Controlled Environment Agricultural (CEA) for Space:

Some Observations from NASA Studies

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Vertical Agriculture Workshop

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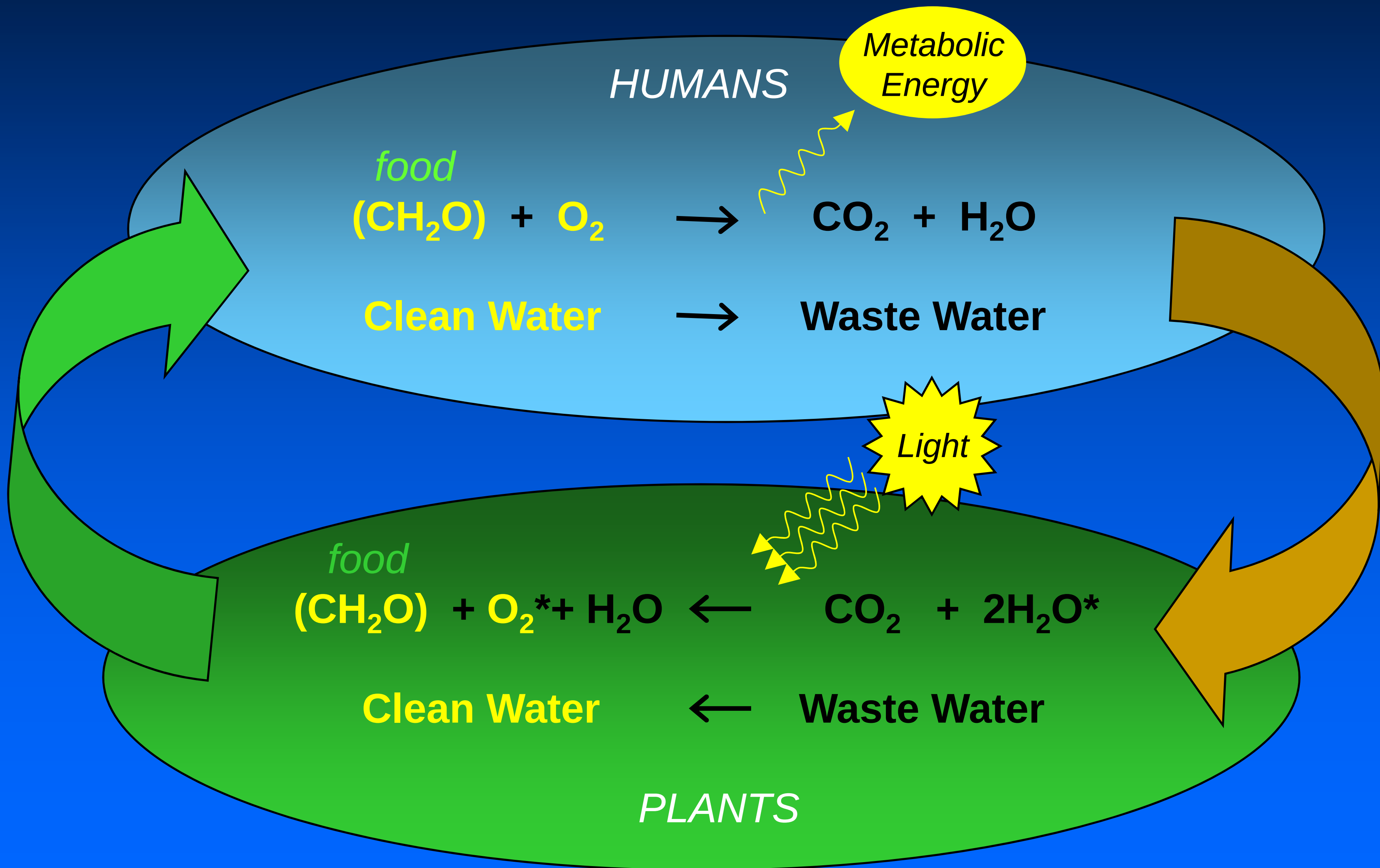
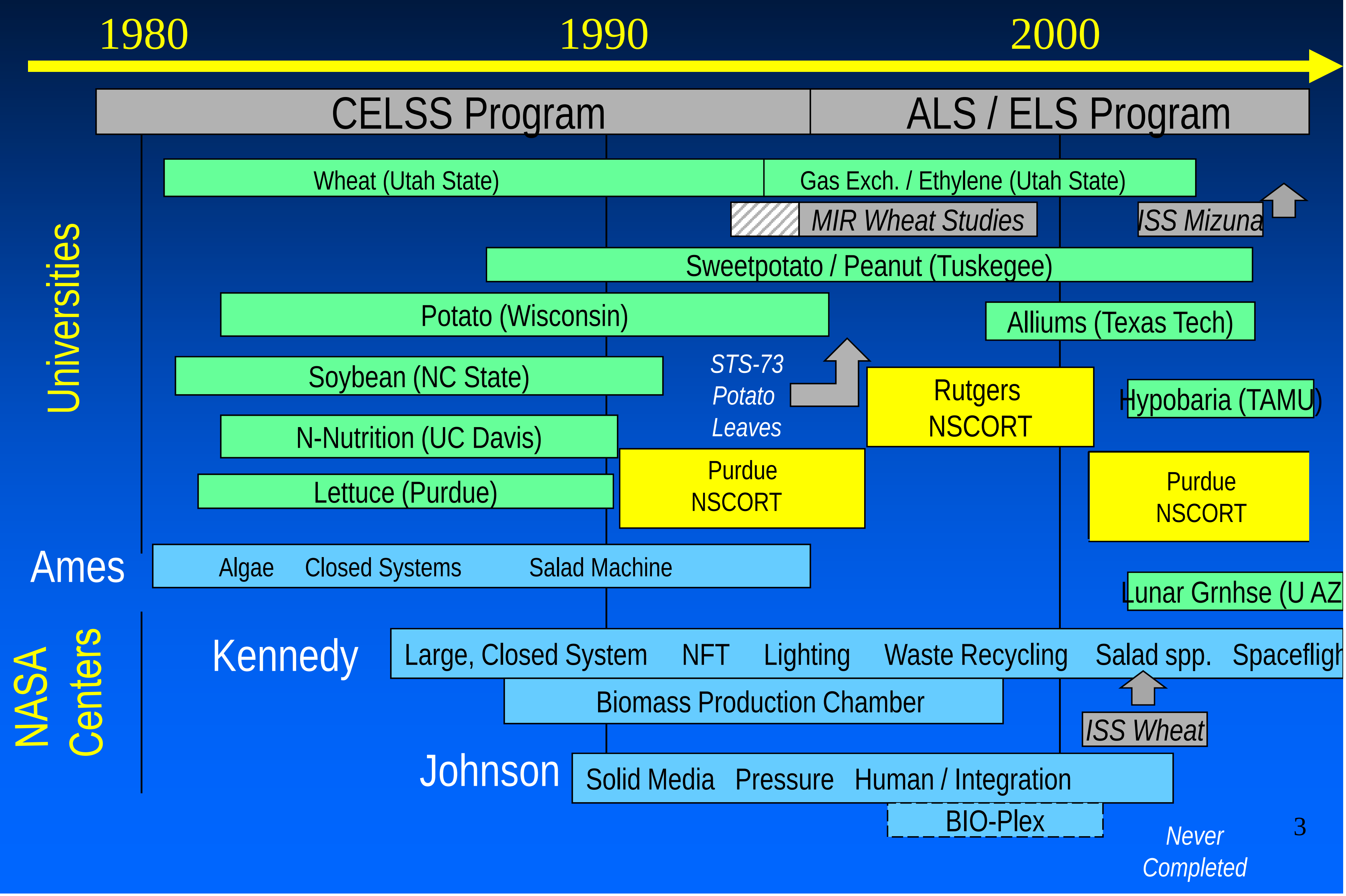
Plants for "Bioregenerative" Life Support



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, harvesting, pollination, propagation
- Environmental considerations
  - photoperiod, temperature, mineral nutrition
- Processing requirements
- Dwarf or low growing types

Recirculating Hydroponics with Crops

Wheat / Utah State

Soybean
KSC

Sweetpotato
Tuskegee

Rice / Purdue

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

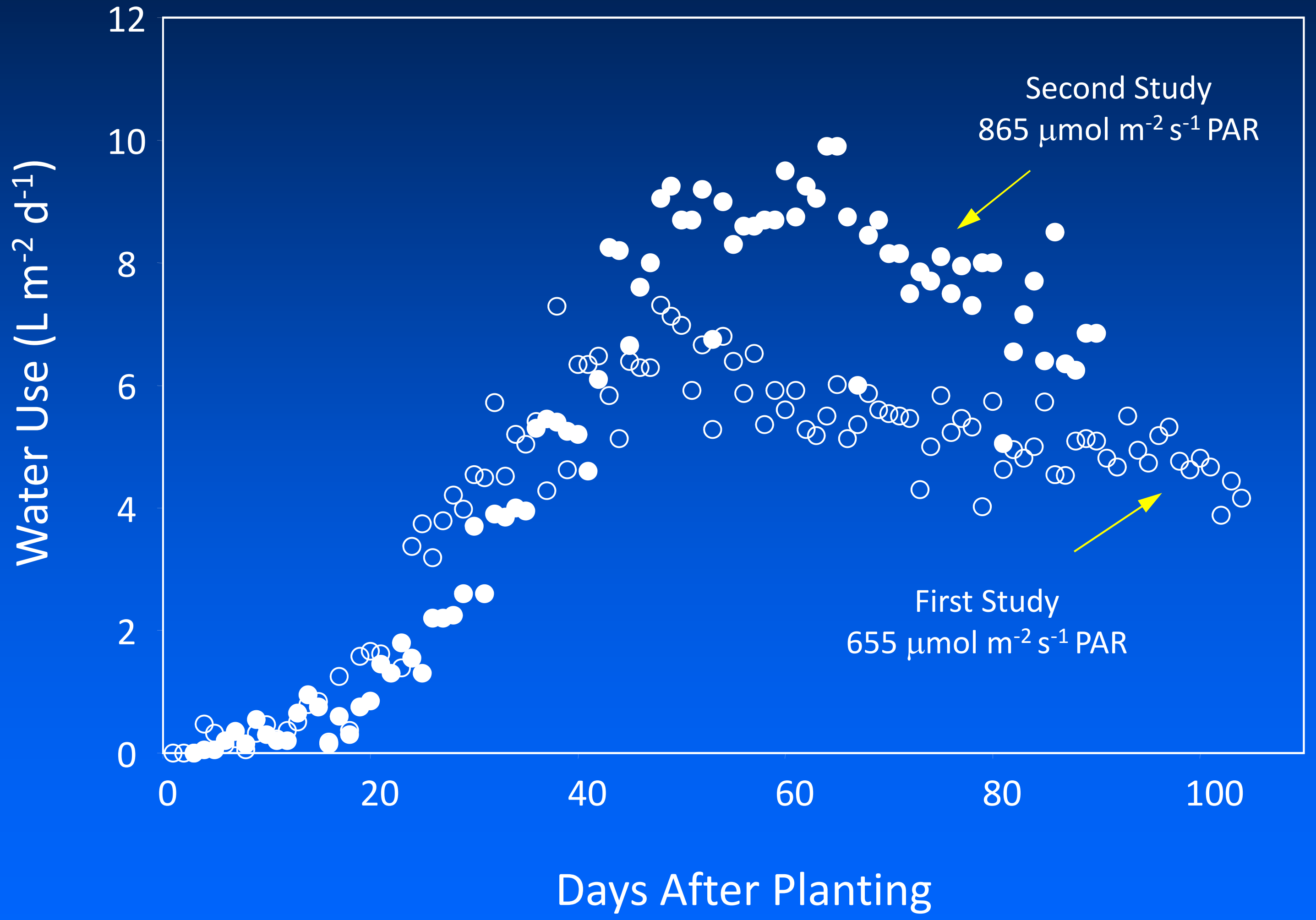
Wheeler et al., 1999. Acta Hort.

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

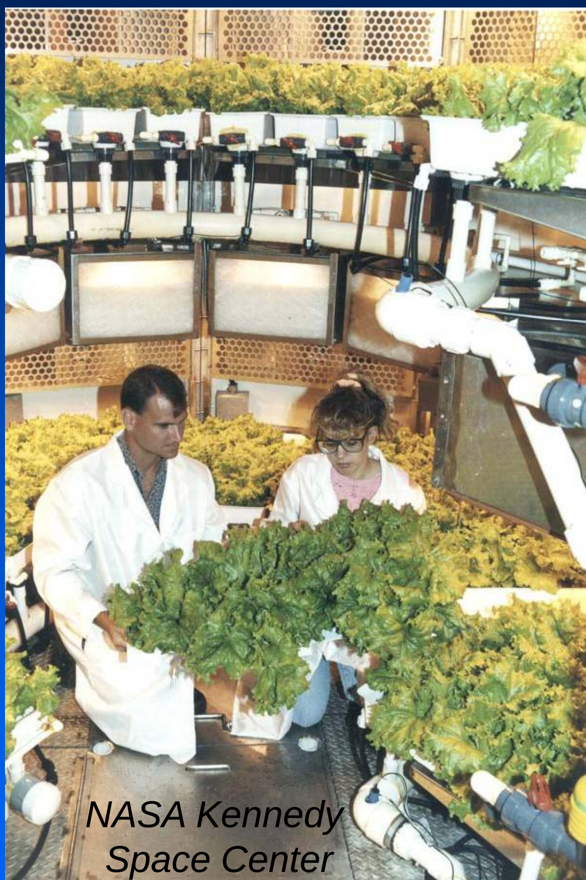
Fig. 7

Evapotranspiration from Plant Stand (potato)

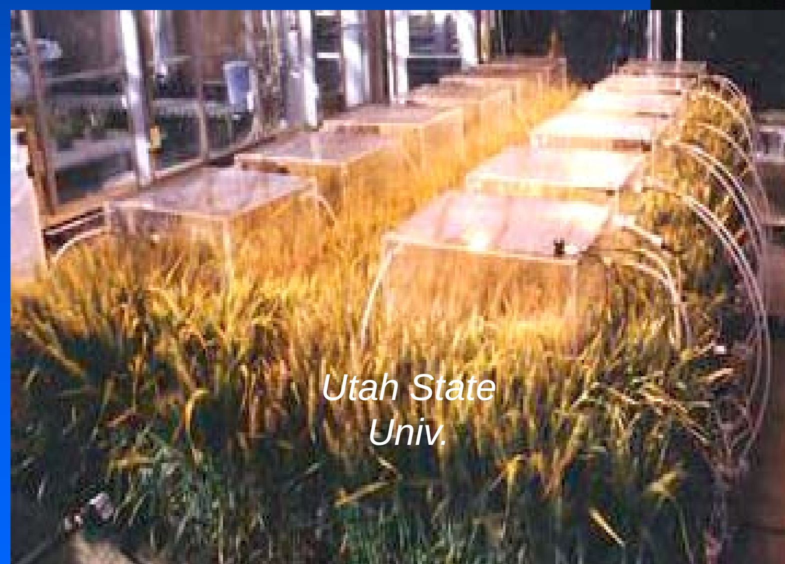


Wheeler. 2006. Potato Research 49:67-90.

High Yields from High Light and CO_2 Enrichment



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.

Potential Energy Conversion to Biomass

From Loomis and Williams. 1963. Crop Science 3:67-72

Assuming a maximum 12% conversion efficiency from PAR to biomass[1]

1.6 g dry mass / mol PAR

[1] Radmer and Kok. 1977. BioScence. Actual instantaneous conversion efficiencies of~10% reported from some controlled environment studies ; e.g., Wheeler et al. 1993. Crop Sci; Gerbaud et al. 1998. Physiol. Plant.

Some Upper Limits to Energy Conversion and Productivity

Field Crops Observations[1]

Crop	Productivity	Photosynthetic Energy Conversion Efficiency [2]
	(g DM m^{-2} d^{-1})	(%)
Tall Fescue	43	7.0 (UK)
Maize	40	6.8 (US)
Sudan Grass	52	6.0 (US)

NASA CEA Studies

Crop	Productivity	Radiation Use Efficiency
	(g DM m^{-2} d^{-1})	(g DM mol^{-1} PAR)
Wheat	61	1.44 Utah State[3]
	130	0.67 Utah State[4]
Potato (12⇨24 h photoper.)	45	0.97 Univ. Wisc.[5]
(12 h photoper. only)	38	1.15 Univ. Wisc.[5]

[1] *D.O. Hall. 1976. FEBS Letters*

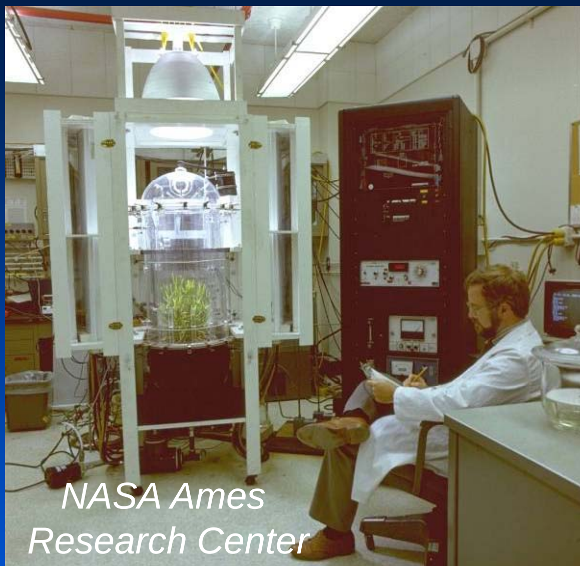
[2] *Original data based on total solar irradiance; table data reflect efficiency based on PAR (400-700 nm)*

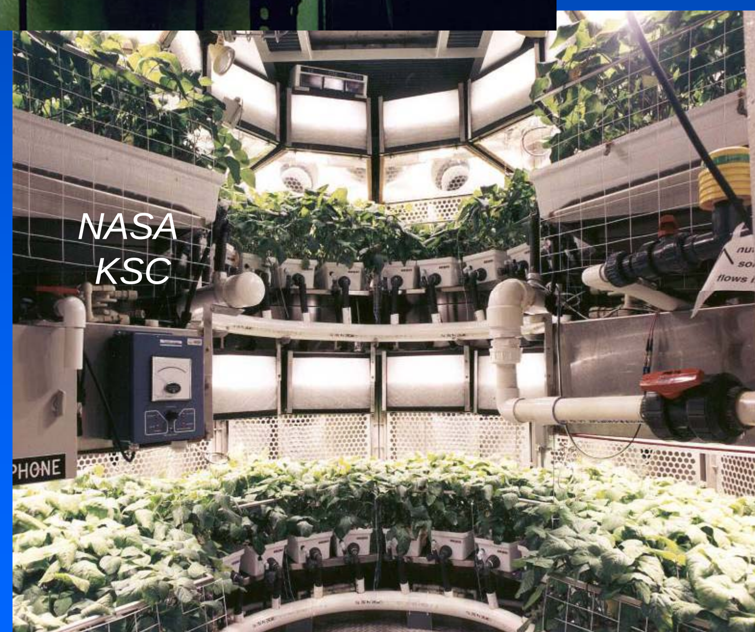
[3] *Monje and Bugbee. 1998. Plant Cell Environ (estimated)*

[4] *Bugbee and Salisbury. 1988. Plant Physiol.*

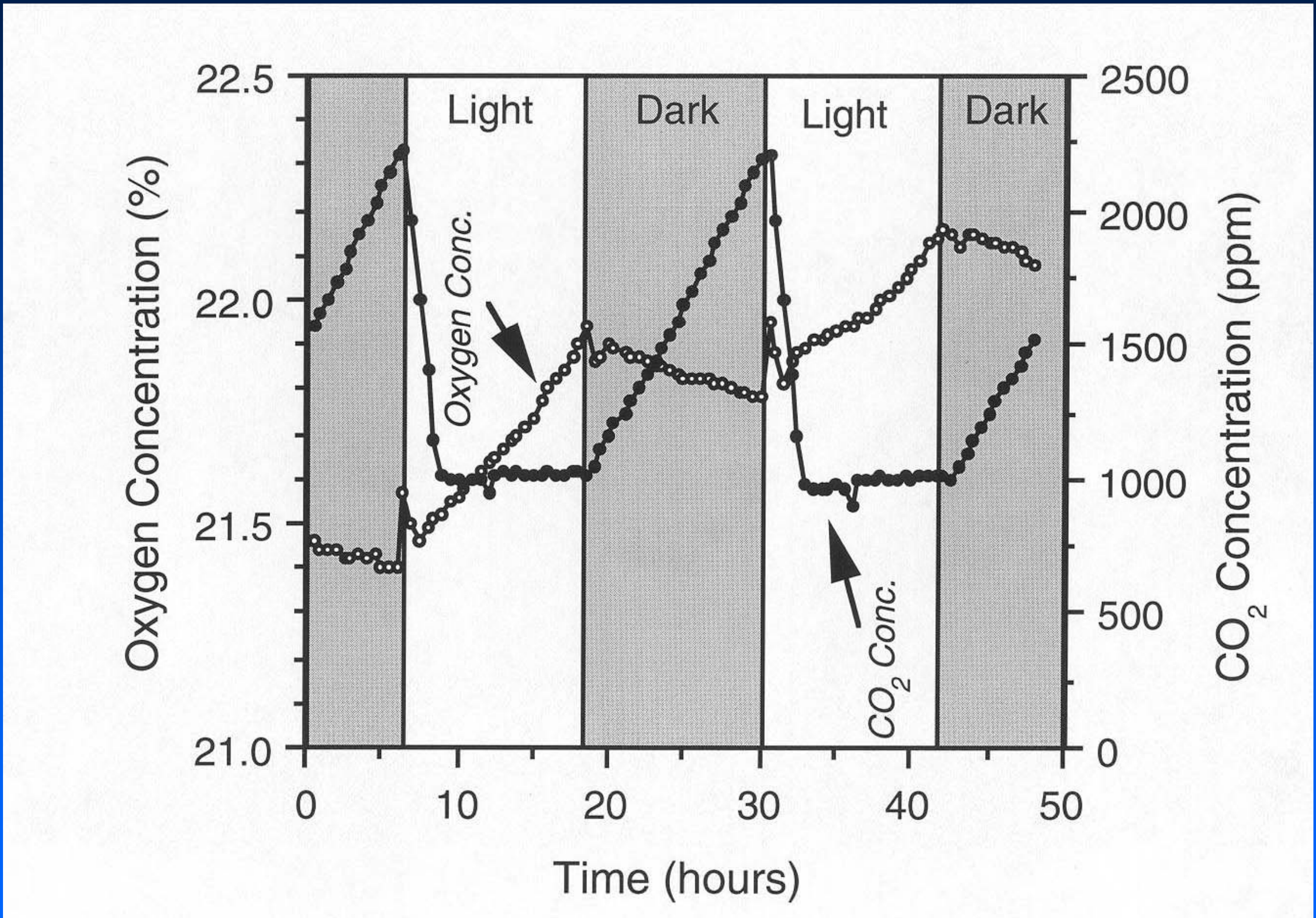
[5] *From Wheeler, 2006. Potato Res. (assumes transplanting to increase PAR absorption).*

Closed Systems Issues



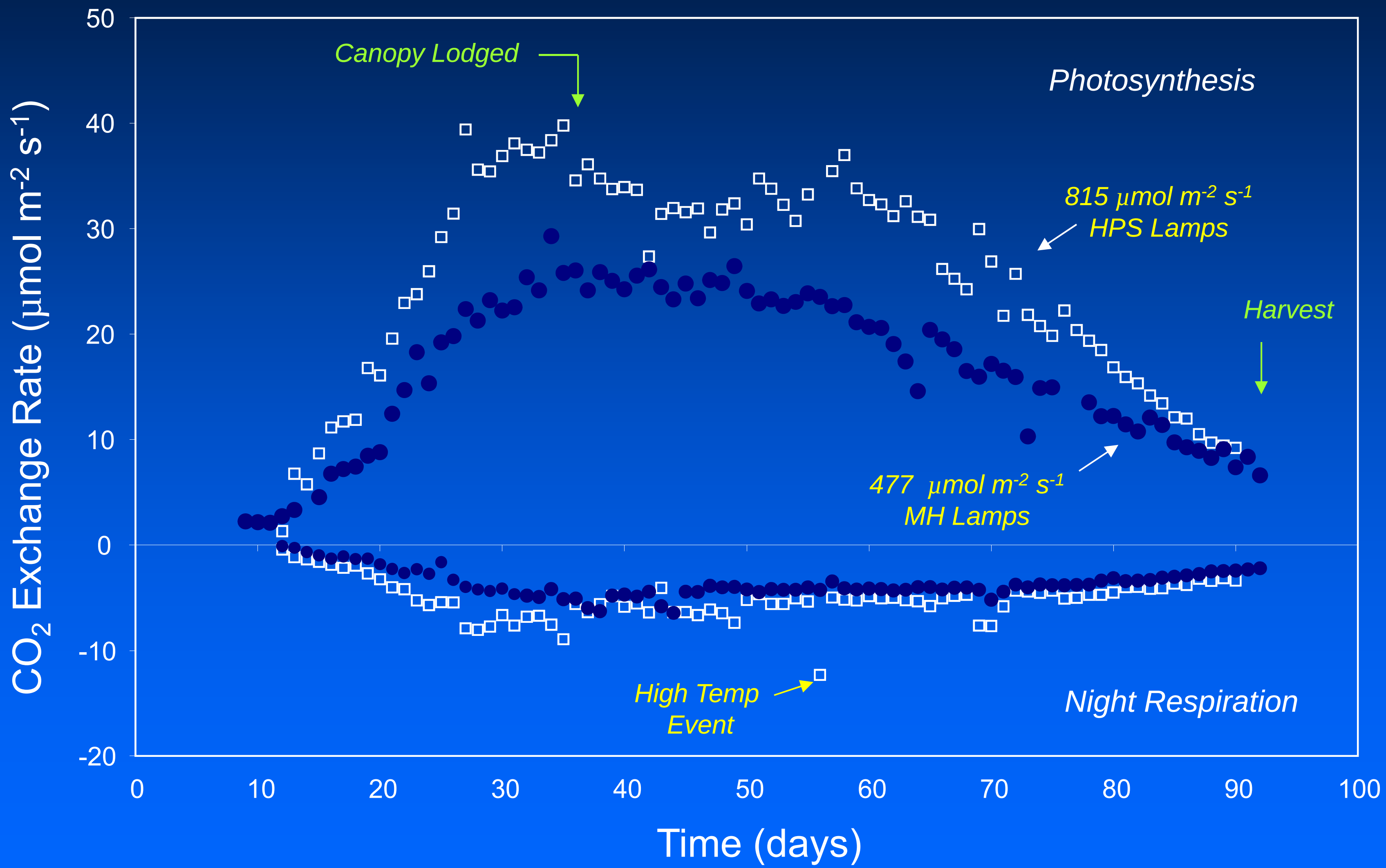


Canopy CO_2 Uptake / O_2 Production
(20 m^2 Soybean Stand)



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

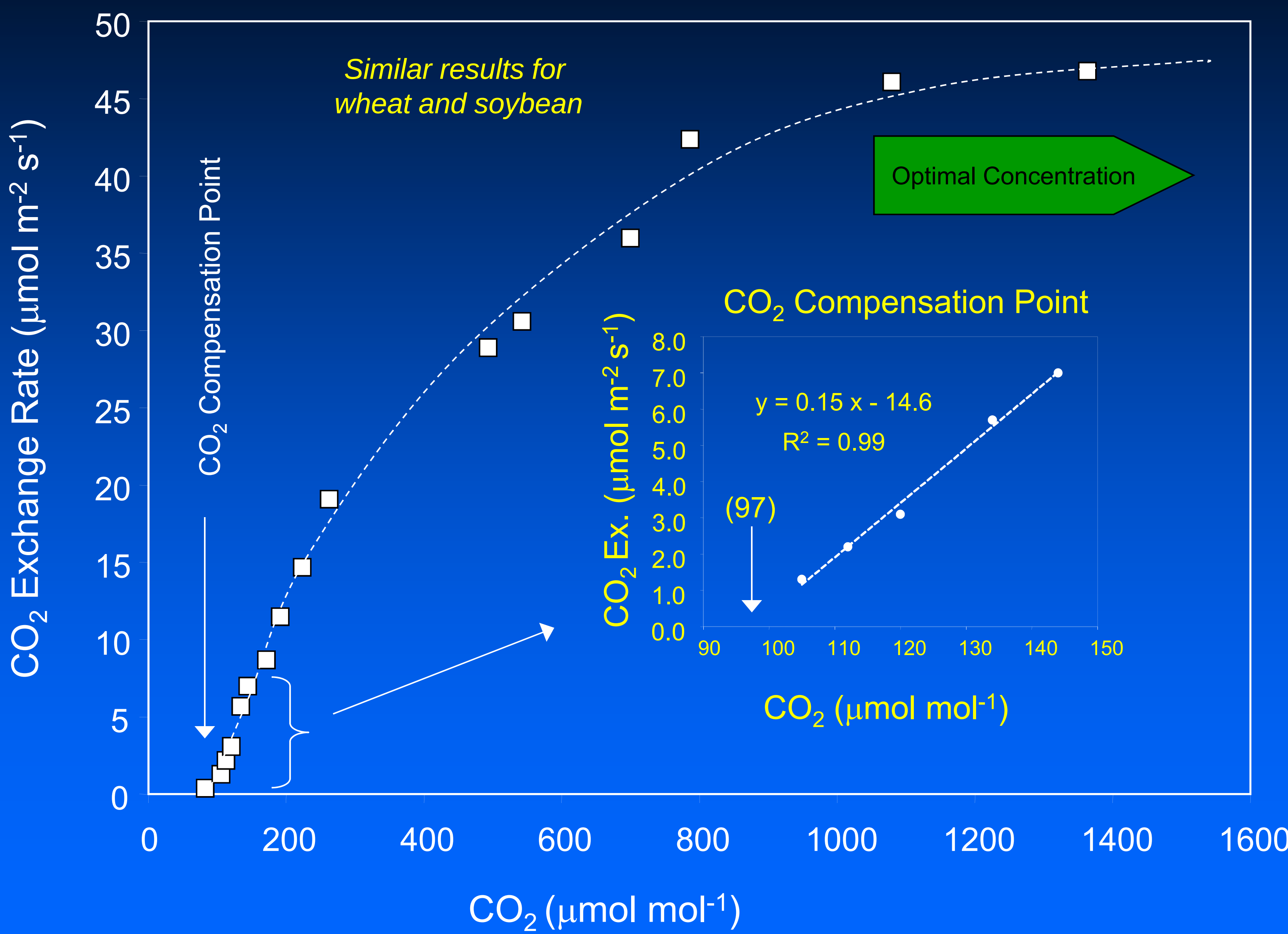
CO_2 Exchange Rates of Soybean Stands



Wheeler et al., 2004. EcoEngineering.

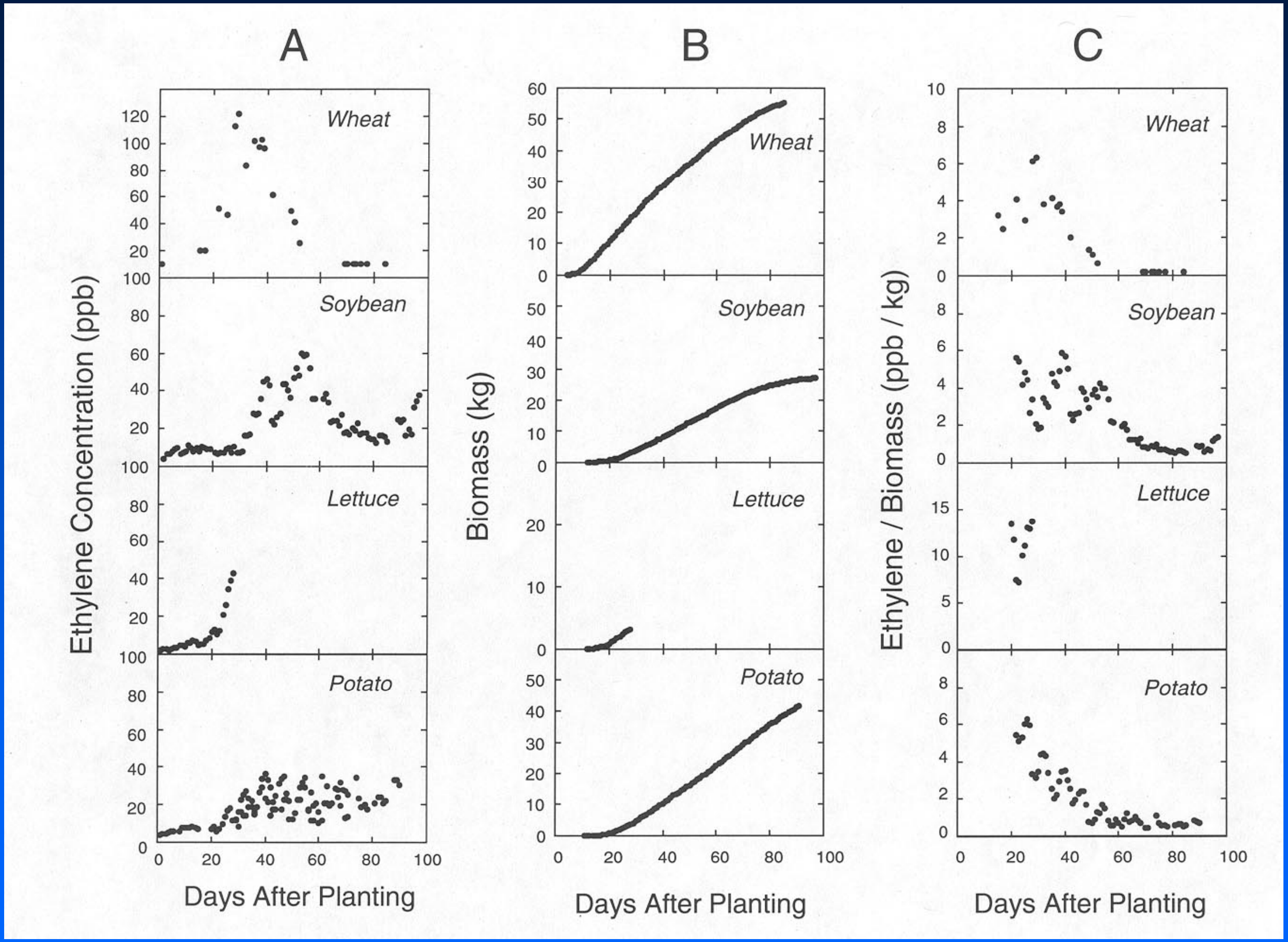
Effect of CO_2 Concentration on Photosynthesis (potato)

Fig. 6



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

Canopy / Stand Ethylene Production



Wheeler et al. 2004. HortScience 39:1541-1545.

Ethylene in Closed Systems

Epinastic
Wheat Leaves
at ~120 ppb

Epinastic
Potato Leaves
at ~40 ppb

NASA’s Biomass Production Chamber (BPC)


External View - Back

Control Room


Hydroponic System

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

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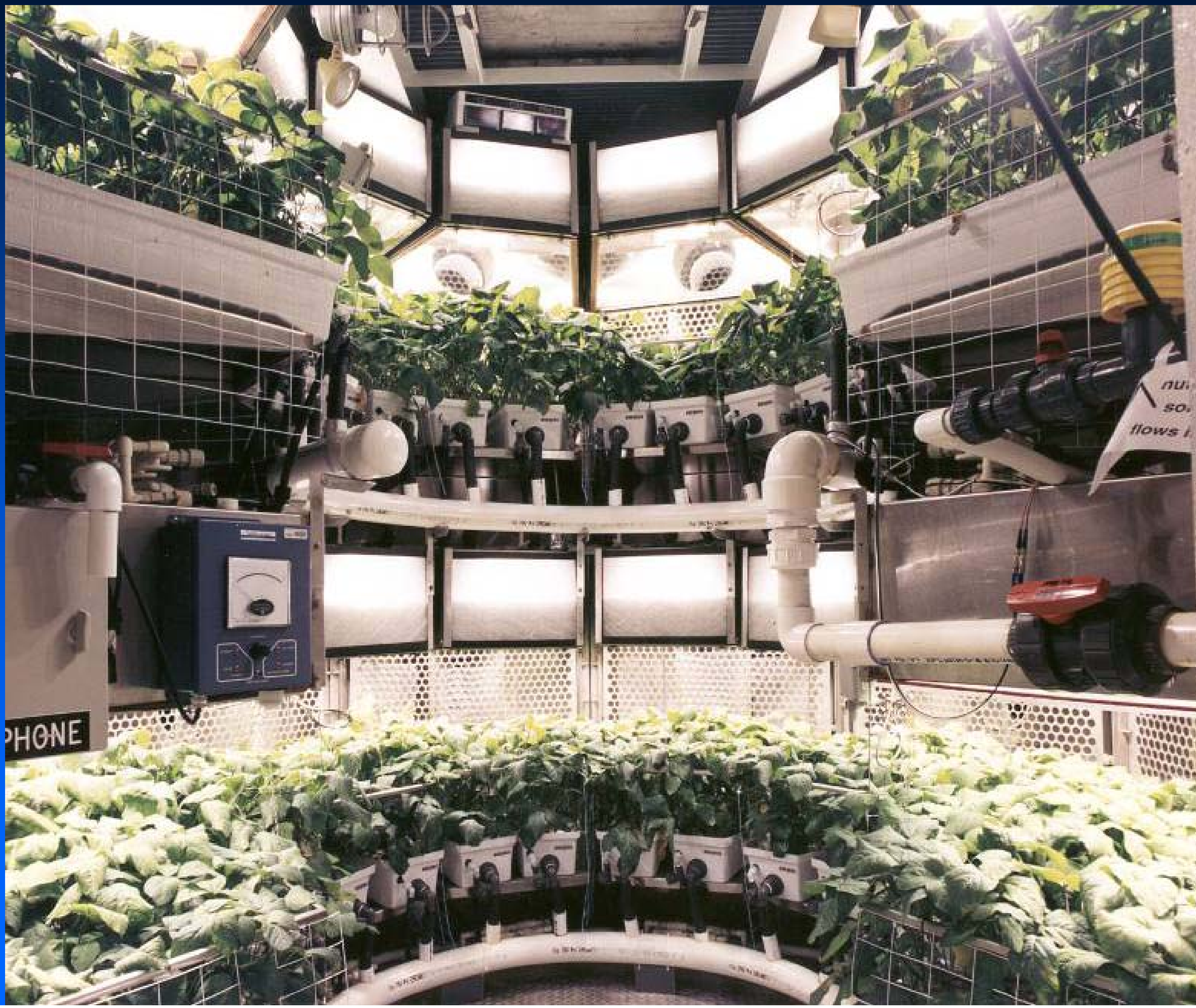


Wheat

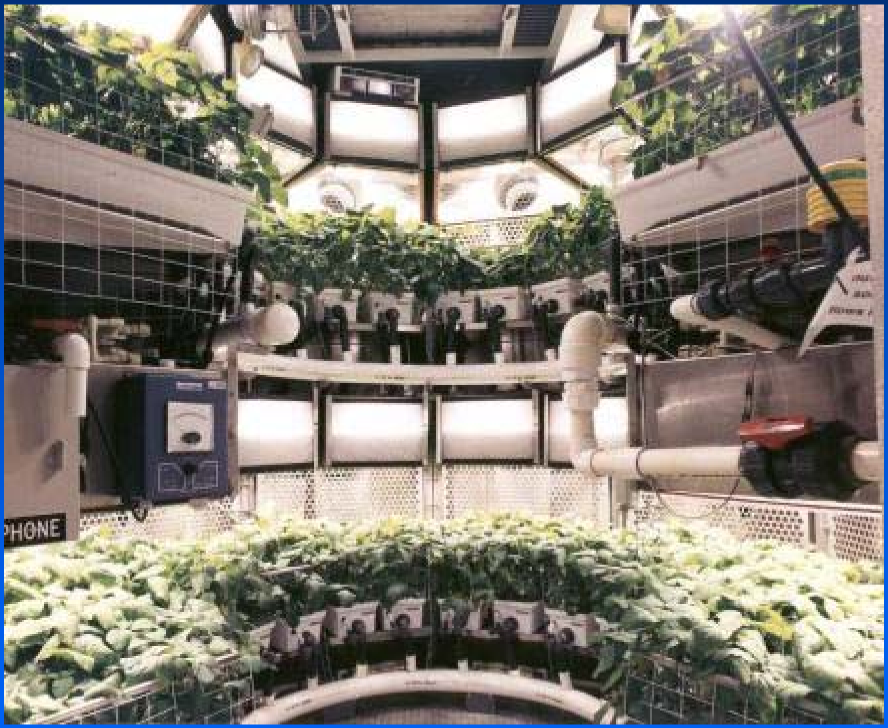
(Triticum aestivum)

planting

harvest

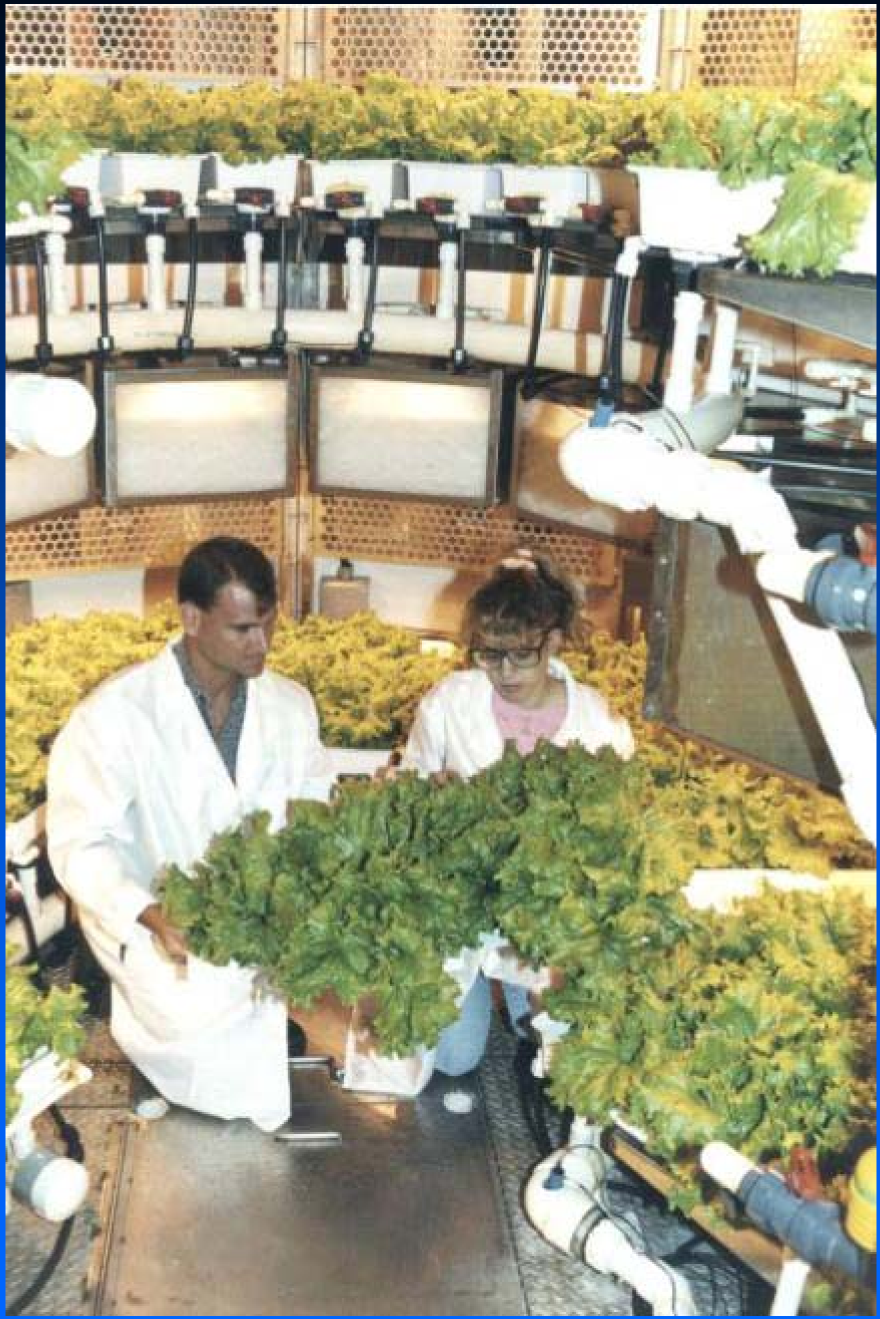
Soybean

(Glycine max)



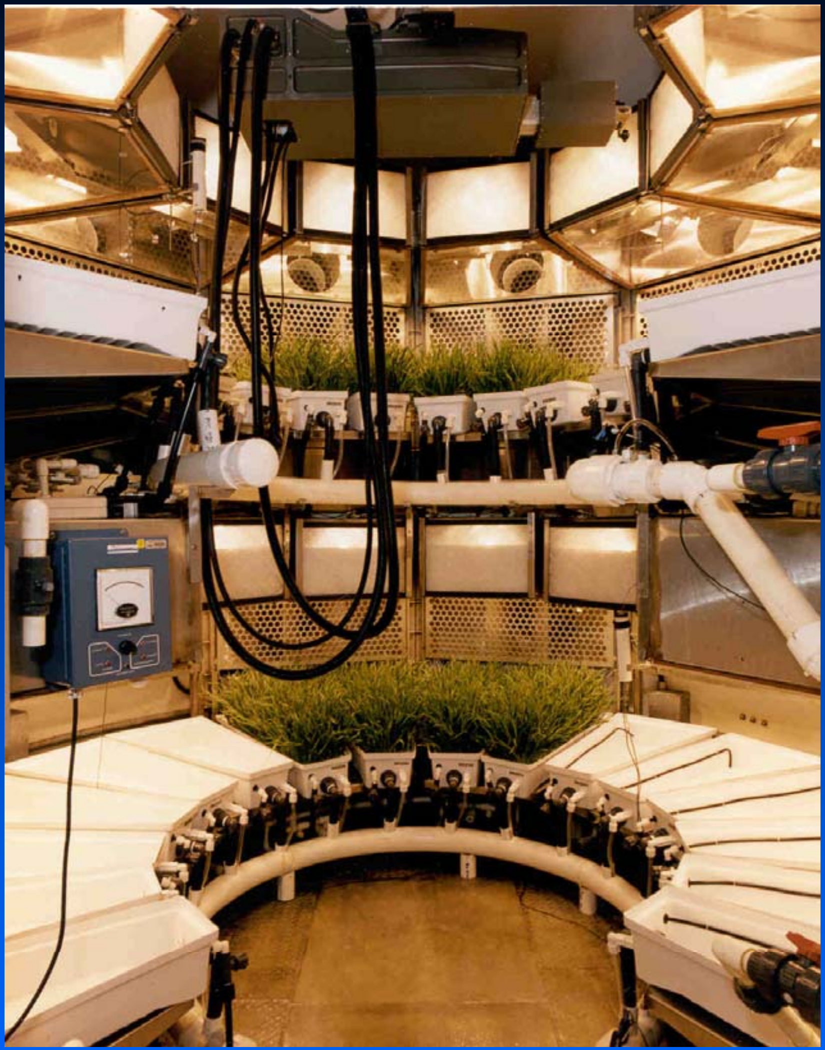
Lettuce

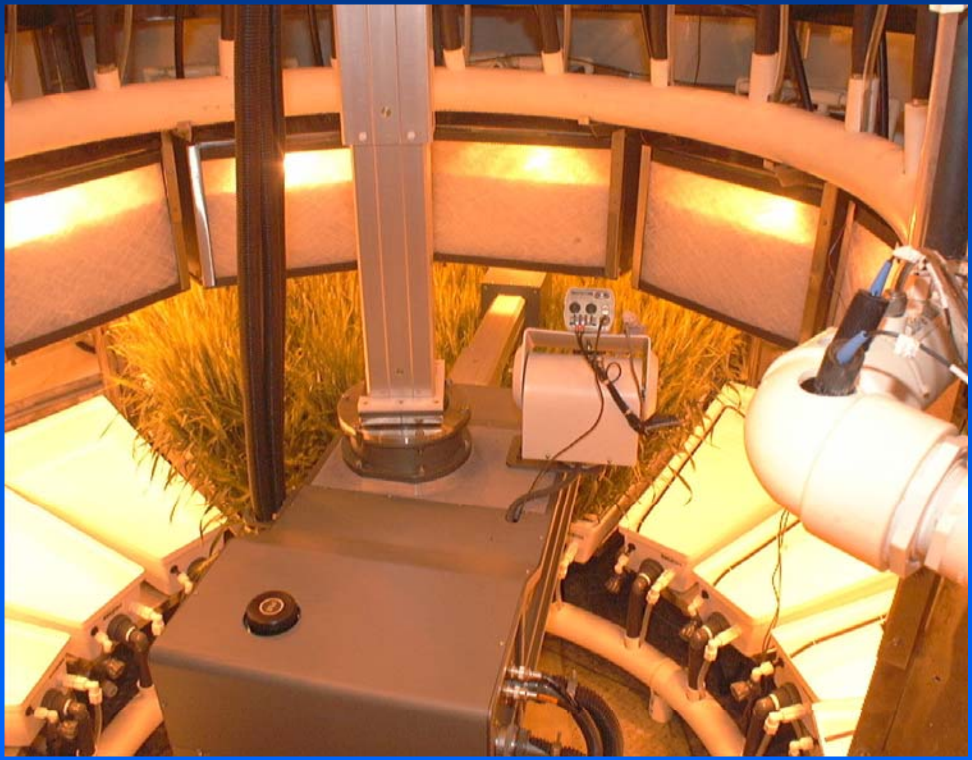
(Lactuca sativa)



Potato
(Solanum tuberosum)

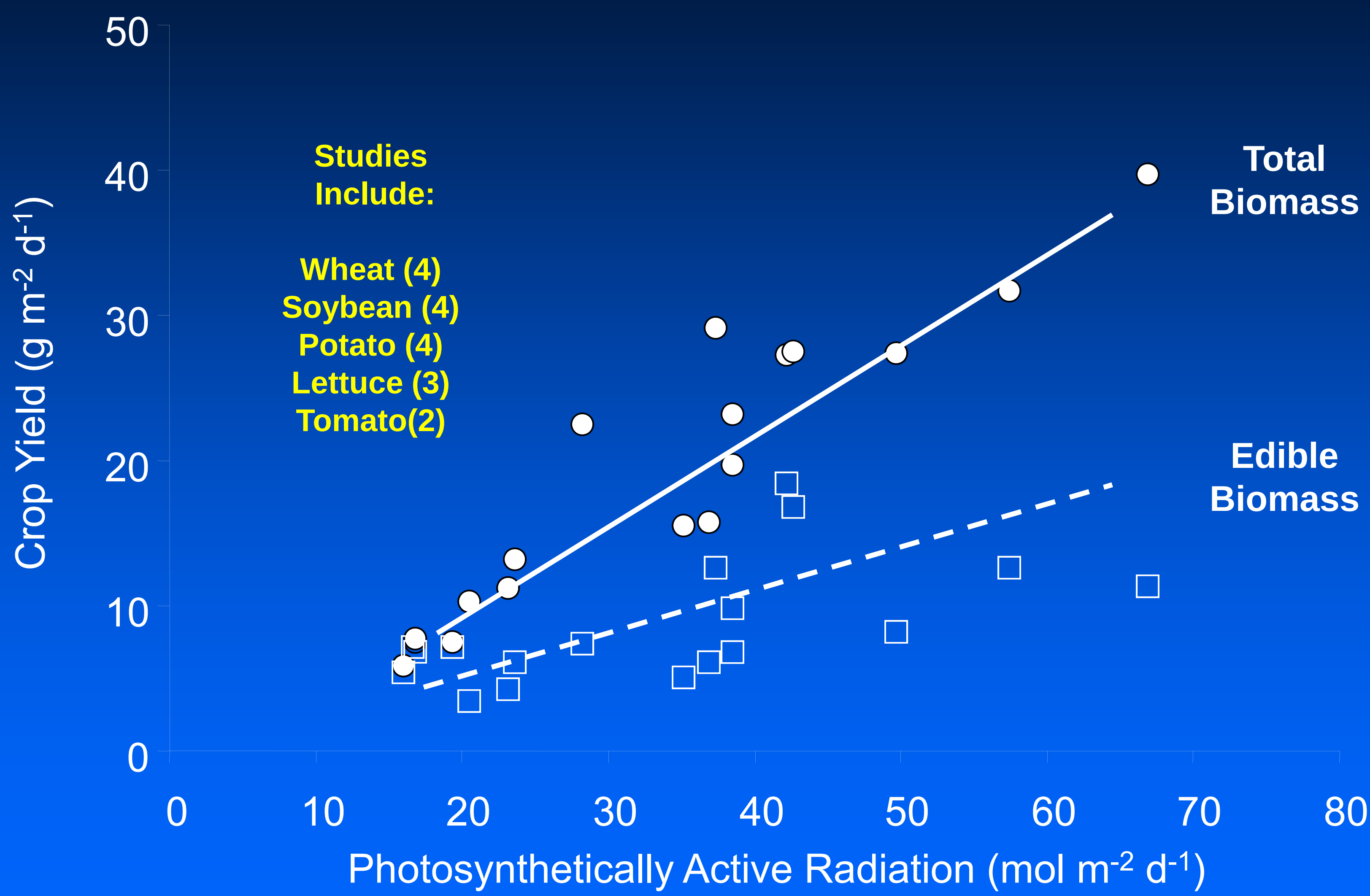
Automation Technologies for CEA





ALSARM Robot in NASA
Biomass Production Chamber

Effect of Light on Crop Yield



Wheeler et al. 1996. Adv. Space Res .

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!!

The Importance of Lighting

--Electric Lamp Options

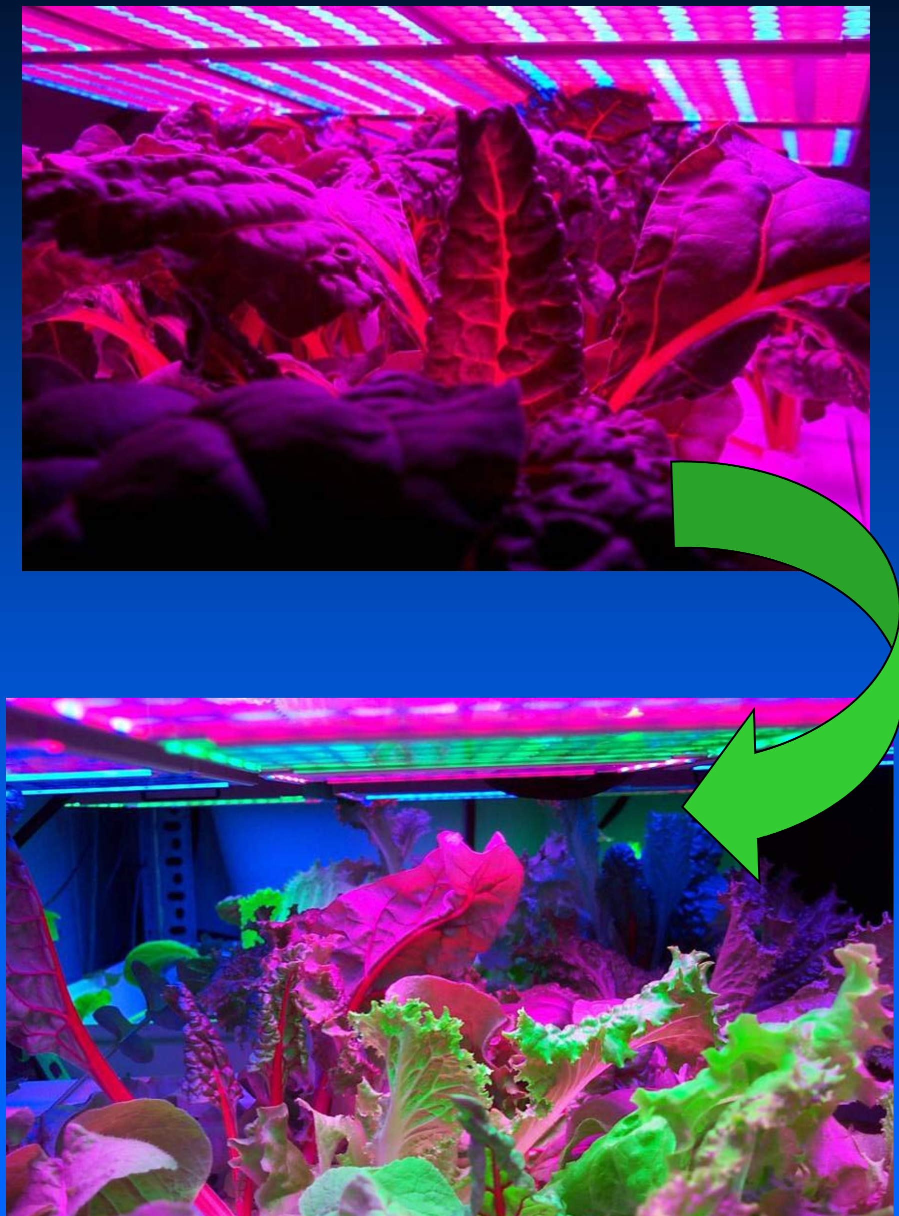
Lamp Type	Conversion* Efficiency	Lamp Life* (hrs)	Spectrum
• Incandescent/Tungsten**	5-10%	2000	Intermd.
• Xenon	5-10%	2000	Broad
• Fluorescent***	20%	5,000-20,000	Broad
• Metal Halide	25%	20,000	Broad
• High Pressure Sodium	30%	25,000	Intermd.
• Low Pressure Sodium	35%	25,000	Narrow
• Microwave Sulfur	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

Some NASA Related References:

Bula et al. 1991. HortSci 26:203-205.

Barta et al. 1992. Adv. Space Res. 12(5):141-149.

Tennessen et al. 1994. Photosyn. Res. 39:85-92.

Goins et al. 1997. J. Exp. Botany 48:1407-1413.

Kim et al. 2004. Ann. Bot. 94:691-697.

Solar Collector / Fiber Optics For Plant Lighting

2 m^2 of collectors on solar tracking drive (SLSL Bldg, 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

Current Testing: Crops for Supplemental Food

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

Phytofarms: A Pioneering Effort at CEA and Vertical Agriculture

- Located in DeKalb, IL; Noel Davis, President and Founder
- Operated from late 1970s through 1980s
- Approximately 1 acre of growing area in a two-story facility
- Hydroponic production of lettuce, spinach and herbs
- Used over 1000, 1000-W water-cooled HPS lamps. Thus the facility drew ~ 1 MW of power and consequently shifted most of their demand to off-peak hours.

Phytofarms
DeKalb, IL

Phytofarms, DeKalb, IL

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DeKalb, IL