Space Farming
Challenges & Opportunities

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IFT 2017, June 25 -28, Las Vegas, NV
Earth = Our “Bioregenerative” Life Support System

Wheeler, 2016
On Earth, explorers ‘live off the land’

- Crew = 33
- 2 years – elk hunting and fishing
- Learned food technology from native tribes
In space, explorers need *in situ* food production

- Space Farming enables colonization of space
  - **Sustainable:** minimize logistics of resupply
  - **Supplies:** Light, CO$_2$, O$_2$, Nutrients, Water, Soil, Seeds, Plant chamber
  - **Crew Psychological well-being:** green Earth
  - **Food Systems:** palatable, nutritious and safe source of fresh food (*limited shelf-life*)
Task: adapt 1g agriculture to fractional g locations
Opportunities: Commercial Uses of Cislunar Space

Cislunar Econosphere

LTO \( \Delta V = 0.33 \)

LEO \( \Delta V = 0.53 \)

GEO \( \Delta V = 3.77 \)

\( \Delta V \) in (km/s)

LEO
- ISS
- Remote Sensing
- Commercial Station
- Communication
- Space Control
- Debris mitigation
- Science
- R&D
- Tourism
- Manufacturing
- Propellant Transfer

GEO
- Observation
- Communication
- Space Control
- Debris Mitigation
- Space Solar Power
- Repair Station
- Satellite Life extension
- Harvesting

High Earth Orbit
- Science / Astronomy
- Communication Link
- Way Station
- Propellant Depots
- Repair Station
- Lunar Solar Power Sat
- Manufacturing
- Planetary Defense

Lunar Surface
- Science / Astronomy
- Lunar
- Observatory
- Human Outpost
- Tourism
- Mining
- Oxygen/Water
- Regolith
- Rare Earth Elements
- HE3
- Manufacturing
- Fuel Depots

Existing market / Emerging market / Future market
NASA – Prepares for missions to Mars

The Earth Reliant, Proving Ground, and Earth Independent periods are divided into phases, with a capstone demonstration defining the gate between each phase and the next. All activities are part of an integrated strategy that builds from experience gained in the Earth Reliant period, and informs objectives, capabilities, and missions in the Proving Ground and Earth Independent periods.

**Human Exploration and Operations Exploration Objectives, 2016**

**Deep Space Gateway** – crewed spaceport in lunar orbit – access lunar surface & deep space

**Deep Space Transport** – reusable vehicle to travel to Mars and return to the gateway

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*There are several other considerations for ISS end-of-life*

**Figure 4.0-1 Exploration Phases**

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March 20, 2017
Commercial uses of Cislunar Space

Part 1: TODAY
- Research
- Communications
- GROSS SPACE PRODUCT $330B/YR
- POPULATION ‡5

Part 2: 5 YEARS
- Space Manufacturing
- Commercial Habits
- GROSS SPACE PRODUCT $500B/YR
- POPULATION ‡20

Part 3: 15 YEARS
- LED Tourism
- Maintenance & Operations
- XEUS
- GROSS SPACE PRODUCT $900B/YR
- POPULATION ‡300

Part 4: 30 YEARS
- ACES Transports Finished Parts
- EML.1 Transports Raw Material
- GROSS SPACE PRODUCT $2.7T/YR
- POPULATION ‡1,000

BEAM – Bigelow Expandable Activity Module

ESA – Moon Village & Amazon Moon Deliveries
Space Farming = f ( Plant/Microbial Biology & Engineering )

Research Issues

- Sensory mechanisms: Gravity sensing and response to mechanisms in cells, plants & microbes.
- Radiation effects on plants/microbes
- Plant/microbial growth under altered atmospheric pressures
- **Spaceflight syndromes**: Responses to integrated spaceflight environment, microbial ecosystems and environments, changes in virulence of pathogens.
- Food safety
- Plant – Microbe Interactions

Hardware Issues

- **Performance**: Mitigate spaceflight syndromes for adequate plant growth
- Mass, power & volume restrictions
- Role in life support systems
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).
Plant Growth Systems

Low Light

Light
300 µmol/m²s

Light
600-1000 µmol/m²s

NASA’s Bioregenerative Life Support Testing

1980
- CELSS Program
- Wheat (Utah State)
- Gas Ex./Ethylene (Utah State)
- STS-73 Potato Leaves
- Soybean (NC State)
- N-Nutrition (UC Davis)
- Lettuce (Purdue)
- Algae
- NFT Lighting
- Waste Recycling
- Solid Media
- Pressure Human / Integration
- BIOPlex

1990
- ALS / ELS Program
- Sweetpotato / Peanut (Tuskegee)
- Potato (Wisconsin)
- Onion (Texas Tech)
- Algae
- Closed Systems
- Solid Media
- NFT Lighting
- Waste Recycling
- Solid Media
- Pressure Human / Integration
- BIOPlex

2000
- LSHS Program
- ISS Mizuna Utah St./KSC
- ISS VEGGIE Lettuce (KSC)
- Advanced Plant Habitat ISS
- Advanced Plant Habitat ISS
- Solid Media
- Pressure Human / Integration
- BIOPlex

2010
- ISS VEGGIE Lettuce (KSC)
- Advanced Plant Habitat ISS
- Solid Media
- Pressure Human / Integration
- BIOPlex

2030

Universities
- Ames
- Kennedy
- Johnson
- Small Companies

NASA Centers
- Ames
- Kennedy
- Johnson
- Small Companies
Recirculating Hydroponics with Crops– Record yields vs Field

Wheat / Utah State

Soybean
KSC

Sweetpotato
Tuskegee

Rice / Purdue

Conserve Water & Nutrients
Eliminate Water Stress
Optimize Mineral Nutrition
Facilitate Harvesting
Will this work in partial g?

Cultivar Comparisons and Crop Breeding

Several Universities:
Cultivar Comparisons
- wheat, potato, soybean, lettuce, sweetpotato, tomato

Utah State:
- Super Dwarf Wheat
- Apogee Wheat
- Perigee Wheat
- Super Dwarf Rice

Tuskegee:
- ASP GM-Sweetpotato

Dwarf Pepper ↑ and Tomato ↓
Plants for Future Space Missions

- **International Space Station** (plant experiments—salad crops)
- **Crew Exploration Vehicle** (supplemental crops Mars transit)
- **Lunar Lander** (no plants)
- **Lunar Outpost** (supplemental foods)
- **Martian Outpost / Colonies** (supplemental foods ⇒ autonomous life support)
Bioregenerative Life Support

Integrate physico-chemical and plant-based life support systems
Salad Machine – Transit / Orbit

• **Scale – Expand from Experimental to Production**
  - 150 g/d = daily: 25 g salad for Crew of 6
  - 1 m² Planting area

• **Performance criteria:**
  - Productivity – maximize
  - Consistency – robust, repeatable
  - Crew Time – minimal

• **Spacecraft**
  - Cabin air – CO₂, VOCs
  - Limited Power & Volume
  - Water load to ECLSS
  - Microgravity Effects

Nakamura, Monje & Bugbee AAIA 2013
Make Soil on Surface Systems

- CO2
- Plants
- Soil
- Biochar/Compost
- Edible
- Inedible
- Biomass
- CO2
- CDRA
- Sabatier
- CH4
- O2
- hv

* Soil Amendments ISRU
Questions?
Light, Productivity, and Crop Area Requirements

![Graph showing the relationship between light, area required, and productivity.]

- **Area Required (m² / person)**
  - Y-axis ranging from 0 to 140
- **Productivity (g m⁻² day⁻¹)**
  - Y-axis ranging from 0 to 30
- **Light (mol m⁻² day⁻¹)**
  - X-axis ranging from 0 to 80

- **Area**
  - Decreases as light increases
- **Productivity**
  - Increases as light increases

- **Bright Sunny Day on Mars**
  - Lower productivity compared to Earth

- **Bright Sunny Day on Earth**
  - Higher productivity compared to Mars
NASA’s Biomass Production Chamber (BPC)