Bioregenerative Life Support for Sustainability in Space

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Human Life Support Requirements:

Inputs

	Daily Rqmt.	(% total mass)
Oxygen	0.83 kg	2.7%
Food	0.62 kg	2.0%
Water (drink and food prep.)	3.56 kg	11.4%
Water (hygiene, flush laundry, dishes)	26.0 kg	83.9%

TOTAL 31.0 kg

Outputs

	Daily	(% total mass)
Carbon dioxide	1.00 kg	3.2%
Metabolic solids	0.11 kg	0.35%
Water	29.95 kg	96.5%
(metabolic / urine		12.3%)
(hygiene / flush		24.7%)
(laundry / dish		55.7%)
(latent		3.6%)

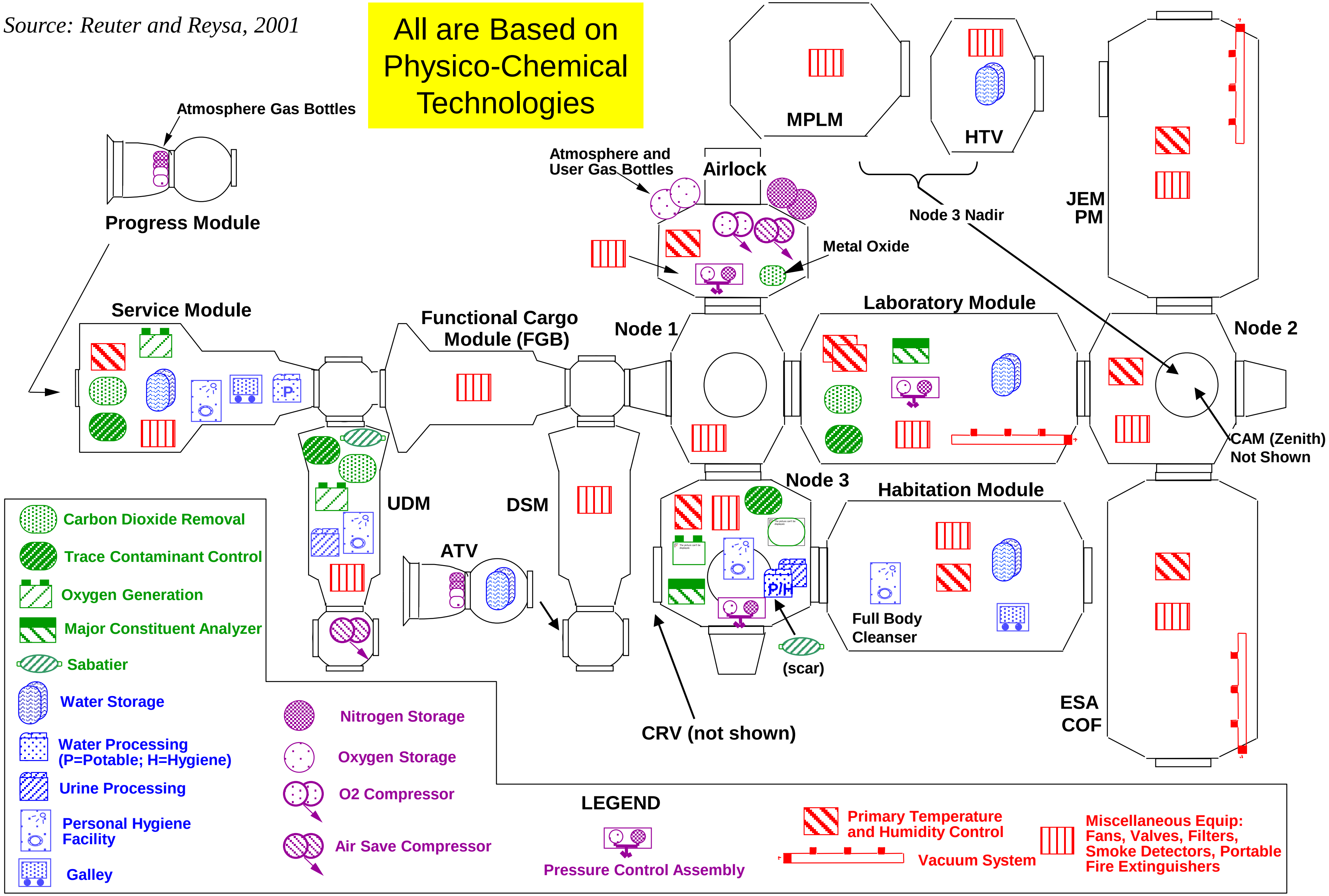
TOTAL 31.0 kg

Source: NASA SPP 30262 Space Station ECLSS Architectural Control Document
Food assumed to be dry except for chemically-bound water.

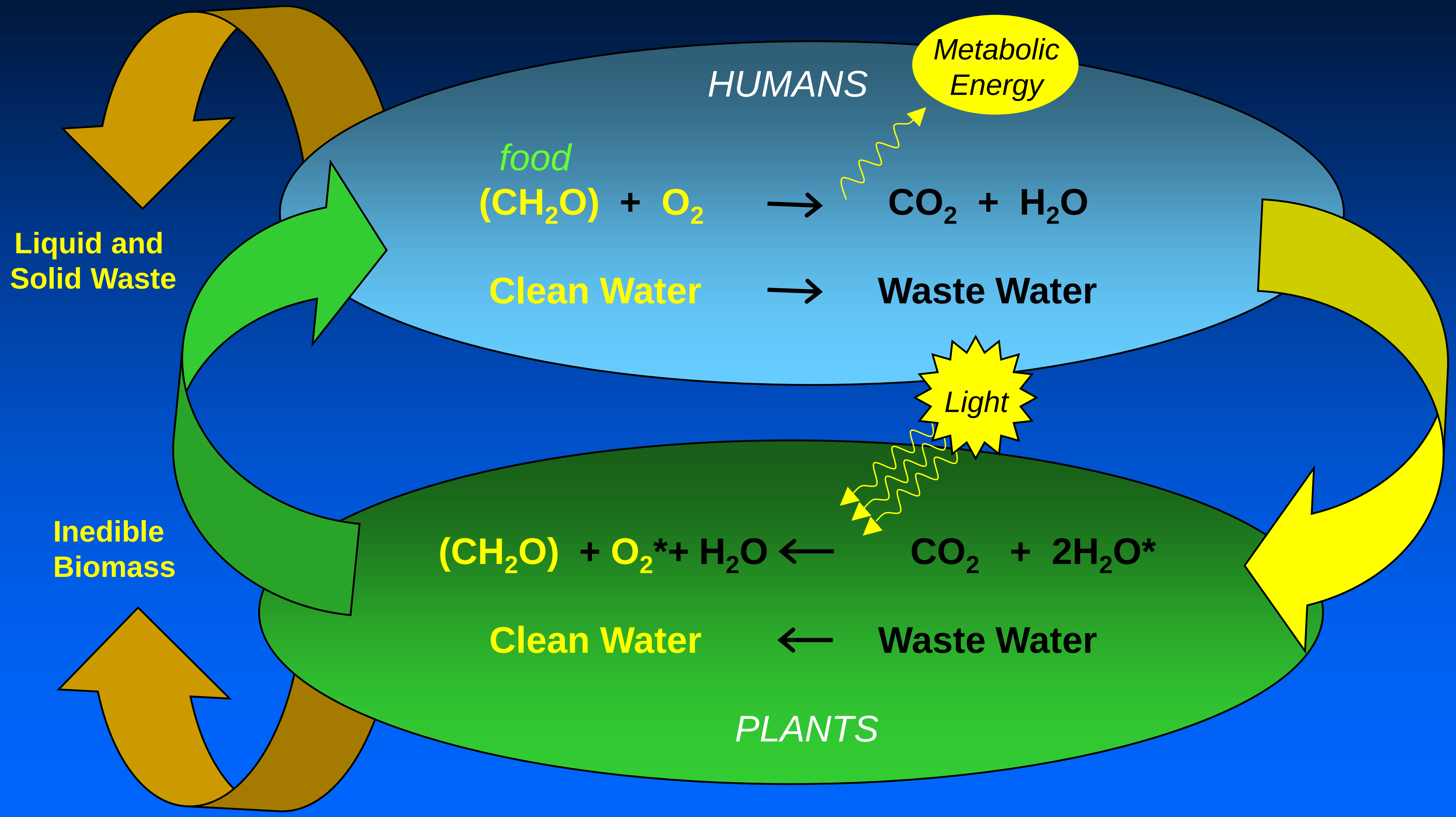
International Space Station Life Support Systems

Source: Reuter and Reysa, 2001

All are Based on Physico-Chemical Technologies

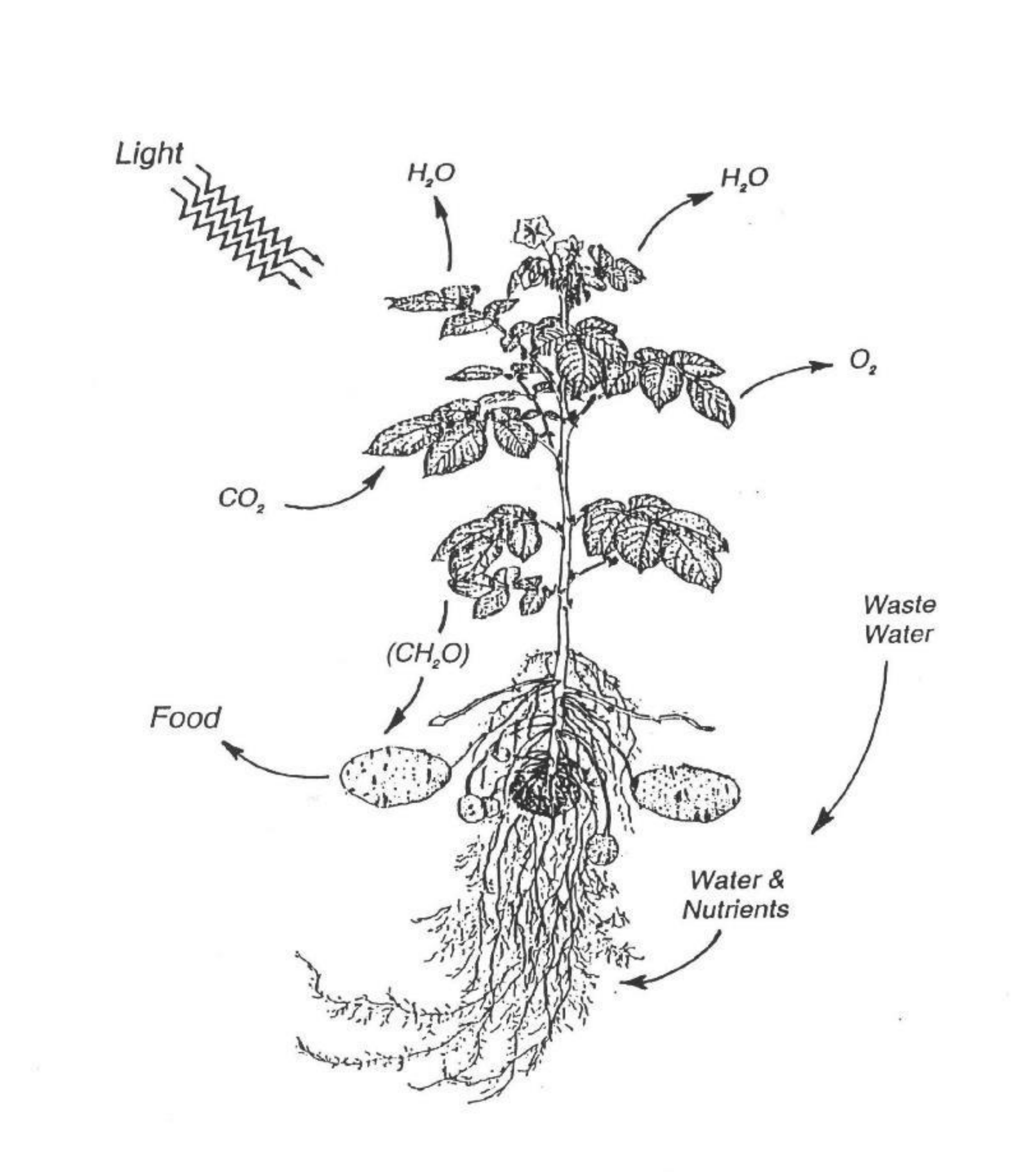


Plants for "Bioregenerative" Life Support

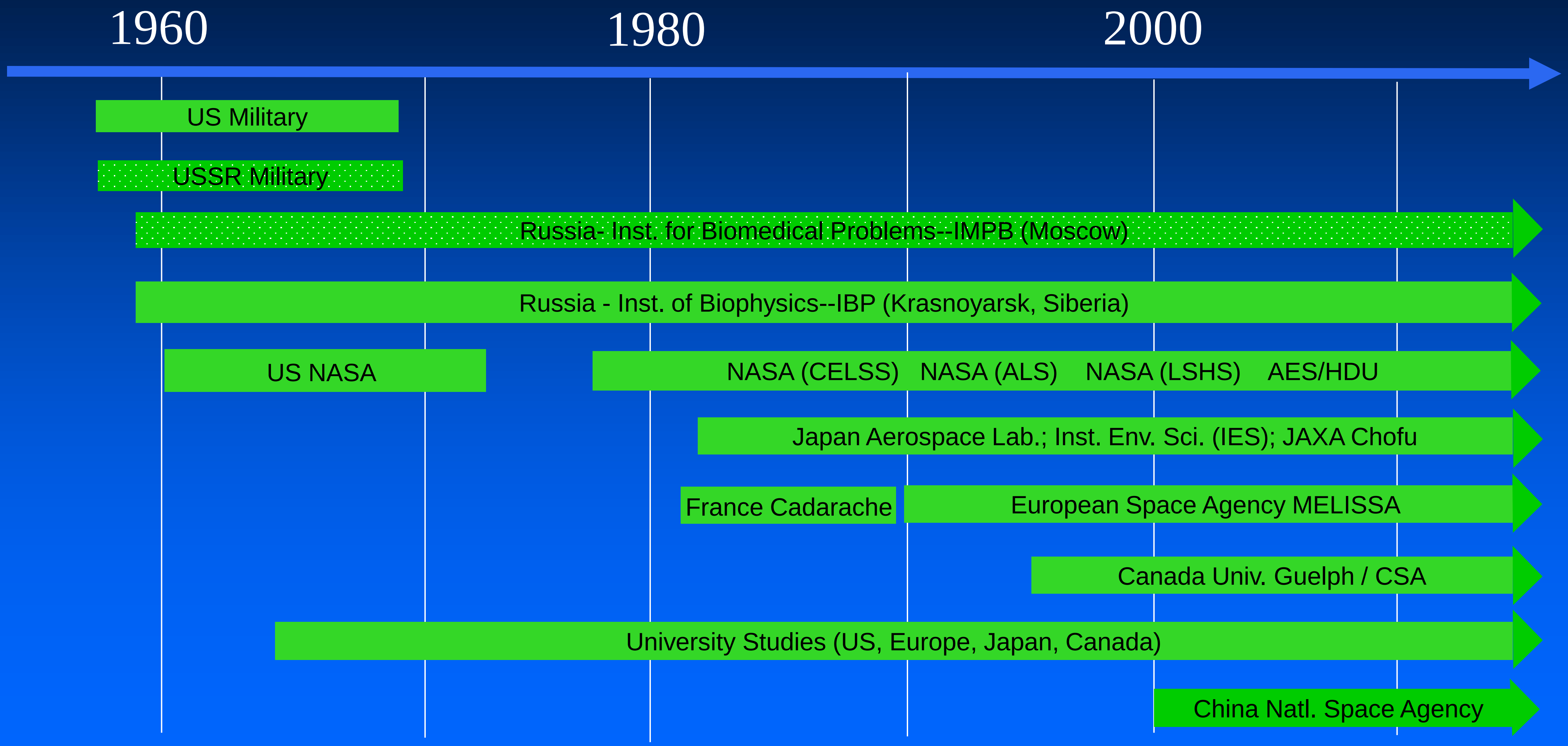


Wheeler et al., 2001. In: Tako et al. (Eds.) Proc. IES CEEF.

A Life Support Machine for Space Travel



Bioregenerative Life Support Testing Around the World



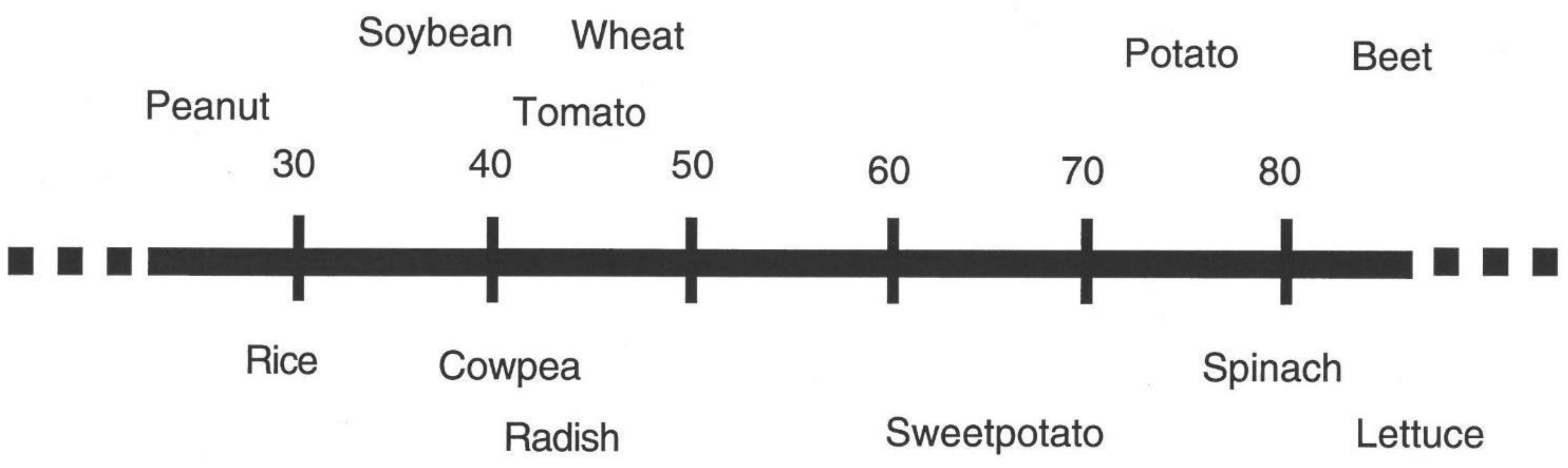
Controlled Environment Agriculture for Space

- Space habitats must be pressurized with a controlled atmosphere (including temperature, pO_2, pCO_2, RH, light)
- Mass, power, volume, and "crew time" can be limited
- Water is costly to resupply and must be recycled *(hydroponic systems can use 5-10 L m^{-2} day^{-1})*
- Nutrient and fertilizer will be costly to resupply, and inedible plant biomass and urine could be a source of nutrients. *(~90 kg of fertilizer needed per person per year to provide all their food calories)*

Crop Considerations for Space

- High yielding and nutritious (CHO, protein, fat, micronutrients)
- High harvest index (edible / total biomass)
- Dwarf or low growing types
- Environmental considerations
  - light, temperature, mineral nutrition, CO_2, pressure
- Horticultural considerations
  - planting, watering, harvesting, pollination, propagation
- Processing requirements

Harvest Index of Various Crops



* *Data gathered from controlled environment tests at KSC Breadboard Project and other CELSS literature.*

Targeted Crop Selection and Breeding for Space

Selection of Existing Rice Genotypes

Targeted Wheat Breeding

'Apogee' Wheat   'Perigee' Wheat

Photos courtesy of Bruce Bugbee, Utah State Univ.
Bugbee et al., 1997. Crop Science

USU APOGEE WHEAT
USU PERIGEE WHEAT
SUPER DWARF RICE
MICRO TINA TOMATO
TRITON PEPPER
HOYT SOYBEAN
EARLIGREEN PEA

Genetically Engineered "FT" Plums *Developed by USDA ARS*

Early Flowering and Fruit Set

Plums and Tree Fruit

No Dormancy Requirements

Overexpression of FT flowering gene in plums (ARS researchers) resulted in dwarf growth habit and early flowering

Srinivasan et al., 2012, PLOS ONE; Graham et al., 2015 Grav. Space Research

NASA's Biomass Production Chamber

20 m^2 growing area; 113 m^3 vol.; 96 400-W HPS Lamps;
400 m^3 min^{-1} air circulation; two 52-kW chillers

Wheeler. 1992. HortScience

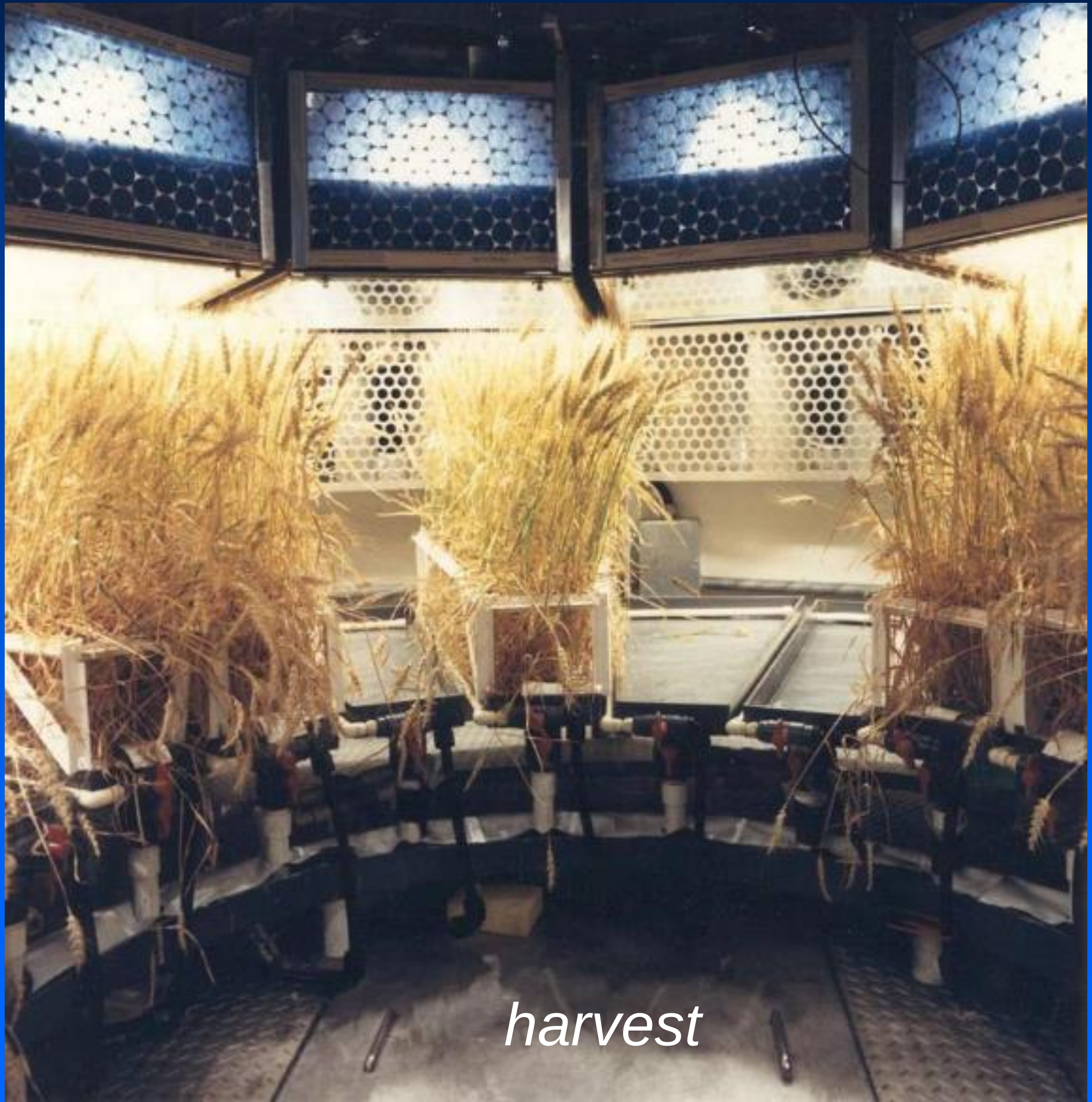
NASA’s Biomass Production Chamber

Kennedy Space Center, FL, US

Perhaps the world’s first example of a “vertical farm”

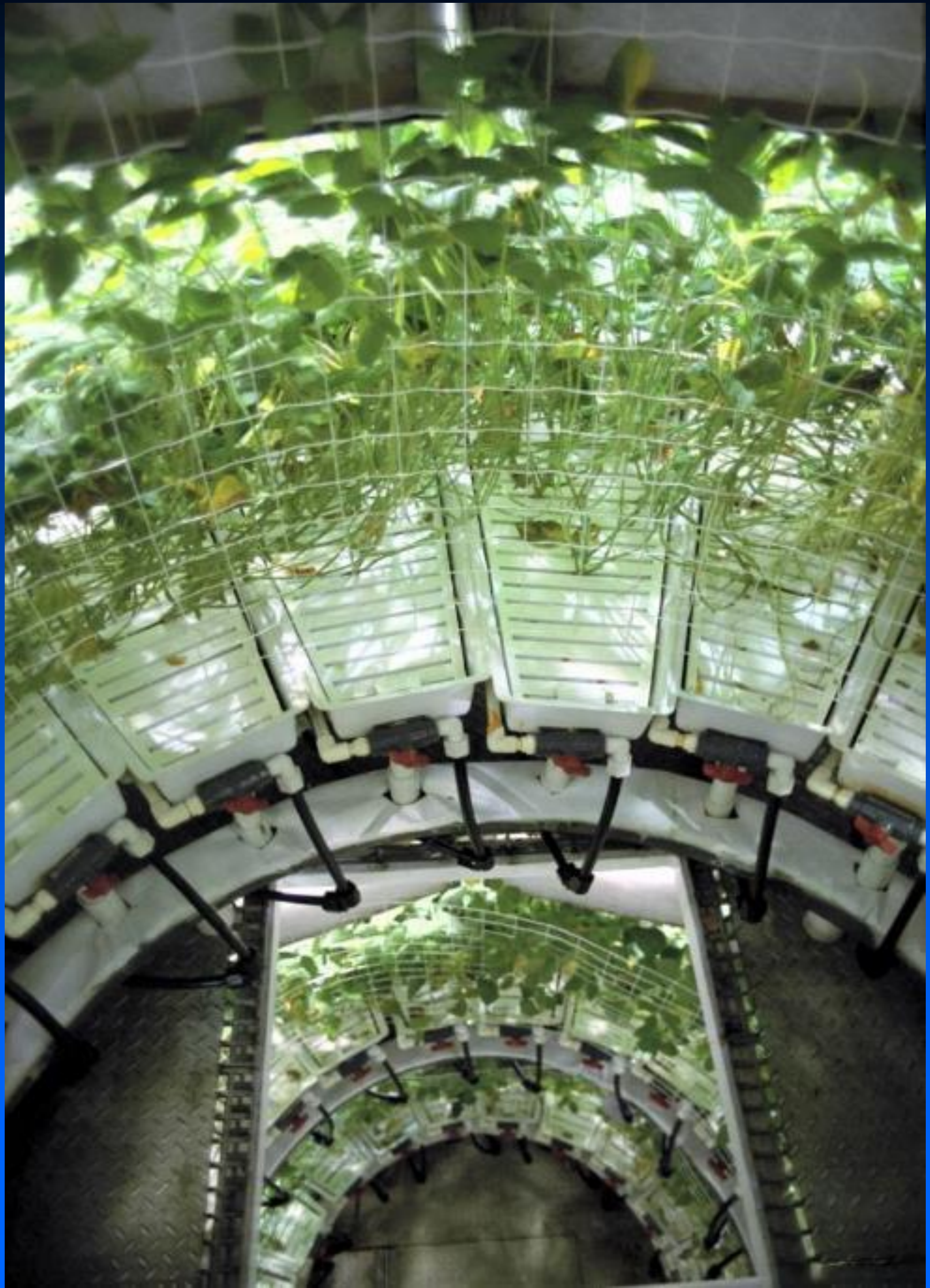
Wheat

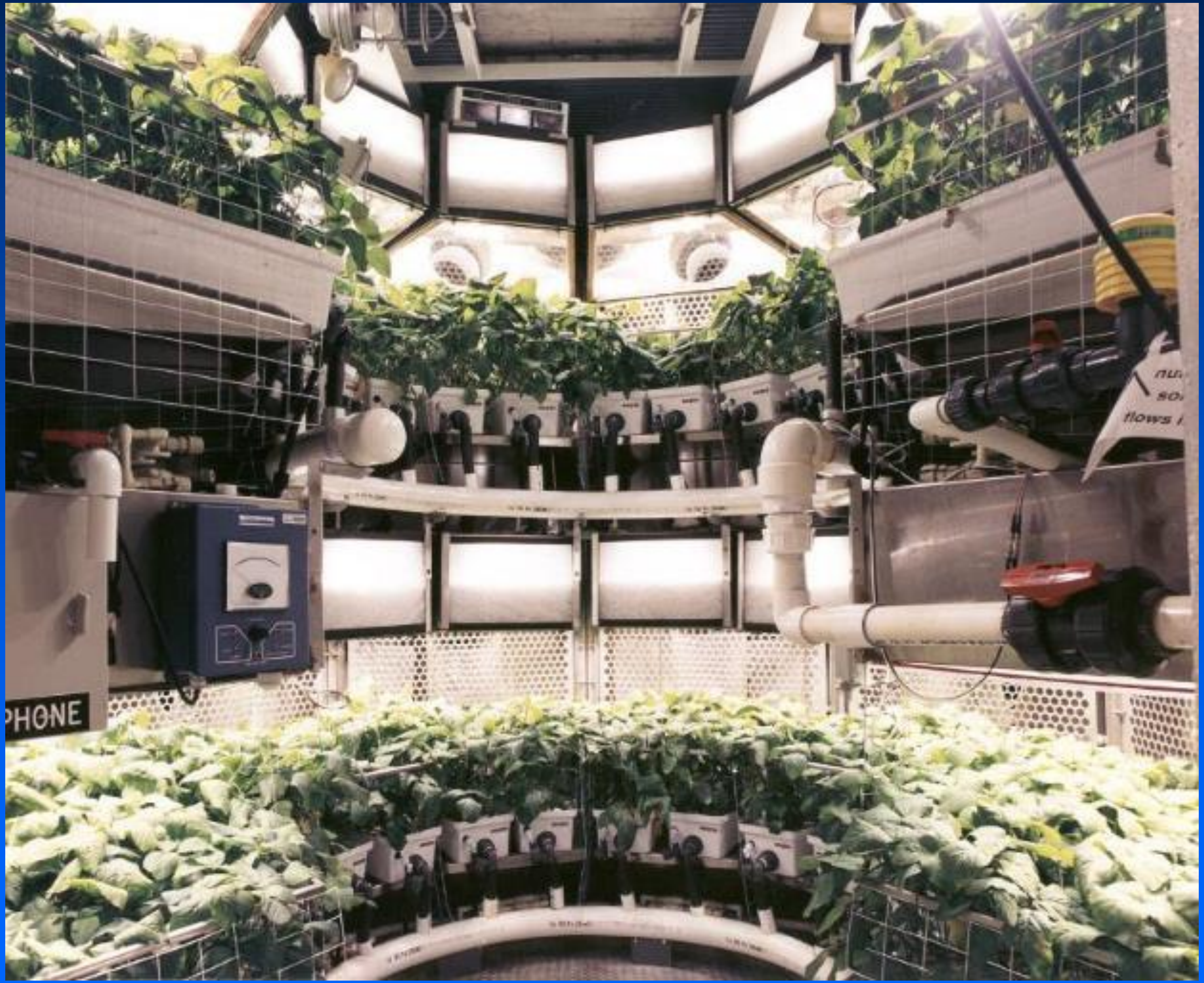
(Triticum aestivum)



All plants were grown using
Nutrient Film Technique
(NFT) hydroponics with
no soil or solid media

Soybean
(Glycine max)

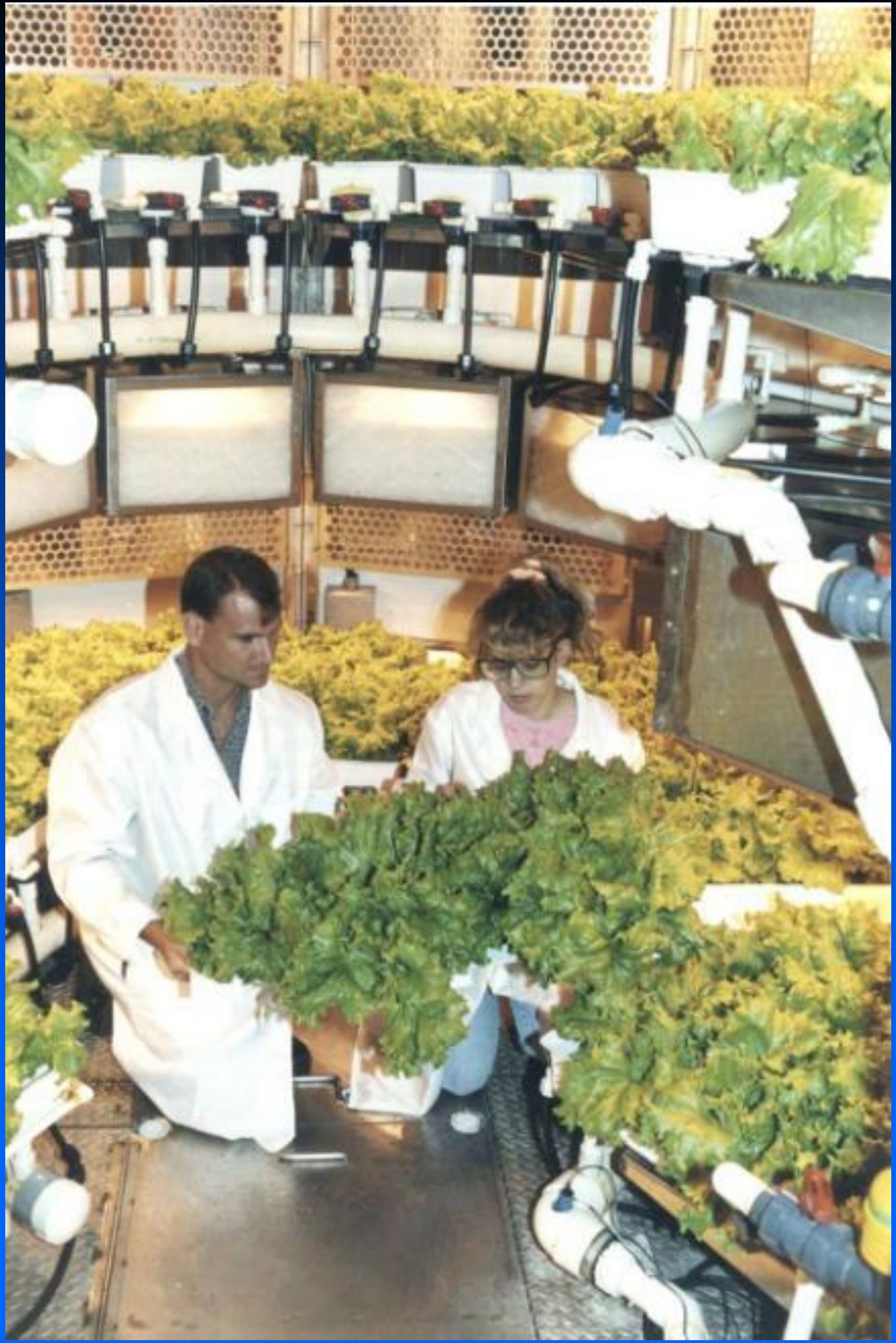




Potato

(Solanum tuberosum)

NASA's NFT approach now used by "seed potato" growers.



Lettuce

(Lactuca sativa)

Photo courtesy of AeroFarms Inc.

Vertical Farming 30 Years Later !

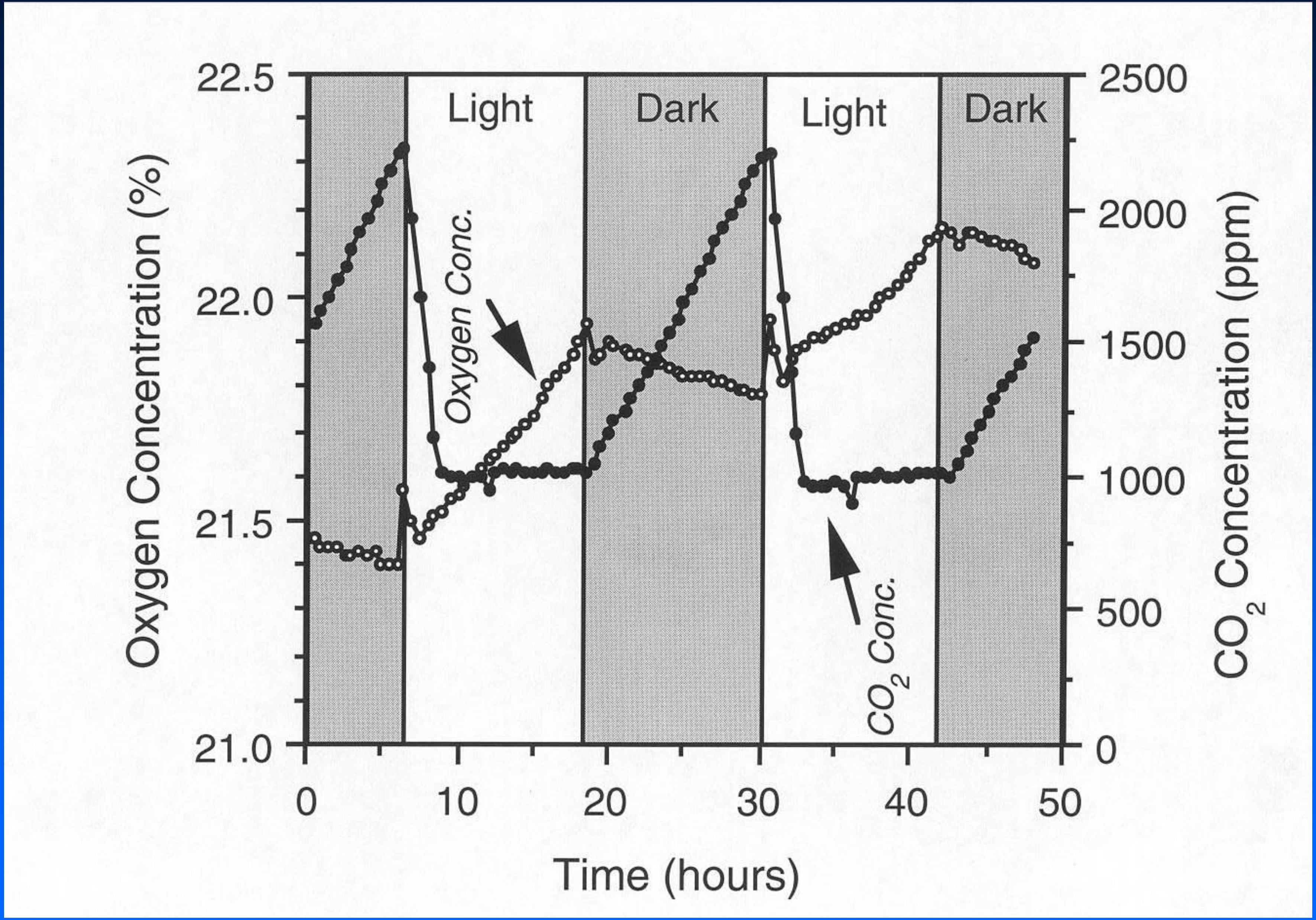
Photo courtesy of Plenty Inc.

Photo courtesy of Bowery Inc.

Photo courtesy of Illumitex Inc.

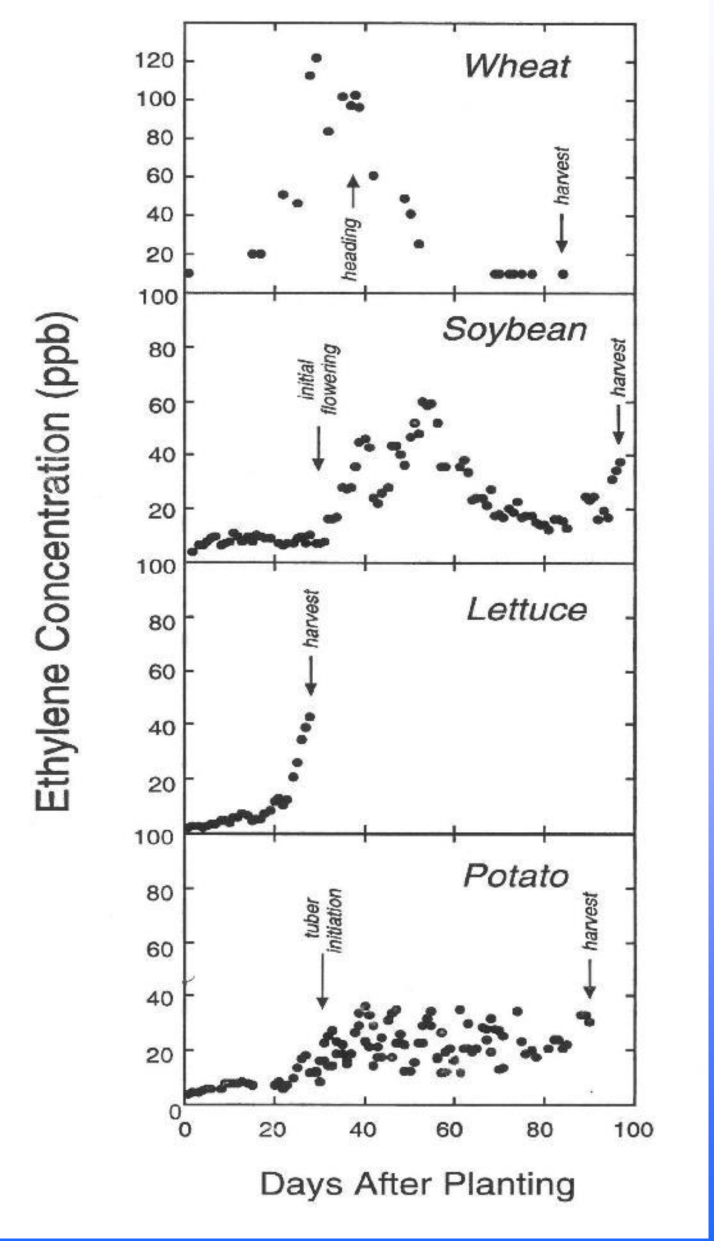
Closed System CO_2 Uptake / O_2 Production

(20 m^2 Soybean Stand)



Wheeler. 1996. In: H. Suge
Plants in Space Biology.

Ethylene Production by Crops



Wheeler et al. HortSci. 2004

Epinastic
Potato Leaves
at ~40 ppb

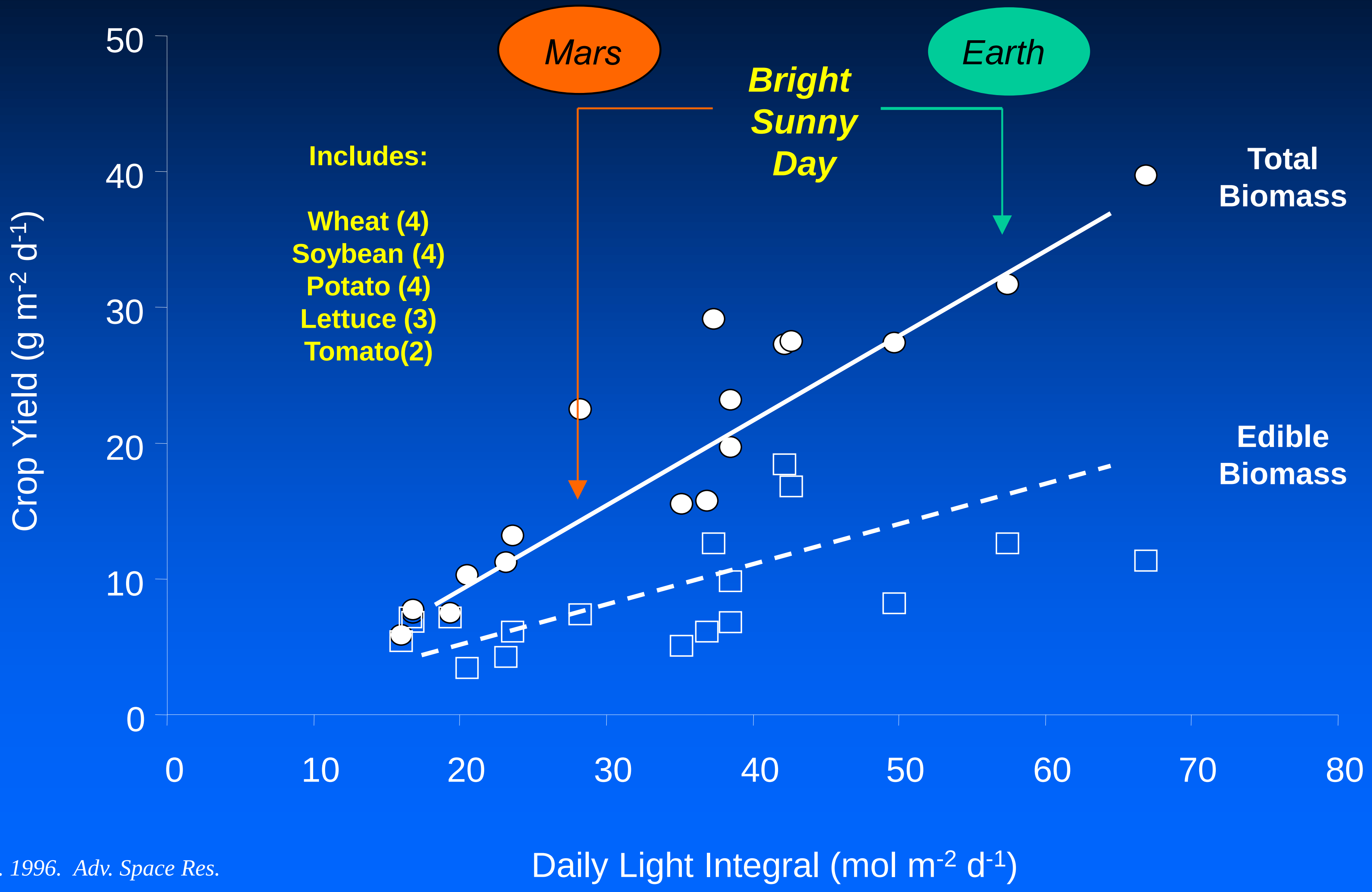
One Human and 11 m^2 of Wheat !

(all the O_2 needed for a 15-day test)

Nigel Packham at NASA's
Johnson Space Center

Photos courtesy of NASA Johnson Space Center

The Importance of Light for Crop Yield



Wheeler et al. 1996. Adv. Space Res.

Lighting for Plants in Space

Red...photosynthesis, germination
Blue...photosyn., phototropism, morphogenesis
Green...human vision, canopy penetration
Far-red…morphogenesis, germination, more

L
E
D
s

Patent for Using LEDs to Grow Plants was Developed with NASA Funding at University of Wisconsin In 1990

Bula et al. 1991. HortSci.; Goins et al. 1997. J. Ex. Bot.; Yorio et al. 2001 HortSci.; Kim et al. 2004 Ann. Bot.; Massa et al. 2008 HortSci.

Photos Courtesy of NASA

Solar Collector / Fiber Optics For Plant Lighting

2 m^2 of collectors on solar tracking drive (NASA KSC)

Up to 400 W light delivered to chamber
(40-50% of incident light)
Takashi Nakamura, Physical Sciences Inc.

Photos Courtesy of NASA
Nakamura et al. 2010. Habitation

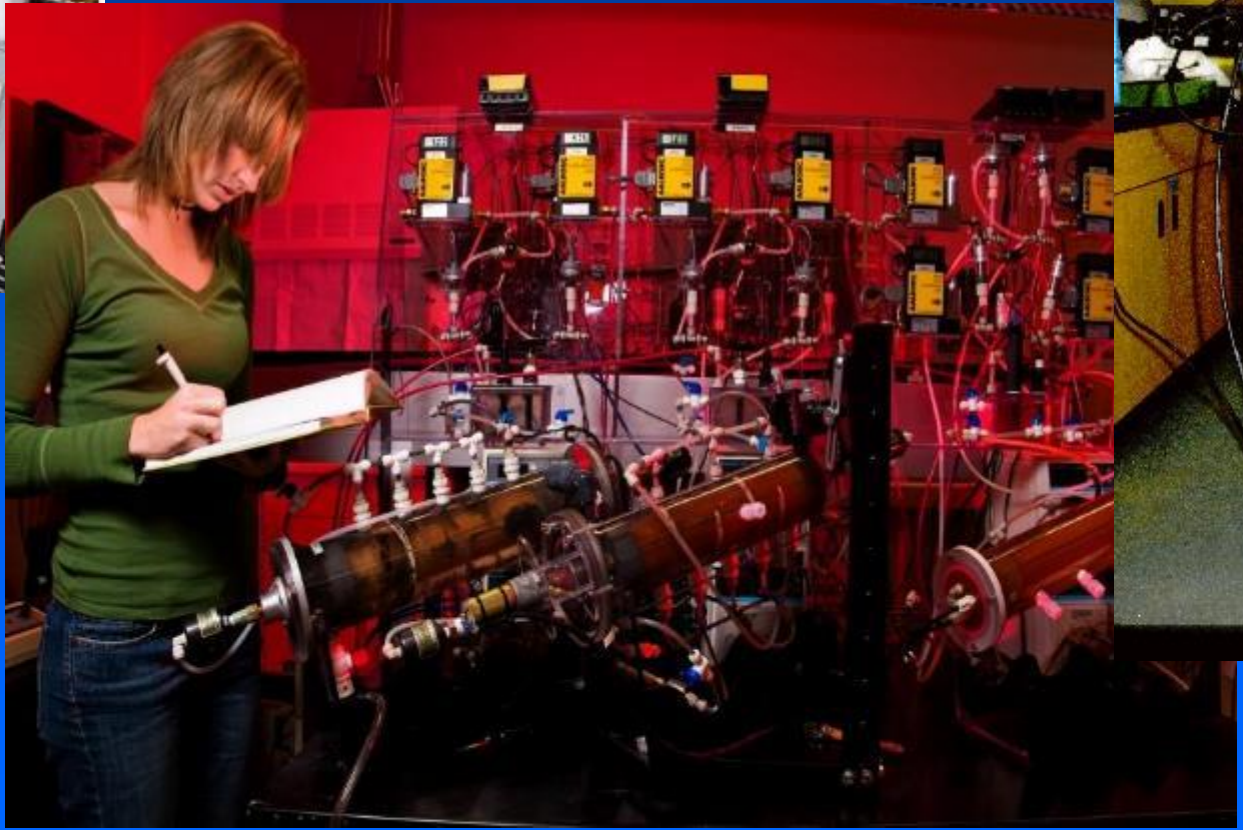
Waste Processing for Nutrient Recyling

← Composter and Continuously Stirred Tank Reactors → for Inedible Plant Biomass

Use Effluent or Solids to Grow Plants

Hollow Fiber Membrane Bioreactors for Urine Treatment →

Use Effluent to Grow Plants



Further Improvements in System Closure

→ *Conversion of Inedible Biomass Into Food or Other High Value Products*

- Fish for Food (Aquaculture) →
- Fungi for Food
- Insects for Food (Entomaphagy)

- Aquaponics →

Growth of Crops on Recycled Nutrients

Potatoes growing on ½ X Hoagland Solution (left) and on recycled bioreactor effluent (right)

Current NASA Crop Testing Supplemental Fresh Foods

Small Fruits

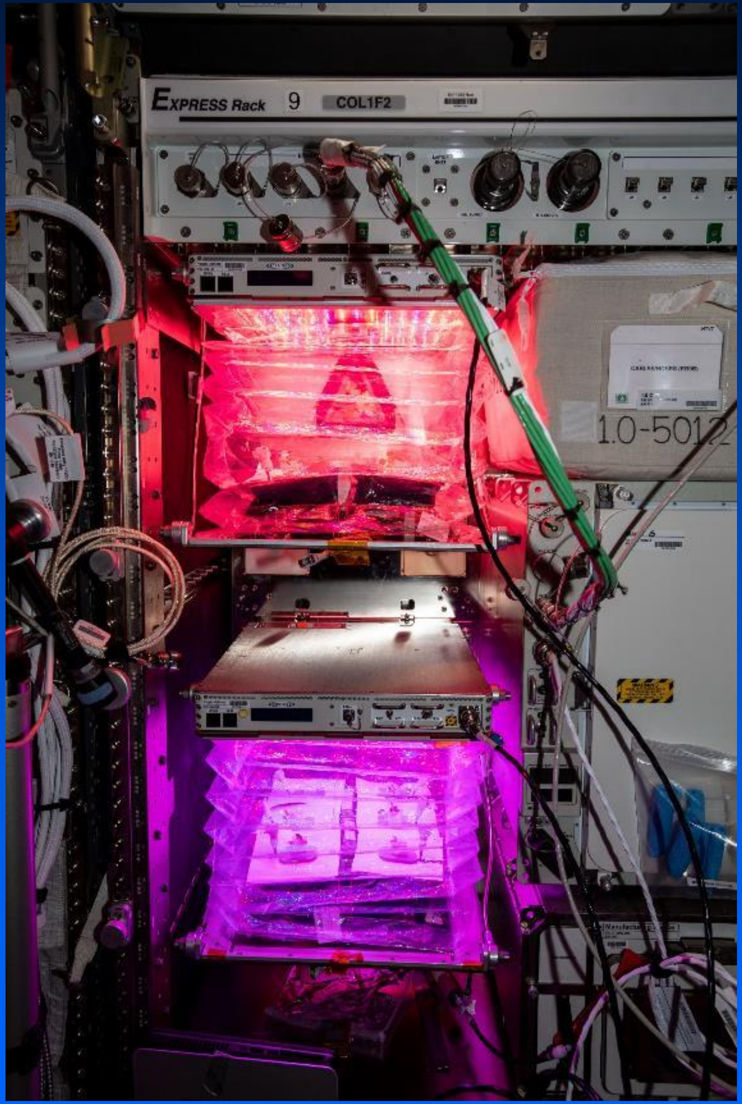
Leafy Greens

Closed Chambers for CO_2 Exposure and VOC Measurements

Chambers for Exposing Plants to VOCs, or Monitoring VOCs

Exposing Plants to Super-Elevated CO_2

Current Plant Chambers on ISS



Veggie (Open to Cabin Air)

APH (Closed with Internal Control)

Fresh Food on the International Space Station

VEGGIE Plant Chamber

Photos courtesy of NASA

Astronauts Peggy Whitson
and Jessica Meir

Mizuna Mustard
Grown Veggie

More Vegetables Grown on the Intl. Space Station

Chile Peppers in Advanced Plant Habitat (APH)

Astronauts Sampling Wasabi Mustard

Pak Choi in Veggie

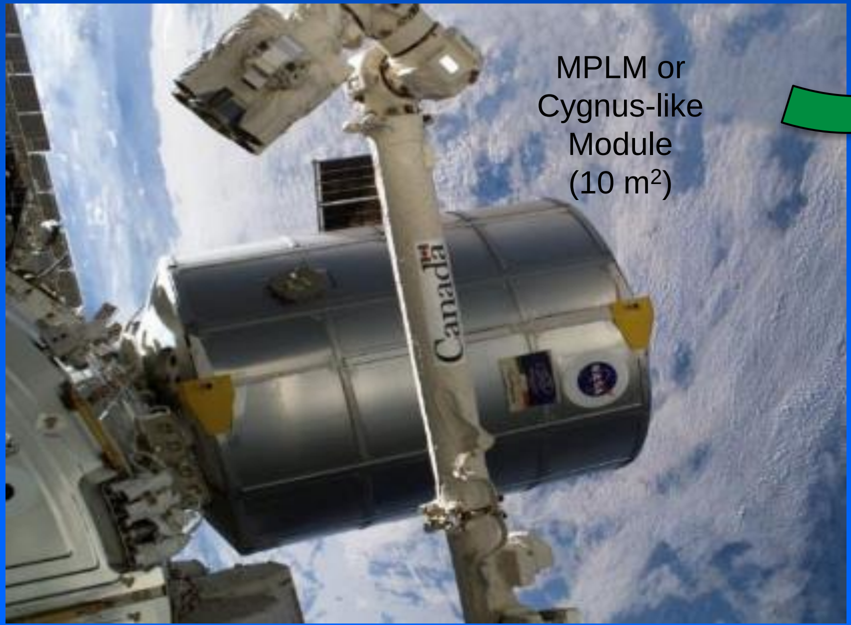
Radishes in APH

Photos courtesy of NASA

Sequential Development for Space Agriculture

Astronauts
Christina Koch
& Jessica Meir
←

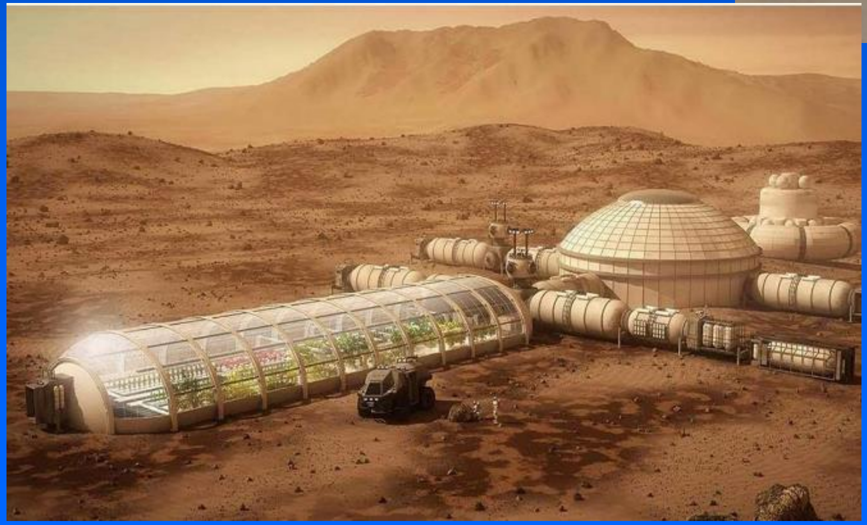
Photos and diagrams
Courtesy of NASA



Lunar and Mars Greenhouses

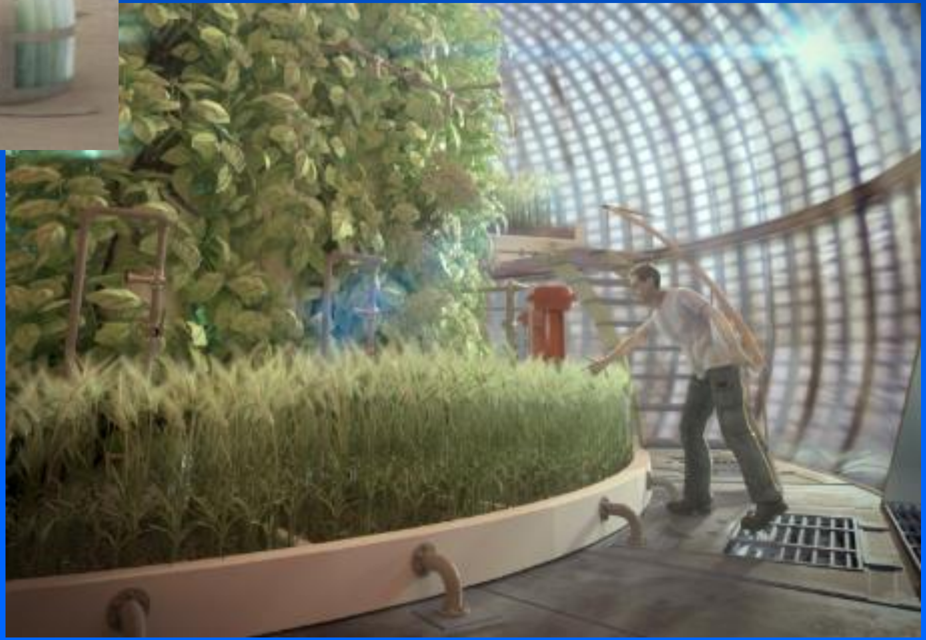
Graphics Courtesy of NASA's Big Idea Challenge

Bottom Graphics Courtesy Heather Hava, Univ. of Colorado

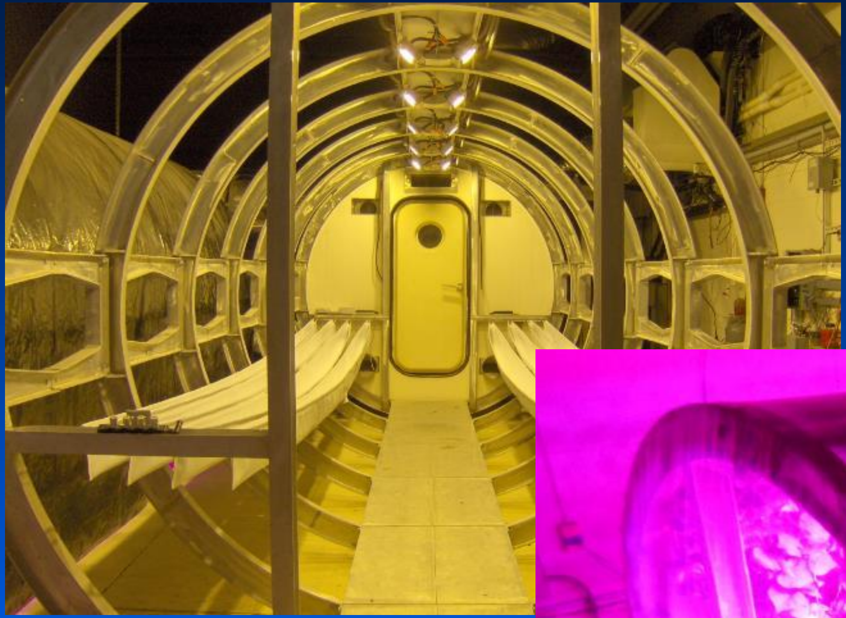


Inflatable Structures with Ice for Radiation Shielding

Mars Greenhouse Concept Courtesy Bryan Versteeg ⇐



Deployable Greenhouse Concepts



Innovative Collapsible, Deployable Greenhouse Structures for Space Including Flexible Hydroponic Troughs Suspended by Cables
Photos Courtesy of Univ. of Arizaon

Plants and Living in Remote Environments

Plant Growth Chamber
Design and Operations
at the US South Pole
Station in Antarctica

Lessons Learned from NASA CEA Research

- Recirculating hydroponics (NFT) works for a wide range of crops, including rootzone crops. Trees and shrubs?
- Yields for many species essentially limited by lighting; 2-4 X record yields obtained with wheat and potato.
- 1 g dry mass / mol PAR close to upper limit for light conversion
- Some crops can be affected by ethylene as low as 40 ppb
- Approximately 20 m^2 plants can provide O_2 for one human
- Approximately 50 m^2 of plants (crops) can provide food for one human

Bioregenerative Life Support on the Moon and Mars?

Thank You !

Thanks to my Colleagues at NASA’s Kennedy Space Center