NASA's Interests in Bioregenerative Life Support

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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%)

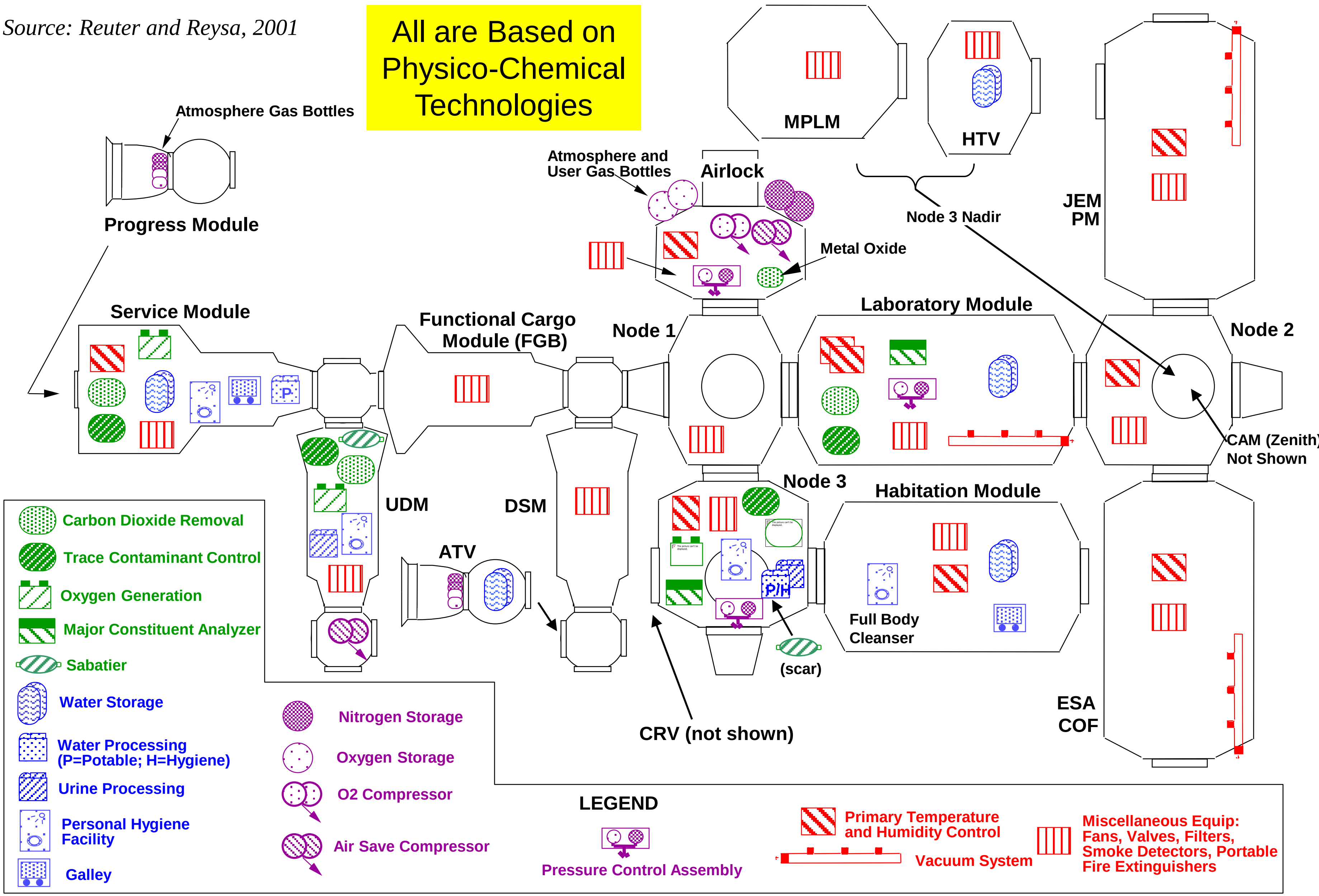
TOTAL 31.0 kg

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

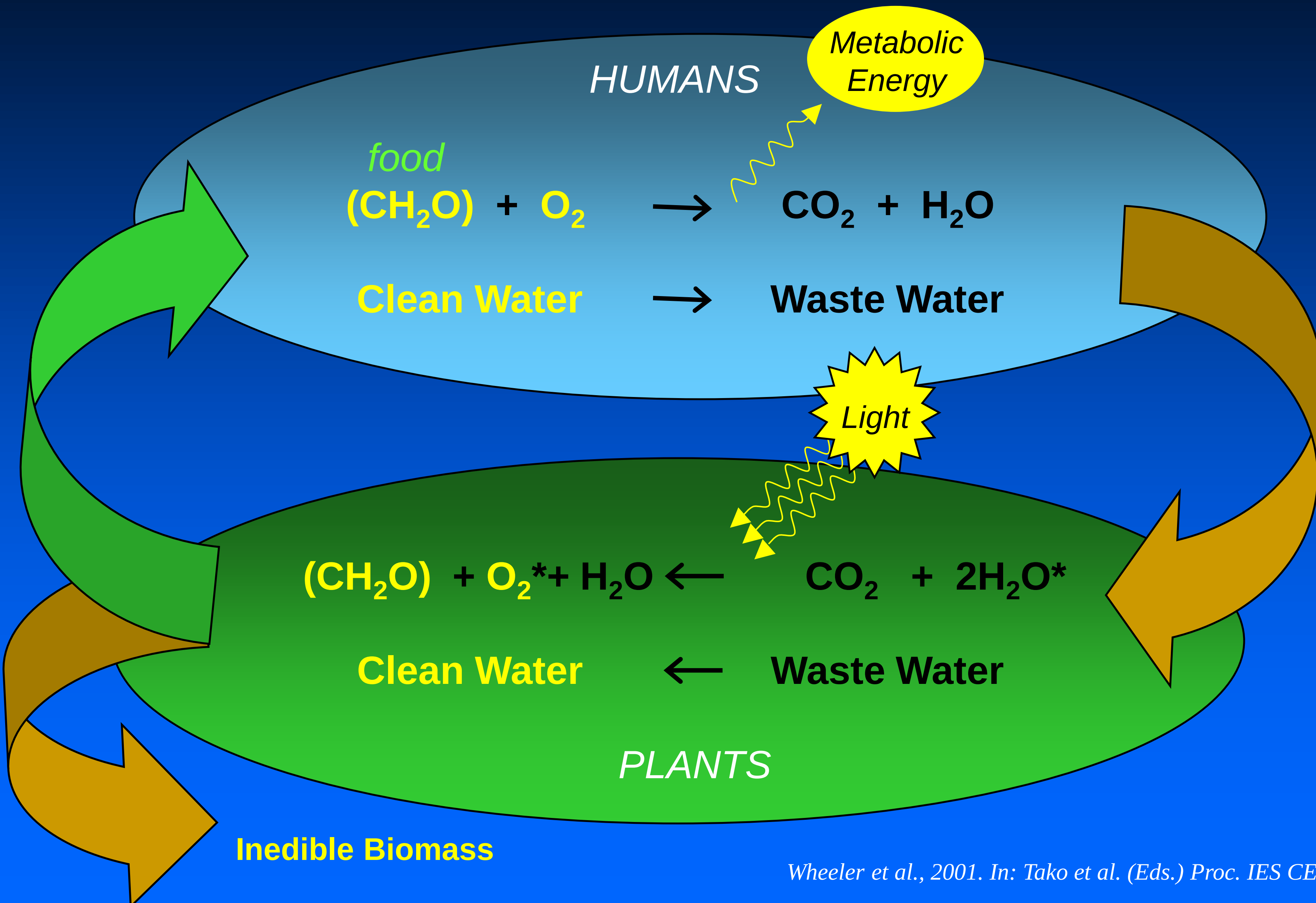
International Space Station Life Support Systems

Source: Reuter and Reysa, 2001

All are Based on Physico-Chemical Technologies



Plants for Life Support

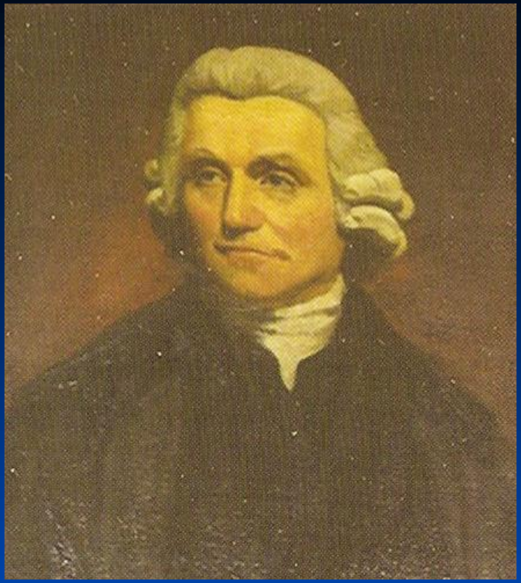


Wheeler et al., 2001. In: Tako et al. (Eds.) Proc. IES CEEF.

Bioregenerative Life Support

Early references:

- Greg, P. 1880. Across the zodiac. (recently reprinted by BiblioBazaar, 2006).
- Tsiolkovsky, K.E. 1926. Exploration of world space with rockets. Kaluga (*In Russian*).
- Ley, W. 1948. Rockets and space travel. The future of flight beyond the stratosphere. The Viking Press, New York, NY, US. 374 pages.
- Specht, H. 1952. Toxicology of travel in the aeropause. In: C.S. White and O.O. Benson (*eds.)* Physics and Medicine of the Upper Atmosphere, University of New Mexico Press, Albuquerque.
- Bowman, N.J. 1953. The food and atmosphere control problem on space vessels. II. The use of algae for food and atmospheric control. J. British Interplanetary Soc. 12:159-167.
- Myers, J. 1954. Basic remarks on the use of plants as biological gas exchanges in a closed system. J. Aviation Medicine 25:407-411.



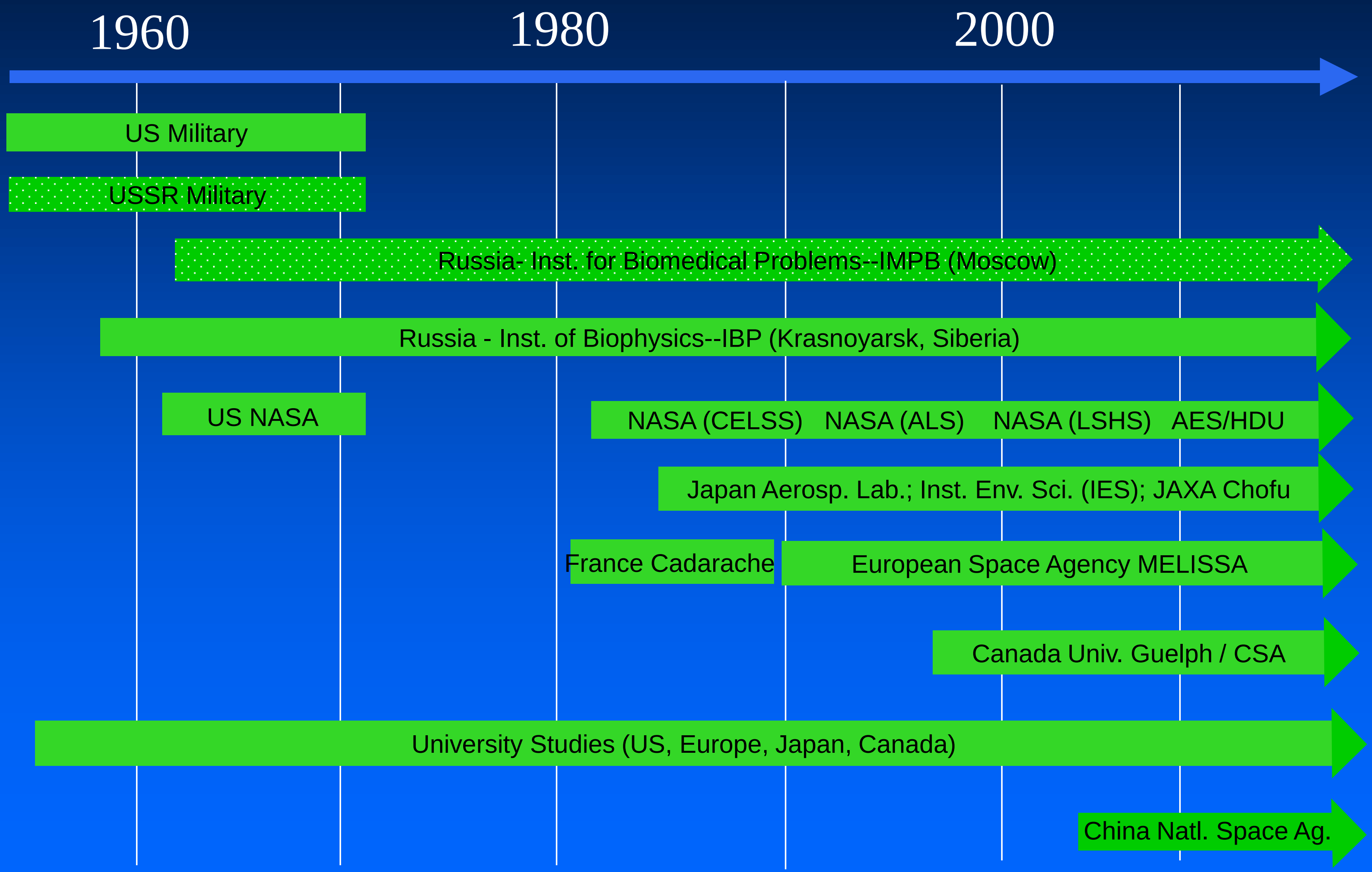
Joseph Priestley--1772

“Patron Saint” of Bioregenerative Life Support

“I have been so happy as by accident to hit upon a method of restoring air, which has been injured by the burning of candles and I have discovered at least one of the restoratives...it is vegetation”

“...when I first put a sprig of mint into a glass jar standing inverted in a vessel of water; it had continued growing for some months [and] I found that the air would neither extinguish a candle, nor was it at all inconvenient to a mouse...”

Bioregenerative Life Support Testing Around the World



Crop Considerations for Space

- High yielding and nutritious (CHO, protein, fat)
  - Secondary Metabolites—e.g., antioxidants, lutein, zeaxanthin, Vit. C, Vit. B1, Vit. K.
- 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

Some Crops for Life Support

Hoff, Howe, and Mitchell (NASA)[a]	Salisbury and Clark (NASA)[b]	Crops Used in BIOS-3 (Russia)[c]	Tako et al CEEF (Japan)[d]	Waters et al. (ESA / Canada)[e]
Wheat	Wheat	Wheat	Rice	Lettuce
Potato	Rice	Potato	Soybean	Wheat
Soybean	Sweetpotato	Carrot	Peanut	Potato
Rice	Broccoli	Radish	Sweetpotato	Sweetpotato
Peanut	Kale	Beet	Sugar Beet	Rice
Dry Bean	Lettuce	Nut Sedge	Carrot	Bean
Tomato	Carrot	Onion	Tomato	Beet
Carrot	Canola	Cabbage	Spinach	Cabbage
Chard	Soybean	Tomato	Shungiku	Broccoli
Cabbage	Peanut	Pea	Chinese Cabbage	Cauliflower
	Chickpea	Dill	Pea	Carrot
	Lentil	Cucumber	Onion/Leek	Kale
	Tomato	Salad spp.	Komatsuna	Onion
	Onion		Pepper	
	Chili Pepper			

[a] *Hoff, Howe, and Mitchell (1982);* [b] *Salisbury and Clark (1996);* [c] *Gitelson and Okladnikov (1994).*
[d] *Tako et al. (2010);* [e] *Waters et al. (2002)*

Targeted Crop Selection and Breeding for Space at Utah State University

Selection of Existing Rice Genotypes

Targeted Wheat Breeding

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

'Apogee' Wheat 'Perigee' Wheat

Genetic Engineering Tools

Early Flowering and Fruit Set

No Dormancy Requirements

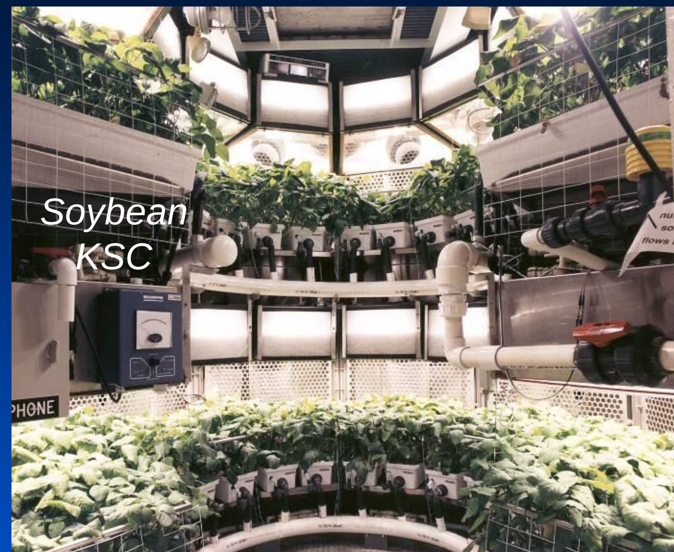
Overexpression of FT flowering gene in plums (ARS researchers) resulted in dwarf growth habit and early flowering

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

Water and Nutrients for Growing Crops

Recirculating Hydroponics

Wheat / Utah State



Soybean KSC

Sweetpotato Tuskegee

Rice / Purdue

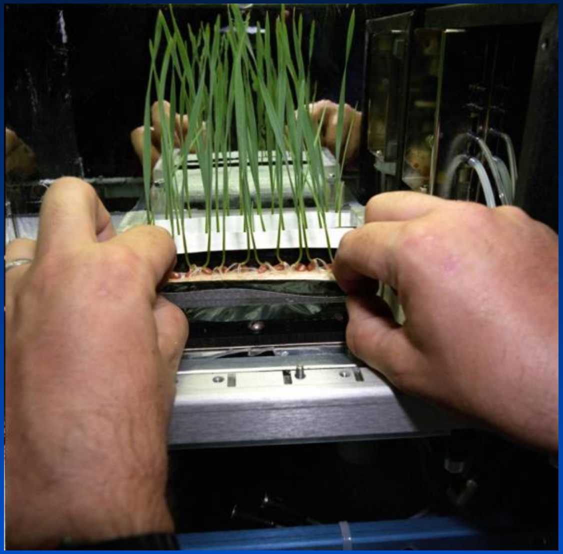
Conserve Water & Nutrients
Eliminate Water Stress
Optimize Mineral Nutrition
Facilitate Harvesting

Wheeler et al. 1999. Acta Hort.

Root Zone Crops in Nutrient Film Technique (NFT)

Wheeler et al., 1990. Amer. Potato J. 67:177-187; Mackowiak et al. 1998. HortScience 33:650-651

Watering Systems for Weightlessness -- Special Challenges



Porous Ceramic Tubes to Contain the Water

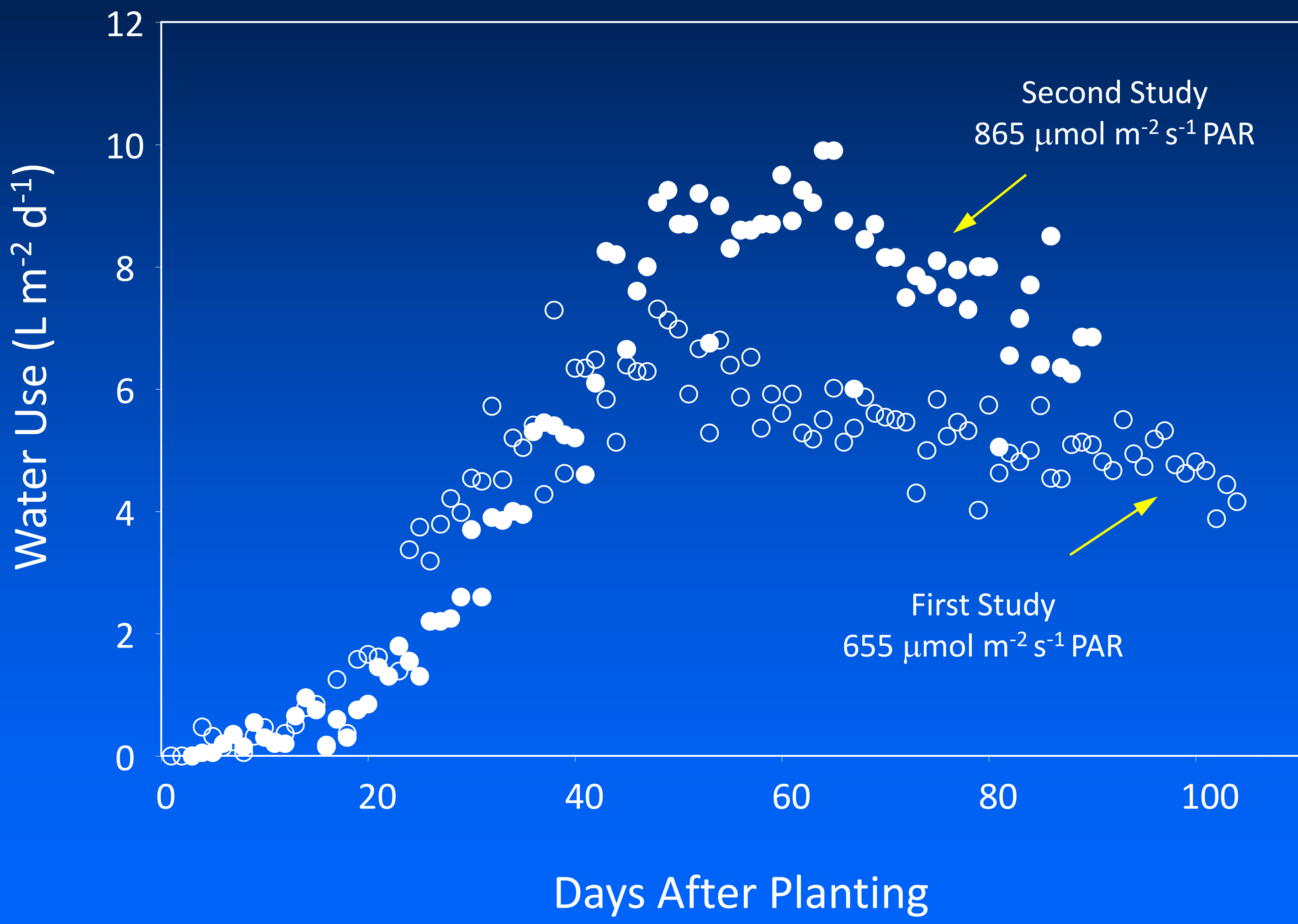
Dreschel and Sager. 1989. HortScience
Morrow and Crabb. 2000. Adv. Space Res.

Porous Ceramic to Sub-irrigate Growing Media

Fig. 7

Evapotranspiration from Plant Stands (potato)

→ *Dealing with the water requirements for CEA*

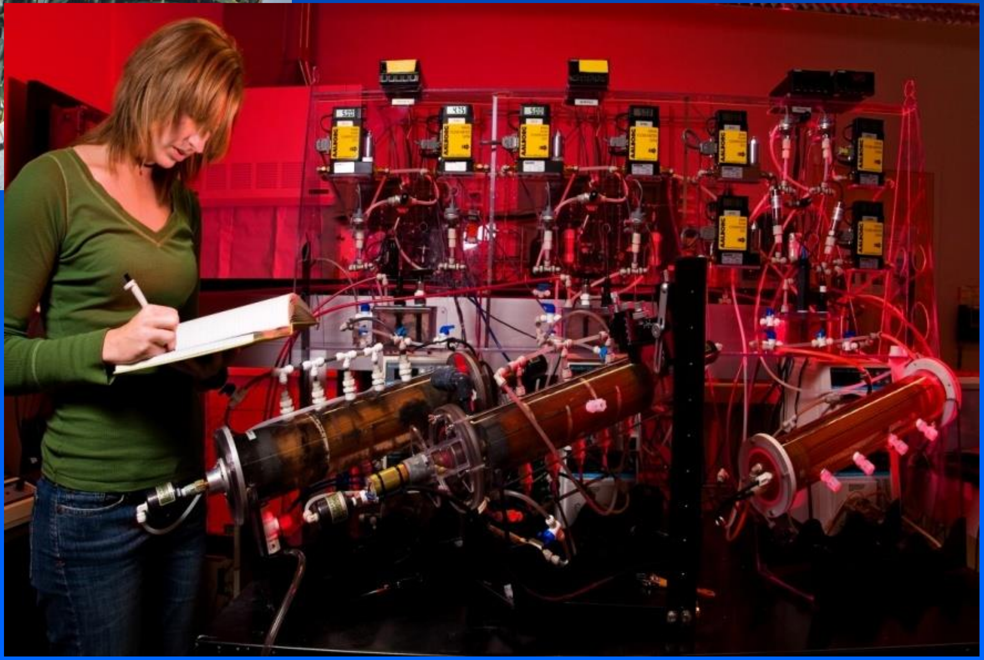


Wheeler. 2006. Potato Research 49:67-90.

Waste Water Treatment Systems

Plants for Purifying Gray Water

Bioreactors for Water Processing



Morales et al. 1996. FEMS Microbial Ecol.
Rector et al. 2007. J. Membrane Sci

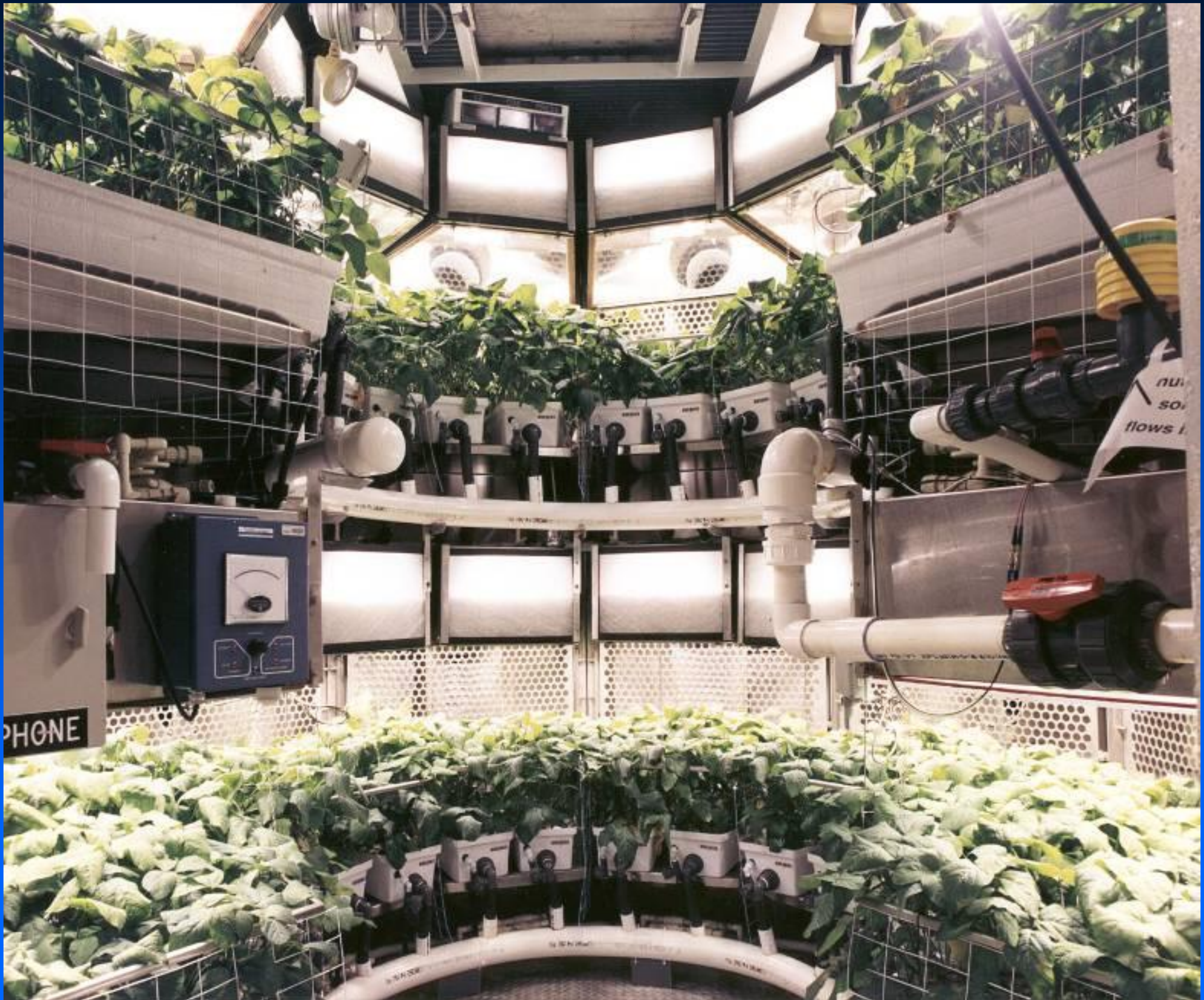
NASA's Biomass Production Chamber (BPC)

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 (BPC)

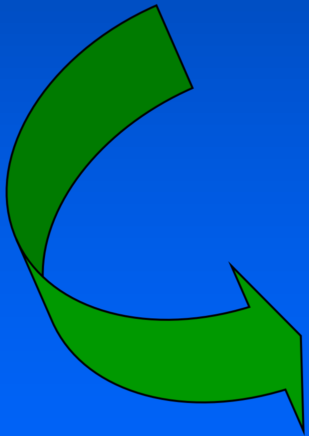
…an early example of a Vertical Agriculture Systems



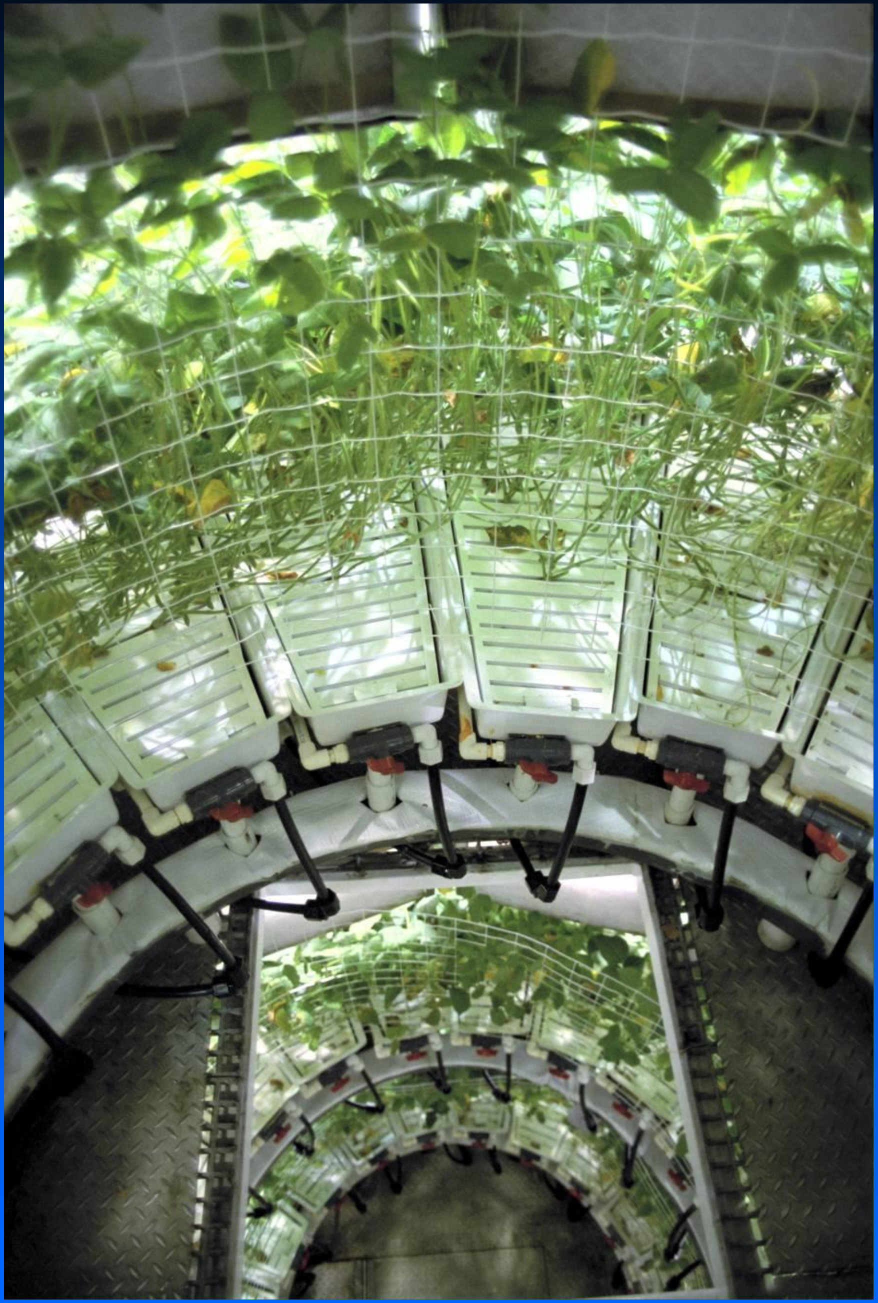
Wheat

(Triticum aestivum)

planting



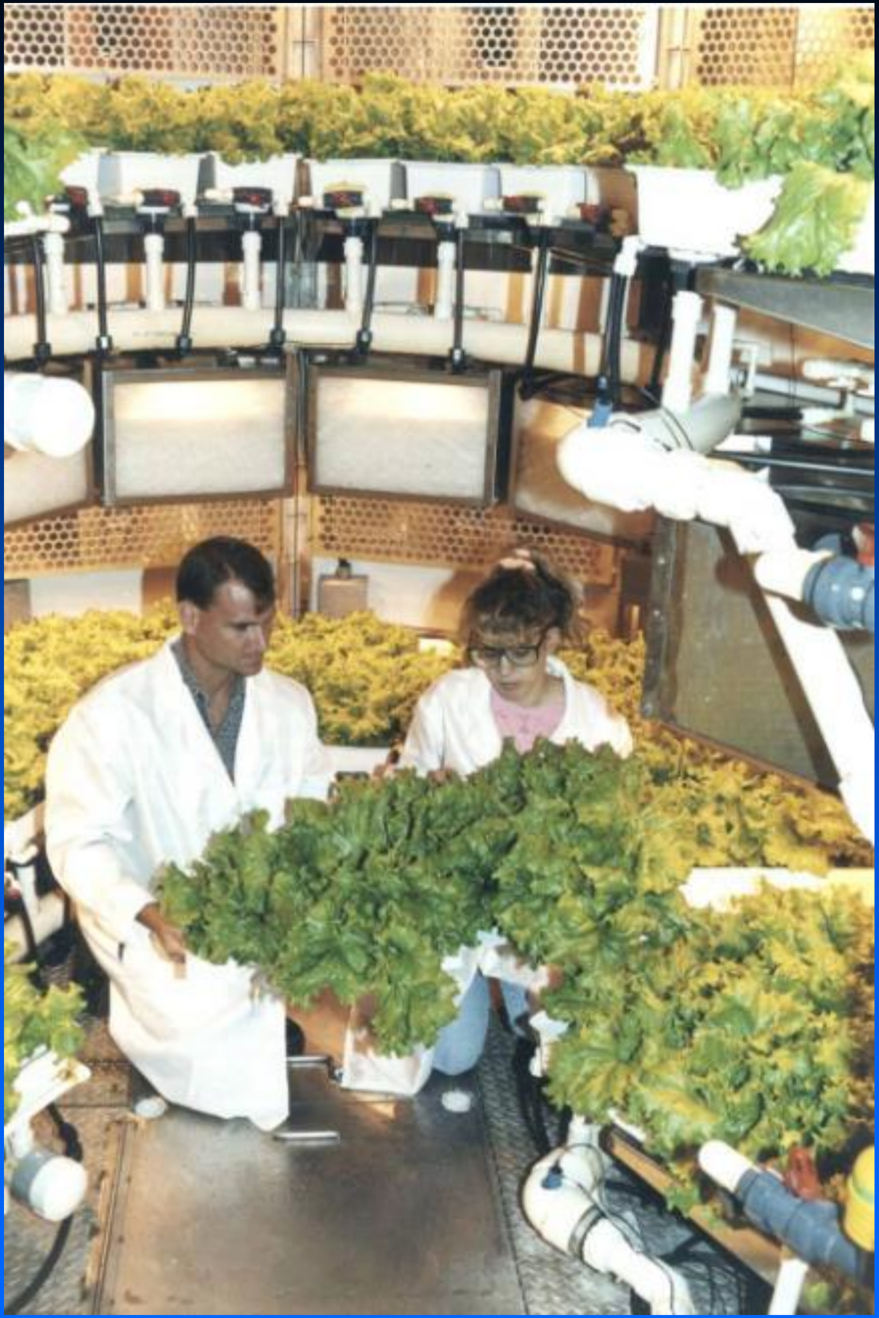
harvest



Soybean

(Glycine max)

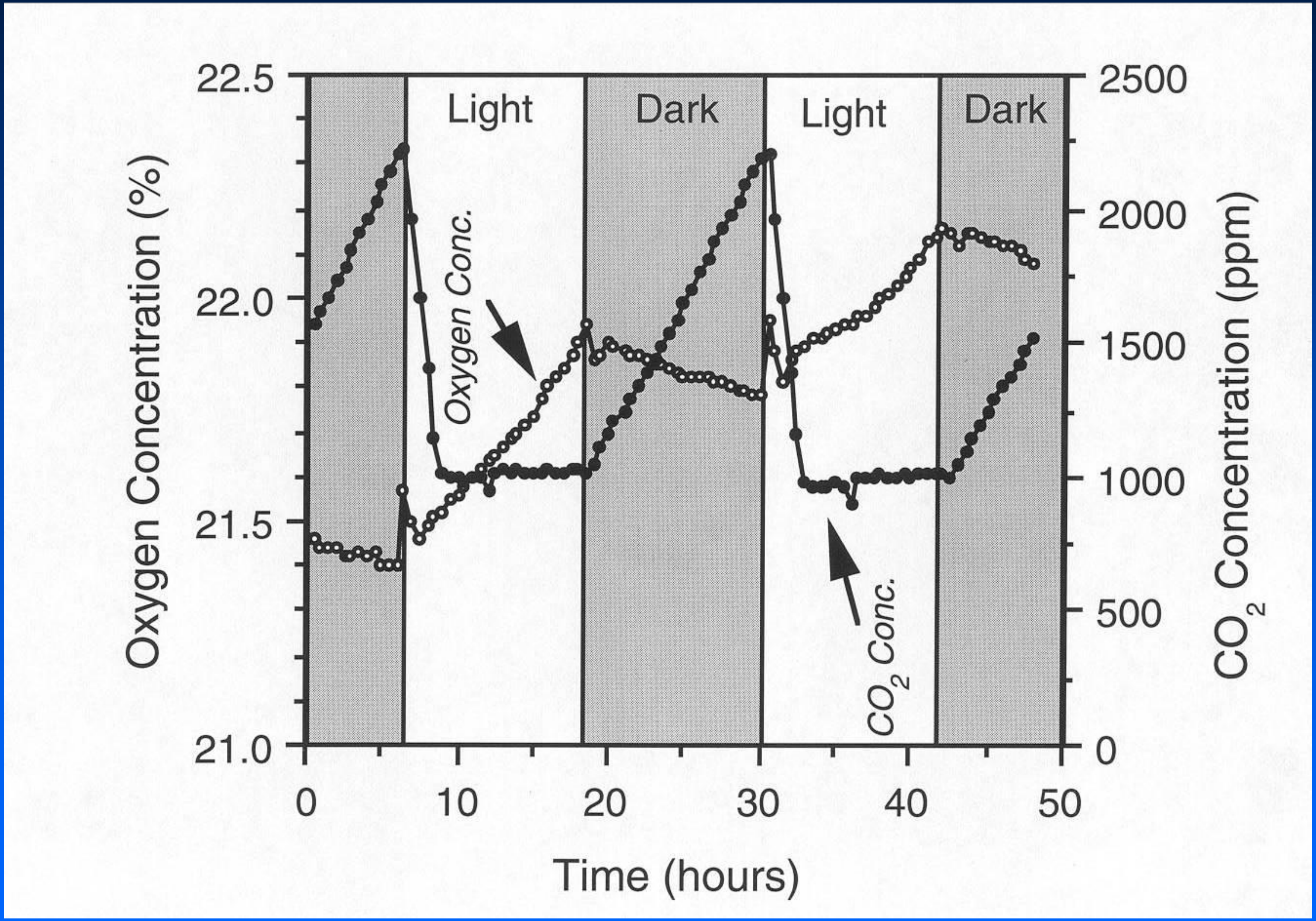
Lettuce
(Lactuca sativa)



Potato

(Solanum tuberosum)

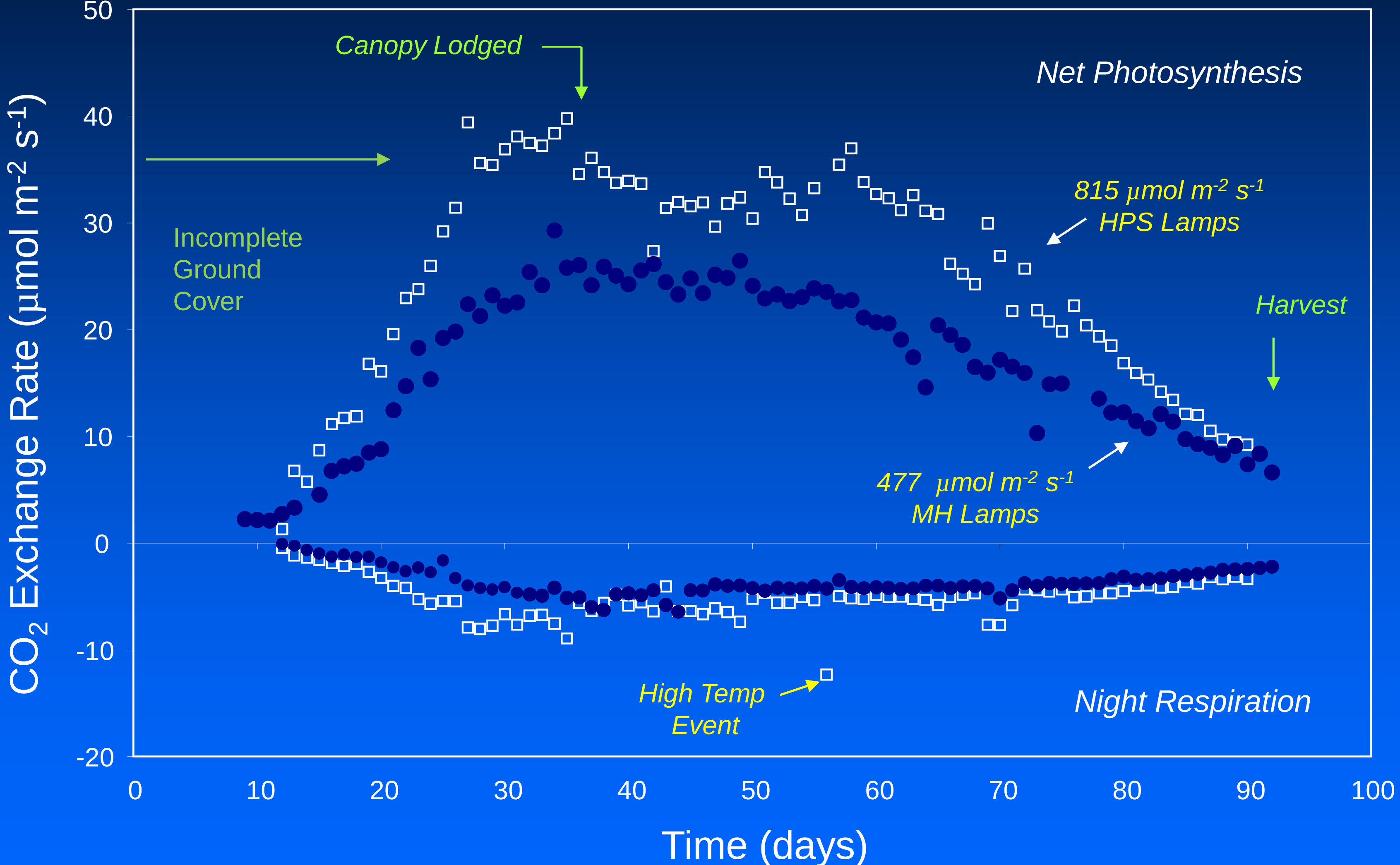
Canopy CO_2 Uptake / O_2 Production
(20 m^2 Soybean Stand)



Wheeler. 1996. In: H. Suge (ed.) Plants in Space Biology.

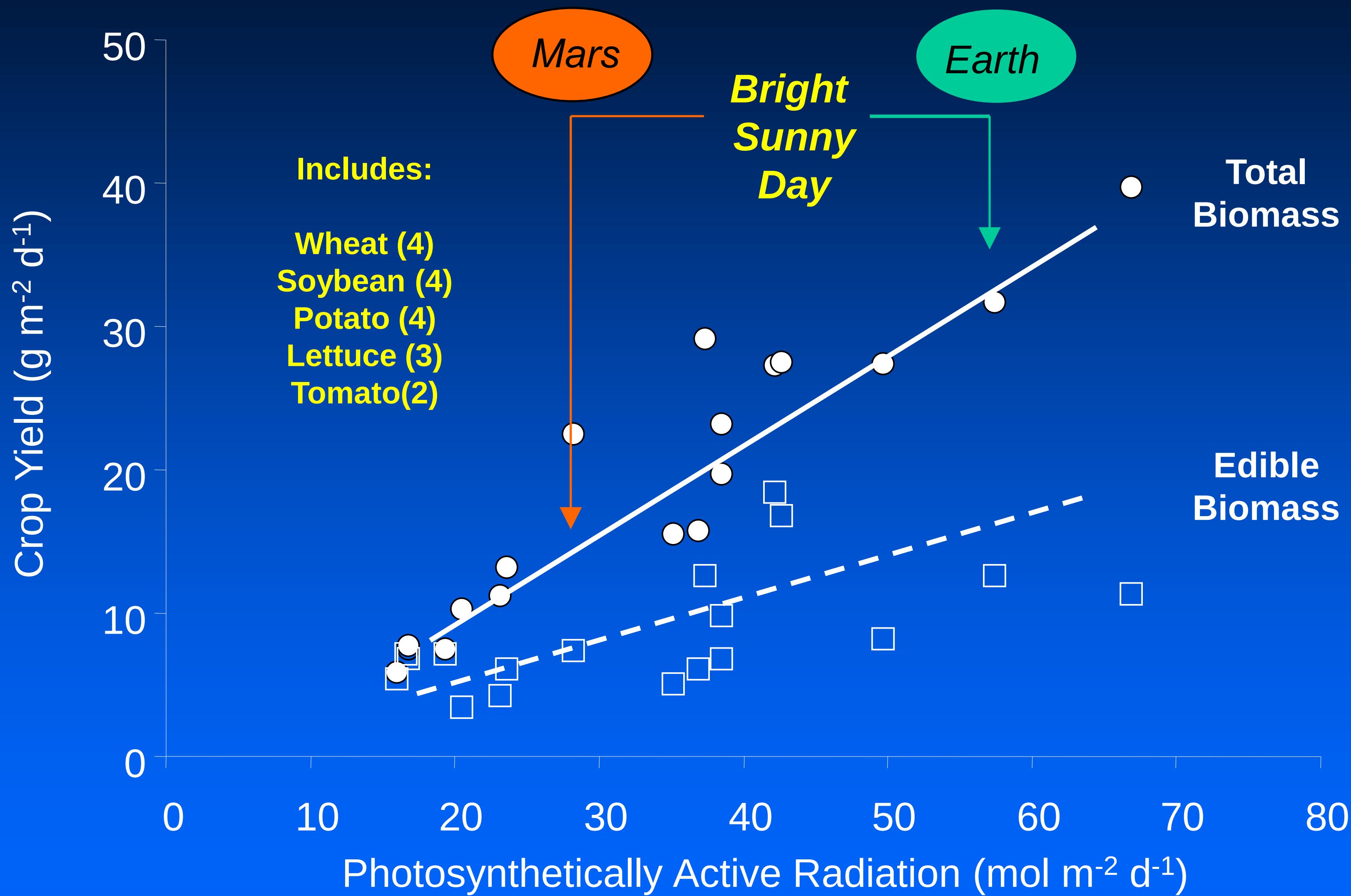
CO_2 Exchange Rates of Soybean Stands

Real-time physiological tracking of CEA systems



Wheeler et al., 2004. EcoEngineering.

The Importance of Light for Crop Yield



Wheeler et al. 1996. Adv. Space Res.

LED Studies

Red...photosynthesis
Blue...photomorphogenesis
Green...human vision

Goins et al. 1997. J. Ex. Bot.; Kim et al. 2004 Ann. Bot.

North American Patent for Using LEDs to Grow Plants Developed with NASA Funding at University of Wisconsin – WCSAR

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.

Nakamura et al. 2010. Habitation

Some other Benefits of Plants in Space

- Fresh Foods
  - *Colors*
  - *Texture*
  - *Flavor*
  - *Nutrients*
- Bright Light
- Aromas
- Gardening Activity

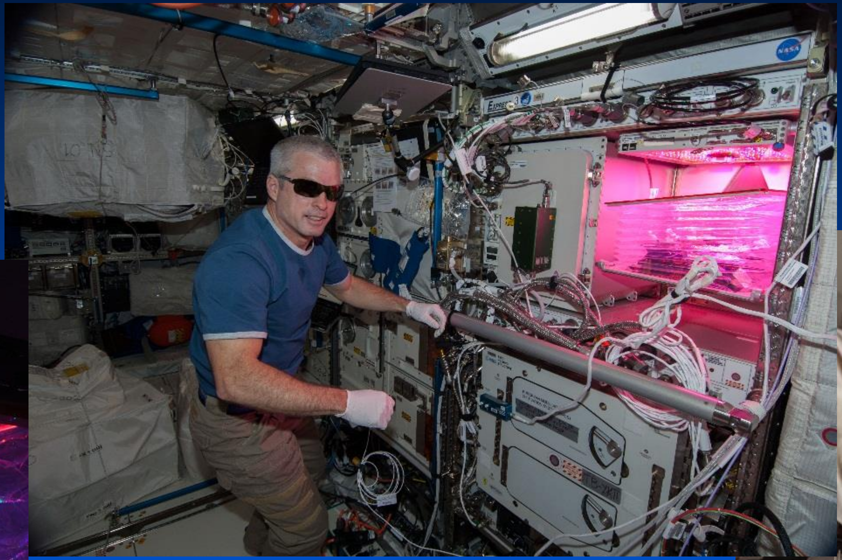
Kliss et al. 2000. Advances in Space Research

Plant Chamber at US South Pole Station

Plants and Human Well-Being—Biophilia Concept? (E.O. Wilson)

Photo courtesy of Phil Sadler, Univ. of Arizona

Current Plant Testing on the International Space Station—VEGGIE Plant Chamber

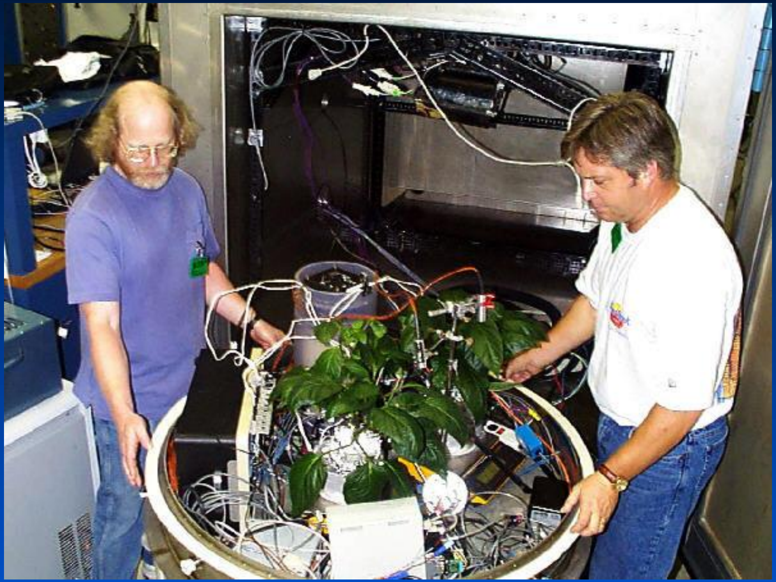


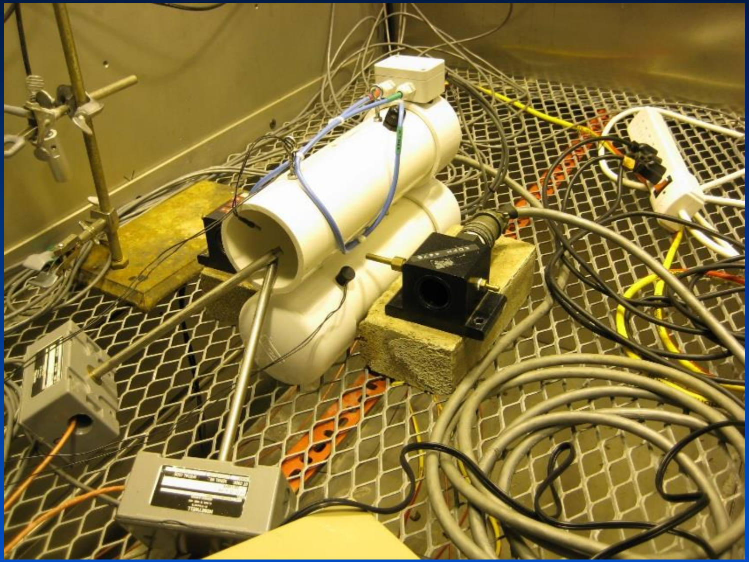
Passive Capillary Watering

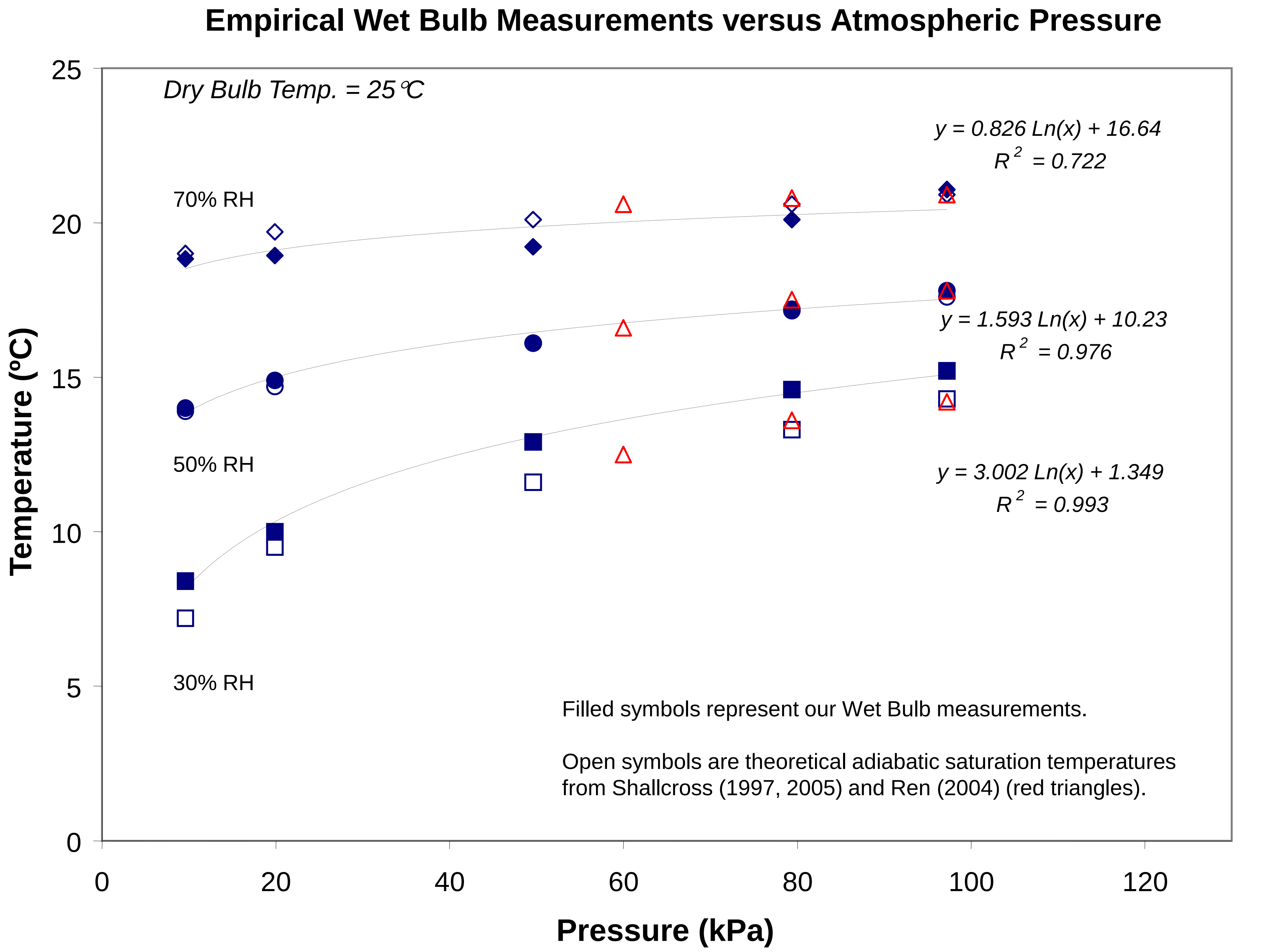
Sequential Development for Space Agriculture

Kliss et al. 2003, Adv. Space Res.

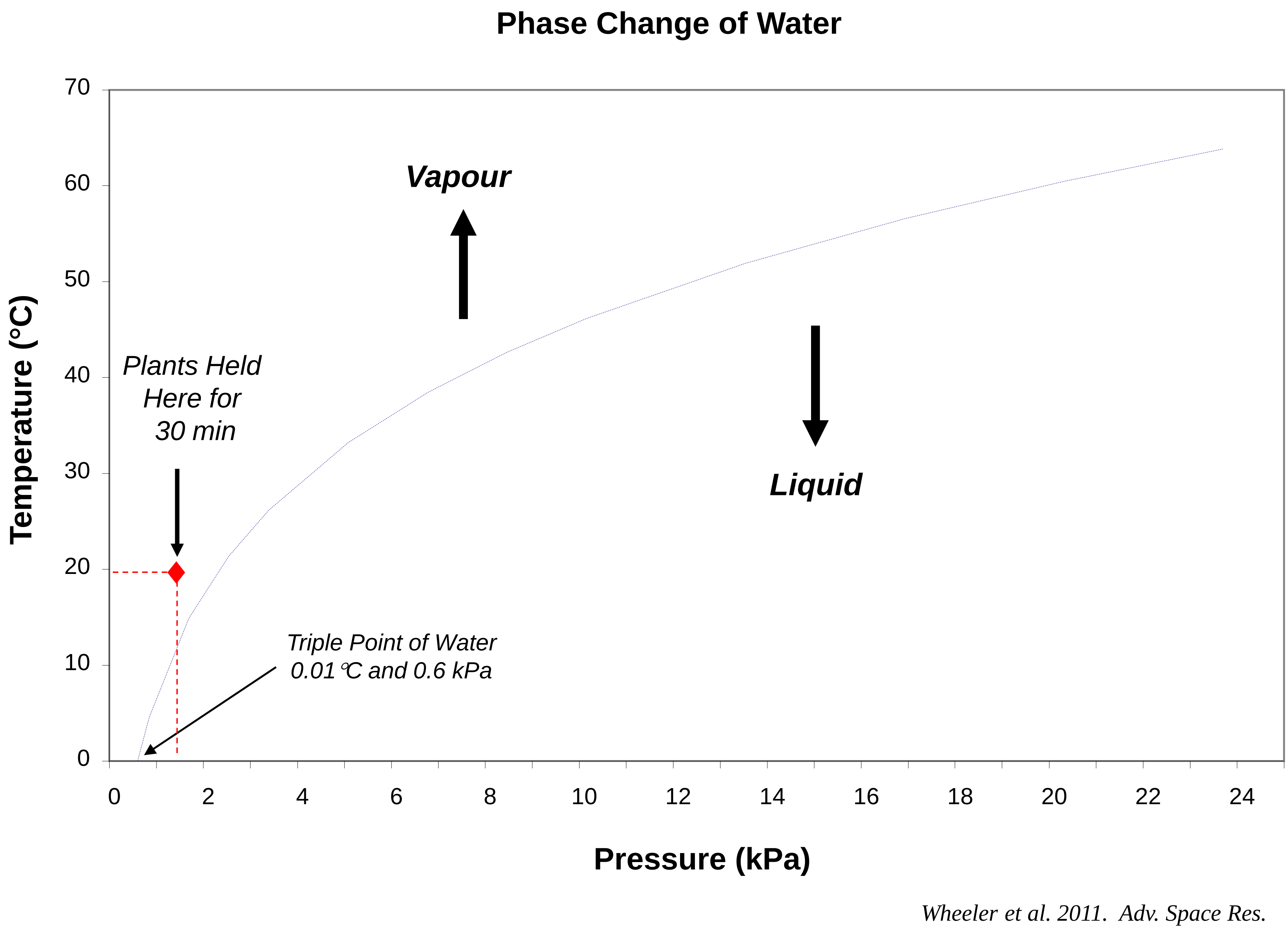
Some Collaborations Between NASA and University of Guelph







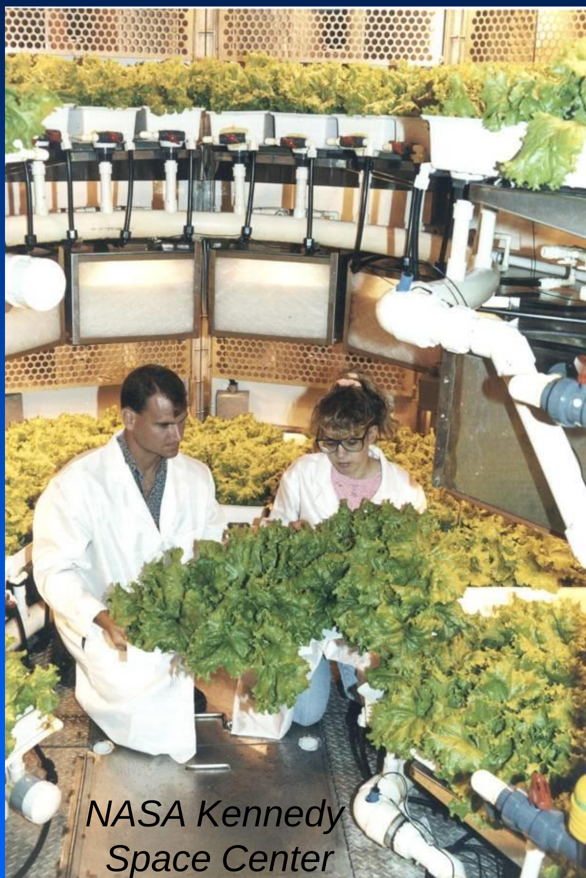
Empirical Wet Bulb Measurements versus Atmospheric Pressure
Dry Bulb Temp. = 25℃
y = 0.826 Ln(x) + 16.64
R 2 = 0.722
70% RH
y = 1.593 Ln(x) + 10.23
R 2 = 0.976
50% RH
y = 3.002 Ln(x) + 1.349
R 2 = 0.993
30% RH
Filled symbols represent our Wet Bulb measurements.
Open symbols are theoretical adiabatic saturation temperatures
from Shallcross (1997, 2005) and Ren (2004) (red triangles).
Temperature (ºC)
0
5
10
15
20
25
0
20
40
60
80
100
120
Pressure (kPa)


Phase Change of Water
Vapour
Liquid
Plants Held Here for 30 min
Triple Point of Water 0.01 ℃ and 0.6 kPa
Temperature (°C)
Pressure (kPa)
0
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16
18
20
22
24
Wheeler et al. 2011. Adv. Space Res.

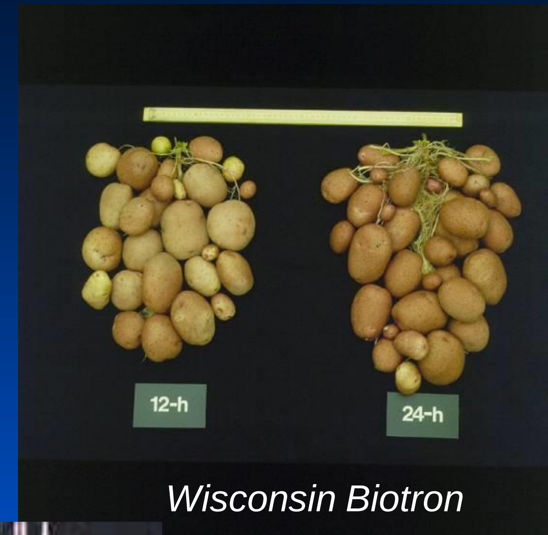
Some Lessons Learned from NASA CEA Research

- 20-25 m^2 of crops could provide all the O_2 for one person, and 40-50 m^2 all of the food (dietary calories)
- Better adapted crops are needed—short growth, high harvest index, improved nutrition
- Energy efficient lighting is key to sustaining high yields
- CEA systems require large quantities of water (e.g., 50 L m^{-2}) and this water must be recycled.
- Up to 90 kg of fertilizer would needed per person per year, emphasizing the need for recycling nutrients.
- Plants can provide psychological benefits to humans—this needs further study.
- The use of agriculture for space life support will likely evolve sequential, as mission infrastructures expand.

High Yields from NASA Sponsored Studies



Wheat - 3-4 x World Record
Potato - 2 x World Record
Lettuce-Exceeded Commercial Yield Models



Bubgee, B.G. and F.B. Salisbury. 1988. Plant Physiol. 88:869-878.
Wheeler, R.M., T.W. Tibbitts, A.H. Fitzpatrick. 1991. Crop Sci. 31:1209-1213.

Technologies from "Space" Agriculture

LEDs for growing plants--
patented through NASA
funded center at Univ.
of Wisconsin, ca. 1990

Potatoes in NFT at NASA KSC 1992, ↑
and at commercial "seed potato"
facility (Sklarczyk Farms, MI) 2016 ↓

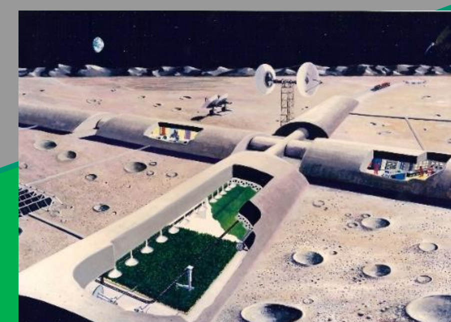
Impact of Plants on Life Support Options Depends on Mission

Short Duration Missions

Longer Durations

Autonomous Colonies

Stowage and Physico-Chemical



Bioregenerative

Supplemental Food
0.5 – 5 m^2 plant area

“More” Food, Partial O_2, CO_2 removal
5 – 25 m^2 plant area

Most Food, all O_2, all CO_2 removal
25 – 50 m^2 plant area

Wheeler. 2004 Acta Hort.

Kennedy Space Center Advanced Life Support Group 2003

One of Kennedy Space Center's Hard-Working Researchers!

Dr. Tom Graham with USDA Deputy Secretary Krysta Harden and 4-H Students