *Repetition of nutrition assays to get statistically valid data and assess variability is important* for the data to be useful in planning the crew diet. *Studies need to examine how nutrition and palatability parameters may vary depending on how the plant is grown*, including mapping non-ideal conditions because they may be necessary due to other vehicle or system constraints.

Other questions need to address *how can the candidate crops be grown to minimize vehicle resources*? Early system studies have demonstrated that volume is one of the most expensive resources on a spacecraft that a growing plant consumes, due to the mass of the overall vehicle structure. There are several specific examples. One important strategy in the design of the plant growth system appears to be changing how much volume the plant is allocated at various points in its life cycle. *How well do plants grow in systems that change their location and allocated volume over the life of the plant*?

As the plants reach maturity, *how can plants be grown to maximize productivity per volume on the spacecraft*? Depending on the type of crop, the answers to this question could vary significantly. For lettuces and other leafy greens, *do batch harvests or "cut and come again" harvesting of only some leaves at a time maximize the useful production over the total life of that plant*? Both have been tried on the ISS, but statistically relevant data is needed, as is data on a lot more crops like determinate versus indeterminate tomato varieties. If comparison of ISS data to ground tests shows repeatably equivalent results for a type of plant, then more affordable ground studies can be used to maximize these results. Determinate or batch harvested crops are likely to drive the system design to planting one plant at a time in a "Pick-and-Eat" system, since the crew still cannot preserve and store a "seasonal harvest". But for intermediate and fully closed systems, preservation or processing in large batches may be more efficient.

For plants like tomatoes and peppers, their growth habits on Earth typically include dropping lower leaves as they get taller and the upper canopy of leaves shades the lower canopy. Would upward growth of tall plants be stunted if light were available at all heights? Would the plant simply become more productive if light were available at all heights? These studies need to be examined for the specific candidate food crops identified and prioritized by the tests discussed earlier, not just for model organisms.

Mechanical stimulation has also been shown to change the canopy architecture in bell peppers[20]. Interestingly, while fewer fruit were produced by the mechanically stimulated plants, the total fruit volume, fresh mass, and dry mass were not reduced. If this effect is strongly useful, *is ventilation design enough to produce a stimulation effect to reduce plant size without reducing edible biomass production*? *What mechanical stimulation that could be provided by robotic or automated systems would be useful to increase productivity without damaging the plants*?

Different plants also respond to preferred temperatures, humidity levels, or day-night cycles of light. In order for a system to grow different kinds of plants for a crew diet, it may not be possible to give each plant the optimal conditions. For the crops of interest, research needs to determine *which environmental parameters are most important to maximize edible biomass production for each crop*? Studies have shown direct correlations between light intensity and CO_2 uptake by plants[21]. Studies have also examined lighting intensity and wavelength to determine what is photosynthetically useful to the crops[22]. For some crops, growth rate is equivalent to edible biomass growth rate. For example, studies have shown that the crop growth rate (g FW m-2 d-1) of 35 day old radish, lettuce, and onion generally resulted in rates that increased firstly with increasing PPF, and secondly, with supplemental CO_2[23]. But for food production it needs to be determined for more crops *whether increased light or tailored wavelengths actually leads to increased edible biomass production for the crops of interest*.

Humans have been modifying plants to optimize agriculture and food for millennia, and spaceflight is no exception. Dwarf plants are already under consideration for spaceflight[24,25], and studies need to continue to answer key questions about them, and possibly add more varieties that could have better performance for nutrition or robustness in the spaceflight environment. Genetically modified foods may also provide unique opportunities to change the growth habit of a plant to save volume, or maximize productivity with constant fruiting and flowering.

Studies on dwarf plum trees demonstrate how this may allow crops that would not have been considered to be reasonable for spaceflight to enter consideration[26].

Robustness and reliability are important considerations when designing spacecraft systems, and these needs apply to biological systems in the spacecraft as well. Studies are needed to explore the sensitivity and recovery potential of the desired crop plants to a range of scenarios. Conventional agriculture is interested in plants that are resistant to drought or pests, including making genetic modifications, but these are unlikely to be major concerns on a spacecraft. Some stressors would be constant, such as the microgravity environment, a non-ideal temperature, humidity, or light cycle environment, and the radiation environment of deep space. Other biological system work has shown that mechanical failures in the system can induce stressors, such as a control failure changing the pH of a watering solution, or nutrient levels becoming too high or too low until a repair can be made. Microgravity can also induce stress due to fluid flow in and around the plant if it is not controlled well enough, such as the water stress and fungal growth on zinnia's that was seen in some of the VEGGIE experiments[27]. These kinds of robustness may also be of interest to other indoor, controlled environment agriculture systems. Research is needed to determine *what promising crop plants are the most robust in the face of environmental or off-nominal event stressors*? Much of the research focused on productivity, which requires moderate to significant levels of environmental control and analysis, as well as biomass calculations or nutrition assays. But success in a recent education collaborations suggests that at least some of this research may be able to be generated in different ways, including significant citizen-science contributions. NASA's collaboration with Fairchild Tropical Botanic Garden in Miami, Florida will test hundreds of plants in classrooms in the Miami-Dade county area[31]. Some of these cases will have non-ideal scenarios or induced failures through either human error that is a natural part of the learning process, or issues like power outages and loss of environmental control that are not in the control of the experimenters. Specific crops that recover after these events will have demonstrated robustness, and should be considered favorably for future investigation.

Most modern agriculture is based on monocropping to optimize production with industrial equipment and techniques. But companion plantings such as the traditional "Three Sisters" of corn, squash, and beans have also been very successful in the history of human agriculture. Early tests of larger scale closed environment plant growth systems that would be applicable to intermediate or fully closed food systems tended to use monoculture approaches, grouping groups of the same crop together. But in order to create variety and interest in the crew diet with limited volume for early "Pick-and-Eat" systems, a polyculture approach of growing multiple plants with shared watering systems has been suggested. This could also provide the crew autonomy in picking what to plant over time in a long duration mission. However the disadvantages of mixed cropping systems include competition for light, nutrients, and water, possible allelopathic interactions, complicated nutrition and irrigation management, and complication of mechanized planting and harvesting. To date, no allelopathic interactions have been observed between onion, lettuce, and radish plants grown in mixed crop scenarios, and radish yields increased slightly in mixed cropping approaches. Initial findings suggest that mixed-cropping may allow more efficient canopy coverage and greater yields than monocultures[28]. More research will be needed on the candidate crops to determine *what crops can be grown together and what changes in productivity happen as a result?* Allelopathy is a broad term that can describe many specific interactions[29]. Resources for home gardeners can be found that suggest that one of the most popular plants to discuss for addition in Pick-and-Eat systems, tomatoes, could have negative interactions with cabbage (already part of early VEGGIE Pick-and-Eat demonstrations) and potatoes (a common assumption in intermediate and fully closed food systems[30]. These studies should also *examine the feasibility of plants of different levels of maturity growing together*. Any seasonality in-space will be artificially induced, and while Mars has seasons of its own that may effect vehicle design, they won't align for crops evolved for Earth seasons. Thus, a small crew is likely to want a frequent periodicity to the availability of many "Pick-and-Eat" crops. Staple crops with longer growing cycles would also likely need to be staggered, even if they are processed in larger, less frequent batches.

Genetic modifications may also provide opportunities to design crops that are more resistant to stressors, or deliberately designed to thrive in new environments.

In addition to finding plants that can tolerate stress, for future intermediate or fully closed systems that will potentially include autonomy, *research is needed to identify and document signs of stress in a way that a sensor, photo, or optical system could identify them for the crops of interest*. Early prototypes are exploring the feasibility of these systems, but data is needed to feed their development.

A second major group of questions about the plants themselves is research needed to generate the data sets that will be required to integrate the plants with the spacecraft or life support ECLSS. Regardless of whether or not the plants are considered as a mass-saving contribution to the system, there will be noticeable impacts, and dramatic changes in the ECLSS architecture for intermediate and fully closed food systems. *For each crop plant, at each*

point in its life cycle, how much CO_2, O_2, and humidty will be added to or removed from the cabin air? How does this vary depending on environment conditions including lighting, CO_2, and humidity? Steady state averages are not sufficient for system integration. For example, many plants release carbon dioxide back into the air in dark-period respiration when lights are off[21]. This could cause a range of complications, from nominal control cycles different from what vehicle planners designed to, to managing a power failure contingency in which carbon dioxide levels increase in the vehicle even faster than expected. Studies of trace contaminants released from plant growth systems to date have generally shown that the trace gases are of the type that the ECLSS system is already prepared to manage. However, for intermediate or fully closed systems the quantities could drive design changes. Other questions are a result of specific decisions in the life support system. How does the plant respond to residual iodine or silver biocides in the potable water? What levels of biocides are tolerable and what is the fate of those materials in the plant tissue? The Spacecraft Water Exposure Guidelines (SWEGs)[32] are based on certain assumptions about total consumption, which could be reexamined if the plants accumulated the same material in edible tissue that the crew also consumed. Other system integration concepts have included feeding the plants with human waste, which may be diluted or partially processed some other way.

Physical science investigators are also looking for ways to quantify the success criteria for maintaining appropriate water and air or oxygen control in the root zone to set requirements for the crop growth system. For the crops in question, *what is the required balance of nutrient rich water and oxygen or air that is required in the root zone to keep the plants healthy*? Flow calculations may be able to be derived if biologists can quantify the definition of an acceptable environment in the root zone, and the transport of nutrients and oxygen in and waste out of the root zone. Flooding and drought are both understood to cause significant stress to most plants, but the definition of success is much less clearly defined.

As genetic analysis tools become more capable and more prevalent, science and engineering disciplines are gaining a new appreciation for the complexity of our relationship with the world of microbial life. Nitrogen fixing bacteria and nitrifying bacteria are perhaps the most commonly discussed bacteria relevant to agriculture and plant growth. Aerobic or anaerobic bacteria for composting are also studied for agricultural purposes. But in order to design an operational system, research needs to be done to determine *what is the definition of a healthy rootzone microbial community to enable plant growth?* Overall, there are synergies between the plants and beneficial microbes (both bacteria and fungi) in the rhizosphere and phyllosphere of plants.

If system approaches are oriented at keeping the system as clean as possible, determining the minimum level and makeup of this community could be important. It is also important to understand *how does a healthy root zone microbial community differ in microgravity or a deep space environment than it does on Earth?* Again, these questions will need to be answerd for a range of crops, and the answers are likely to have different implications for root crops for intermediate and fully closed systems. At this point, initial research is needed just to collect the data to determine what that community is. Samples have been taken from NASA's VEGGIE experiment for processing, but the sequencing is not yet complete. This information needs to be compared with ground tests of VEGGIE systems, but also to other controlled environment agriculture systems. Comparisons across a range of controlled environment systems, like hydroponics, aeroponics, aquaculture, as well as conventional agriculture would also help determine whether this varies more depending on the crop or on the growing system. It is important to characterize the entire community, because bacteria that may be benign to the plant and not identified as providing a useful mechanism could be a problem for crew health or general habitat hygiene. It is also important to define *how does the root zone microbial population change over time?* As well as *how resilient is the root zone microbial population after system upsets or dormancy?* It may be necessary to develop techniques to deliberately inoculate a plant growth system with the appropriate microbial communities. Or it may be necessary to design systems with controls to minimize inoculation from populations elsewhere in the spacecraft, including the crewmembers. It is also important to *understand the microbiome of the spacecraft overall*, and whether it is different with and without plants present. There could be positive and negative changes to the spacecraft microbiome that occur from sustained closed environmental, which could potentially include the introduction of new types of pathogens.

Induced environment questions include the effects of contaminants from plants on conventional life support trace gas control systems, or concerns about the effect residual biocides commonly used in spacecraft systems might have on plants.

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IV. Physical Science Questions

The overall need for input to the plant growth system from physical science is information how to design a water and gas management system for the plant growth systems. The system must be highly reliable, with a very long life. It must be robust, which means it can handle startups and perturbations, and ideally work in environments from 0-g to 1-g to maximize commonality of experience across experiments. It needs to be scalable to a range of sizes of plants and their roots, and to a widely varying number of plants growing in the same vehicle installation. Managing the water system isn't a static equilibrium question, because oxygen and nutrients must be maintained at acceptable, if not optimum levels, while the plants are actively absorbing them. Answering questions on microgravity fluid flow will require activities that bridge the gap from pure scientific research to applied research. Reviewing previous experiments shows that basic research has been conducted already that illustrates many phenomena that are relevant to fluid flow and control (water and oxygen) to plant roots. Capillary forces, droplet sizes, mixed slug flows of air and water are all relevant to potential watering system designs. Being able to translate these results across gravity environments and predict behavior of the same system in new environments is also important. The microgravity compatible designs should take into account how they could evolve to operation in a gravity field to enable the most reuse of knowledge from system experience. The bulk of the biological research conducted on the plants would be conducted on Earth, and the most useful results will come from matching the conditions as closely as possible to the spacecraft system environment.

The initial question is *how can the delivery of nutrient rich water and oxygen to the root zones of plants be controlled in microgravity*? Initial experiments need to be conducted across a broad range of possible solutions. These include solid porous or particulate media, possibly used together, with active and passive control, aeroponics, hydroponics, nutrient film techniques, membranes, as well as a range of methods for introducing and controlling water to the grown media. These initial experiments do not need to include living plants. However, they should consider what the root patterns will be in or on the media. The experiments need to demonstrate water delivery to the root zone, but they also need to demonstrate water removal. The water delivery also needs to ensure that air and oxygen can be sufficiently delivered to the plants.

A second question is *how does the design provide sufficient mixing or mass transport at the roots of the plants*? This question should be applied to the same root zones in question, but different types of instrumentation or observation may be necessary to examine local conditions as opposed to bulk transport. Modeling would also need to take into account the results of experiments without plants and add the impact of generation and removal rates from transport through the plants roots.

Another question is *how does the design of the water and oxygen flow control interact with root growth changes*? In a "Pick-and-Eat" system, this question is especially relevant to system designs in which plants are moved to different locatiosn within the growing volume during their life cycle to optimize volume. Deliberate root restriction may also be part of the root zone design, and the void fraction of the media will change over time as the roots develop[33]. For planetary surface systems, it will be especially important for starchy tuber crops where the primary edible product would be in the root volume.

Physical scientists must also help address *how can an overall water and gas control system be designed to manage humidity levels in the shoot and leaf zone, and recyle transpired water back to the watering system* to avoid excessive burden on the vehicle life support system? Many condensing heat exchangers have operated as part of plant growth systems and overall vehicle life support systems, but they have had their challenges. For cost-effecitve plant growth as part of the food or life support system, these components must be designed to be highly reliable with a long life. For a "Pick-and-Eat" system deployed for NASA's Mars mission architectures, multiple cycles of start-up, shut-down, and dormancy between missions will be required. Microbial control to avoid fouling will likely be an important consideration, but it must be solved in such a way that it does not harm the plants or a healthy root zone microbiome. If they are providing local control to a specific growth area, they will potentially have to deal with even more start-up and shut-down between growing periods.

Other areas of physical science are also important to the design of the plant growth system beyond microgravity fluid flow questions, but are lower priority. For the near term, in-space "Pick-and-Eat" systems, modern LED lighting technology was assumed to be sufficiently mature for the design of new systems. For large scale planetary systems, optics and materials science may need to be brought to bear to find efficient ways to utilize local natural sunlight. To maximimize production, controlled environment growth systems typically provide much more lighting intensity than natural sunlight, and can be tuned to provide the wavelengths most useful to the plants being grown. The natural light that arrives at Mars is weaker in intensity than even natural light at Earth

Finally, physical sciences may be required for basic research to determine *how can the systems enable separations to make closed loop biological life support systems cost effective*. Complete food systems will require

technologies to manage carbon dioxide and oxygen in the plant growth environment and the crew environment in a different way than current spacecract systems. Human waste is often considered a useful source of nutrients for plant growth[34], but excessive sodium or inappropriate forms of nitrogen are a problem. Methods for easily separating sodium from other useful plant fertilizing mineral compounds (providing nitrogen, phosphorous, potassium) or possibly acids and bases for controlling nutrient solution pH ould be helpful. Intermediate and full-scale plant systems will also produce substantial quantities of inedible biomass that need to be managed. Recycling them to useful components in microgravity, or doing it highly efficiently in gravity but with the mass and volume constraints of spacecraft may also require innovations from physical sciences.

V. Technology Development Questions

All of the knowledge gathered through research pursuits must be integrated into technology development projects to build successful systems in order for plant growth to become an operational part of spacecraft and habitat life support and food systems. At all scales, the plant growth system itself needs to optimize water and nutrient delivery management, local environmental control including lighting, physical structure and operations, sensors and automation. But other technologies will become necessary for intermediate and fully closed system applications.

The most *critical near term technology need is a reliable, microgravity water and nutrient delivery system for the "Pick-and-Eat" system*. The passive watering system designed for VEGGIE did not perform as originally planned, and through active monitoring and control by crew observation and actions, several (mostly) successful iterations of plant growth have been possible. But this detailed level of attention likely will not be sustainable at larger production rates of "Pick-and-Eat" crops. As system scale increases, recycling water transpired through the plants leaves will also likely be important. Many different systems are successfully used on Earth, hydroponics or aeroponics, or various solid media solutions, but will perform differently in microgravity, as the VEGGIE results show. With proper design and demonstration these designs may be able to take advantage of capillary forces in delivering or revmoving water.

The watering system must be designed hand in hand with any media the roots will grow in, with any strategies for volume optimization that require moving the plants, and the seeding methods. For example, NASA is investigating methods of immobilizing seeds in a dissolvable sheet or strip, since gravity will not hold them down in place on a soil substrate. But if these need to be wetted during germination, the water system and any root media must deliver sufficient water to the seeds without washing them away. The design of the root media or structure must also decide how much is disposable and how much is reusable. Solid porous media that stays fully wetted is being investigated because of the ease of pulling roots off of the material. In this case, the connection to water delivery would be consistent, though accumulation and precipitation of minerals in the porous solid will need to be examined.

The design of a watering system for intermediate mission crops like potatoes may require a unique solution. In these cases the volume in the root system will change dramatically over time as the tubers develop. Additionally, the edible product must be removed from the watering and growth media system. If any of these plants are also going to ultimately be grown in microgravity, free water or particulate from growing media could become a serious concern!

The design of the watering system and growth media also needs to take into account microbial control and contamination. The VEGGIE system water delivery is essentially dead-ended flow into each media pillow, and the pillows are discarded after each harvest. But if the water system involves recirculation, *how is microbial life controlled in the watering system to maintain operation, allow the healthy rootzone microbiome, but prevent pathogen growth*?

Microbial control is also an important part of ventilation system design. Ventilation is necessary for thermal control and transport of carbon dioxide to and oxygen from the leaves of the plants. But any air pulled from the spacecraft or habitat cabin needs to be sufficiently filtered or else risk introduce human pathogens into the growing space. It could also be part of a hazard control process to have ventilation that can blow away from the plant growth system toward crewmembers if they are need to interact with the plants.

Since necessary microbes are also understood as an important part of the system, and synthetic biology is becoming a powerful field for manipulation of microbial life, it is a reasonable question to ask whether engineered biological systems should be considered a technology. At this point, however, the conclusion was that there are still far too many open questions left to define and understand the existing microbial system. Considerably more research would need to be done to understand any optimization that could be done, and how it would be controlled and managed. Definition and interplay with the microbiome of the rest of the spacecraft or habitat and the human crewmembers also is not well enough understood. Therefore investing in biological technology to manipulate the

microbial environment of the plants can't be a priority with clear goals until that background is much better understood.

One technology development that may be needed is the ability to sample and assess microbial life on the food products. In testing on Earth, leaves of lettuce or other greens to be tested are put into a blender and homogenized so they can be tested with conventional plating methods. This would be difficult to accomplish in microgravity, though it could be useful in surface systems. The complex geometry of leaves makes it difficult to swab or wipe the surface and get representative samples. For crops like radishes, with tiny ridges on the surface it would be even more difficult. Technology is in development already for in-space DNA sequencing, and PCR based techniques to determine the presence or absence of target bacteria. But technology may be required to acquire samples from leafy vegetables in microgravity. Some vegetables, such as waxy surfaced peppers may be able to be swabbed. Strawberries (of interest for high vitamin C) would be very difficult to sample given the fruit structure and external seeds.

Other technologies related to system hygiene are also part of food safety and reliable biological system performance. Industrial practices for commercial controlled environment agriculture can help provide a lot of insight and direction in these areas, though they may have to be adapted to the constraints of spaceflight systems. While the seeds used in the VEGGIE were sanitized before launch, the protocols used in commercial controlled environment agriculture receive considerably more processing. More elaborate procedures could be applied to the first generation of seeds. In long missions where seeds generated from the last crop are used to plant the next, these techniques could become important but that need is low priority at this point in time.

The mechanical design of the water and nutrient system, and the rooting area must be designed so that it can be cleaned. It must be designed for repeated startup, shutdown, and dormancy or cleaning operations. In conventional agriculture, one of the things that fallow fields accomplish is a chance to break the cycle of infestation from pests that are specifically targeting one crop. While a entire growing cycle isn't necessary, time to assess and clean the system to break cycles of growth from undesirable microorganisms.

Another key question for each scale of plant growth systems is *how do we manage the waste and inedible biomass from the plant growth system?* The initial greens demonstrated in VEGGIE as "Pick-and-Eat" crops leave only the roots as inedible biomass, though the seed pillows are also waste. Adding tomatoes and peppers will increase the waste biomass. The periodic waste from two VEGGIE units production is inlikely to create a large issue on the ISS, but at larger scale rates with daily harvests for supplementing the crew diet, the waste could create issues. The inedible biomass will have significant moisture content. Unlike any leftover shipped food, most of which would have been preserved with radiation or retort processes, there will still be bacteria and fungus on the surface, which could become a problem if large amounts of biomass are stored in the wet trash on ISS in the same way as current trash. Drying technologies will help release water held up in the plant, and also reduce microbial activity and undesirable decomposition. Reclaiming water will become more important as the scale of plant growth increases. The biomass also has substantial carbon and hydrogen held up in it. In substantially closed or fully closed systems, the carbon will need to be liberated as carbon dioxide to be recycled to the plants again. Other waste processing technologies may be able to reclaim nutrients to be used as fertilizer. Compost

Mechanization, robotics and automation, and autonomous system technology are all categories that will be important to plant growth systems. Even for "Pick-and-Eat" systems, some sort of mechanization may be useful in creating variable-volume growth chambers in order to fit more plants, at different points in their life cycle, into the overall volume allocated for plant growth. Plant growth systems may have a range of environmental control, from only ventilation, to closed humidity and temperature control with water returned to the root zone, to actively controlled carbon dioxide levels and ethylene removal. Control systems involving sensors for health monitoring or active control of these systems will also be necessary. Detecting problems in the plants themselves will require different technologies. One option may be software to analyze photos of the leaf canopy and identify problems that would require adjustment of the settings of the water or environment control system. Initial steps would be *how can the system detect that the plants are beginning to show signs of stress?* More complex systems would be able to answer *what steps should the system take to bring the plants back to ideal health?*

In earlier studies, lighting technologies were an important need to make plant growth systems affordable. But modern LED lighting technology has made great improvements in efficiency. Until the scale of plant growth systems becomes very large, lighting technologies are not a high priority for NASA specific development.

VI. System Architecture & Design Questions

System architecture questions are those which examine the interplay of choices in the plant growth system design and operation and the rest of the mission and vehicle design. The answers to these questions are not

necessarily going to be consistent, but the input data necessary and the process for determining optimal answers would likely be similar across many missions. Mission scale analysis can identify drivers for optimizing the plant growth system. More detailed system analysis is needed to understand the integration of the plant growth system with the vehicle or habitat ECLSS.

Systems engineers and mission architects need to play an important role in designing plant growth systems in order to minimize their impact on the mission if they are a necessity for nutritional or psychological gaps, or if they are to have any chance of trading well against conventional stored food sytsems. The VEGGIE system was never intended to be a large scale food production system. But since it is the first operational system for food production that NASA has flown, it makes a useful case for examining system impacts and trade offs if it were expanded to a larger scale. The VEGGIE system does have disposable components, but it is also relatively lightweight and power efficient compared to more capable research grade plant growth chambers that have flown to ISS. Analysis was performed to calculate the impact of an example case using 16 VEGGIE units to continuously produce about 400 g of "Pick-and-Eat" salad crops per day, using ISS EXPRESS (EXpedite the PRocessing of Experiments for Space Station) racks. The EXPRESS racks are designed with four spaces big enough for a VEGGIE unit, but for this analysis it was assumed they could be optimized with the additional "drawer" spaces to hold 6 VEGGIE units each. The simplied mass estimate results are not a complete Equivalent System Mass study, but they show the relative contributions of the VEGGIE mass compared to the spacecraft integration and volume cost, and the system power.

Table 1. Comparison of VEGGIE and vehicle mass costs for an example continuous "Pick-and-Eat" system

Component	Mass	Contribution
24 VEGGIE Total Mass	305 kg	6%
4 EXPRESS Rack Total Mass	1450 kg	30%
Structure Mass (Equivalent System Mass of Spacecraft Volume)	2420 kg	49%
System Power of 1.44 kWe as Mass (Equivalent System Mass of Spacecraft Power)	687 kg	14%
Mass of Water Holdup	39 kg	1%

The VEGGIE system is already light weight, and the design of this plant growth system is a relatively minor contribution to the system cost. The installation cost of being in an EXPRESS rack and using its utilities is 5 times higher. And the cost of building the vehicle volume larger to accommodate four more racks is 10 times higher than the mass of the VEGGIE. The power cost, using LED lights, is only about twice the cost of the mass of the VEGGIE. These results suggest that finding ways to get more plant growth into the equivalent volume of the vehicle is the most important improvement for operational "Pick-and-Eat" systems. EXPRESS racks, while convenient, also add substantial mass burden which may not be necessary for future installations in cislunar space. Previous studies using sodium lamp technology used to show that power costs (and cooling costs) were very expensive, but the VEGGIE LED lights are a relatively minor contributor. The VEGGIE itself, and the water in it, are the lowest contributors. Next generation systems should still try to minimize mass of the component delivered per plant growth area, but it is likely not the most important contributor to a future design.

The other aspect of this analysis that becomes obvious is that the vehicle masses are very large compared to the grams per day of food production, with a 49 year breakeven time if the seed pillows are assumed to be made reusable (though without fertilizer mass added), and no breakeven if they are not. Admittedly, a mass comparison of "Pick-and-Eat" salad crops to stored food is not a very useful comparison. These vegetables do not tend to be calorically dense, and shipped foods are often dehydrated and fortified – meaning many more salad crops could be required to replace an equivalently nutritious vegetable dish from stored food. (Analysis is ongoing to examine intermediate diets with more calorically dense crops.)

Based on these results, however, another analysis was conducted to examine what savings could be achieved with volume optimization across the growth cycle of the plant. The VEGGIE design allocated one seed pillow area per plant at all times, regardless of the height or diameter of the leaf canopy at the time. By only changing height alone, volume could be reduced by 50-85% for lettuce, and by 22-36% for tomato. Most commercial growers of lettuce in a greenhouse or controlled environment do change the planting density by starting with much less growth media for seeds and seedlings than for the mature plant.

Integration questions should examine *how should water is managed between the plant growth system and a vehicle or habitat, and how carbon dioxide and oxygen exchange impact the life support system*? Early analysis has been performed with the Virtual Habitat (V-Hab) tool to examine the impact of a "Pick-and-Eat" system on spacecraft[35]. The initial analysis explored what would happen if a full ISS rack of VEGGIE units, with 0.92 m^2 of lettuce growing area and 0.92 m^2 of tomato, was integrated in three different potential locations on the ISS: the Columbus module, the Japanese Experiment Module (JEM), or the US Lab module. The plants only produce 4.2% of one

crewmember's oxygen need, and consume 4.5% of one crewmember's carbon dioxide production. But it requires 3 kg of water per day, which is slightly more than a crewmember's need. Dynamic simulation of atmosphere carbon dioxide, oxygen, and humidity levels is also possible while taking into account the performance of the rest of the life support system.
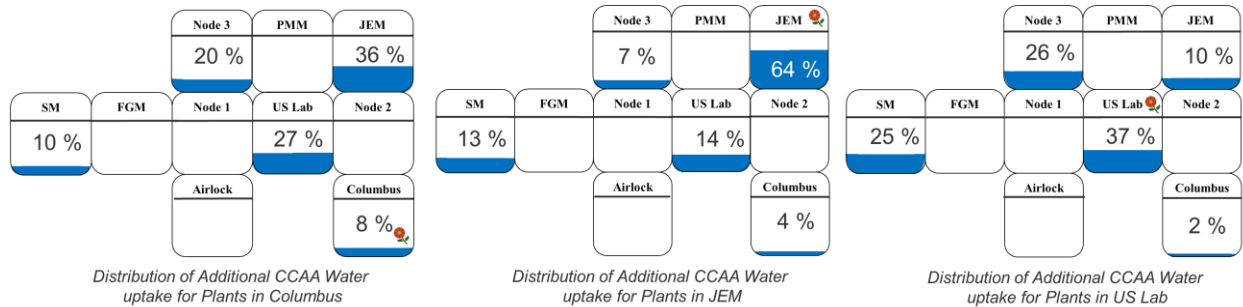

Figure 1. Distribution of condensate collected in each ISS module depending on location of plant growth modules

Using calculations like this, it will be possible to compare the transpiration rate of the plants with the expected vehicle capabilities for controlling humidity in the vehicle. One *early trade that should be made is determining whether the system is atmospherically open to the vehicle, with similar humidity levels and water shared with the life support sytem, or whether the plant growth system should have its own closed humidity control system*. Many plants prefer higher levels of humidity than what is typically selected for spacecraft levels to prevent condensation on walls and surfaces. Dedicated humidity control for a small system may seem like an additional system cost. But if that humidty control is performed at a higher dewpoint, it may be less of an impact than increasing the size of the low temperature cabin condensing heat exchanger.

Integration calculations requiring simulation will be even more important for larger scale systems. But *validated models are needed that accurately predict the oxygen, carbon dioxide, water vapor, and water exchange for all of the crops being considered*.

This analysis will also be an important in scheduling system operations.

VII.   Conclusions

Envisioning future spacecraft and exploration missions is often one of the most enjoyable parts of a career in aerospace, but designs must be data driven to know whether they are providing improvements to the state of the art. Identifying key knowledge gaps will lead to defining what ground and flight tests can help to address these gaps to feed information to future system design efforts. This framework could help NASA and other interested communities evolve from research capabilities to a true operational system.

Acknowledgments

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