Developing Bioregenerative Food Systems for Life Support

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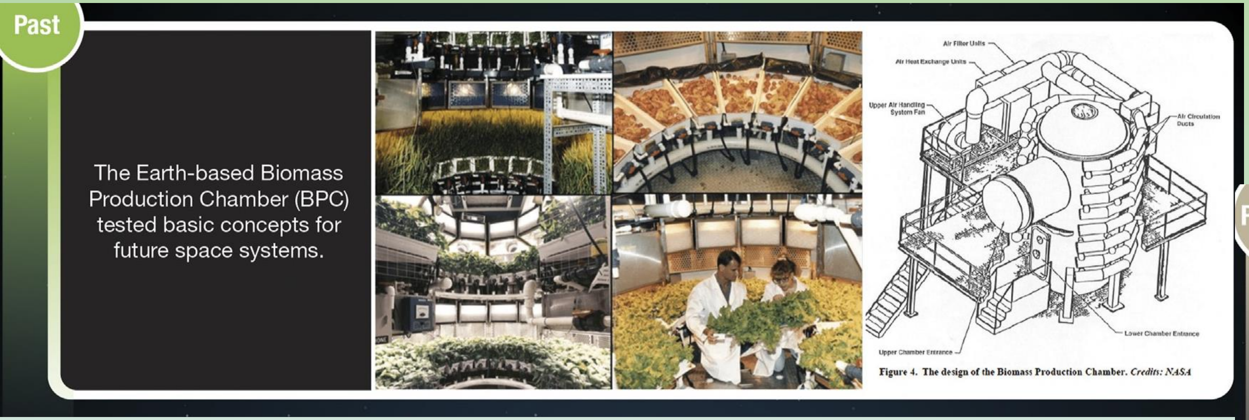
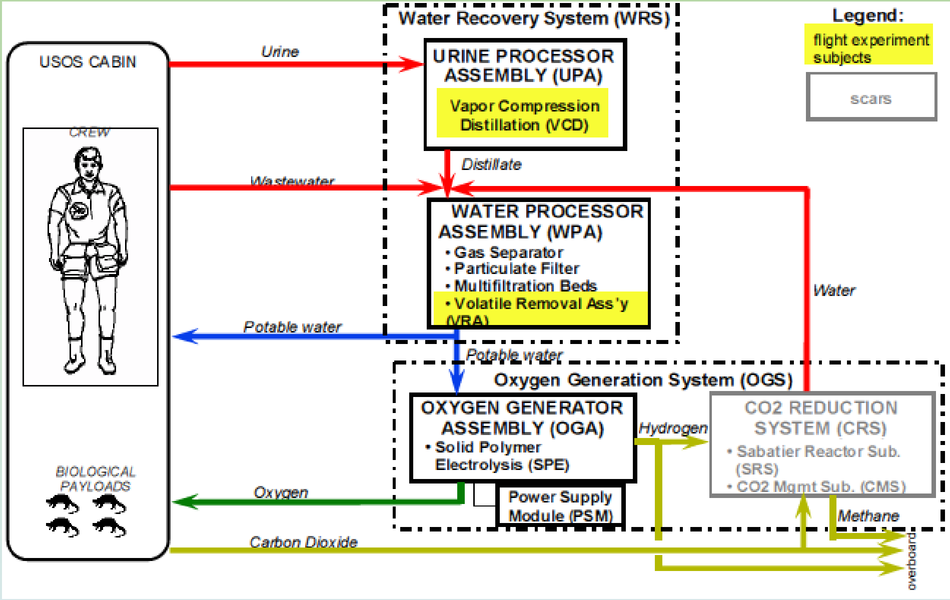
Controlled Environment Agriculture – landwirtschaftliche Produktion der Zukunft?
Hans Eisenmann-Forum für Agrarwissenschaften der Technischen Universität München

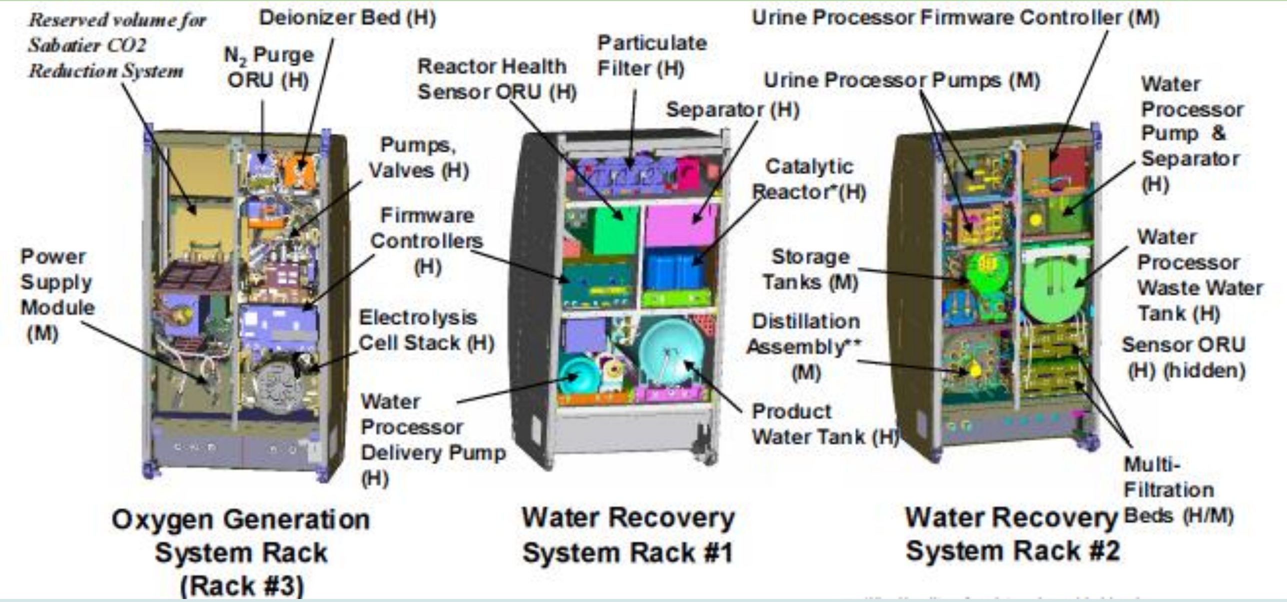
29 September 2022

Space Crop Production

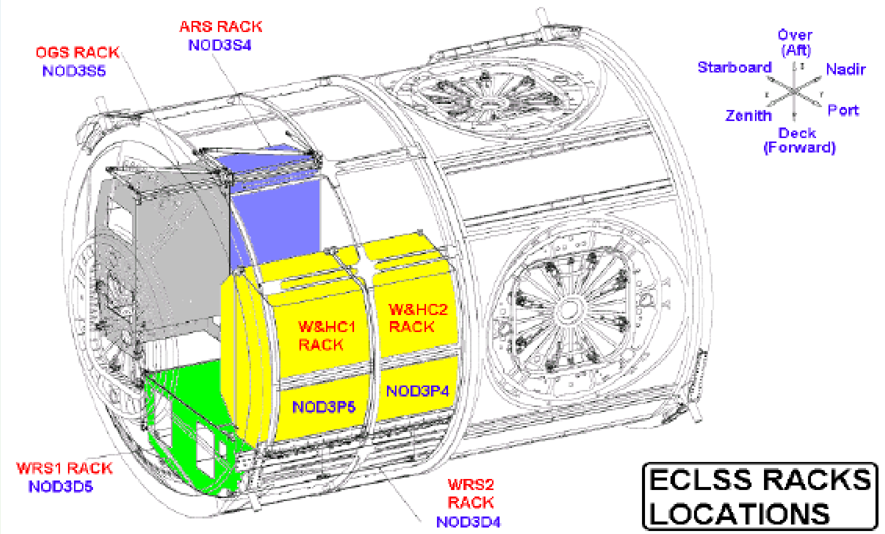


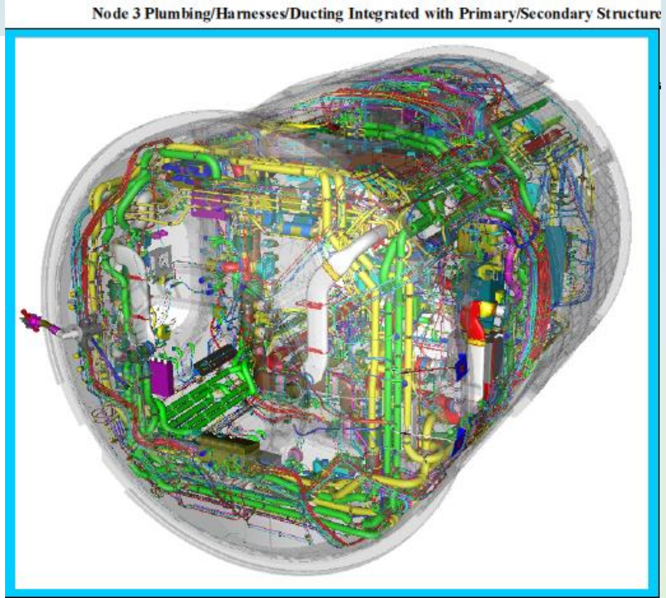
Regenerative Life Support - ISS





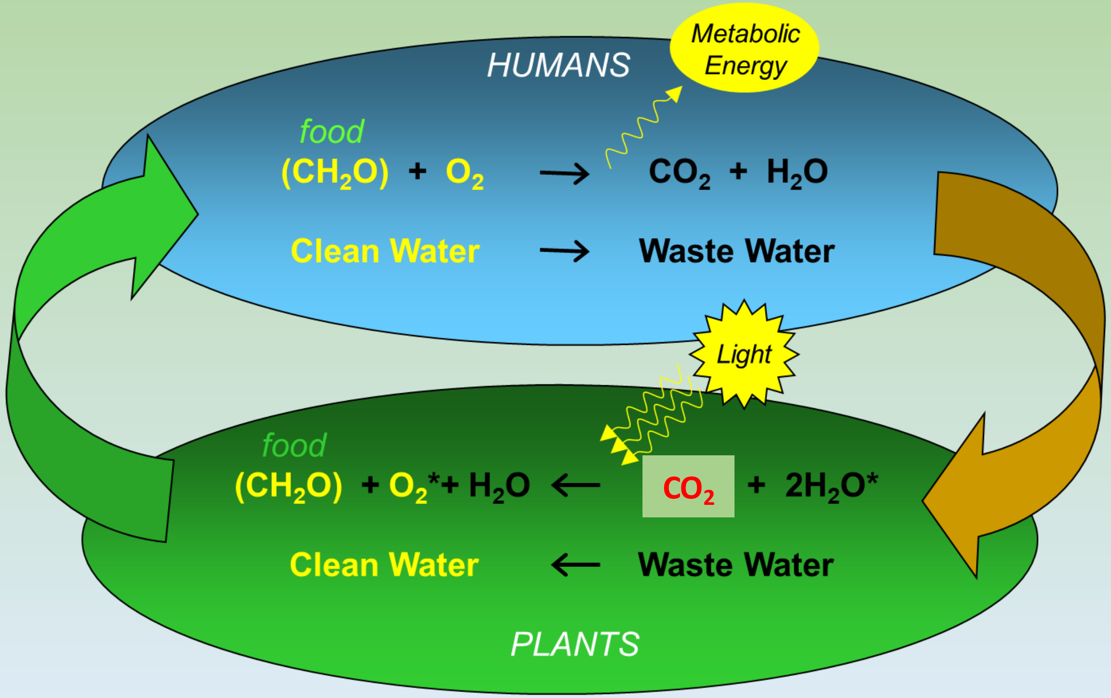
- Physical - chemical systems
- Viable life support systems function within the mass, volume and power limitations of spacecraft
- Food is shipped to spacecraft

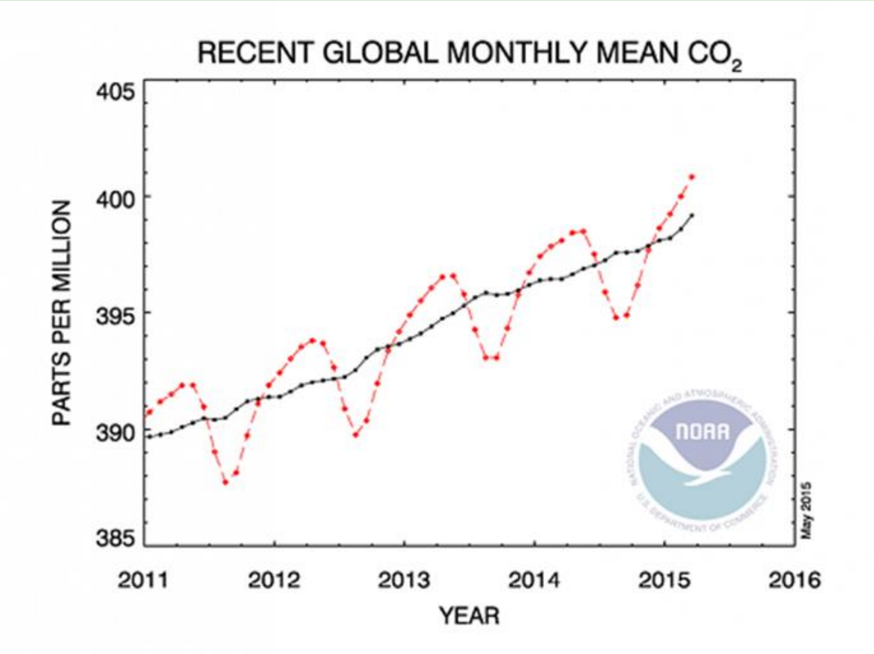




Monje 2018 ICES-2018-252
Mitchell NASA/CP—2004-213205/VOL1

"Bioregenerative" Life Support

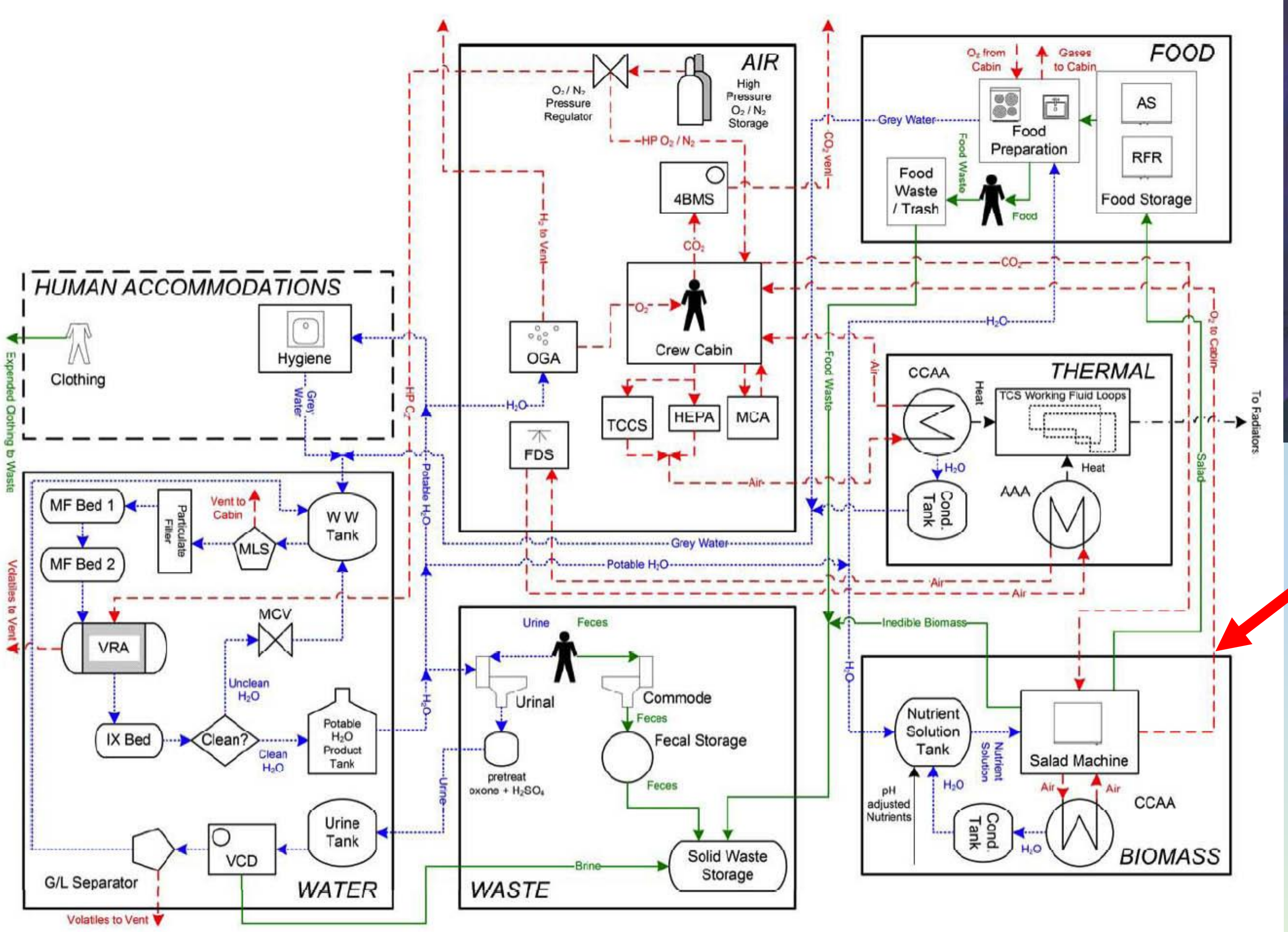


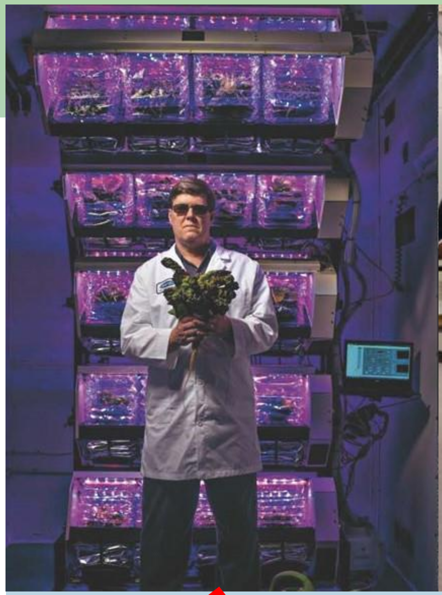


- Plants provide 4 bioregenerative functions - Crop production, CO_2 removal, water recycling, and oxygen generation in bioregenerative life support systems (BLSS).
- CO_2 removal on Earth: CO_2 sensor in Mauna Loa - measures CO_2 uptake in the summer and CO_2 increase in the winter – slope increase as CO_2 release from fossil fuels > uptake.

Wheeler 2016

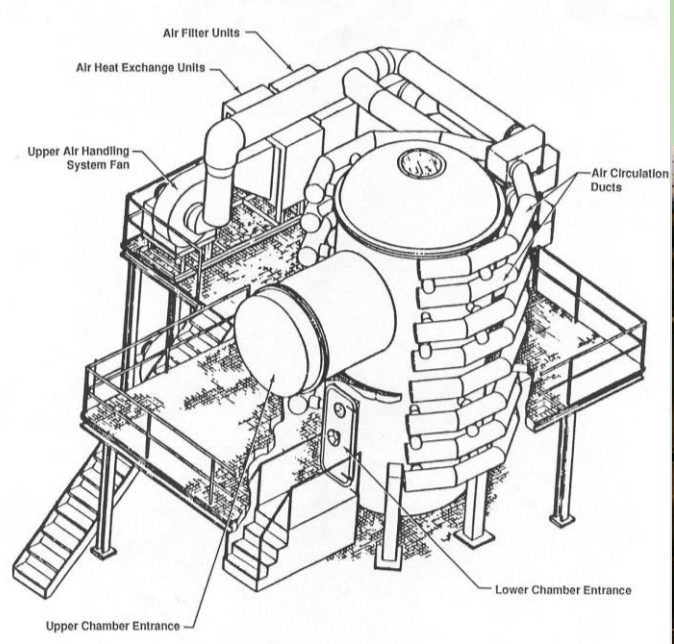
BLSS = Regenerative LS + Plants



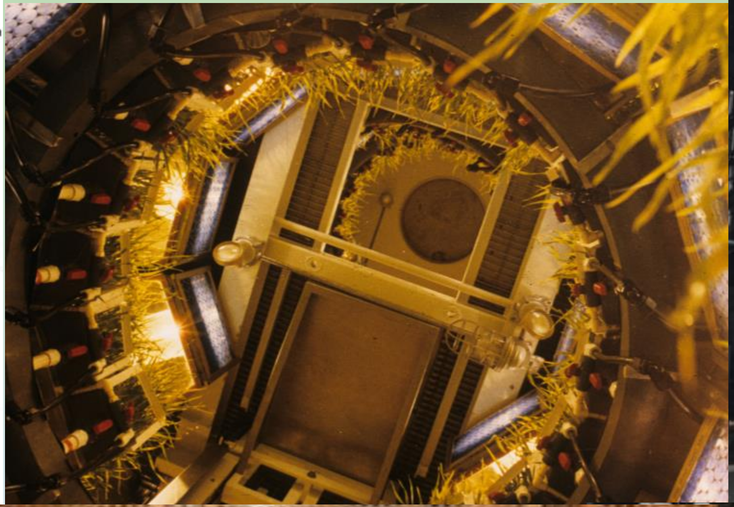


Adding crop production modules to a regenerative LSS provides a bioregenerative food system for the crew

KSC Biomass Production Chamber



First Vertical Farm – 4 levels

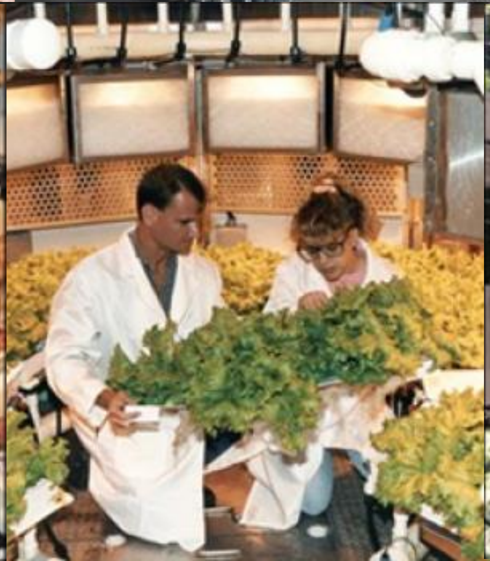


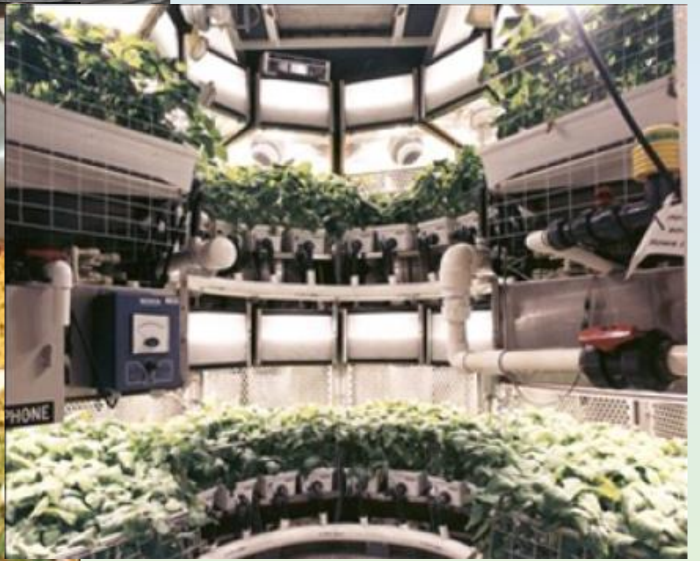
BPC – 1988-2000
20 m^2 hydroponic NFT

Staple crops – wheat, potato, soybean, rice

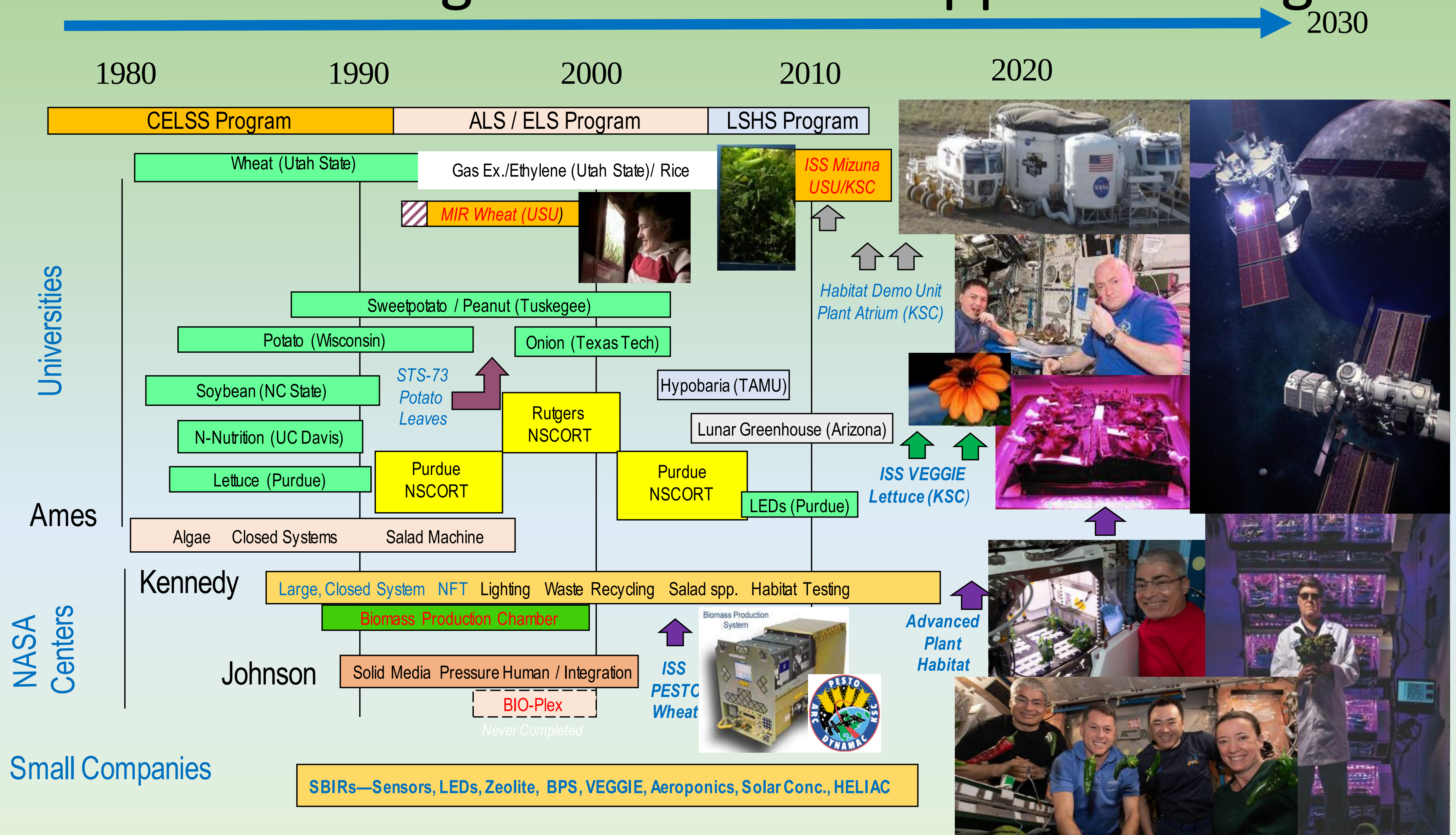
Also, lettuce, tomato, and radish.

Wheeler 2016, Dreschel 2019



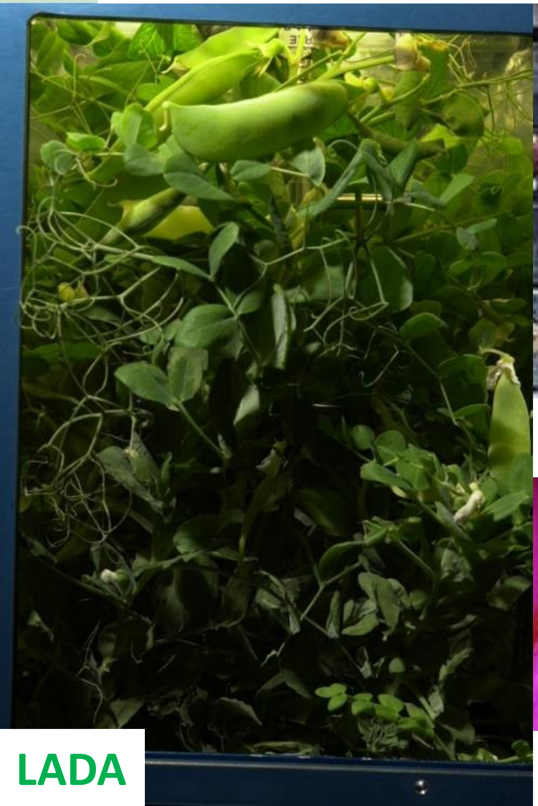


NASA - Bioregenerative Life Support Testing



In space, explorers need *in situ* crop production

- Space Farming - enables exploration of space:
  - **Sustainable:** minimize logistics of resupply – distance from Earth
  - **Resources:** Light, CO_2, O_2, Nutrients, Water, Seeds. **Plant chambers** – Watering /Imaging systems
  - **Crew Psychological Well-Being:** green Earth (smell and taste)
  - **Food Systems:** tasty, **nutritious and safe** source of fresh crops – **Long duration missions**



Space Crop Production Systems

- Designed to mitigate the **risks of inadequate food and nutrition** during long duration NASA exploration missions (>3 years). Processed /pre-packaged food loses nutrients during processing / storage and may not have the same taste when consumed.
- Provide **fresh 'Pick-and-Eat' crops (lettuce, radish, peppers)** grown *in situ* for crew consumption during Mars transit and surface habitat missions.
- **Supplement the astronaut food system** with bioavailable vitamins and amino acids that degrade during long term storage.

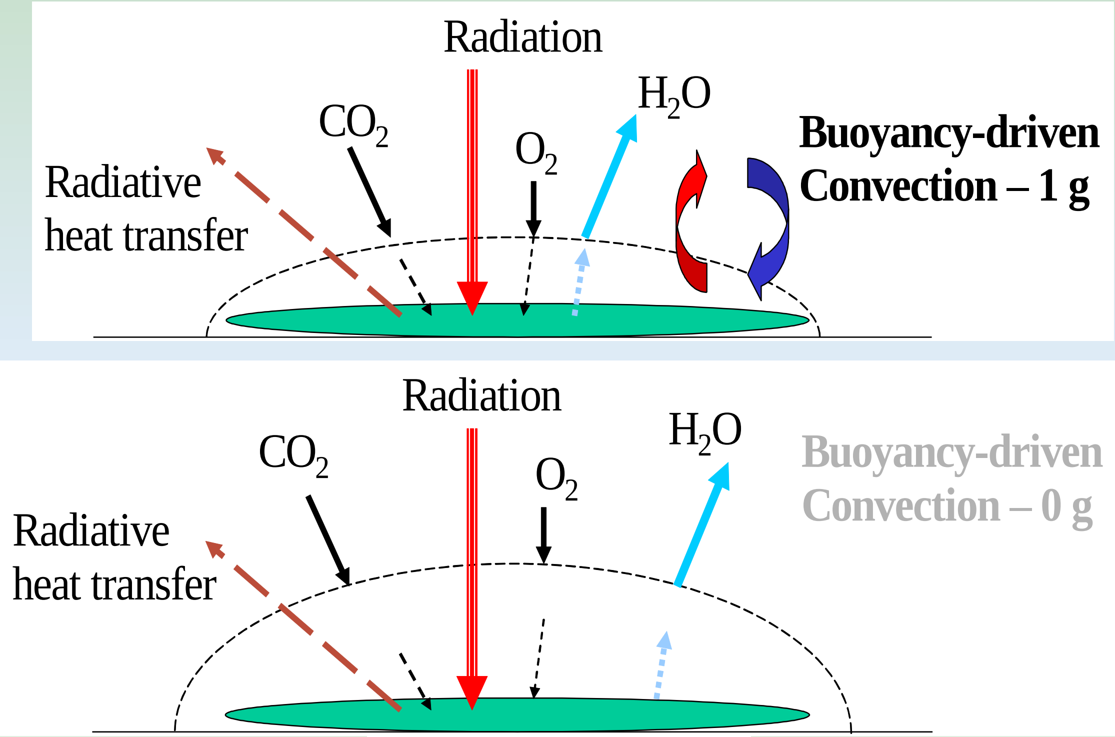




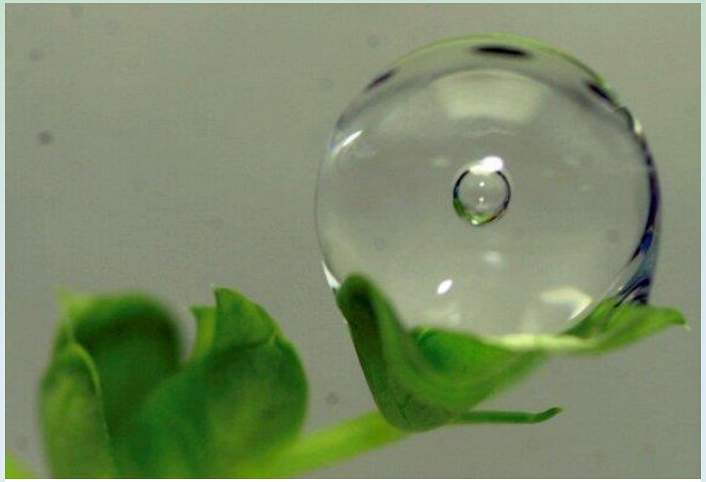
Space-Flight Environment

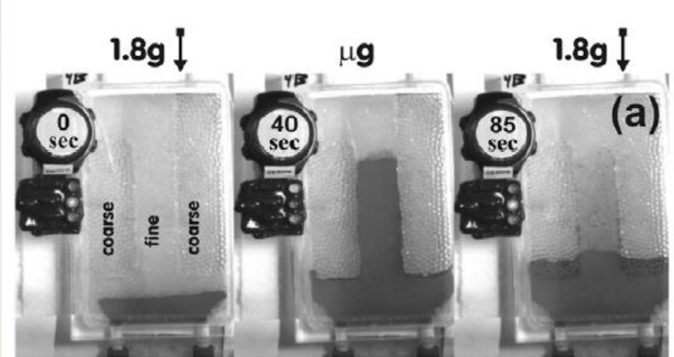
The absence of gravity induces physical effects that alter the microenvironment surrounding plants and their organs.

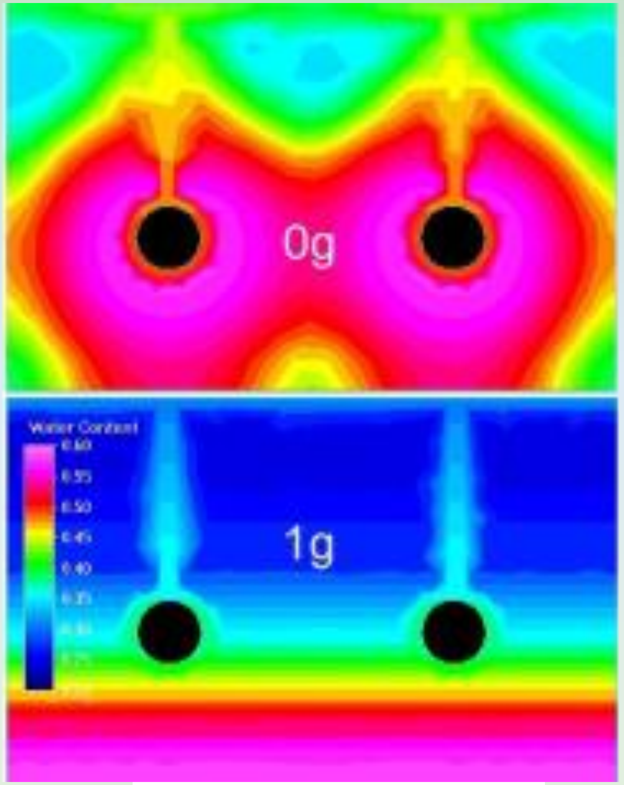
These effects include: increased boundary layers surrounding plant organs, and the absence of convective mixing of atmospheric gases. In addition, altered behavior of liquids and gases is responsible for phase separation and for dominance of capillary forces in the absence of gravitational forces (moisture redistribution)



Monje et al. 2003





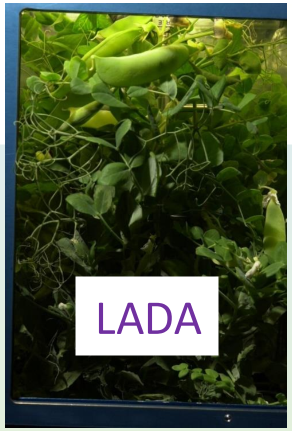


Jones and Or, 1998

Plant Biology - Growth using granular media

Plant Growth Systems in Space

Salyut Space Stations	Mir	Space Shuttle	International Space Station (ISS)
Oasis Series	SVET	Plant Growth Unit (PGU)	Advanced Astroculture (ADVASC)
Vazon	SVET-GEMS	Plant Growth Facility (PGF)	Biomass Production System (BPS)
Malachite	Vazon	Astroculture (ASC)	Lada
Biogravistat/Magnetobiostat	Svetoblok	Plant Generic Bioprocessing Apparatus (PGBA)	European Modular Cultivation System (EMCS)
Svetoblok	Astroculture (ASC)		Plant Experiment Unit (PEU)
Phyton Series			Advanced Biological Research System (ABRS)
			VEGGIE



APH

Zabel et al. Life Sci. Space Res. (2016)

Veggie - Select Crops for growth at elevated CO_2 (3000 ppm) and 40% RH

Advanced Plant Habitat Facility

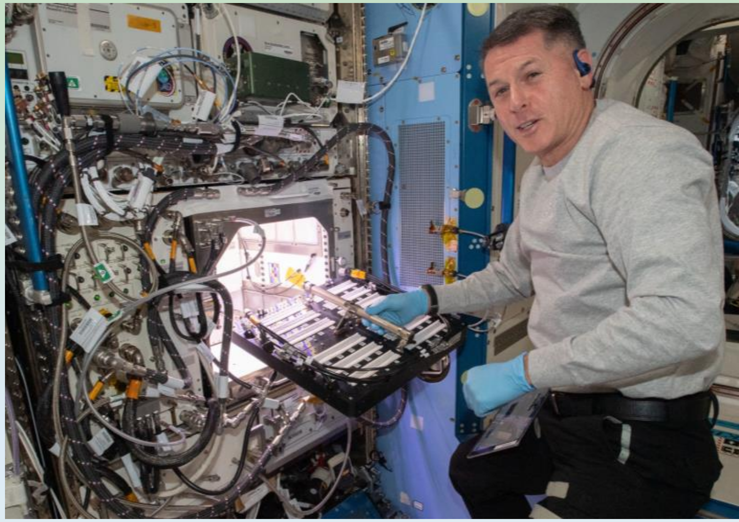
SPACE PLANT BIOLOGY
APH
ADVANCED PLANT HABITAT
Large Plant Research Facility

Conduct plant research supporting space biology and food production projects on the International Space Station.

Plants are grown in the Science Carrier (SC) of the APH, (0.2 m^2 instrumented) root module. The SC is packed with media, seeded on Earth, and transferred dry to the APH facility on ISS. The plant experiments are initiated when the SC is installed in the APH and fully wetted.

APH 1st Plant Test – Tech Demo:

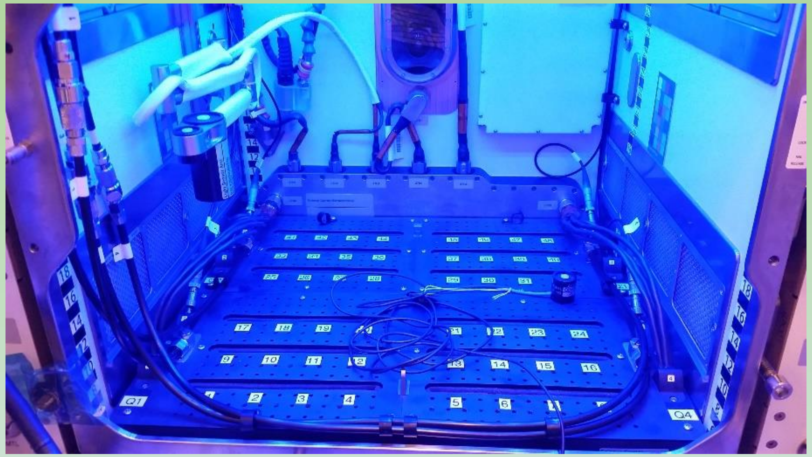
- Initiated First Plant Test on 22 Jan 2018 - verify that science is supported on APH.
- Install pre-planted SC: WT Arabidopsis and Apogee semi-dwarf wheat
- Two-week growth of WT Arabidopsis and 33 days of wheat conducted to demonstrate adequate plant growth on APH facility.
- Demonstrate and evaluate performance of on-orbit watering protocols.



APH Literature:

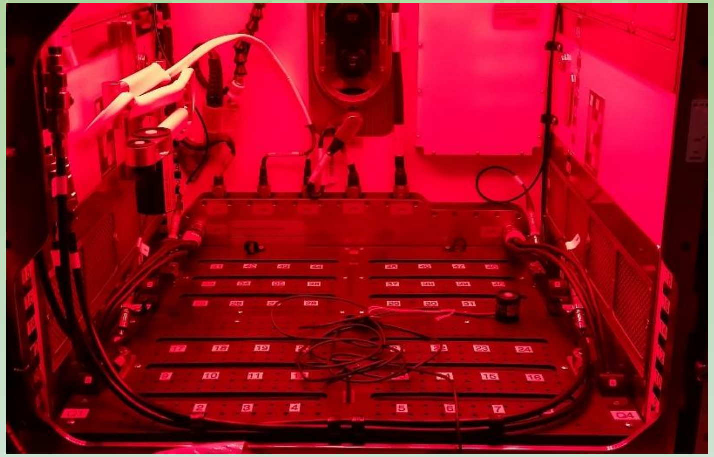
Morrow et al. “A new plant habitat facility for the ISS,” ICES-2016-320, 2016.
Monje et al. “Hardware Validation of APH on ISS: Canopy Photosynthesis in reduced gravity”, Frontiers Plant Sci, 2020.

APH - Spectral Quality & Intensity



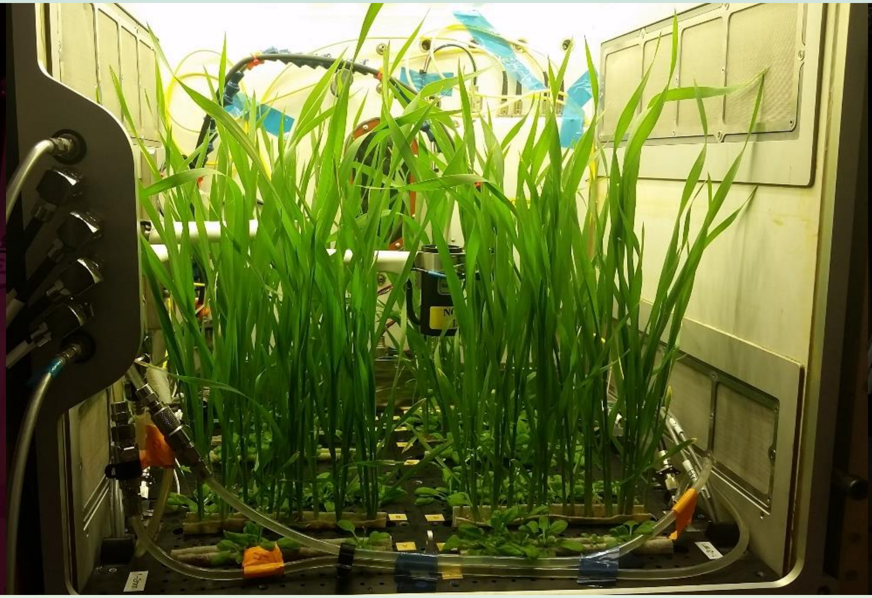
0-400 μmol m^{-2} s^{-1} at 450 nm ±10 nm

0-100 μmol m^{-2} s^{-1} at 525 nm ±10 nm

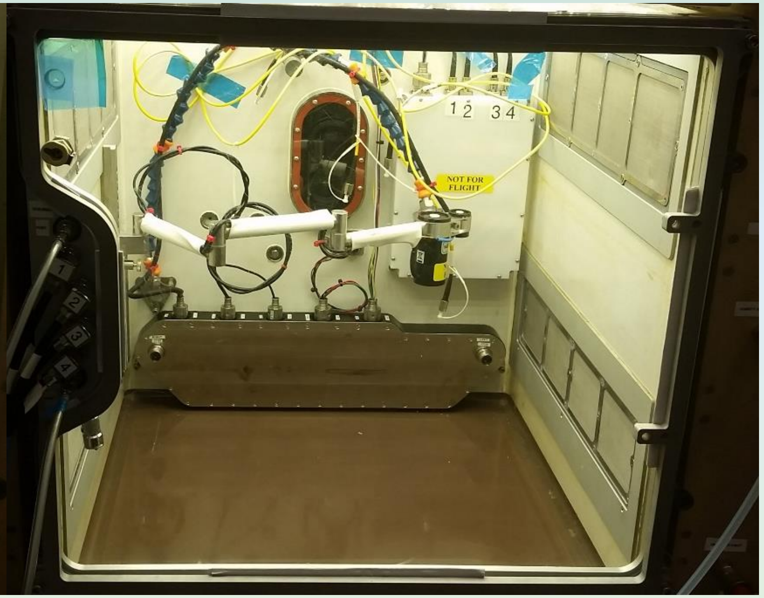


0-600 μmol m^{-2} s^{-1} at 630 nm ±10 nm

PI Mixture

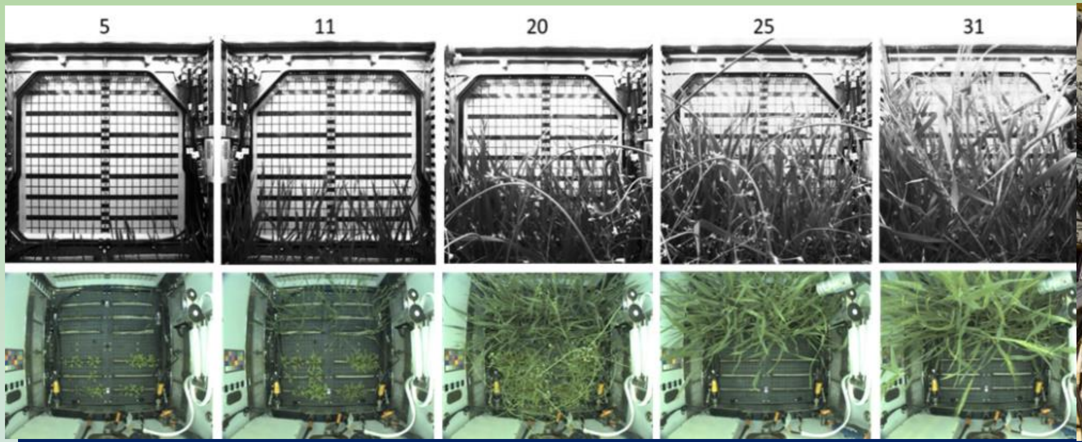


IR 0-50 μmol m^{-2} s^{-1} at 735 nm ±10 nm



W 0-600 μmol m^{-2} s^{-1} at 400-700 nm

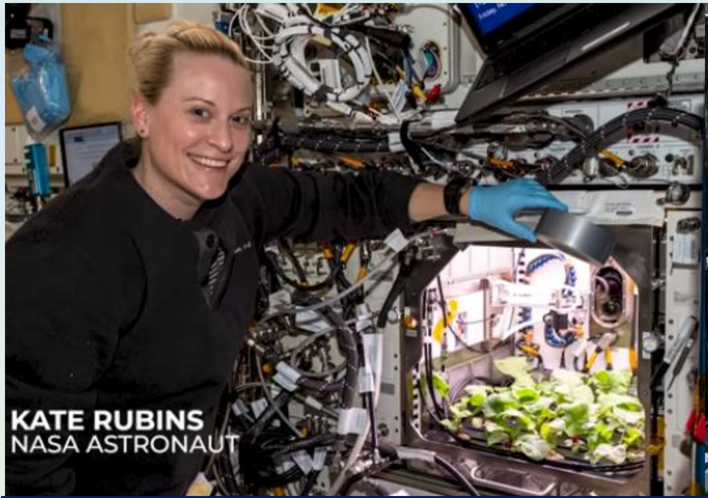
APH Experiments on ISS



APH 1st Plant Test - Technology Demonstration – Hardware and Science Validation

Monje et al, Frontiers Plant Sci 2020

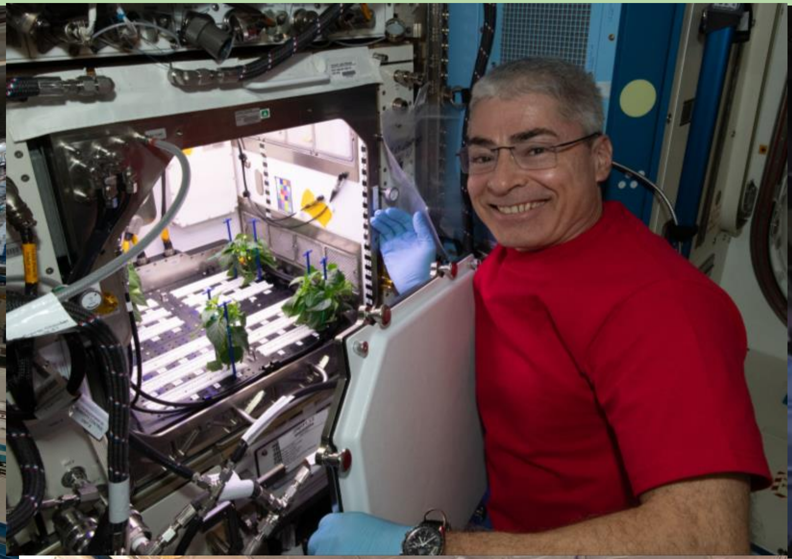
PH-01 - PI: Norman Lewis - An Integrated Omics Guided Approach to Lignification and Gravitational Responses: The Final Frontier



New life support concepts must be demonstrated to sustain large crew sizes in cislunar space.

PH-02 – PI: Karl Hasenstein – Assessment of Nutritional Value and Growth Parameters of Space-grown Plants - Radish

APH Experiment – PH-04

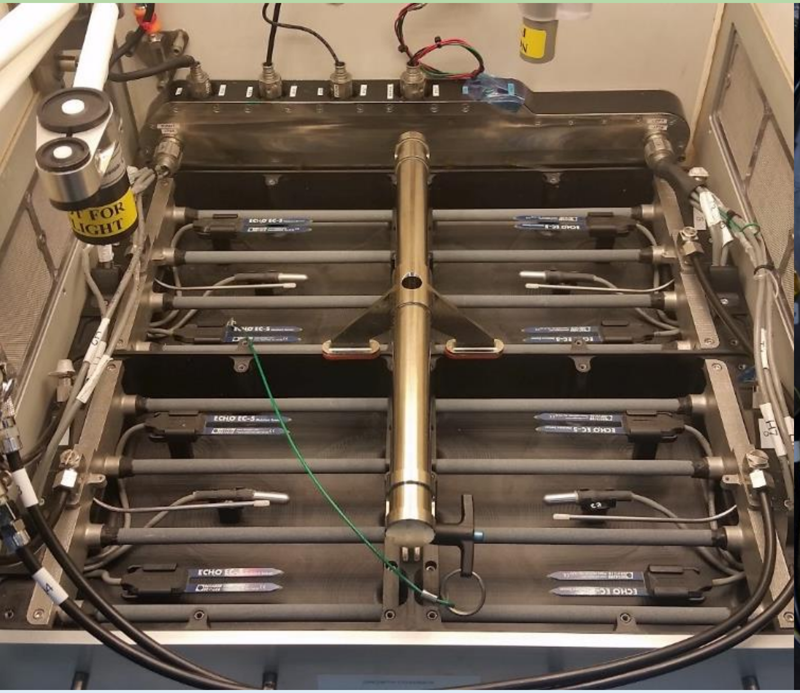


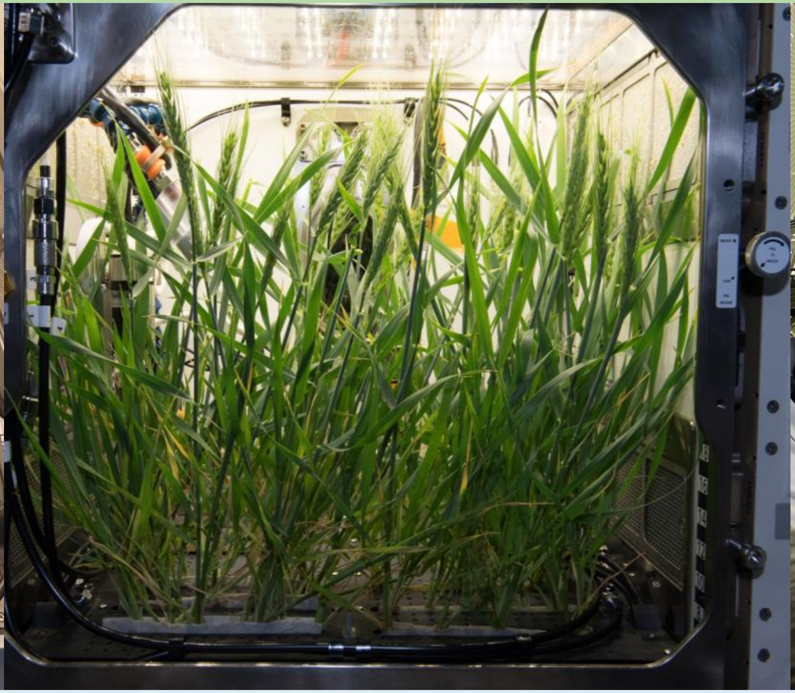
Longest spaceflight plant experiment to date 120 days – previous PESTO at 73 days

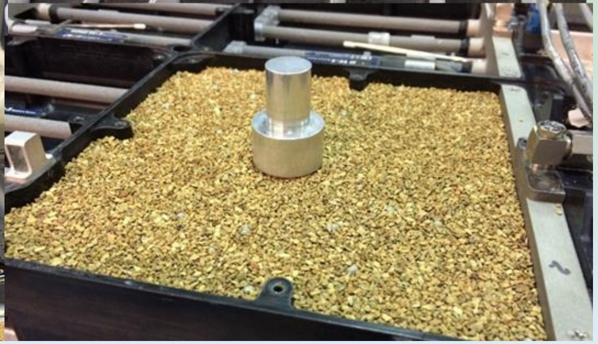
PH-04 PI: Matthew Romeyn - Technology Demonstration

Growth of New Mexico Hatch Green Chile as a Technical Display of APH's Capabilities

Using granular media is not sustainable







Scaling APH - 0.2 m^2, 1 kg media/quadrant - producing 13 crops of Outredgeous lettuce per year (365 days/28-day growth cycle) produces 104 lettuce plants (two 50.9 g plants/quadrant).

Production: 5.3 kg of lettuce per year **Inputs:** ~52 kg of media and 0.6 kg of fertilizer

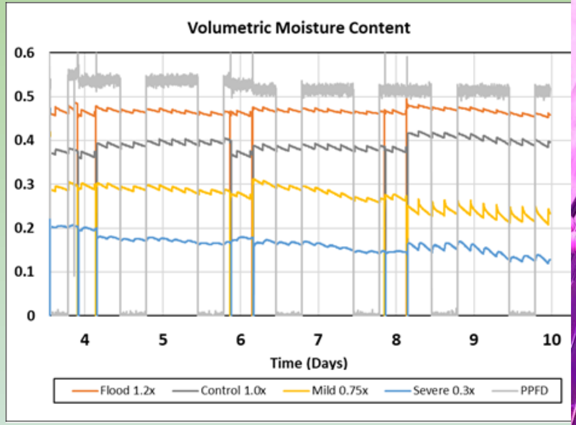
APH – cropping efficiency = **0.10 kg of edible mass per kg of resupply mass**.

Gaps in space crop production

- Space crop production systems for use on ISS, the Moon and Mars must be sustainable and ensure food safety. Paradigm shift: single grow-out biology experiments-> sustainable food crop production systems.
- Watering systems - sustainable (high cropping efficiency) and allow post-harvest sanitization to support multiple crop cycles - soilless cultivation.
- Plant health monitoring systems - developed for early stress detection and to ensure food safety – imaging systems.
- Select/ engineer new crops - small, high harvest index, grow in spacecraft (elevated CO_2 ,low humidity, low pressure x deep space radiation x partial gravity) - breeding, molecular biology.
- Space crop production system design – simple, robust, sustainable, minimize crew intervention, and provide nutritious and palatable crops.

Plant Health and Food Safety

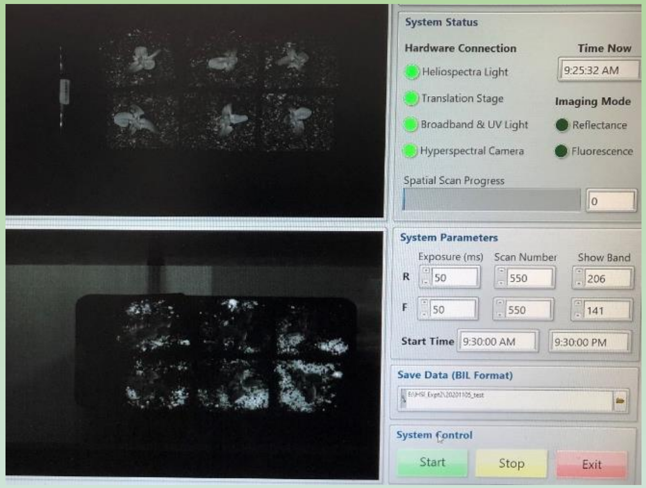
Grow plants



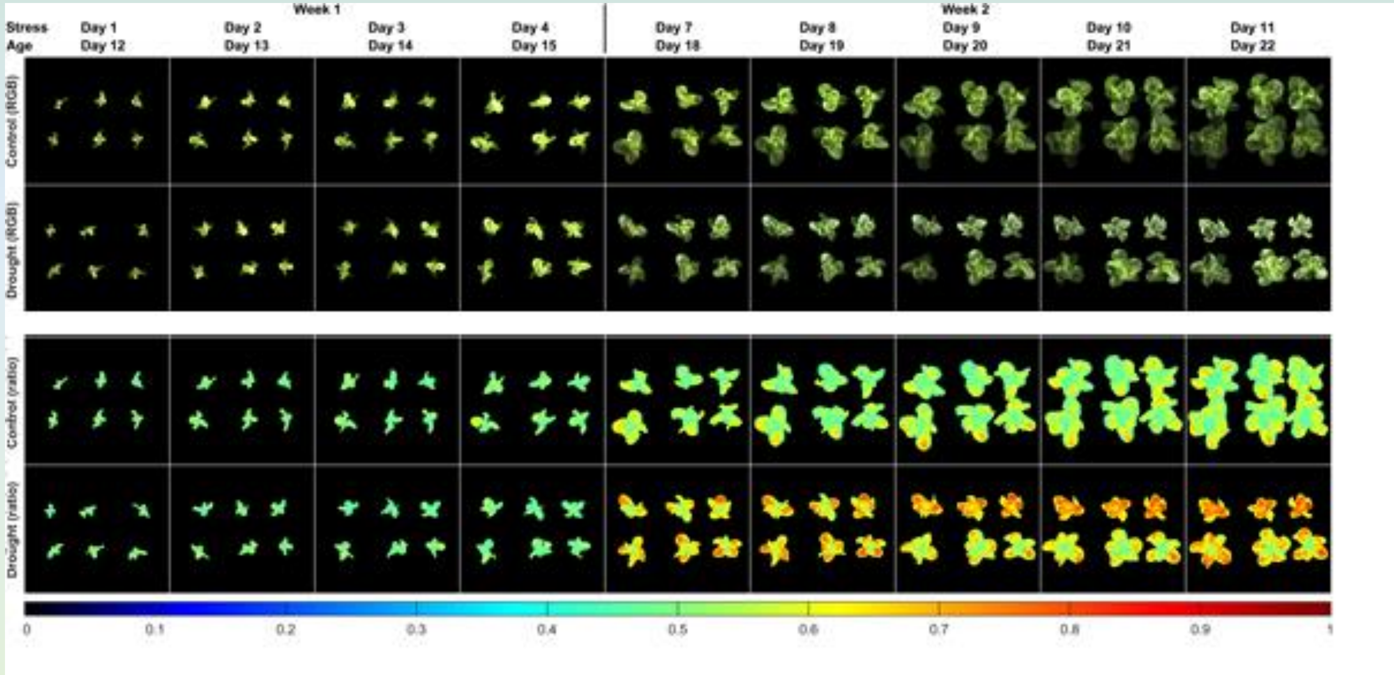
Impose stress treatments

28-day cycles

Image plants



Collect / process Images



- Hyperspectral – reflectance and fluorescence
- Crop and mask images
- Develop vegetation indices using AI
- Target early stress detection - drought
- Verify crop health and food safety

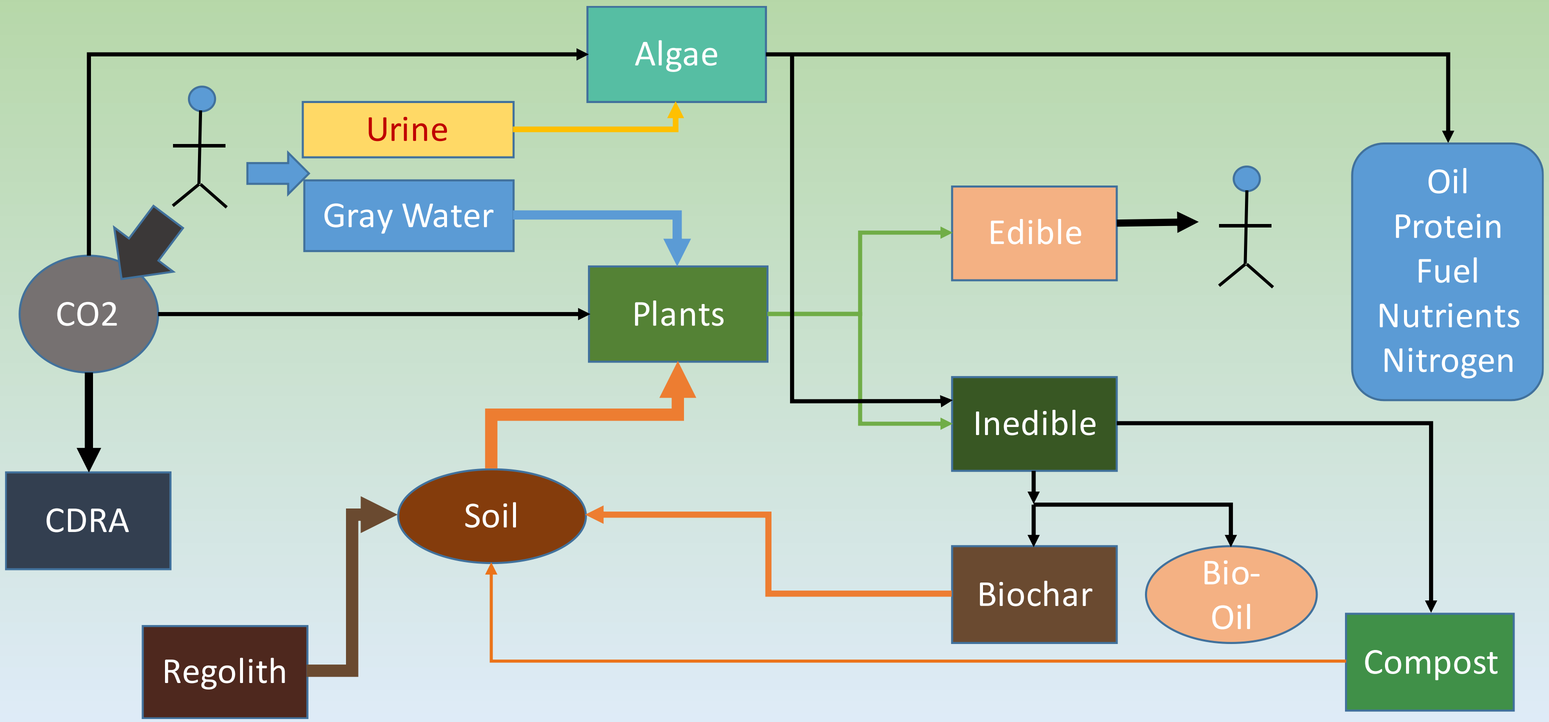
Monje et al, ICES-2019-289

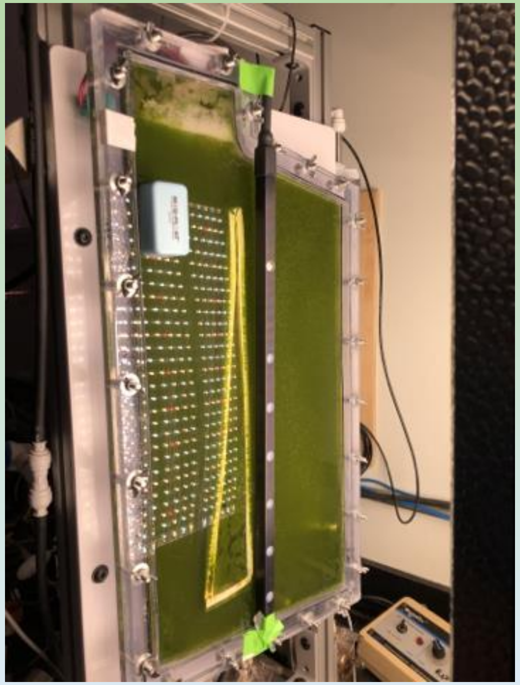
Lunar Missions – grow plants in partial gravity

- Water behavior and radiation shielding affect plant growth indirectly:
  - On Earth (1 g), 'well-drained' soil – supplies root zone sufficient moisture and oxygen for active nutrient uptake; Earth shields crops from radiation.
  - On ISS (0 g), moisture redistribution reduces aeration to roots causing poor growth; Earth shields crops from radiation.
  - On Moon/Mars (1/6 and 3/8 g), insufficient data to predict fluid distribution in soil, or impact of partial gravity x deep space radiation effects on crop growth.
- Task: Export 1-g agricultural methods to partial gravity habitats
  - Demonstrate sustainable soilless watering systems to optimize plant growth
  - Characterize plant responses to deep space radiation



BLSS – Recycle nutrients from wastes





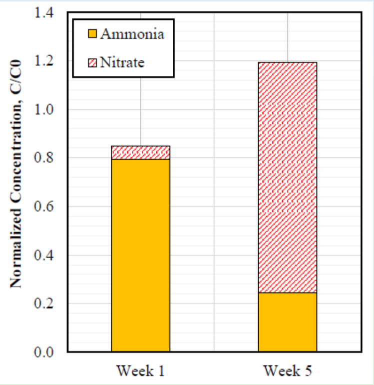
PMBR – Photobiological membrane reactor at KSC

- Convert NH4+ rich waste (urine) into NH_4:NO_3 fertilizer
- Algal Biomass converted to biochar for amending regoliths

Saetta et al., 2022

Table 1. Major water quality parameters of the AnMBR effluent/PMBR influent.

Parameter	Concentration
Total Nitrogen, mg/L as N	203
Ammonia, mg/L as N	263
Nitrate, mg/L as N	0.1
Chemical Oxygen Demand, mg/L	322
Total Organic Carbon, mg/L	107
pH	7.3
Conductivity, µS/cm	3595



Conclusions

- Crop production is a key component of biological life support systems – feeds the crew, removes CO_2, cleans water, and produces O_2.
- Space crop production system design – simple, robust, sustainable, minimize crew intervention, and provide nutritious and palatable crops.
- Advances in space crop production systems are applicable to vertical farming practices on Earth.

Questions?

Acknowledgments

This work was funded in part by NASA's Biological and Physical Sciences Division, NASA Advanced Exploration Systems Program, and by USDA -ARS, Food Safety