**Topical: Recommendations for Spaceflight Research to Enable Crop Plant Growth Systems for Exploration**

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**Introduction:** Plant biology research in space has provided key insights into cellular and molecular systems and their adaptation to microgravity. Continued understanding of the basic function of plant systems in space will provide core knowledge essential for determining how crop plants may, in the future, support a food and behavioral health system for planetary missions. With the right level of support, NASA’s Biological and Physical Sciences Division (BPS), in partnership with the NASA Human Research Program and the NASA Systems Capabilities Leadership Teams, can deliver evidence-based crop plant growth technologies and approaches to enable future long-duration spaceflight missions to Mars.

Crop plant growth systems that leverage fundamental space biology research can help provide supplemental nutrition and variety to the astronauts’ diet, while also providing a meaningful activity to support their behavioral health and performance. Crops grown in space must be healthy and viable to sustain crew health and performance, or these crops will induce additional stress, and open questions remain that must be answered to support effective growth of healthy crop plants. Additionally, for NASA to leverage the benefits of a healthy crop growth system, an *autonomous* system that maintains crop health and productivity, but still allows beneficial human interactions, is needed.

**Future Direction: Research to Ensure Healthy Space Crop Plant Production**

Crop plants that will provide nutritious and highly acceptable bioactive supplements to the packaged diet will have to be grown effectively during future exploration missions. Additionally, if crop plant growth systems are designed with human behavioral health in mind, they may also provide a connection to nature and to Earth, enhancing wellbeing. This endeavor requires close integration of plants and crewmembers as well as the associated plant-human microbiomes, and there remains a lack of knowledge in areas related to this complex closed ecosystem.

Limited knowledge exists on the stability of crops grown during spaceflight (Anderson et al., 2017; Hawkes et al., 2017). Knowledge is still lacking on the effects of plant-human biome interactions in the spaceflight environment, and how microbiomes evolve over time in this environment (Mahnert et al., 2015; Space Studies Board, 2012)—topics that were raised in the previous decadal survey and are not yet well researched. Most BPS research to date has been performed using non-crop plants and may not translate well to the broader variety of plants planned for the space diet. Knowledge is also lacking on the effects of plant-hardware biome interactions in the spaceflight environment (e.g., Carter et al., 2013). These microbiome impacts have implications for the health of both crop plants and humans. It is possible that plant pathogens could be transmitted to the crops, and increased virulence or other radiation-induced changes on *in situ* microorganisms could be transmitted into this environment through the seeds, crop plant growth materials, crewmembers, or other hardware (Schuerger et al., 2021; Gilbert et al., 2020; Taylor, 2015; Bijlani et al., 2021). Food safety could also be a concern if human-associated microorganisms that cause illness live on or in crop plant tissues. To date, these have been detected in fresh produce grown on the ISS only in levels below concern for human health (Khodadad et al., 2020), but how this may change with longer duration missions or with smaller spacecraft is undetermined.

Maintaining optimum crop plant health in the spaceflight environment also depends on non-biological factors. More knowledge regarding the impacts of microgravity and partial gravity on crop plant growth, such as how microgravity affects delivery of water, oxygen, and fertilizer nutrients to the root zone of crops, how to control ventilation to optimize photosynthetic gas exchange, and how to use customized light to achieve desired nutrition and flavor are all areas where more data is needed for a variety of crop plant types. Although NASA has funded some studies in this area, it has yet to be determined if the results are applicable to crop plant production in space, and open questions remain to solve these challenges. Crop plants must be healthy if they are to provide any behavioral health benefits to astronauts, and diseased or stressed plants may, in turn, become harmful to crew behavioral health if they cause stress and anxiety. ***Recommendation #1: Support crop plant research in the spaceflight environment to enable healthy, productive crop growth systems that can act as a countermeasure for human health and performance risks in future exploration missions*.**

**Evidence—Crop Plant Growth to Support Behavioral Health.** Research conducted in analogs of the isolation conditions of spaceflight has demonstrated that limiting the variety and fresh foods, such as replacing a daily meal with a high-density food bar, is associated with weight loss and adverse behavioral health trends (Sirmons et al., 2020). Such food system trades may be acceptable during short duration operations, but can present greater risk for long-duration exploration missions. Crop plant growth may offer benefits including a source of fresh foods, as well as meaningful work and a connection to Earth.

There remains little debate on the acceptability of crop plants to help enhance future food systems during exploration missions. Crews routinely share, through platforms such as social media and journaling, the benefits of having fresh foods available throughout their long-duration missions on the ISS. In his reports of ISS astronaut journals, Stuster (2010, 2016) identifies “food” as one of the most discussed categories overall, with crewmembers noting fresh fruit is a “welcome change”; eating fresh produce as they are delivered appears to be a coveted event.

Furthermore, terrestrial research indicate that plants and natural settings are effective sources of psychological restoration (Berto, 2014) and that these benefits may partially extend to viewing green natural settings via a window or pictures (Horiuchi et al., 2014; Ryan et al., 2014), such as viewing plants in the enclosed Advanced Plant Habitat on ISS. Research in academic and office settings has demonstrated some improvements in cognitive, behavioral, and subjective performance when exposed to indoor plants (Gilchrist et al., 2015; Kim et al., 2018; Lin et al., 2013; Nieuwenhuis et al., 2014); medical research further indicates that the presence of live plants may improve surgical recovery times and pain management, and reduce subjective stress (Beukeboom et al., 2012; Park & Mattson, 2009). There exists substantial anecdotal evidence that plant growth in space enhances behavioral health.

Scott Kelly, during his one-year mission in space, famously discussed his experience caring for a zinnia flower in the Veggie plant growth system (Kelly & Dean,2018). The zinnias were grown through plant pillows, small rooting packets that contain substrate, fertilizer, and germination wicks along with attached seeds (Schuerger et al., 2021). These pillows were developed and tested with support from the ISS program and BPS. Kelly notes, “once the zinnias are my personal project, it becomes incredibly important to me that they do well” (Kelly & Dean, 2018, p. 344). While essentially providing a case study, Kelly’s experience is important given he spent close to one continuous year in space, after previous six-month mission. He details the concerns that arose when the zinnia plants were struggling to survive, and his involvement in ensuring that they receive the right care, demonstrating the importance of this activity in the context of his mission. While Kelly’s experience shows benefit of a plant, given limited resources, research should focus on *crop* plants, which have potential to benefit both nutrition and behavioral health.

Relatedly, extended duration spaceflights missions will lack sensory stimulation inherent with isolation and confinement (Stuster, 1996; Suedfeld and Steele, 2000). Presently, ISS crews receive a robust behavioral support system that is largely dependent on close proximity to Earth; this system includes bonus foods for crew preference and special occasions, resupply vehicles delivering novel and personalized gifts from home (including, at times, fresh fruit), real-time communication with loved ones, and meaningful leisure activities such as Earth-viewing photography, as evidenced by the large volume of Earth photos taken by crews on the ISS. However, exploration class missions may include only virtual depictions of Earth, in addition to a small habitable volume and no or limited resupply, which prohibits many of the existing effective measures to enhance behavioral health. A healthy and operationally feasible inflight crop growth system may offer a sustainable measure to boost behavioral health that is largely Earth-independent.

The science that ensures optimal crop plant growth is critical for providing a robust system that remains resilient in the spaceflight environment. As crews invest themselves in this meaningful activity, and in the context of prolonged isolation and confinement, it is important to consider the potential for deleterious effects if the crops are not resilient to the hazards of spaceflight (e.g., fail or die), thus being ineffective as a countermeasure and instead being detrimental to crew wellbeing.

Crop plant growth offers the potential to provide a rich, dynamic, sensory pleasing experience, and as Kelly highlights, it also provides a meaningful activity, all of which will be especially important during prolonged periods of isolation and reduced sensory stimulation. Preliminary data from the currently ongoing Veggie research study on the ISS demonstrates that interacting with crop plant growth systems provides positive sensory stimulation for taste, smell, and sight, as well being a meaningful activity that promotes wellbeing and connections with Earth and fellow crewmembers.

**Future Direction: Research to Understand Functional Allocation/Autonomous Systems for Crop Growth**

When it comes to autonomous systems and human interactions with the crop plant system, various aspects/levels of autonomy should be considered. The term “*autonomous system”* in this context, can refer to crewmembers operating and making decisions independently from ground support personnel, or alternatively, operations without significant astronaut involvement. The latter type of autonomy might involve some aspects of remote teleoperations where ground controllers can monitor crop status and act accordingly, or Artificial Intelligence (AI) monitoring and robotic crop tending, with sensors and control systems reacting to plant growth *in situ*. Fundamental plant biology research in space is needed to inform such autonomous systems of the level of care needed for plant growth during future missions.

Interestingly, Kelly’s experience with the Zinnia inadvertently provided a lesson in autonomous care; during the Zinnia test on ISS, the Veggie experiment team switched from defining crew procedures and roles in crop care, to a more astronaut-driven crew-decisional operation, where ground teams provided a care guide (Massa et al., 2017) and were available to answer questions while astronauts cared for plants based on their real-time observations. This approach, as Kelly further notes in his book, provided a great example of how future crews may work independently on their way to Mars. Crew-decisional plant care on the ISS has been repeated several times with other astronauts and crops since that experiment, with crews creatively finding solutions to hardware issues (e.g., Peggy Whitson developing a new way to add water to a malfunctioning plant pillow), novel horticultural approaches (e.g., Mike Hopkins testing seed transplanting in microgravity), and plant production challenges (e.g., Mike Hopkins and Megan McArthur developing methods to pollinate plants in microgravity).

Hence, an additional area where more information is needed is on the automation/crew time strategy to maintain plant environments. Testing in the spaceflight context is relevant because unique systems, processes, and procedures are implemented on the ISS. Preliminary data is being gathered on the ISS regarding what plant growth activities crewmembers enjoy and benefit from, and what activities are burdensome or taxing. These data will help inform future automation strategies for different mission scenarios. During certain exploration missions, crew may have periods of light workload (e.g., during transit missions to/from Mars), and during these times, crop tending may provide the crewmembers with meaningful work that they can perform without taking away from other mission-critical activities. A Mars surface mission, alternatively, may have considerably less available time. Depending on the duration and scale of the mission (e.g., sustaining missions), crop growth facilities may be larger than on the preliminary missions. In these situations, it might be necessary to automate most crop growth activities using AI/robotics, with the possibility that astronauts could directly intervene/disable automation in cases where they would like to or need to interact with the plants, such as harvesting ripe produce for dinner. Remote operations from ground controllers may be most feasible in low Earth orbit or lunar scenarios but would not be practical for a Mars surface mission given the communication time lag with Earth-based mission support.

**Leveraging advancements and testing, refining, and validating for spaceflight.** Industry is making great strides in “Digital Horticulture” (Tran & Chang, 2021), and NASA may be able to reap the benefits, focusing related research endeavors on NASA-specific needs. A team of horticulture and AI experts recently won the International Autonomous Greenhouse Challenge, beating a team of expert human growers. The winning team used AI to achieve 6% greater yields and 17% higher net profit, while using less CO2, heating, and water. High crop yields and efficient use of resources will also be important to future space travelers.

A three-phase technology deployment roadmap for autonomous growing was proposed by the winners of this challenge, which may be a good starting roadmap for NASA as well. The first phase, connectedness, is characterized by sensor and operational data capture, with the human in a primary monitoring role, tending the crops based on dashboards of information. This would be useful for missions where crew want to have an active role in crop management. The second phase involves a digital twin model—a virtual simulation of the growing environment. This phase involves advanced analytics and predictive modeling. Machine learning is used to make predictions based on historical data. Crewmembers could use the model to gain a better understanding of causes and impacts, and to experiment with different climate and care options. The third and final stage, autonomous growing, is characterized by a full AI implementation, allowing the crop growth system to make automated decisions. This would be the ideal solution for a larger planetary crop growth scenario, freeing up the crew for other tasks. The crew would always, however, have ultimate authority, and the power to override the system. While these advances may provide a starting point and preliminary data, these systems are at a low technology readiness and substantial investment will be required for advancement, particularly in the NASA-specific environment.

Major challenges need to be solved in the area of crop health monitoring in the context of spaceflight, with considerable ground-based crop research needed over the next decade to develop substantial data sets that will enable AI decision making for robotic systems. These data sets need to be collected in space-relevant environments and cover the gamut of candidate crops in nominal and off-nominal conditions to allow predictive modelling. ***Recommendation #2: Support research in the spaceflight environment that leverages advancements in autonomous systems/automation* *to enable crop plant growth systems as a countermeasure for human health and performance risks, in future exploration missions*.**

In summary, crop plant growth systems can enhance behavioral health during long-duration missions, by increasing the variety of food and providing meaningful, sensory-rich activities. Spaceflight research focusing on plant biology and on autonomous care is needed to ensure crop growth systems serve as a countermeasure, and not a stressor, during future exploration missions.

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