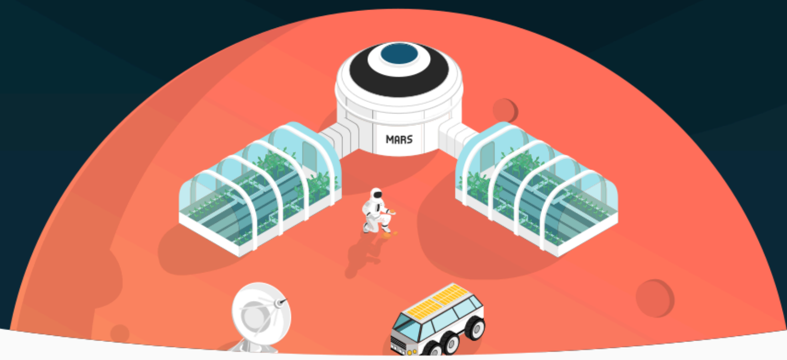
3rd Annual International Space Ecology Workshop

Oct 11-12, 2024
0800-1600 Pacific Daylight Time

Closed System Ecology | Crop Production and Waste Recycling | BLSS and CELSS



The global Space Ecology Workshop is a free, virtual 2-day conference that connects academia and industry to advance the science and art of supporting diverse life in space.

Welcome Space Ecology Professionals!

Welcome to the 3rd Annual Space Ecology Workshop, an international forum for discussing the ecological aspects of sustainable space habitation. We believe that there is a need to promote and organize closed ecological and bioregenerative life support (CELSS/BLSS) research internationally and reignite interest in an ecological systems approach to space habitation, especially given the current momentum for deep space exploration. We share a mutual vision of artificial closed loop ecosystems that exploit a combination of biological, ecological, and electromechanical processes to support human life.

Closed ecological systems will enable indefinite, sustainable human exploration of space as well as sustainable living on Earth. Many prior needs assessments point out similar gaps in knowledge and technology, and many obstacles remain in realizing this vision. We believe that advances will be made when we coordinate efforts and socialize these concepts globally. We hope this workshop can provide inspiraΘon and momentum to that end, and that there will be many more. We are so glad you've joined us!

Major Themes Include:

Enabling a Sustainable Presence in Space: Maintaining a permanent presence in space is untenable without a degree of self-sufficiency. We discuss technologies that contribute to mission longevity by enhancing crew health, closing material or energy loops, and replacing or reimagining physio-chemical life support systems.

Closed Ecological Systems for Deep Space: The understanding and development of artificial ecosystems are critical to achieve long term goals in life support and physical and mental health needs for crew. A major goal of this workshop is to coalesce research on closed ecological systems: highlight applicable existing research, identify gaps in knowledge, and coordinate future high-priority research.

Crop Production and Waste Recycling: Closing the material loop in food production and waste recycling systems is necessary to reduce reliance on regular resupplies. Extensive space agriculture will be a prerequisite for space habitats with permanent residents. Topics of interest include: improving yield, designing with automation, crop cultivar selection, and water and nutrient delivery systems.

2024 Space Ecology Workshop Agenda

Day 1, October 11, 2024. All times in Pacific Daylight Time (PDT)

8:00-8:15am	**Opening Remarks** Patrick Grove, The Spring Institute for Forests on the Moon
8:15-9:00am	**Featured Speaker** Gioia Massa, NASA KSC: *Space Crop Production Gaps and Challenges*
9:00-9:40am	**Morning Presentations** Yvette Gonzalez: *Bioastronautics Research in Suborbital Spaceflight, Parabolic, and Cave Analog Environments Informing Sustainability* Celine Klots: *Microbial Resilience and Adaptation for Space Exploration: A Step Towards Sustainable Bioastronautics*
9:40-10:00am	**Coffee Break**
10:00-11:20am	**Morning Presentations, Continued** Sharon Doty: *Plant-microbial partnerships for reduced nutrient and water requirements* Frieda Taub: O2/CO2 & pH Dynamics in Microbe, Algae, Daphnia Closed Ecosystems: Lessons from Decades of Experiments Luis Guzman: *Diatoms in Lunar subgravity in the ISS* Matthew Paddock: *Harnessing Synthetic Biology for Biomanufacturing in Space: from Fermented Foods to Industrial Enzymes*
11:20-12:30pm	**Lunch Break**
12:30-1:15pm	**Featured Speaker** Gabrielle Caswell: *Humans in the Ecosystem*
1:15-2:15pm	**Afternoon Presentations** Colin Lennox: *Mapping metabolic triplets: visualizing self organizing principles based on Gibbs free energy and an ever adapting ecology.* Oscar Monje: *Space Farming Enables a Cis-Lunar Economy* Donald Coon: *Gas Exchange, Yield and Photosynthesis of Modified Energy Cascade Crop Model*
2:15-2:30pm	**Coffee Break**
2:30-3:50pm	**Afternoon Presentations, Continued**

	Donald Jacques: *A Mobile Closed Loop Ecological System Laboratory: Air, Water, Food, and Waste recycling for One in a Single Lab* Morgan Raimondo: *Endophytes for Increasing Plant Resilience and Survival Under Abiotic Stress* Laura Fackrell: *Introduction to Rhodium Scientific and Astrobotany and Space Ag Capabilities* *<Speaker absent>*
3:50-4:00pm	**Closing Remarks** Patrick Grove, The Spring Institute for Forests on the Moon

2024 Space Ecology Workshop Agenda

Day 2, October 12, 2024. All times in Pacific Daylight Time (PDT)

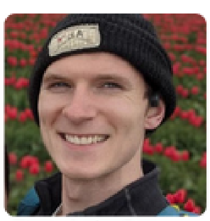
8:00-8:15am	**Opening Remarks** Patrick Grove, The Spring Institute for Forests on the Moon
8:15-9:00am	**Featured Speaker** Volker Hessel, Plants 4 Space: *Modeling of Space Crop Dishes for Astronauts and Digital Twins for Space Agriculture*
9:00-9:40am	**Morning Presentations** Michael Gildersleeve: *NuCLEUS: Advancing Ecological Integration for Sustainable Life Support in Space* Adam Williams: *Regolith to Soils - transforming lunar regolith into soils*
9:40-10:00am	**Coffee Break**
10:00-11:20am	**Morning Presentations, Continued** Clara Laforet: *The Marshian: Automating the Setup of Waste Treatment Systems to Minimize Astronaut Operation Time in Lunar Habitats* Bryce Meyer: *Key Space Farm flows for efficiency: algae, plant crops, and fish.* Mara Leite: *Sustainable plastic production for deep-space 3D printing* Luke Fountain: *A simulated high CO2 spaceflight environment increases plant preference for ammonium as a nitrogen source.*
11:20-12:30pm	**Lunch Break**
12:30-2:10pm	**Afternoon Presentations** Davi Souza: *From vertical farms to space analogs: standardized terrestrial platforms for Space Ecosystem Technology research and training* Gavin Schneider: *Canadian Deep Space Food Challenge Winner - CANGrow* Basava Swamy: *Can Lunar Soil Nurture Plant Growth?* Adam Gelman: *Misadventures in Amending Lunar Regolith Simulant for Crop Production in Hydroponic Systems* Ted Tagami: *Lessons Learned from 10 Astrobotany Experiments to the ISS*

2:10-2:25pm	**Coffee Break**
2:25pm-3:05pm	**Afternoon Presentations, Continued** Adrianna Sanchez: *Mushroom Waste Digestion for Space Applications* Kevin Shaffman: *Phosphorus and Potassium Solubilizing Endophytes as an Approach to in-situ Resource Utilization*
3:05-3:50pm	**Featured Speaker** Jane Shevtsov, Propagule Space Ecology Institute: *How to Build a Biosphere*
3:50pm-4:00pm	**Closing Remarks** Patrick Grove, The Spring Institute for Forests on the Moon

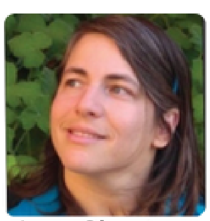
Tips and FAQs

- **Communicating with Speakers and Organizers**: Given the number of attendees, microphones are muted and videos are off by default. However, there are several other ways to communicate with the speakers and with one another:
    - **Zoom Q&A Box for Questions to Speakers**: If you have a question you would like to ask one of the speakers, please enter your questions into the "Q&A" box in Zoom.
    - **Zoom Chat for Comments and Feedback**: Please provide any comments or feedback that you would like to share with the group (other than questions for our speakers), in the Zoom "Chat" box.
- **Will the Workshop be recorded and available to watch later?**
    - **Yes!** The recordings of both days of the workshop (as well as previous years' workshops) will be available on YouTube here:
        - https://www.youtube.com/@spaceecologyworkshop8066
    - Transcripts of the Zoom chat log will also be uploaded to the website after the event (www.spaceecologyworkshop.com)
- **Technical Difficulties**: If you are having trouble accessing anything or have any other technical questions, please message Patrick Grove in Zoom chat. He's there to help!

Space Ecology Workshop Organizers:

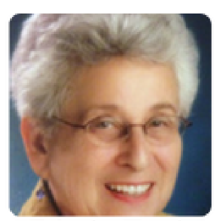


Patrick Grove
The Spring Institute for Forests on the Moon

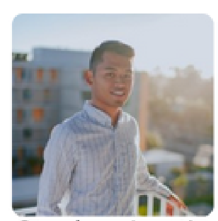


Jane Shevtsov
Propagule Space Ecology Institute; UCLA

Marshall Porterfield
Propagule Space Ecology Institute; Purdue



Frieda Taub
University of Washington



Stephen Lantin
University of Florida; NASA

Presentation Abstracts:

- **Yvette Gonzalez: *Bioastronautics Research in Suborbital Spaceflight, Parabolic, and Cave Analog Environments Informing Sustainability***
  - From parabolic flight to suborbital spaceflight to orbital spaceflight, these platforms and their range of hyper gravity environments serve as laboratories to investigate a complex nexus of biology, medicine, engineering, human health, and space research. Increasing access to the space environment means that we are confronting the bioastronautics challenges of human health, safety, protection, and integrative physiology in real-time. Short duration experiences anywhere from 20-second parabolas, four minute suborbital microgravity, five days in orbit, 10 days on the International Space Station, or seven days isolated in a lunar simulation inside a cave in Portugal - all reveal insights about how we might support life in space over longer periods of time. These environments and their unique conditions allow us to honor decades of space research, experiment, push the limits on theories or technologies, challenge any assumptions we have, fail or advance, share our lessons widely, then adapt quickly so that we better design, better equip, and better prepare ourselves for a long-term context off-planet. These endeavors help us to collectively consider solutions in the form of innovations, mitigations, and countermeasures, but most critically: prevention. Preventing starvation, disease, structural deterioration, etc. In this conversation, I share how to access these environments, how each platform informs research methodologies, why these studies are relevant, how they might push us to rethink resource sharing, and how we can harness outcomes to already shape or develop programmatic, policy, and ethical considerations for space ecosystems.
- **Celine Klots: *Microbial Resilience and Adaptation for Space Exploration: A Step Towards Sustainable Bioastronautics***
  - Innovation Labo is involved in pioneering research in the field of bioastronautics with the aim to enhance human resilience on earth and beyond. Data from space missions has provided information crucial to understanding the impact of extreme conditions – radiation, gravity, isolation - on the microbiome. By studying the adaptation and evolution of probiotic strains under space conditions, scientists at the Tokyo Innovation Lab have developed a platform to bio-prospect and evolve the microbiome’s DNA to produce advanced solutions for agriculture in space. From studying adaptation and evolution of probiotic strains sent to space to evaluating the potential for enhanced growth, stress resistance, and nutritional value of hydroponic cultivation, this research aims to create sustainable solutions that support human health and performance during long-duration space missions and future colonization efforts.
- **Sharon Doty: *Plant-microbial partnerships for reduced nutrient and water requirements***
  - To efficiently use resources at Lunar and Mars bases will require the ability to grow crop plants in the materials available on site. The plant microbiome, including microbial endophytes living within plants and the epiphytes living on the plant surface, has a profound influence on the productivity and resilience of the host plant. Poplar (Populus) and willow (Salix) in their native riparian habitats of bare rock and sand have a diverse microbiome that provides services including fixation of dinitrogen gas , phosphate solubilization, and promotion of overall plant growth and health under abiotic and biotic stresses. Addition of a

consortium of bacteria and yeast strains from wild poplar and willow to cultivated poplar , and other plants, including grasses , rice , and conifers) , likewise increases plant growth, rooting, resource use efficiency (e.g., water and nitrogen), and drought tolerance. Harnessing the power of the plant microbiome will enable growth of plants for agriculture, biofuels, wood production, and human well-being with the limited resources of extraterrestrial habitats.

- **Frieda Taub: O2/CO2 & pH Dynamics in Microbe, Algae, Daphnia Closed Ecosystems: Lessons from Decades of Experiments**
    - (No abstract provided.)
- **Luis Guzman:** ***Diatoms in Lunar subgravity in the ISS***
    - This project involved sending marine diatoms of the genus Phaeodactylum tricornutum into a lunar sub-gravity environment aboard the International Space Station (ISS) as part of MIT's Space Exploration Initiative, Sojourner 2020. The primary objective was to explore the potential for life beyond Earth by highlighting the symbiotic relationship between photosynthetic organisms and aerobic lifeforms, such as humans, thus underscoring the critical role of symbiosis in the evolution of life in space. Over the project's thirty-day duration, P. tricornutum was expected to undergo thirty generations of reproduction, with each daily cycle providing an opportunity to observe ontological differentiation. Born and adapting in the unique conditions of space—exposed to a lower gravitational field and extraterrestrial environmental factors—the diatoms were anticipated to experience fundamental changes in their biology. In this context, the diatoms may be considered extraterrestrial, as their development would be shaped by conditions that do not exist on Earth, offering new insights into how life might evolve in space.
- **Matthew Paddock:** ***Harnessing Synthetic Biology for Biomanufacturing in Space: from Fermented Foods to Industrial Enzymes***
    - Biomanufacturing can provide on-demand production of mission-critical compounds and materials to support long-duration space exploration while circumventing the challenges of transporting materials from Earth. Synthetic Biology Project is developing two biomanufacturing capabilities: BioNutrients and CO2-Based Manufacturing. BioNutrients is an ongoing mission aboard the International Space Station focused on the production of perishable nutrients in an on demand for direct for consumption. The first flight experiment of this project targeted the production of carotenoids: β-carotene and zeaxanthin, in recombinant yeast strains. Since then, the project has expanded to encompass the production of the fermented consumables like yogurt and kefir for use as a nutrient delivery mechanism. The CO2-Based Manufacturing system aims to use in situ resources to allow for biomanufacturing with minimal re-supply required. The manufacturing platform is combined with an electrochemical CO2 conversion system which can produce simple carbon substrates to support microbial based biomanufacturing. A comprehensive ground-based platform for recombinant protein purification is in development with the goal of producing a thermostable carbonic anhydrase enzyme from E. coli utilizing CO2-derived acetate. Our group hopes to propel advancements in space biomanufacturing for long duration space flight by harnessing the tools of synthetic biology.
- **Gioia Massa, NASA KSC:** ***Space Crop Production Gaps and Challenges***
    - As astronauts venture farther from Earth, and stay for longer periods, the space food system will increase in importance. Crop production can supplement a

pre-packaged space diet to provide nutrition and dietary variety for space crews. In future missions, bioregenerative approaches may be used to generate a larger percentage of the diet, as well as help to reduce life support system burdens and resupply from Earth. Plants may also provide behavioral health benefits to crew members living in the isolated, confined environment of a space habitat. A number of unique challenges exist for growth of plants in microgravity and on other reduced gravity surfaces like the moon and Mars. Testing plant growth inside the Veggie and Advanced Plant Habitat (APH) chambers on the International Space Station is allowing us to understand the impacts of gravity and spaceflight on crop growth, nutritional content, acceptability, and the importance of plants to astronauts living and working away from Earth. We are also gaining a better understanding of food safety concerns and the behavior of space plant microbiomes and plant pathogens, but major gaps in knowledge remain. As we move from research towards operational space crop production to enable exploration, there are numerous gaps in technology, knowledge, and practice related to space crop growth that must be addressed. Research and development in key focus areas such as effective water and nutrient delivery at variable gravity levels, autonomous plant health monitoring, growth system cleaning and disinfection, and selection of ideal space crops are needed to fill these gaps. Breeding or engineering custom space crops may impact areas including plant growth and development, plant physiology, produce nutrition, organoleptic acceptability, and post-harvest characteristics, and these may further enable space crop production scenarios. Space crop challenges are multifaceted and require diverse interdisciplinary teams working together to develop effective solutions. Solving these requires an array of skill sets from across the biological and physical sciences, engineering, and human social sciences. Solutions to help ensure food security off-Earth may also translate to more sustainable terrestrial crop production approaches, and regular dialog between industry, academia, and government organizations working in related fields benefit all. Additional help can come from engagement with student researchers at various levels through courses, participatory science projects, and open science activities which can provide useful data. Global coordination and integration between space agencies and partners will be essential.

- **Colin Lennox: *Mapping metabolic triplets: visualizing self organizing principles based on Gibbs free energy and an ever adapting ecology.***
    - (No abstract provided.)
- **Oscar Monje: *Space Farming Enables a Cis-Lunar Economy***
    - Space crop production is needed to support large populations of humans living/working in cis-lunar space. A cis-lunar economy would consist of space tourism, asteroid mining, lunar fuel production, Earth observation, space manufacturing operations, and commercial space stations that will require the deployment of sustainable bioregenerative life support systems. Continuous resupply of shelf-stable food may be suitable while the population of humans in cis-lunar space remains ~10-15, the current population on ISS. However, this may no longer be sustainable as the cis-lunar population rises to 100 or 500. Several issues must be resolved: 1) Where to locate a space farm? 2) What is the energy source for food production? 3) Can robotics help reduce the human footprint? and 4) How to scale current crop systems for large-scale production. Space crop production systems will have to be bioregenerative to minimize resupply from

Earth. Advances in Earth-based vertical farming industries will be needed for large-scale crop production in a lunar base.

- **Donald Coon: *Gas Exchange, Yield and Photosynthesis of Modified Energy Cascade Crop Model***
    - Abstract/Description: This presentation explores the application of the Modified Energy Cascade Crop Model to better understand the interactions between gas exchange, yield, and photosynthesis of bioregenerative life support cropping system modules. By integrating growth chamber experiments with a comprehensive Global Sensitivity and Uncertainty Analysis (GSUA), we assess the robustness and predictive capability of three model versions. The GSUA framework allows us to identify key parameters influencing model outputs, offering insights into the model's sensitivity to various physiological and environmental factors. Experimental data collected under ideal and heat stress conditions provide validation for the model and highlight potential areas for further refinement. The results offer valuable contributions to the ongoing efforts to improve crop modeling accuracy and reliability, particularly in the context of space exploration and life support systems.
- **Donald Jacques: *A Mobile Closed Loop Ecological System Laboratory: Air, Water, Food, and Waste recycling for One in a Single Lab***
    - Closed Loop Life Support is the holy grail of long term space travel. But closing the many loops involved in providing fresh Air, clean Water, varied Food, and full nutrient and mineral recovery through Waste recycling has proven daunting, to say the least. The Mobile Analog Space Habitat incorporates multiple biological species in a working ecological system to close these loops. With two sources of protein, a vegetable garden, plus insects, and Cyanobacteria: we are producing air, recycling water, growing food, and processing our wastes on board the MASH. We are maintaining each population; now we are working to engender reproduction within each of the populations while continuing to harvest from them, in order to bring them each to full productivity. I will present the various modules, and how the ecological flow works in this 300 sq foot space.
- **Morgan Raimondo: *Endophytes for Increasing Plant Resilience and Survival Under Abiotic Stress***
    - Space agriculture faces unique challenges in sustaining plant growth under the extreme conditions of spaceflight, including microgravity and increased radiation exposure. This study investigates the potential of endophytes derived from Populus trichocarpa to improve plant resilience against environmental stressors. Endophytes were isolated from P. trichocarpa in the semi-arid Yakima River area, Washington State, USA. Sterile P. trichocarpa Nisqually-1 were inoculated with 14 individual endophyte strains and assessed under conditions simulating space-related stressors using a novel screening method. Key growth parameters evaluated included biomass accumulation, chlorophyll production, and overall stress tolerance indicators. Two endophyte strains improved plant growth, while several others enhanced chlorophyll content and stress resistance markers, suggesting their potential to promote plant resilience in space environments. Inoculation was confirmed using droplet-digital PCR. Whole genome sequencing of the beneficial bacterial strains elucidated potential mechanisms behind their stress-mitigating abilities, including enhanced antioxidant production, improved nutrient uptake, and modulation of plant stress response pathways. These mechanisms could prove crucial in counteracting the oxidative stress induced by

cosmic radiation and the altered nutrient dynamics in microgravity conditions. Our findings offer a method for screening beneficial endophytes for space agriculture and highlight the crucial role of plant-microbe partnerships in developing resilient crops for closed ecological life support systems. This research contributes to the advancement of sustainable bioregenerative life support technologies, addressing critical needs in microbiome engineering, resource efficiency, and adaptability to the unique stressors of spaceflight. The potential of endophytes to enhance plant performance under multiple stress conditions could significantly impact the development of more efficient and reliable food production systems for long-term space missions and habitats. By improving our understanding of complex biological interactions within closed systems subjected to space-specific challenges, this work supports the broader goal of enabling a sustainable human presence in space through advanced ecological life support systems.

- **Laura Fackrell: *Introduction to Rhodium Scientific and Astrobotany and Space Ag Capabilities***
    - Rhodium Scientific collaborates nationally and internationally with industry, academia, and government to provide space-based life science expertise, NASA mission Integration and operation (MI&O) protocols, and rapid access to the microgravity environment on the International Space Station (ISS). We have applied the Rhodium Quality Industry Compatible (QuIC) Space Process to multiple missions in space with multiple research focuses including astrobotany. Plants have been grown in space since 1982 but there are still many scientific questions. Challenges of growing plants in space include optimizing root growth in microgravity, ensuring adequate lighting, preventing hypoxia, and ensuring nutrient supply. Rhodium has multiple flight-tested, proven and ready-to-launch hardware capabilities applicable to designing projects that help address the challenges of growing plants in space. This presentation introduces Rhodium, its hardware and capabilities for space biotech including focuses on plant science and space ag, and summarizes two current missions where this hardware is being applied. The first mission is a current mission termed LEO Integrated Flori-culture Experiment (LIFE) which uses our SOFIA hardware to conduct a plant growth experiment for comparing root growth for a genetically modified, gravity-insensitive variant of Arabidopsis Thaliana. The second mission is an upcoming space agriculture project that brings together selected Veteran-owned small businesses from the state of Alabama on a collaborative mission to address multiple space and terrestrial agricultural challenges including seed germination and microbiome metabolite production.
- **Gabrielle Caswell: *Humans in the Ecosystem***
    - Space exploration challenges concepts of how humans can survive and thrive in the hostile environment of microgravity. Humans exist with the help, and symbiotic relationship, of their microbiome. A understanding is being gained on how the human microbiome contributes to human health. Appreciating that our microbiome is influenced by the surrounding macrobiome, and the macrobiome, itself, is part of the biome, or Earth's biomass. The clinical manifestations of microbiome changes are beginning to be catalogued, the clinical impact is not yet fully understood. To be successful, longer term space exploration, long haul flights and colonisation, will require a more refined understanding of the human in their ecology.

- **Volker Hessel: *Modeling of Space Crop Dishes for Astronauts and Digital Twins for Space Agriculture***
  - Future long-term human exploration of space will need a supply of resources for astronauts, including fresh food from space farms. This means it is necessary to identify combinations of crops that can be successfully grown together and which provide a balanced and palatable diet for astronauts. We used numerical optimization to identify such combinations, using macro- and micronutritional content as constraints, while optimizing water load needed for crop farming. The food constraints considered were based on the recommendations of the National Aeronautics and Space Administration (NASA), considering up to 36 nutrients and 102 crops. We evaluated 10 scenarios ("space dishes") for daily full-nutrient supply to one astronaut, with four scenarios being vegetarian (crops only) and six being omnivorous (crops and meat). Each scenario was analyzed for the capability of plant growth, including the required planting area and crop growth time and productivity; from the viewpoint of optimizing performance in space. As plants contain both edible and inedible parts and require fertilizer input, respective circularity assessments were made determining the waste generation, degree of recyclability, and overall mass processed, using three common metrics of the circular economy. The space dish identified as optimal was prepared as a salad, to allow judgment on the palatability, i.e., the "space food acceptance," by a small psychology test. These assessments are essential steps toward feasibility in long-term human space missions, for example, to Mars. As Outlook, we will show our concept for digital twin modelling of space plant growth. We invented to use two physical twins instead of the one normally used. A physical-twin sender ("space") and a physical-twin receiver ("Earth replica of space"). Such approach allows, in principle, to repeat the 'one-time space experiments' on Earth for better data accuracy and higher wealth of information. We conducted two experimental studies - one on a 1000 m high mountain (sender; "space") and one exposing a plant to six different climate zones during one growth period.
- **Michael Gildersleeve: *NuCLEUS: Advancing Ecological Integration for Sustainable Life Support in Space***
  - The Nutritional Closed-Loop Eco-Unit System (NuCLEUS) is a prototyped space food production system designed to tackle the ecological challenges of bioregenerative life support systems (BLSS) for long-duration space missions. NuCLEUS integrates plants, fungi, and insects into a modular, symbiotic system where resources flow between species, simulating Earth's ecosystems to provide a continuous food source and life support for astronauts, while recovering nutrients by leveraging species' ecological niches. As the winner of NASA's 2024 Deep Space Food Challenge, NuCLEUS was evaluated based on its design, resource efficiency, and system reliability during a 6-week demonstration at Ohio State University's analog facility. By supporting vital BLSS functions such as food production, air revitalization, and nutrient recycling, NuCLEUS represents a step forward in understanding the complexities of ecological mass balance in closed environments. NuCLEUS has the potential to revolutionize space agriculture, improving astronaut health through diverse, nutritionally balanced diets while minimizing waste and maximizing resource use efficiency. The system's data collection capabilities provide critical insights into nutrient cycles and resource flow, helping to refine models of how ecological systems behave in the space environment. The principles behind NuCLEUS also have terrestrial applications,

    extending from sustainable agriculture to the cultivation of bioactive compounds for pharmaceutical and cosmetic use. The system offers a scalable solution for improving resource efficiency in terrestrial production systems. A collaboration with L'Oréal highlights the system's commercial potential in the production of high-value compounds. NuCLEUS is the product of a multidisciplinary collaboration between academia, industry, and space agencies, representing a new frontier in ecological innovation. By merging ecology with space technology, NuCLEUS opens the door to self-sustaining life support systems that will be critical for human survival in space and resource-limited environments on Earth.

- **Adam Williams: *Regolith to Soils - transforming lunar regolith into soils***
    - An overview of my PhD research around the impact of earthworms on turning regolith into soils.
- **Clara Laforet: *The Marshian: Automating the Setup of Waste Treatment Systems to Minimize Astronaut Operation Time in Lunar Habitats***
    - "The Marshian" is a conceptual design for an artificial waste treatment wetland tailored for efficient, autonomous, low-maintenance processing of human waste in environments with sufficient gravity (e.g., the Moon or Mars). The design is based on the "French Reed Bed" system, a modern alternative to traditional municipal waste treatment plants. Utilizing a series of gravity-fed terraces, The Marshian promotes sediment settlement and leverages microbial and plant metabolisms to reduce nutrient and pathogen levels to safe thresholds. By employing in-situ resources for construction and operation, along with ecological remediation, the design aims to reduce equivalent system mass (ESM) costs to levels comparable with physicochemical alternatives. The set-up phase is the most human-intensive, while the system's operation is fully automated, and maintenance requires only a few hours annually. Automating the set-up phase can significantly reduce the time and effort needed from astronauts. The most significant time-saver would be the automation of transforming regolith into materials like sand, gravel, and pipes. This process not only underpins the creation of The Marshian but also has applications for other lunar constructions, making it essential for both the project's efficiency and the sustainability of lunar operations. Research into existing technologies reveals various methods for automating regolith transformation. Techniques such as robotic regolith collection, electrostatic sorting for gravel size differentiation, microwave extraction of water, and mixing regolith with binders for 3D printing offer practical solutions. Furthermore, calculations have been performed to estimate the necessary quantities of materials, time, and energy for these processes, ensuring that materials can be produced efficiently to meet the project's demands.
- **Bryce Meyer: *Key Space Farm flows for efficiency: algae, plant crops, and fish.***
    - Mass flow is key to planning tanks, filter arrays, and energy requirements. A very interesting and efficient flow is an Algae and Plants to Fish (then to people) flow due to the ability of fish to convert algae into proteins and nutrients for plants. This presentation will cover per person flows, sizing of tanks, footprints, and heat rejection. Will also cover key design structures, machinery, and inputs.
- **Mara Leite: *Sustainable plastic production for deep-space 3D printing***
    - (No abstract provided.)
- **Luke Fountain: *A simulated high CO_2 spaceflight environment increases plant preference for ammonium as a nitrogen source.***
    - Long-duration exploration missions will require a sustainable supply of food to

support human crews. The spaceflight environment contains high concentrations of CO_2 due to release by astronauts that cannot be completely scrubbed. It is therefore crucial to understand plant responses to elevated CO_2 (eCO_2) environments. Nitrogen (N) is crucial for plant survival, though the effects of eCO_2 on plant N uptake remain poorly understood. Shoot nitrate reduction may be reduced at eCO_2, due to reduced reductant availability for nitrate reduction due to reduced photorespiration and increased carbon fixation. Relative growth rate may be reduced at eCO_2 when N is provided only as nitrate and can be unaffected when N is supplied as ammonium, suggesting eCO_2 may drive increased plant 'preference' for ammonium. However, changes in N preference in response to eCO_2 have, to our knowledge, not yet been studied. In this study, novel stable isotope approaches were used in conjunction with hydroponics and isotope ratio mass spectrometry to determine the effect of space station-like eCO_2 (3000 ppm) on preference for ammonium or nitrate in several lettuce varieties previously grown in space, when both N forms are provided equally. All varieties displayed significant ammonium preference irrespective of CO_2 concentration, however the extent of this preference varied. Increased ammonium preference was observed for all varieties at eCO_2 compared to ambient CO_2 (410 ppm), driven by increases in nitrogen uptake which plants disproportionately took up as ammonium. These results suggest that future nutrient formulations should favor ammonium as a major N source for space crop production. Moreover, increased ammonium preference may play a role in future plant-based bioregenerative life support systems with higher ammonium concentrations due to waste recycling. Additionally, this research furthers our understanding of plant responses to future high CO_2 climates, allowing the development of future-proof crops to maintain food security.

- **Davi Souza: *From vertical farms to space analogs: standardized terrestrial platforms for Space Ecosystem Technology research and training***
  - Space exploration is driving the spread of advanced farming technology beyond Earth, revealing a key issue: the limited knowledge exchange between terrestrial and space farming sectors. While space-based agriculture technologies show promise, access remains restricted, leading to a continued reliance on Earth-based experimentation. This emphasizes the need for standardized platforms to efficiently transfer information between these domains, and establish comprehensive metrics to ensure streamlined operations, flexibility, efficiency, and safety. With that, this study aims to evaluate solutions from space-like horticultural systems, such as vertical farming, smart greenhouses, and controlled environment agriculture (CEA), including applications for space analog missions. By integrating hardware and software with sustainable practices, we aim to enhance capabilities towards space ecosystem technology, and support research and training. The potential results demonstrates the capacity to strengthen both terrestrial and space agriculture industries, by creating new business opportunities and preparing the next generation of professionals in these fields. Finally, implementing the presented guidelines can be crucial to increase reliability and innovation through farming platforms to support the design of future ecological systems off-Earth and advance long-term sustainable human missions.
- **Gavin Schneider: *Canadian Deep Space Food Challenge Winner - CANGrow***
  - (No abstract provided.)

- **Ravikumar Hosamani / Basava Swamy: *Can Lunar Soil Nurture Plant Growth?***
    - Lunar exploration has captivated significant attention in recent times through programs such as Artemis. To establish long-term sustenance on the moon, astronauts will have to grow their food on-site. In the present study, we investigated whether ISRO's lunar soil simulant (LSS); LSS-ISAC-1 can nurture crop plants. We assessed the germination and seedling growth response of four important crops—wheat, tomato, groundnut, and cotton to LSS. Our findings revealed that plants significantly struggled with low germination, stunted seedling growth, and increased oxidative stress. This baneful phenotypic and biochemical issues stemmed from LSS's acidic pH, low Electric Conductivity (EC), and severe nutrient deficiency. To mitigate these problems and alleviate inherent toxicity, we enriched LSS with varying amount of CP – 3.125%, 6.25%, 12.5%, 25%, 50%, and 100%. The results showed that LSS supplemented with 6.25% CP in wheat and tomato; 3.125% CP in groundnut, and 25% CP in cotton significantly improved phenotypic and biochemical traits in seedlings. As anticipated, all four crops thrive well on earth soil (ES) and CP per se, outperforming the LSS. This study underscores cocopeat's potential as a promising additive to support crop growth in lunar soil, advancing the in-situ resource utilization (ISRU) strategy for lunar agriculture.
- **Adam Gelman: *Misadventures in Amending Lunar Regolith Simulant for Crop Production in Hydroponic Systems***
    - Plant-microorganism interactions in crop production represent a critical and under-researched aspect of CEA and bioregenerative life support systems (BLSS). Beneficial microorganisms have been shown to enhance plant resistance to pathogens, response to abiotic stress, and ability to uptake nutrients through the roots. The goal of this research is to gain insight into the potential of microbial amendments to facilitate crop growth in a hydroponic system using lunar regolith simulant, a necessary technology to support and sustain human outposts beyond Earth through in-situ resource utilization (ISRU). This research has applications to support NASA's return to the moon as part of the Artemis missions and will also provide insights into the resiliency and resource use efficiency (RUE) of CEA systems. Dwarf tomatoes (c.v. Red Robin) were grown in coco-coir amended lunar regolith simulant (LRS) over 6 weeks, excluding germination and emergence stages. Data collected over those weeks indicates, according to preliminary analysis, that implementation of a commercial inoculant had either no effect or a possible detrimental effect on plant growth and yield. This was not the hypothesized outcome; as such, we are eager to pursue our previously planned microbiome analysis to clarify what may have occurred.
- **Ted Tagami: *Lessons Learned from 10 Astrobotany Experiments to the ISS***
    - (No abstract provided.)
- **Adrianna Sanchez: *Mushroom Waste Digestion for Space Applications***
    - Human space exploration is progressing between this astronautics era (earth-dependent exploration), to an earth-independent future enabled by bioastronautics as envisioned by Tsiolkovsky (1857-1935). The evolution of human space exploration and habitation is being driven now by challenges to support human lunar exploration in the next decade. Currently in LEO supplies of food and other consumables delivered to the ISS produce plastic and food packaging waste. This study investigates the potential of Pestalotiopsis microspora as a bioremediation agent for plastic waste generated during space

missions. As space exploration progresses, effective waste management solutions become crucial for sustainability. Our objective is to optimize the growth conditions of Pestalotiopsis microspora in a liquid medium to enhance its plastic-digesting capabilities. Using spectrophotometry, we analyzed the degradation of various plastic types over time, measuring changes in absorbance to quantify plastic breakdown. Preliminary results indicate that Pestalotiopsis microspora can effectively digest plastics, showing significant mass reduction and corresponding spectrophotometric changes, which reflect metabolic activity during the degradation process. Optimizing growth conditions can significantly enhance the effectiveness of Pestalotiopsis microspora in reducing plastic waste. This research contributes to the development of sustainable waste management strategies in space, addressing critical challenges in developing BLISS. The primary challenge for humanity now is to leave low earth orbit (LEO) behind like training wheels, for the next stepping stone a continuous lunar outpost and human presence on the moon.

- **Kevin Shaffman: *Phosphorus and Potassium Solubilizing Endophytes as an Approach to in-situ Resource Utilization***
    - Nutrient availability presents a critical challenge to sustaining off-world bases and colonies. While early settlers may initially rely on imported nutrients and efficient recycling systems to support small habitats, and to build independent sustainable colonies, pioneers will ultimately depend on in-situ nutrient resources. On the Moon and Mars, phosphorus and potassium—vital elements for plant growth—are present in the regolith at concentrations comparable to Earth soils which support agriculture. However, these nutrients are locked in minerals which limits their availability in plants. On Earth, these soils would be supplemented with fertilizer derived from mined nutrients; however, the Moon and Mars lack concentrated ore deposits, making traditional mining techniques impractical due to the need for heavy machinery, large amounts of water, and hazardous chemicals, all of which are difficult to transport to and use on the Moon and Mars. Plants have evolved symbiotic relationships with fungi and bacteria to extract these nutrients from primary substrates. By cultivating plants in regolith with these symbiotic microorganisms, space pioneers could enhance nutrient availability within artificial ecosystems, reducing the dependency on costly resupply missions from Earth. The Doty lab is investigating how bacterial isolates from pioneer plants growing on Hawaiian lava flows and nutrient poor river banks, which share chemical similarities with lunar and Martian regolith, dissolve mineral phosphorus. Eventually, we plan to test if these microbes enhance plant mineral uptake from JCS-1A and JCS Mars-1A regolith stimulants. Plant associated microbes could play a pivotal role in overcoming the nutrient availability problems facing extraterrestrial colonization.
- **Jane Shevtsov, Propagule Space Ecology Institute: *How to Build a Biosphere***
    - Images of space colonies people actually want to live in almost always include large amounts of green space. However, current space life support systems are entirely physicochemical. How do we go from physicochemical systems with some supplementary vegetable production to bioregenerative systems to biospheres? This talk will outline an element-driven successional framework for doing so based on ecology, evolution, and mathematical modeling. It will discuss key obstacles to building space biospheres, such as the scarcity of key elements, and ways to overcome them. It will also propose principles for the design of both

closed biospheres in space and sustainable economies on Earth.