NASA's Contributions to Controlled Environment Agriculture

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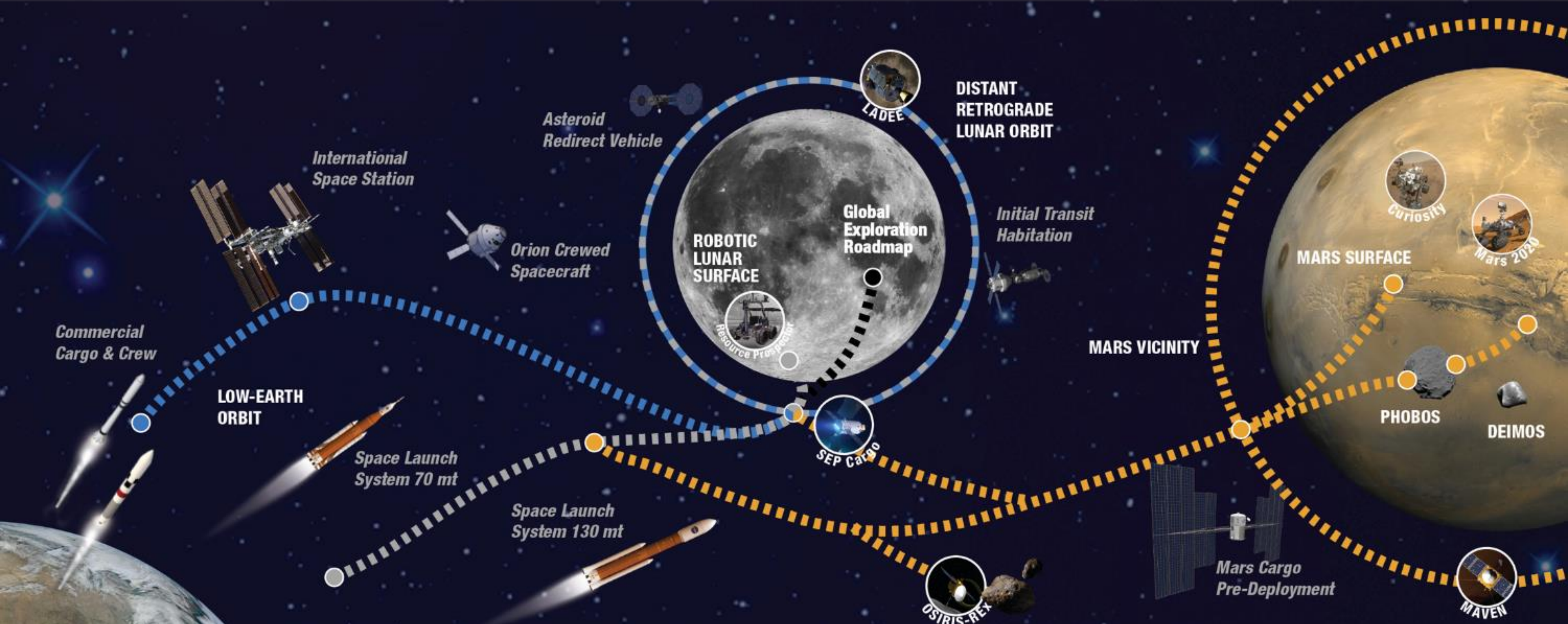
EVOLVABLE MARS CAMPAIGN

A Pioneering Approach to Exploration

EARTH RELIANT | **PROVING GROUND** | **EARTH INDEPENDENT**



THE TRADE SPACE

Across the Board | Solar Electric Propulsion • In-Situ Resource Utilization (ISRU) • Robotic Precursors • Human/Robotic Interactions • Partnership Coordination • Exploration and Science Activities

Cislunar Trades
- Deep-space testing and autonomous operations
- Extensibility to Mars
- Mars system staging/refurbishment point and trajectory analyses

Mars Vicinity Trades
- Split versus monolithic habitat
- Cargo pre-deployment
- Mars vicinity activities
- Entry descent and landing concepts
- Transportation technologies/trajectory analyses

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

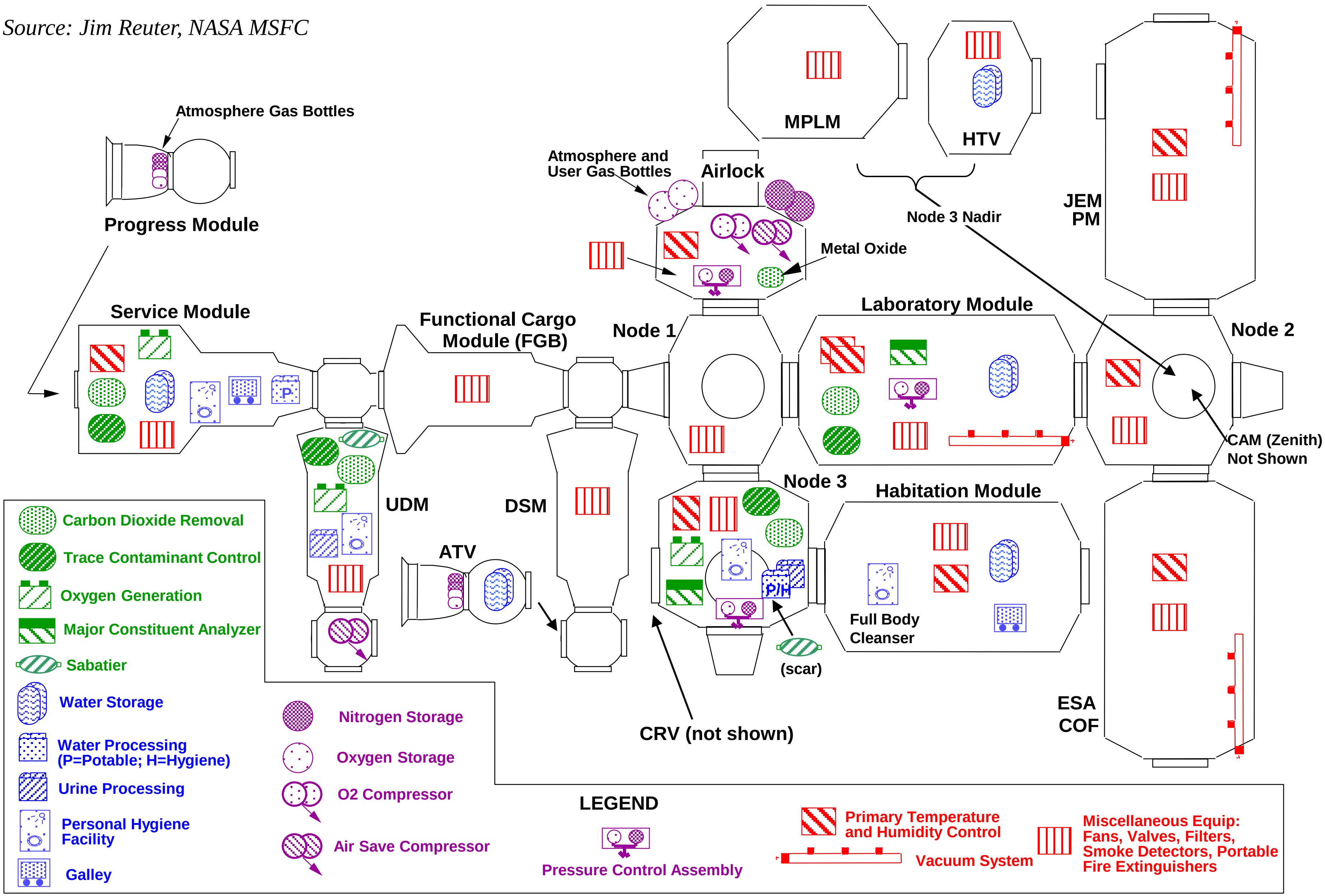
	Daily	(% total mass)
Carbon dioxide	1.00 kg	3.2%
Metabolic solids	0.11 kg	0.35%
Water	29.95 kg	96.5%
(metabolic / urine		12.3%)
(hygiene / flush		24.7%)
(laundry / dish		55.7%)
(latent		3.6%)

TOTAL 31.0 kg

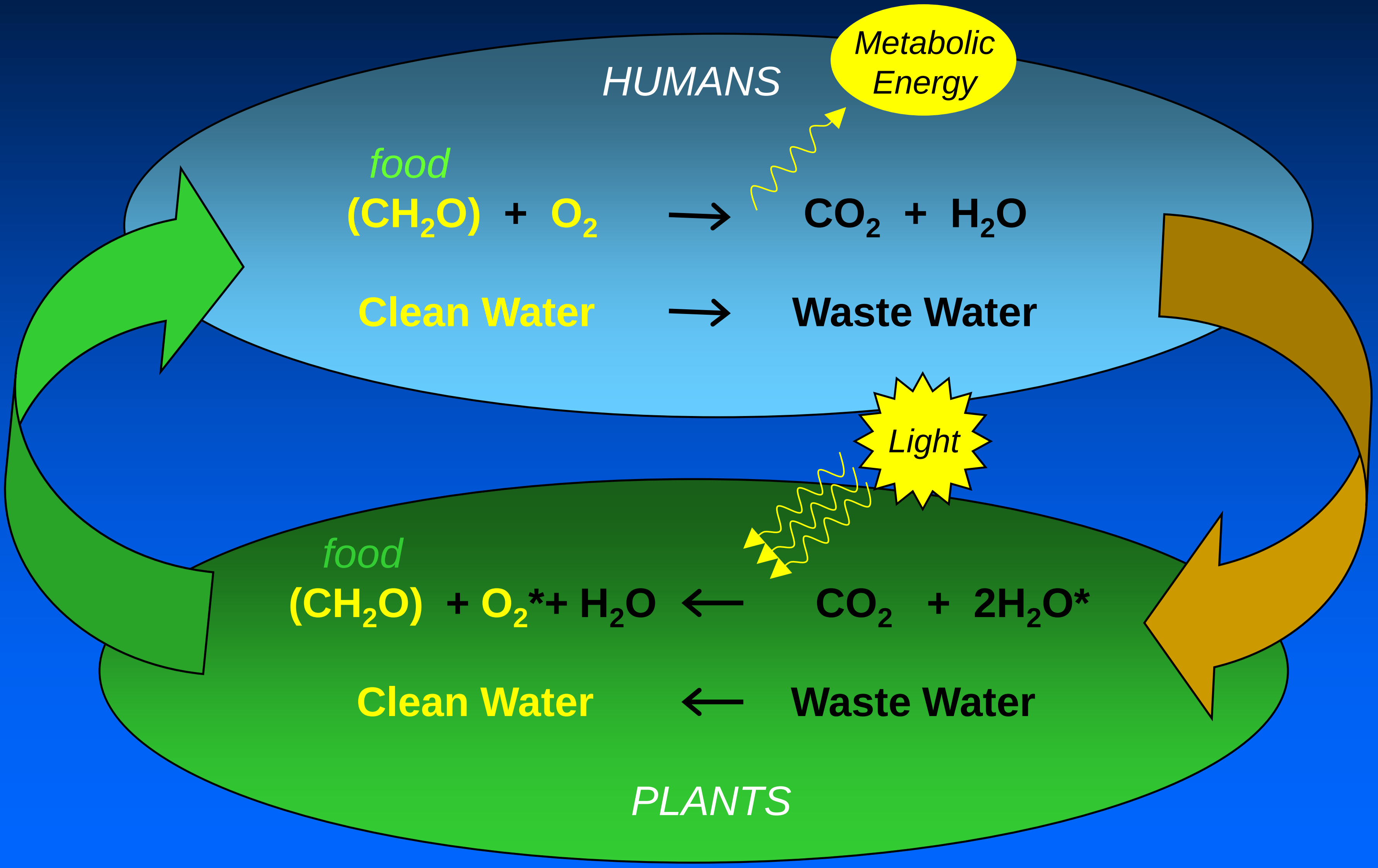
Source: NASA SPP 30262 Space Station ECLSS Architectural Control Document
Food assumed to be dry except for chemically-bound water.

International Space Station Life Support Systems

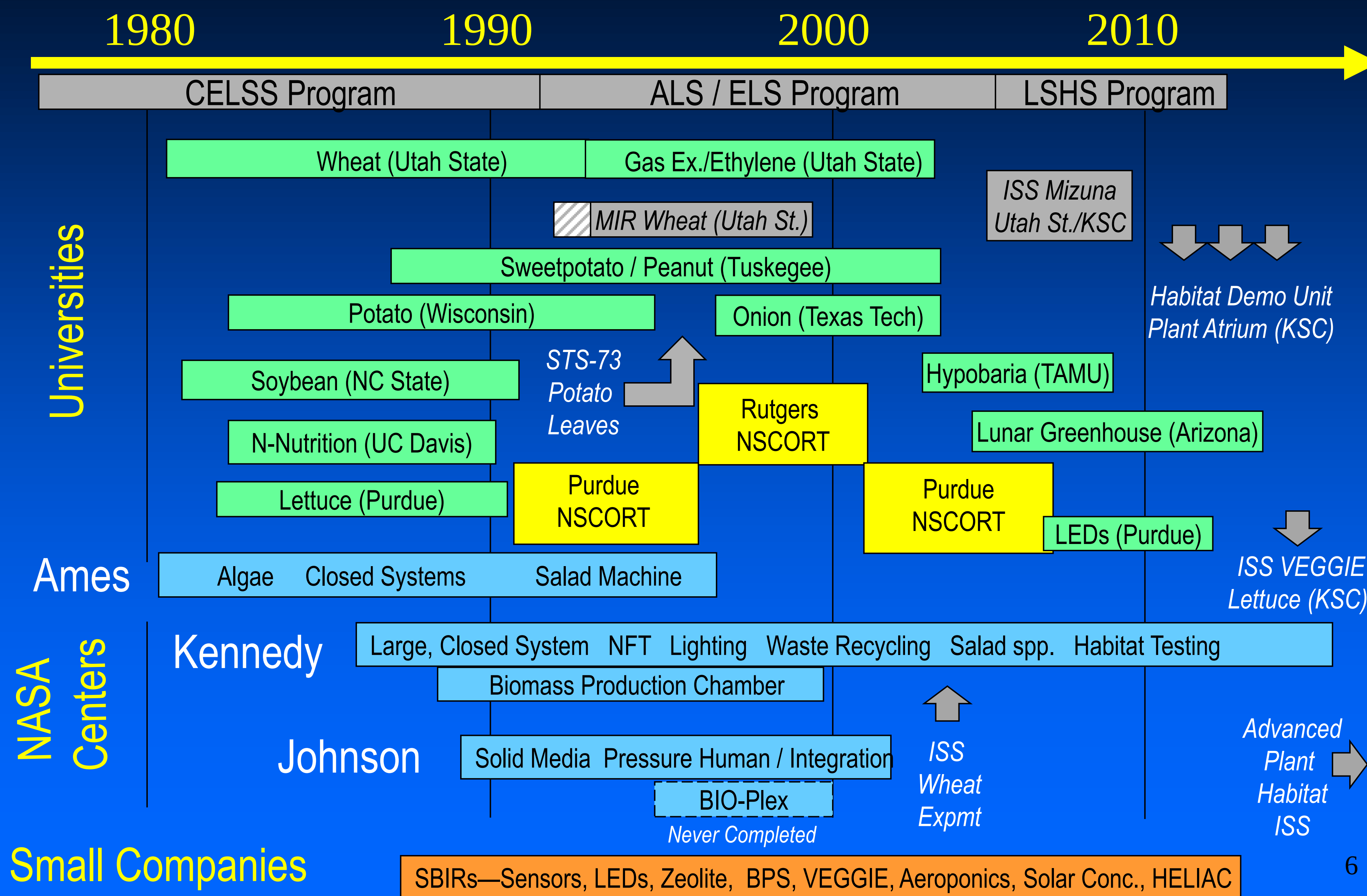
Source: Jim Reuter, NASA MSFC



Plants for Life Support !



NASA's Bioregenerative Life Support Testing



Crop Considerations for Space

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

Some Crops for Life Support

Tibbitts and Alford [a]	Hoff, Howe, and Mitchell [b]	Salisbury and Clark [c]	Crops Used in BIOS-3 Testing [d]
Wheat	Wheat	Wheat	Wheat
Soybean	Potato	Rice	Potato
Potato	Soybean	Sweetpotato	Carrot
Lettuce	Rice	Broccoli	Radish
Sweetpotato	Peanut	Kale	Beet
Peanut	Dry Bean	Lettuce	Nut Sedge
Rice	Tomato	Carrot	Onion
Sugar Beet	Carrot	Rape Seed (Canola)	Cabbage
Pea	Chard	Soybean	Tomato
Taro	Cabbage	Peanut	Pea
Winged Bean		Chickpea	Dill
Broccoli		Lentil	Cucumber
Onion		Tomato	Salad spp.
Strawberry		Onion	
		Chili Pepper	

[a] Tibbitts and Alford (1982); [b] Hoff, Howe, and Mitchell (1982); [c] Salisbury and Clark (1996);
[d] Gitelson and Okladnikov (1994)—diet also included supplemental animal protein and sugar.

Targeted Crop Selection and Breeding for Space at Utah State University

Selection of Existing Rice Genotypes

Targeted Wheat Breeding

‘Apogee’ Wheat ‘Perigee’ Wheat

Water and Nutrients for Growing Crops

Recirculating Hydroponics

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

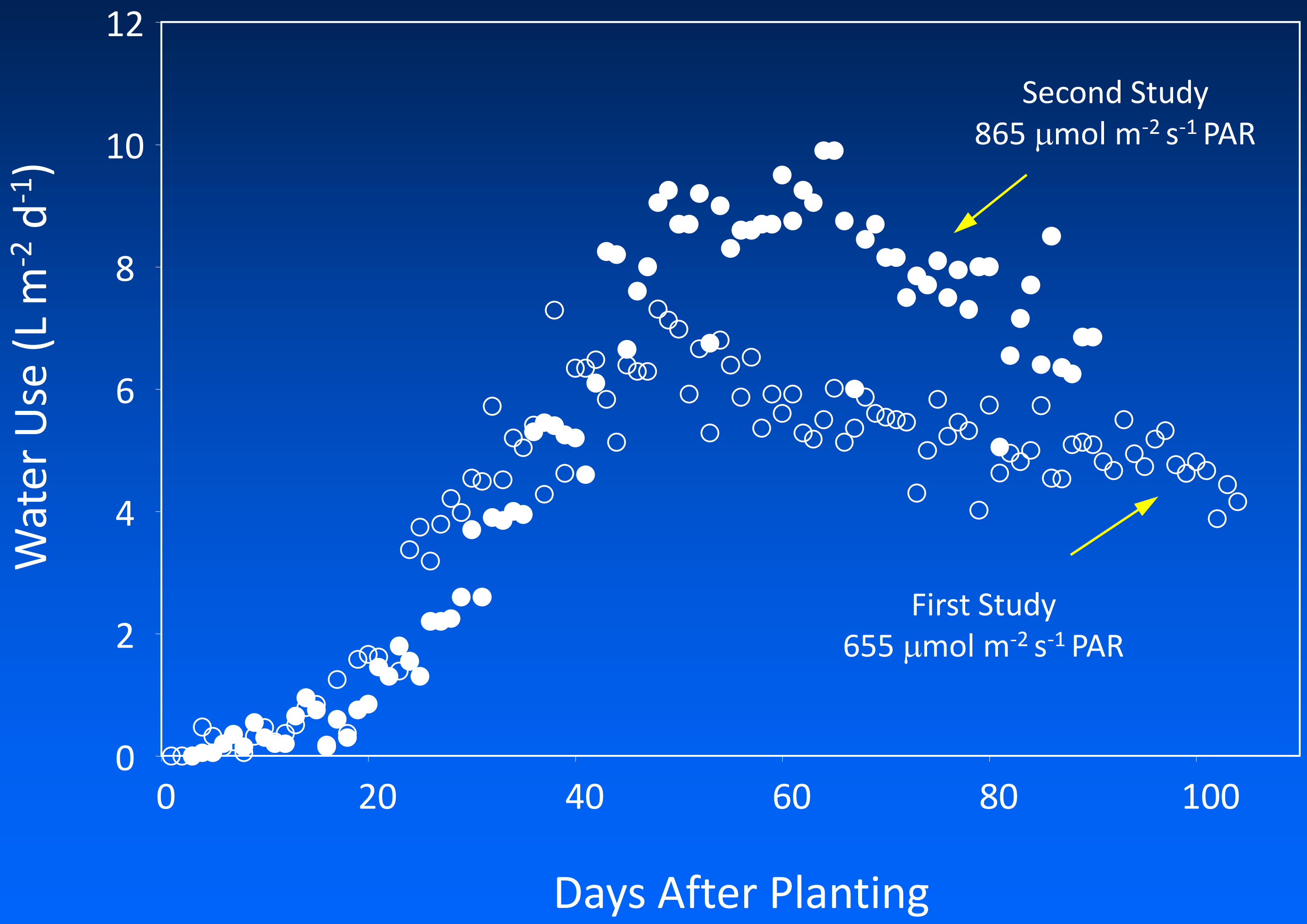
Wheeler et al., 1999. Acta Hort.

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

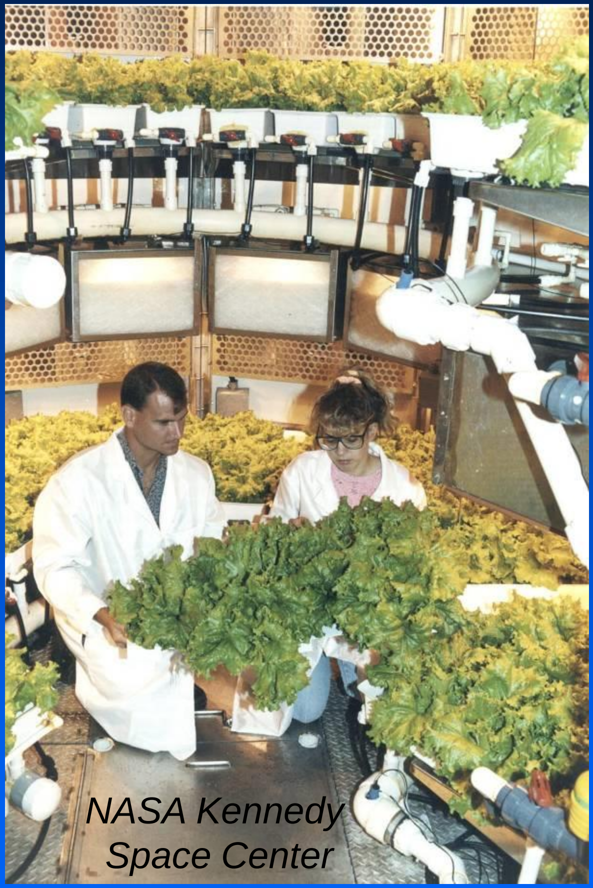
Fig. 7

Evapotranspiration from Plant Stand (potato)

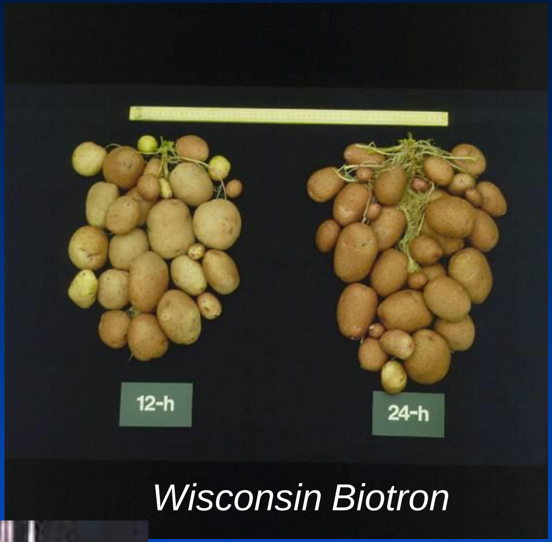


Wheeler. 2006. Potato Research 49:67-90.

High Yields from NASA Sponsored Studies



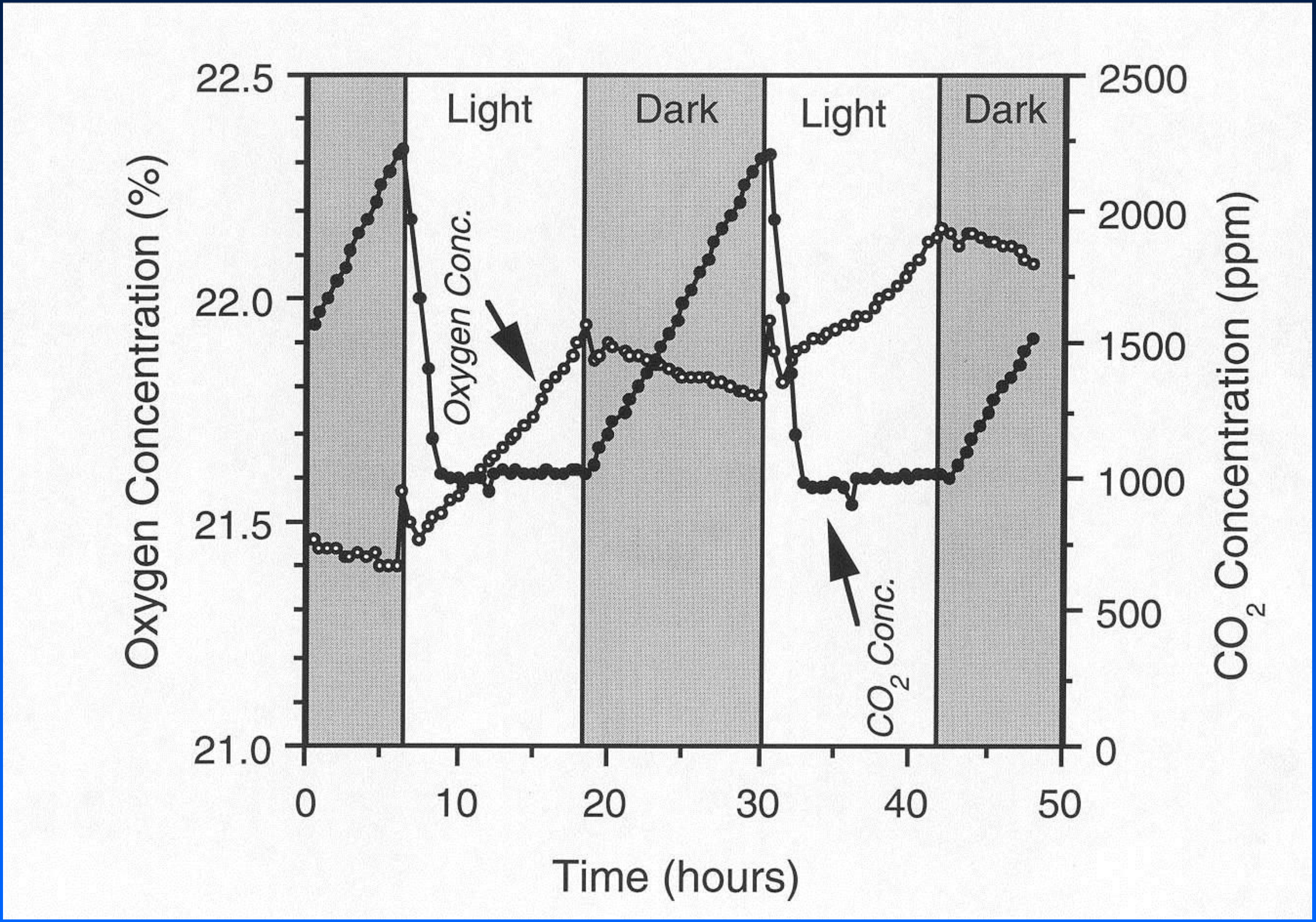
Wheat - 3-4 x World Record
Potato - 2 x World Record
Lettuce-Exceeded Commercial Yield Models



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

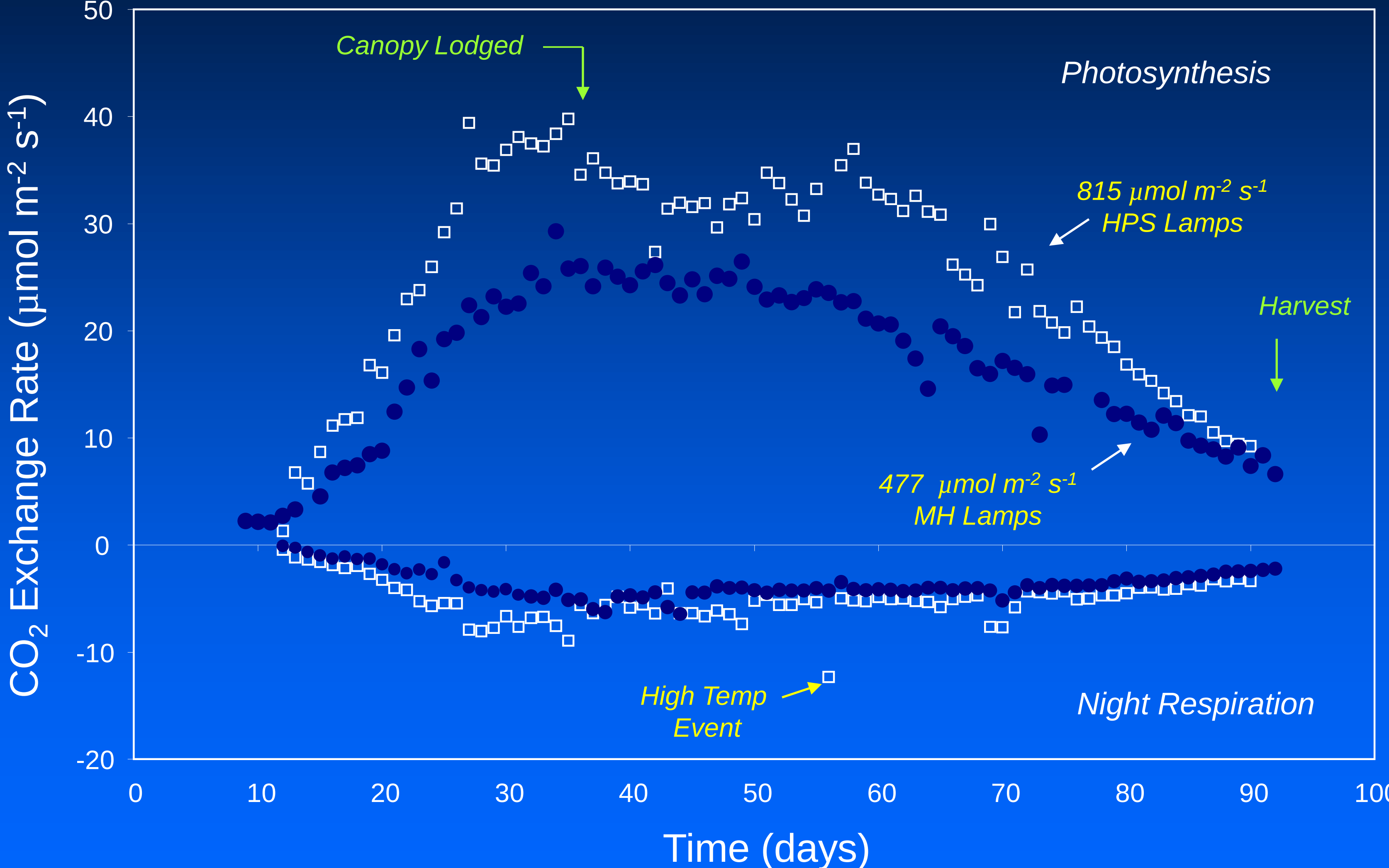
Canopy CO_2 Uptake / O_2 Production

(20 m^2 Soybean Stand)



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

CO_2 Exchange Rates of Soybean Stands



Wheeler et al., 2004. EcoEngineering.

Ethylene Gas in Closed Systems

Epinastic
Wheat Leaves
at ~120 ppb

Epinastic
Potato Leaves
at ~40 ppb

(Wheeler et al., 2004 HortScience)

NASA's Biomass Production Chamber (BPC)

Early Vertical Agriculture !

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

NASA's Biomass Production Chamber (BPC)

…an early example of a Vertical Agriculture Systems

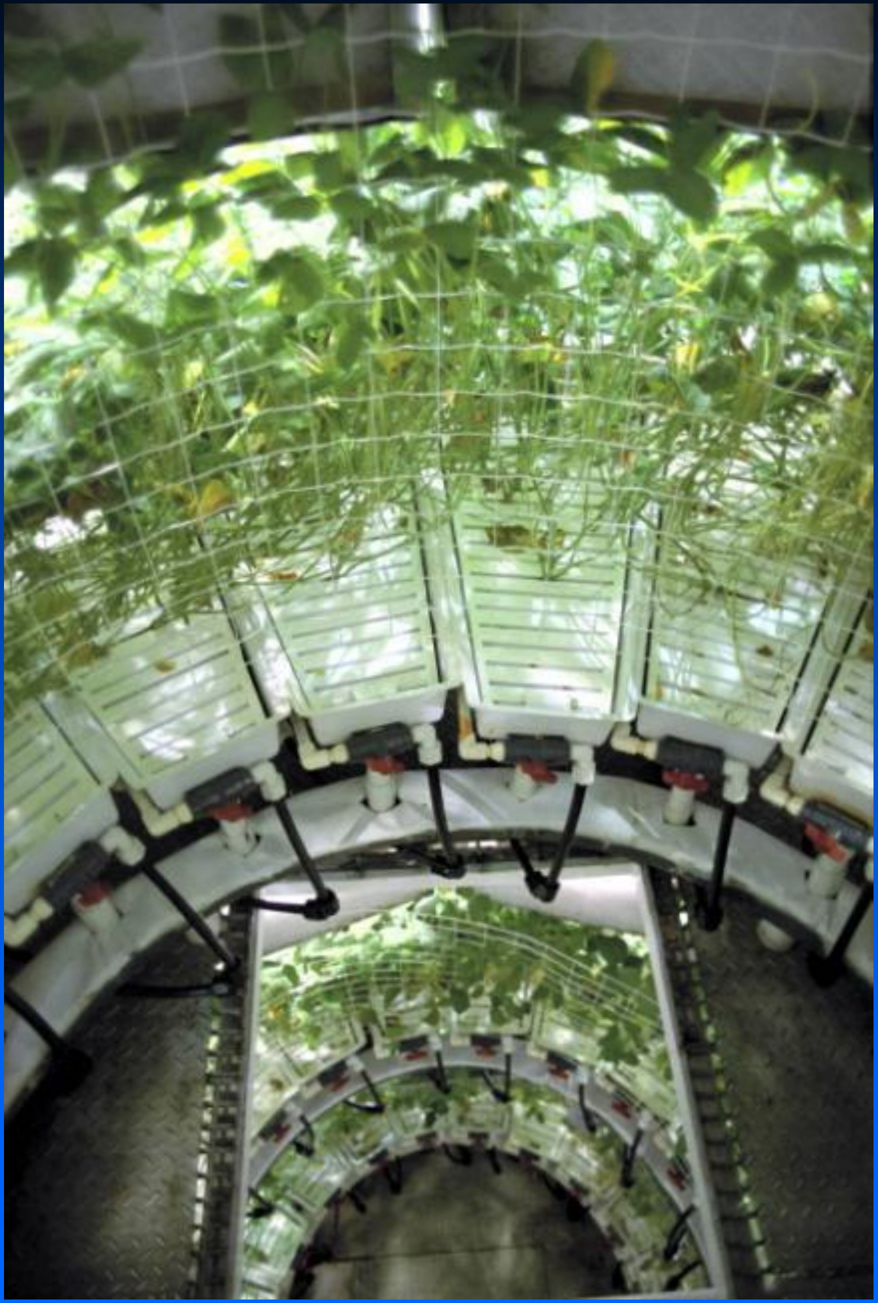
Wheat

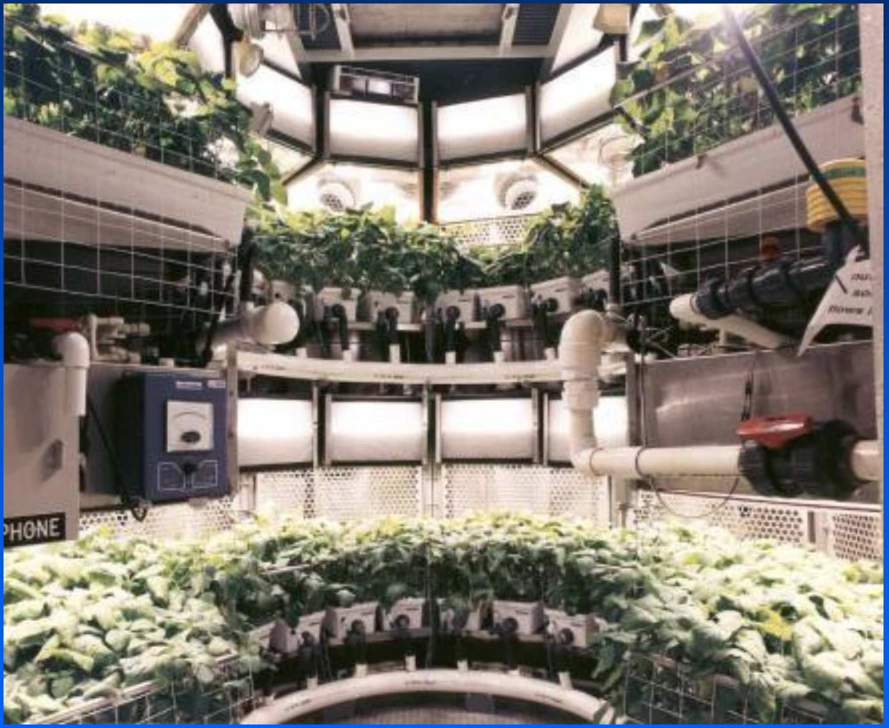
(Triticum aestivum)

planting

harvest

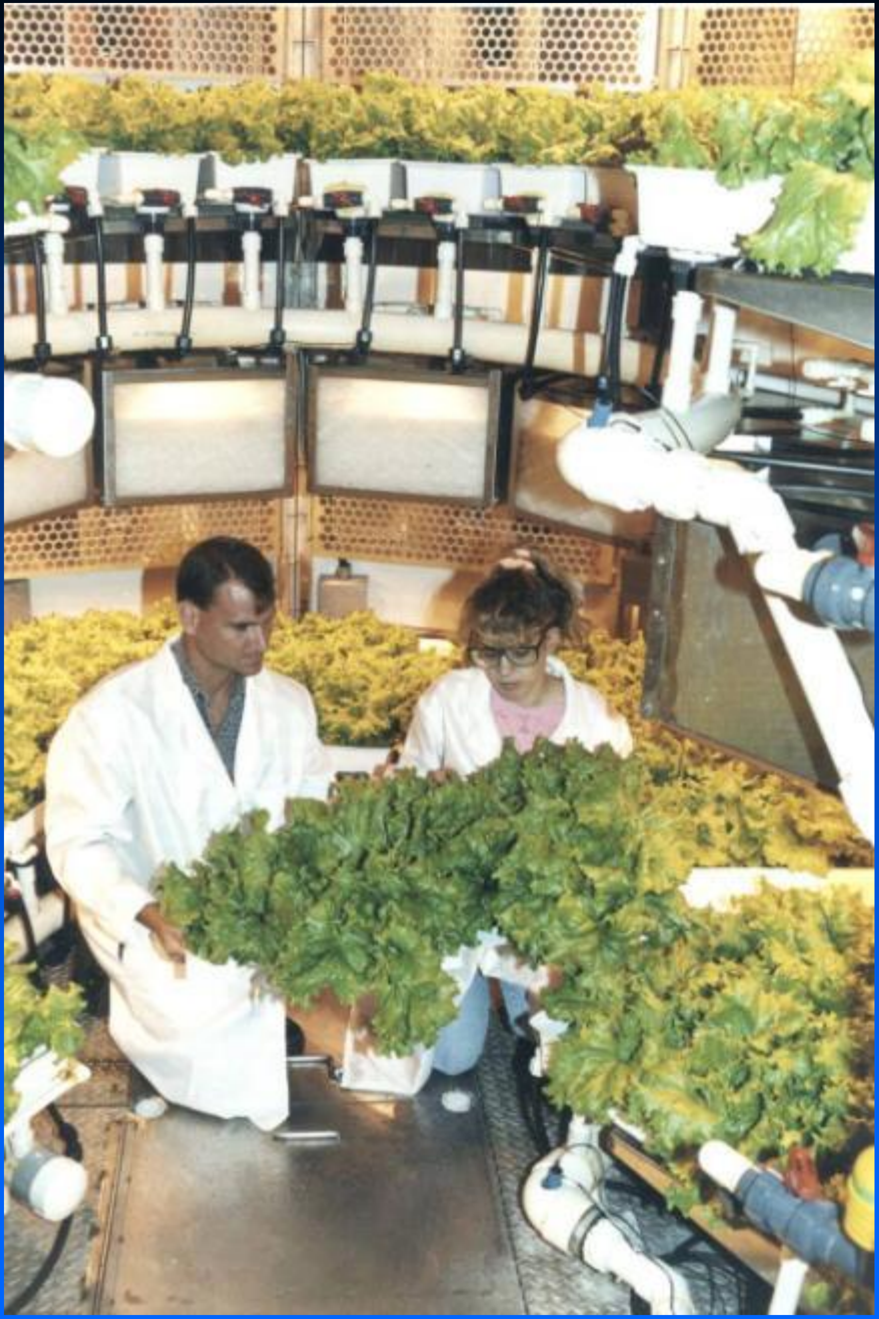
Soybean
(Glycine max)





Lettuce

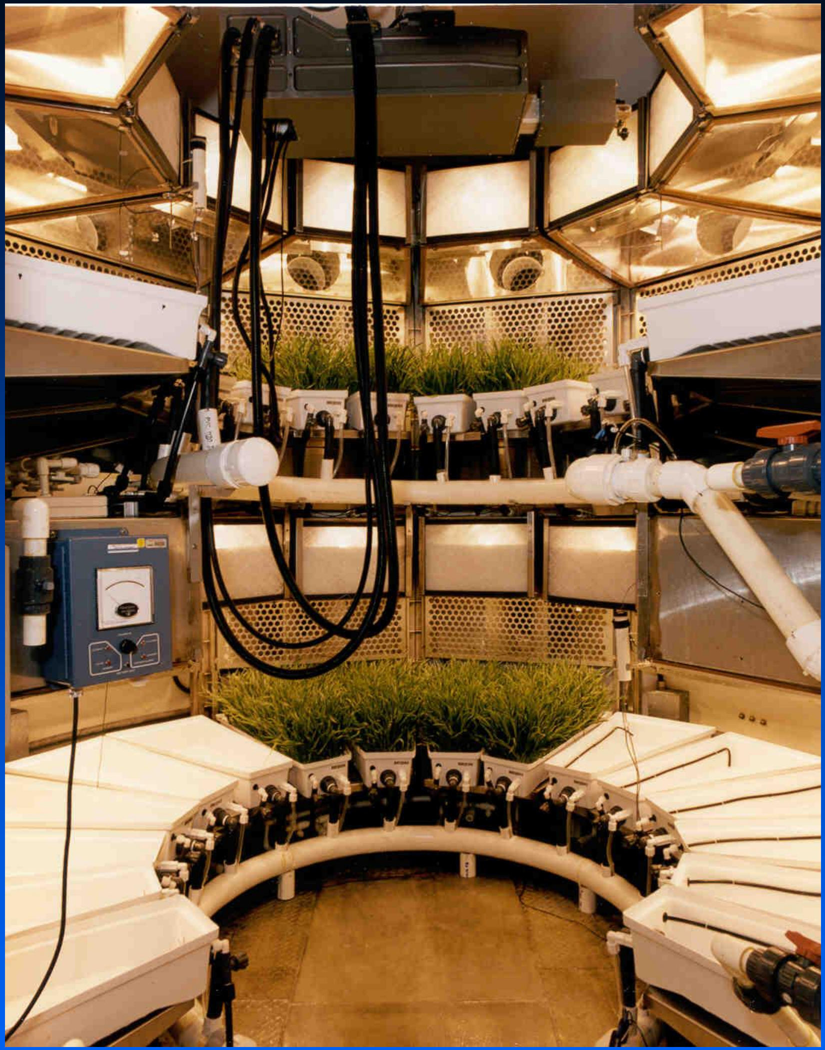
(Lactuca sativa)



Potato

(Solanum tuberosum)

Automation Technologies for CEA



ALSARM Robot in NASA Biomass Production Chamber

Electrical Power for BPC

- 96 400-W HPS lamps with dimming ballasts
- Two 30 kW blowers (400 m^3 min^{-1})
- Two 15-ton (52 kW) chillers for cooling
- 100 kW water heater for air re-heat

→ Not designed for energy efficiency!!

Electric Lamp Options for Lighting

Lamp Type	*Conversion* Efficiency*	*Lamp Life* (hrs)*	*Spectrum*
• Incandescent/Tungsten**	5-10%	2000	Intermd.
• Xenon	5-10%	2000	Broad
• Fluorescent***	20%	5,000-20,000	Broad
• Metal Halide	25%	20,000	Broad
• High Pressure Sodium	30-35%	25,000	Intermd.
• Low Pressure Sodium	35%	25,000	Narrow
• Microwave / RF Sulfur	35-40%+	?	Broad
• LEDs (red and blue)****	>40%	100,000 ?	Narrow

* *Approximate values.*

** *Tungsten halogen lamps have broader spectrum.*

*** *For VHO lamps; lower power lamps with electronic ballasts last up to ~20,000 hrs.*

**** *State-of-Art Blue and Red LEDs most efficient.*

LED Studies

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

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

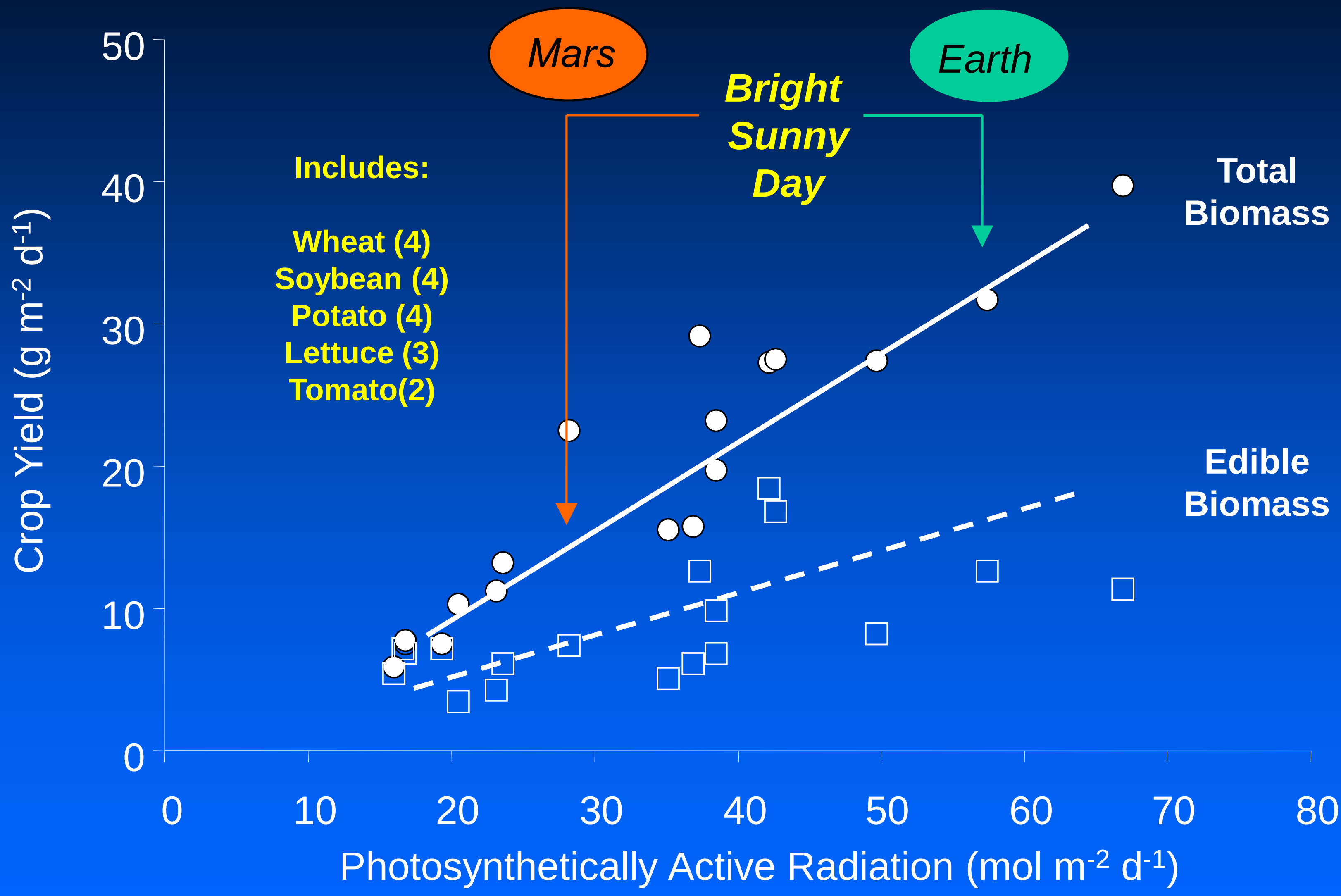
Solar Collector / Fiber Optics For Plant Lighting

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

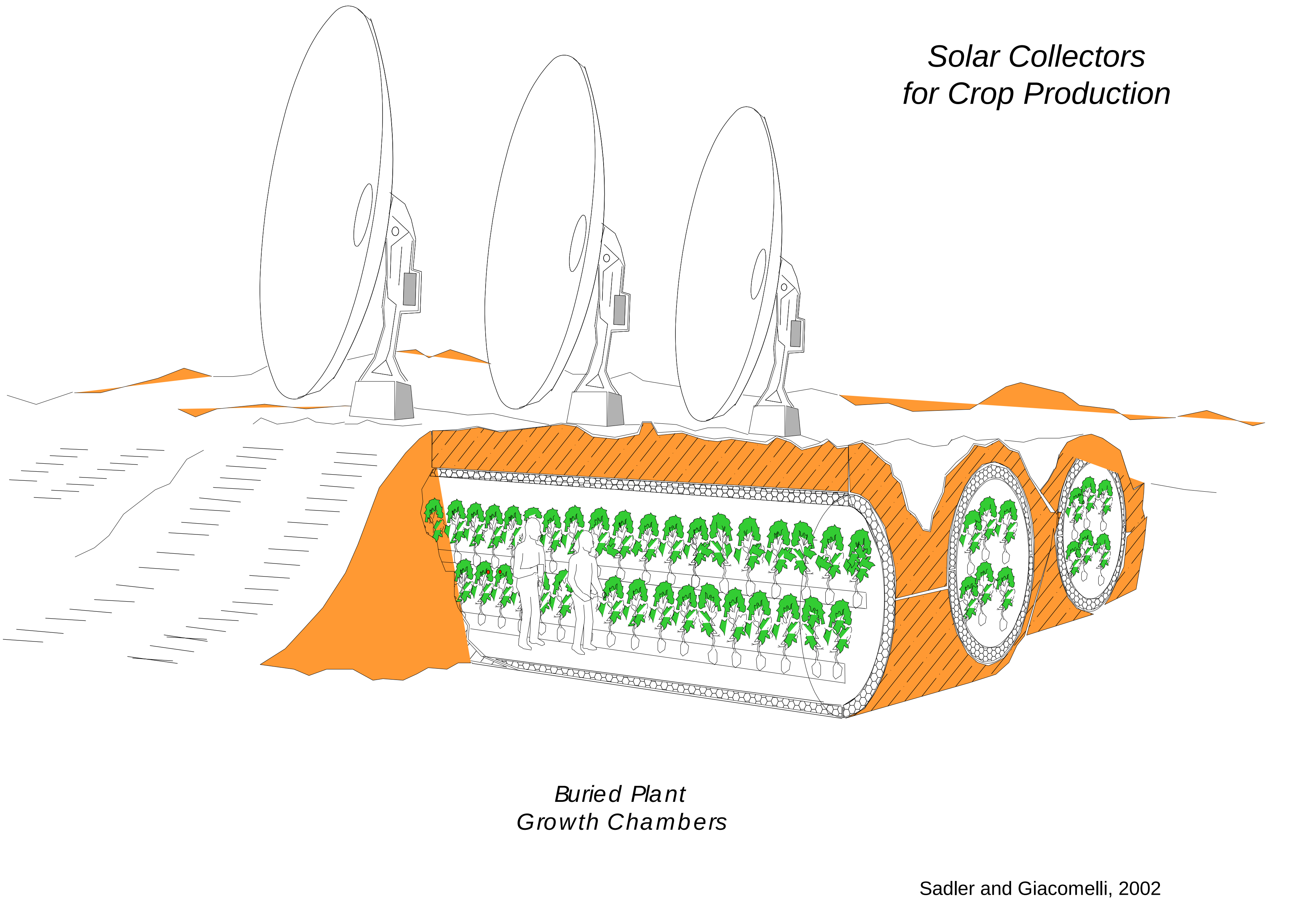
Up to 400 W light delivered to chamber (40-50% of incident light)
Takashi Nakamura, Physical Sciences Inc.

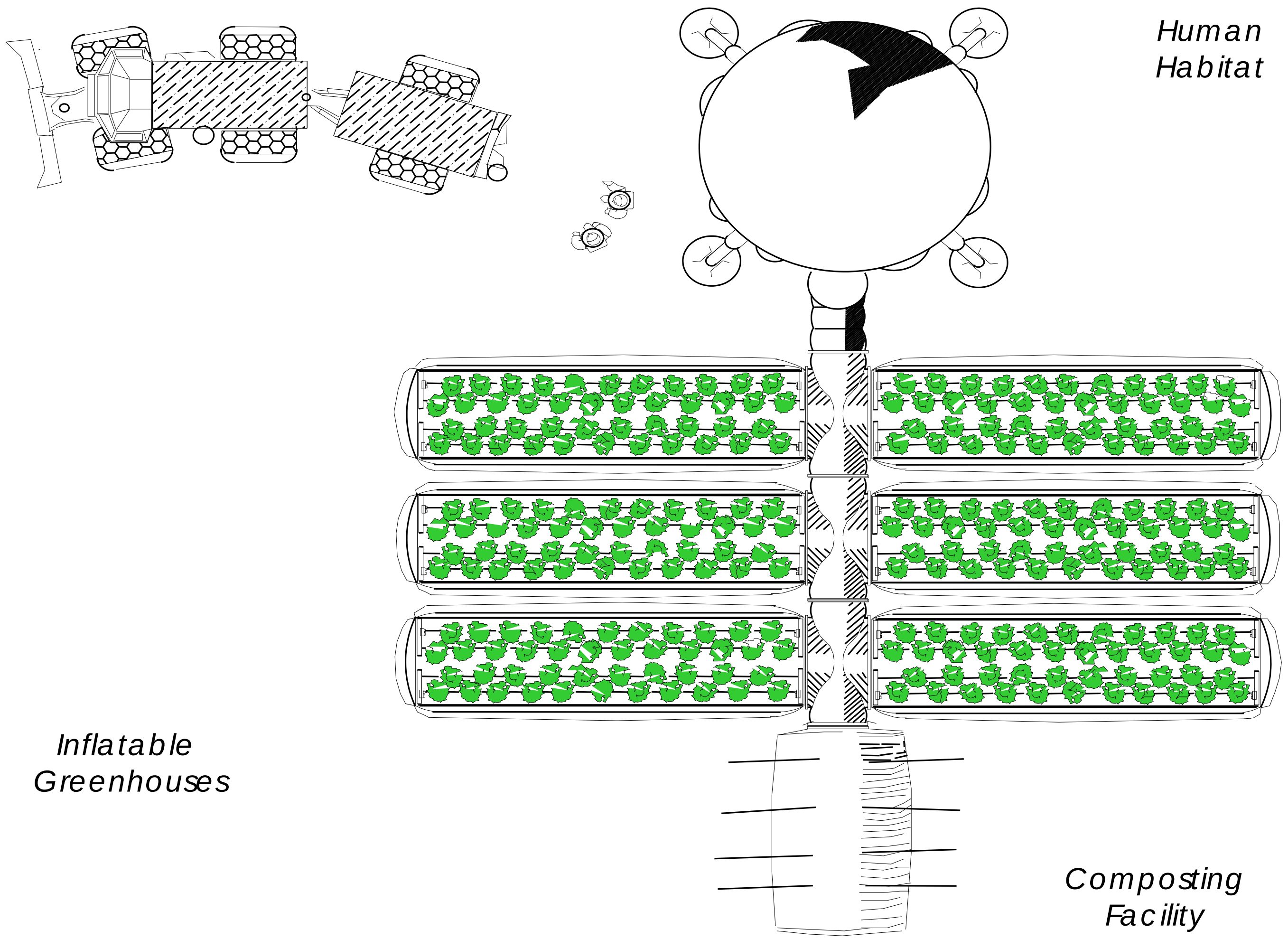
Nakamura et al. 2010. Habitation

The Importance of Light for Crop Yield



Wheeler et al. 1996. Adv. Space Res .

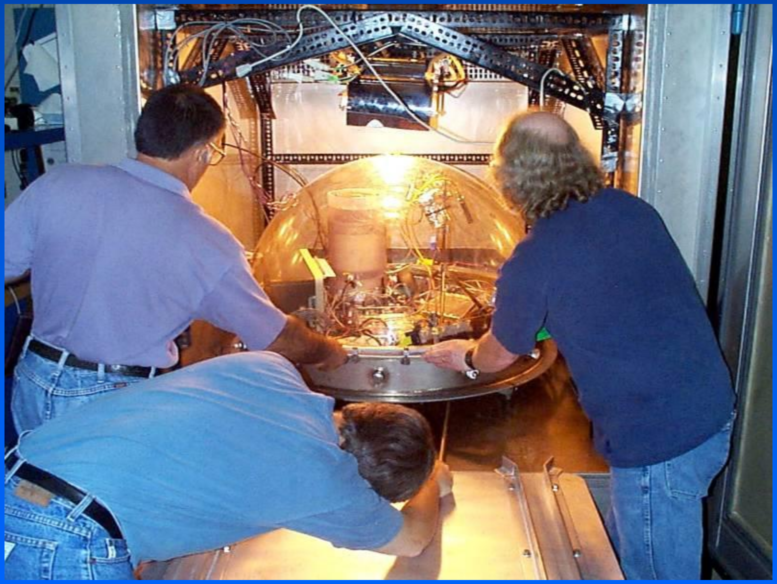

Solar Collectors
for Crop Production
Buried Plant
Growth Chambers
Sadler and Giacomelli, 2002



Sadler and Giacomelli, 2002

University of Arizona Lunar / Mars Greenhouse

Deployable Mars Greenhouse - Low Pressure Systems



Hypobaric Testing with Plants

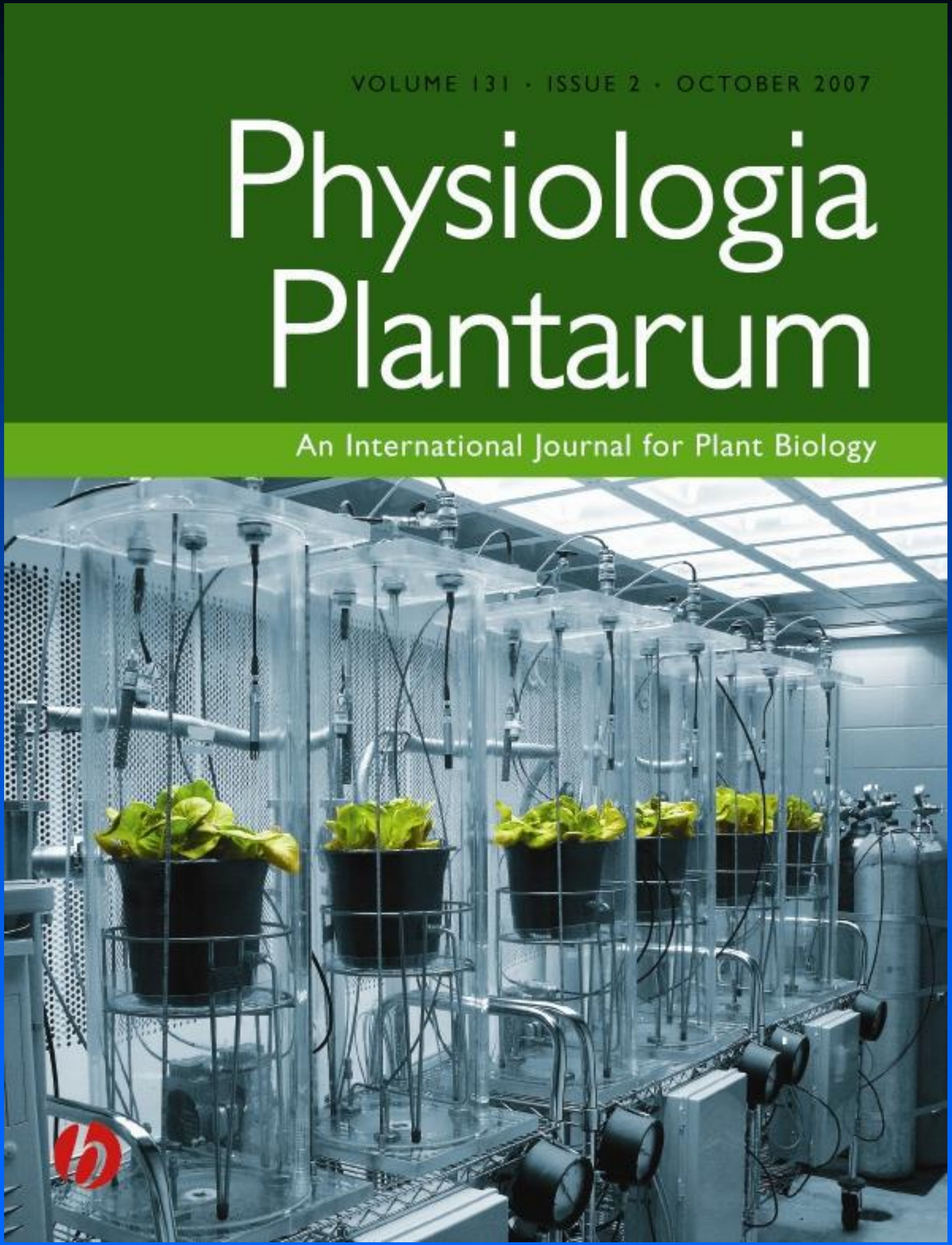
Testing at:

NASA KSC

Univ. of Guelph

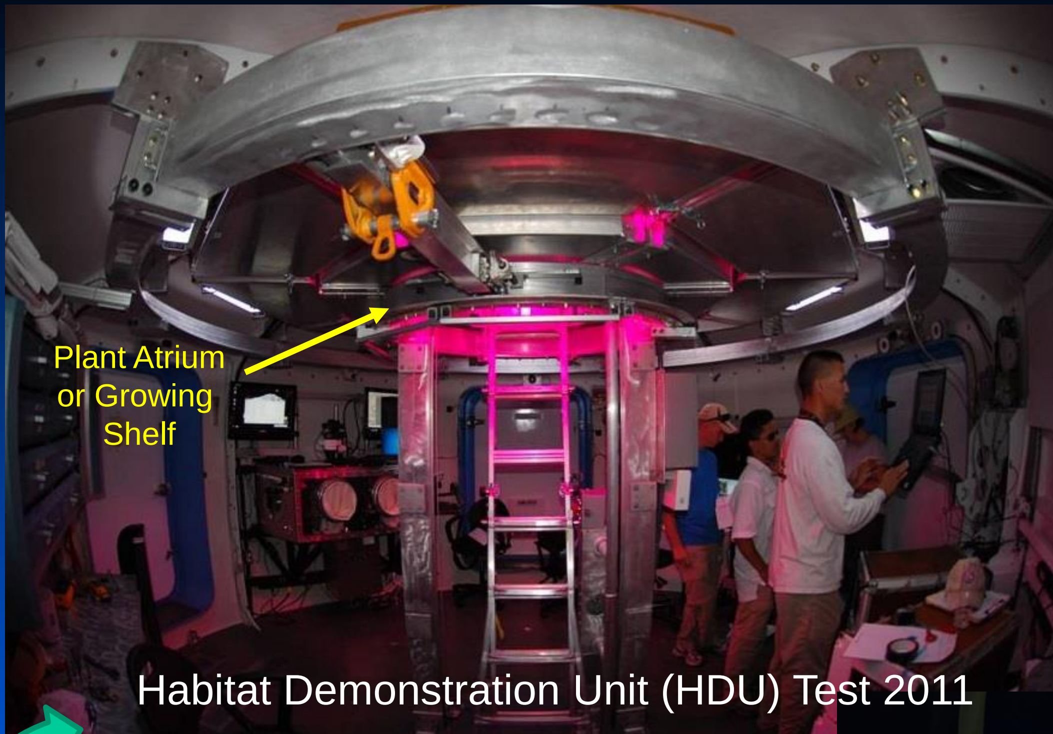
Texas A&M ⇒

Univ. of Florida



Lettuce, radish, and wheat plants exposed to rapid pressure drop (27 days old)

Human Habitats and Crops for Supplemental Food



Habitat Demonstration Unit (HDU) Test 2011

NASA's HDU at Desert Test Site


HDU Test 2012

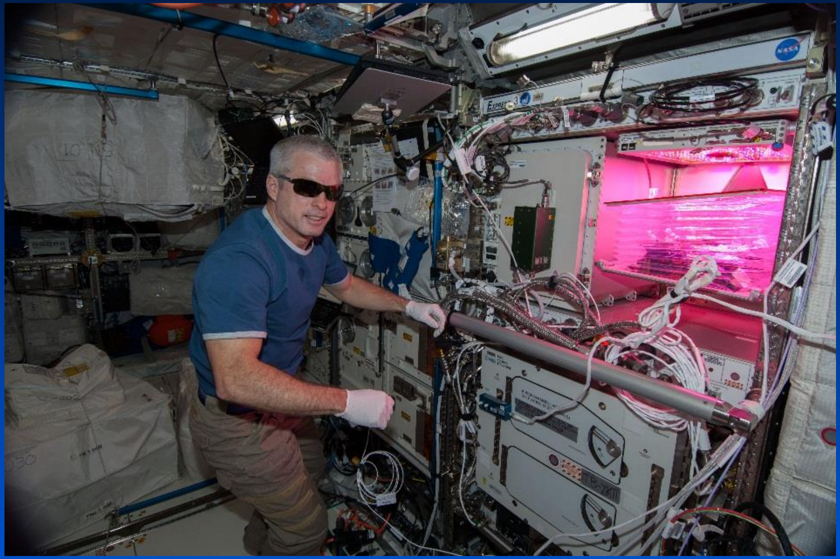
Some other Benefits of Plants in Space

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

Plant Chamber at US South Pole Station

Plants and Human Well-Being

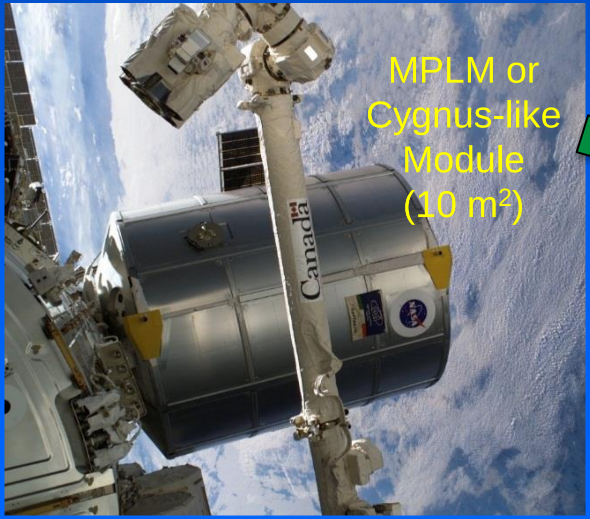
Current Plant Testing on the International Space Station—VEGGIE Plant Chamber



Genetic Engineering Tools

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

Sequential Development for Space Agriculture



Agriculture in Space

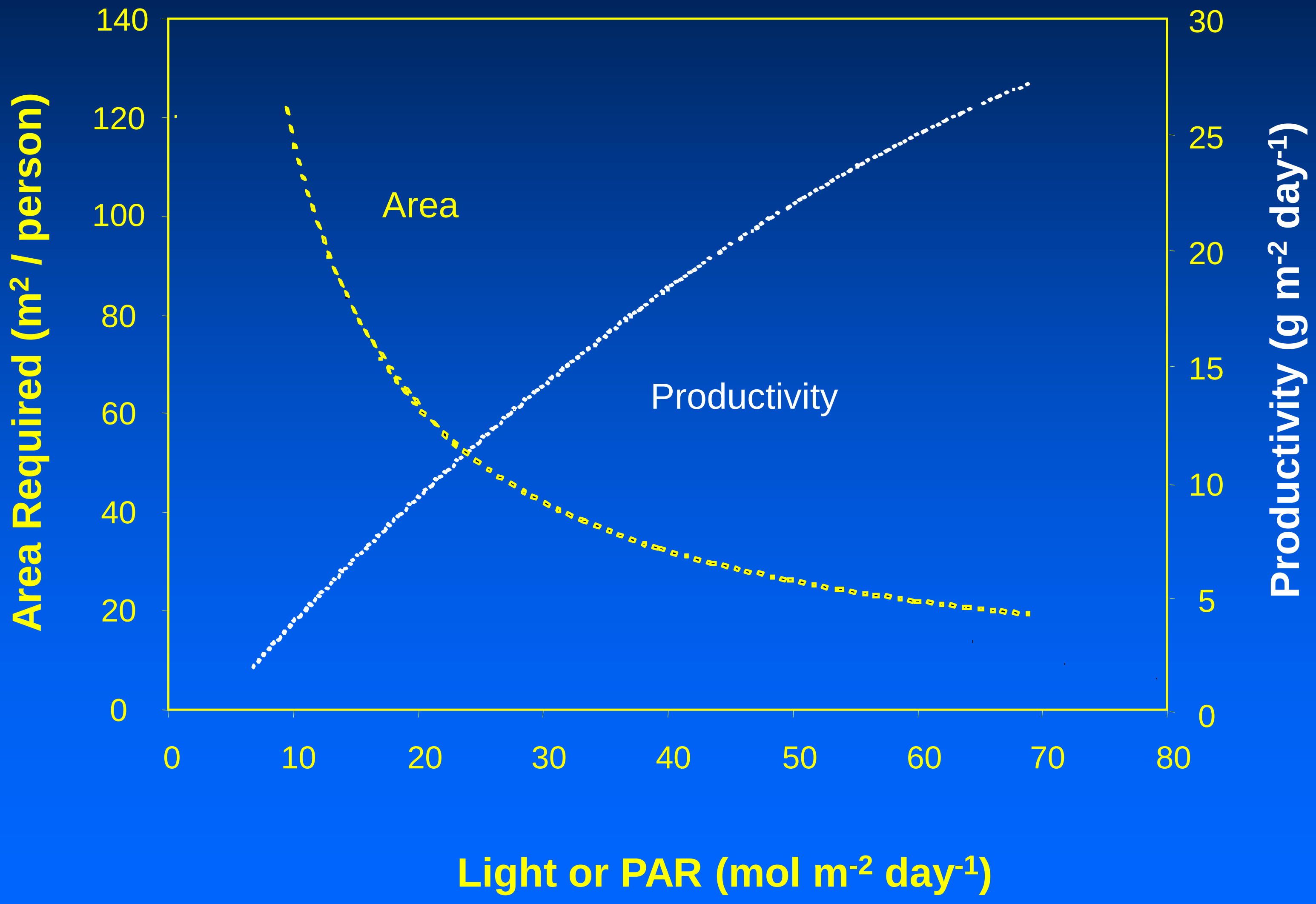
As we explore sustainable living for space, we will learn more about sustainable living on Earth

KSC Advanced Life Support Team, Hangar L, KSC 1994

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—Use genetic engineering?
- 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.

Effect of Light (PAR) on Productivity and Crop Area Requirements



Photosynthetic Radiation at Mars Surface over 2 Martian Years *(J. Clawson, 2006)*

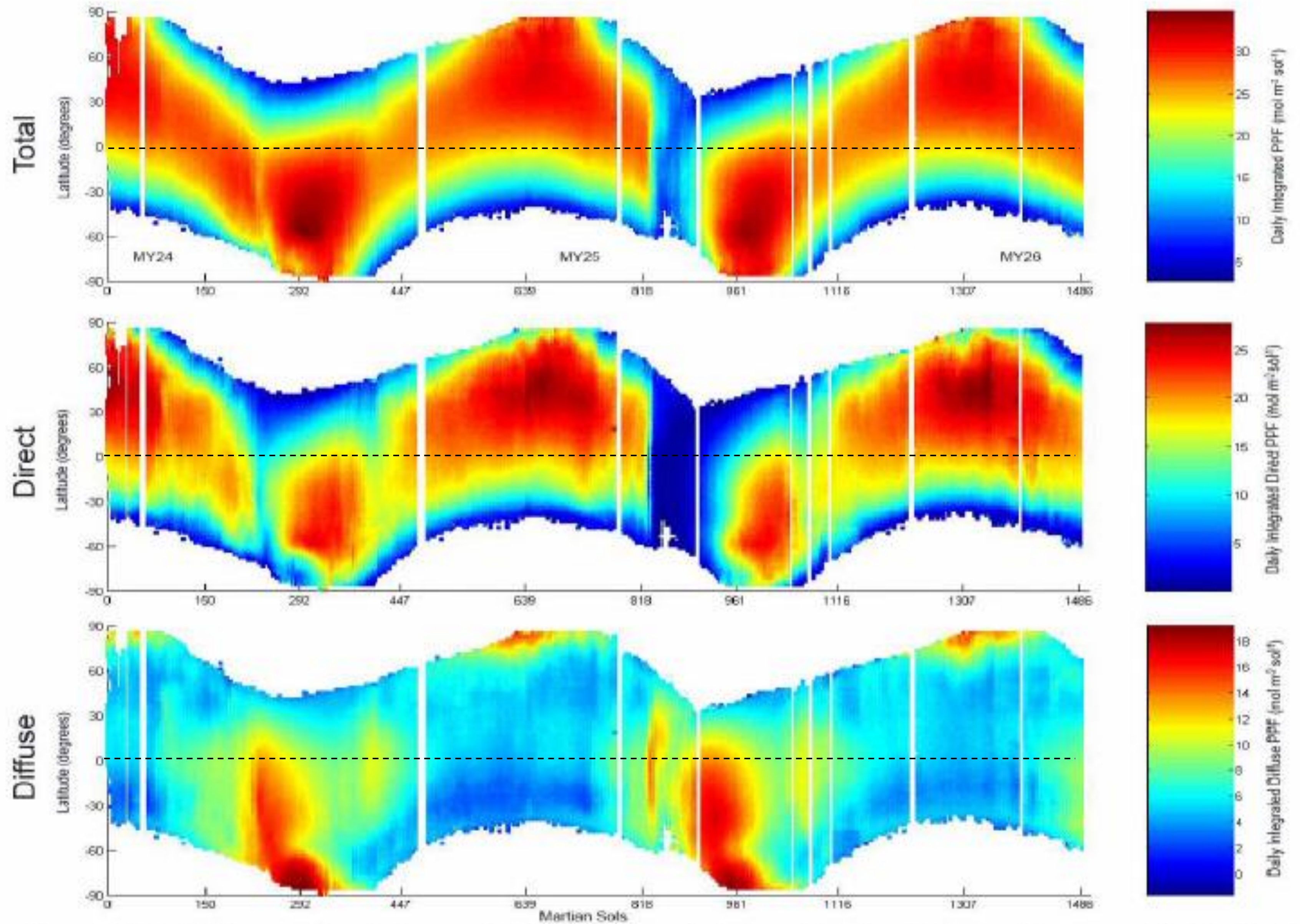
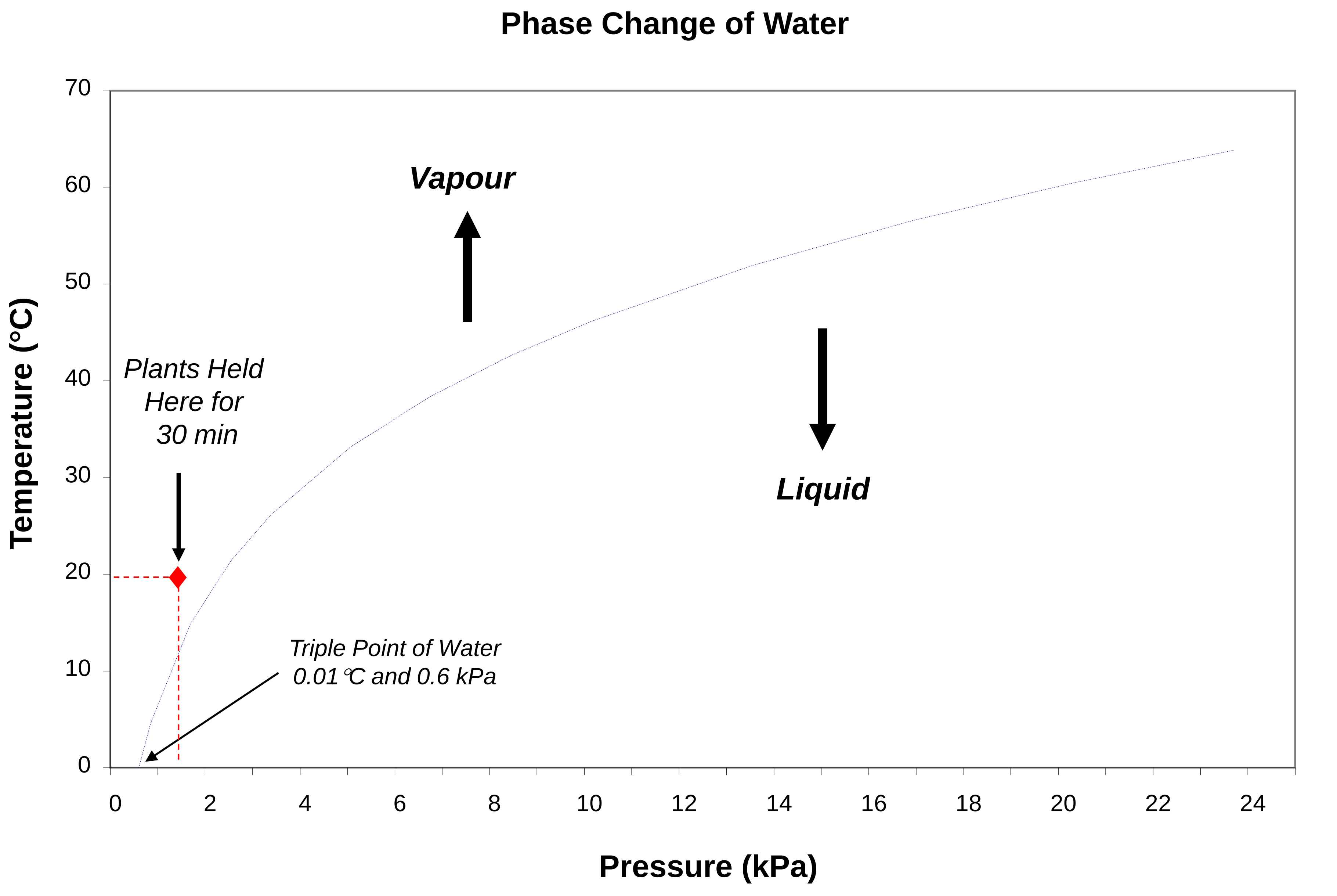


Figure 11 The daily integrated total, direct, and diffuse PPF versus latitude and Martian Sol for two Mars years. The labeled sols correspond to the start of each season on Mars. For example, sol 150 corresponds to the Northern Autumnal equinox.



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