# Controlled Environment Agricultural (CEA) for Space:

## *Some Observations from NASA Studies*

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*Kennedy Space Center, Florida, USA*

Vertical / Urban Agriculture Workshop
Sept 26-27, 2012

## Human Life Support Requirements:

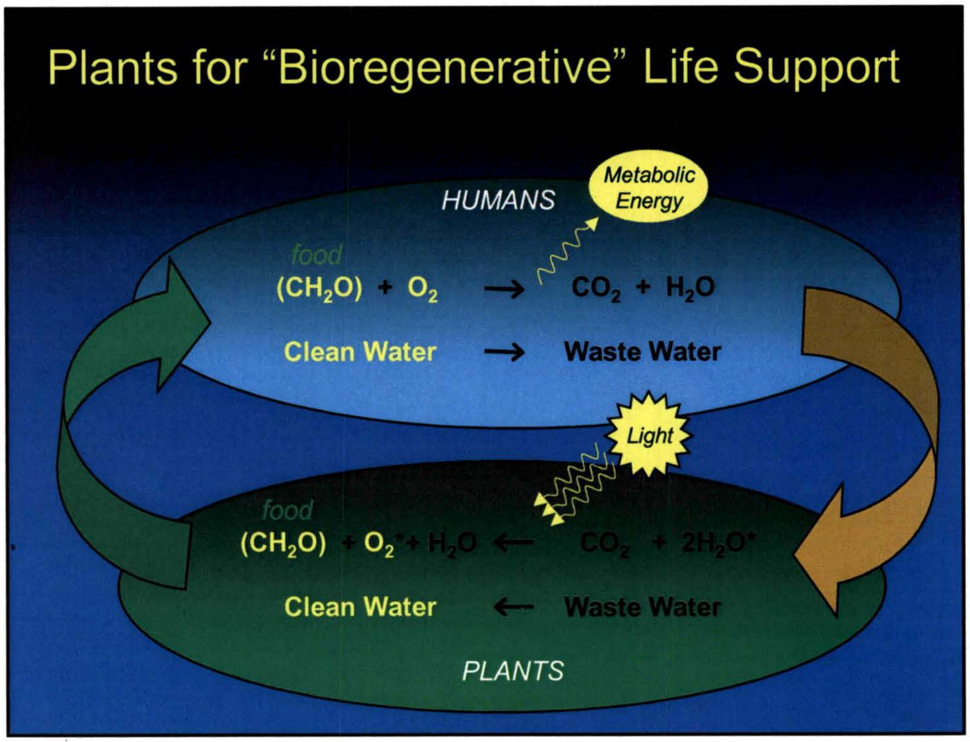
***Inputs***

| | 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*** | |

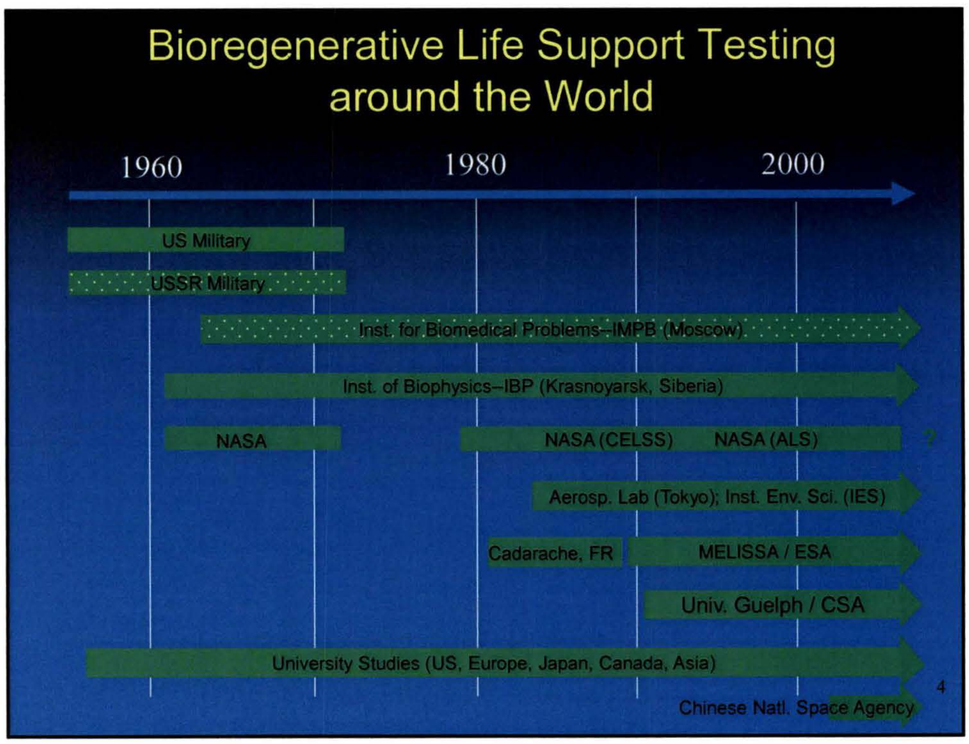
***Outputs***

| | 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*** | |

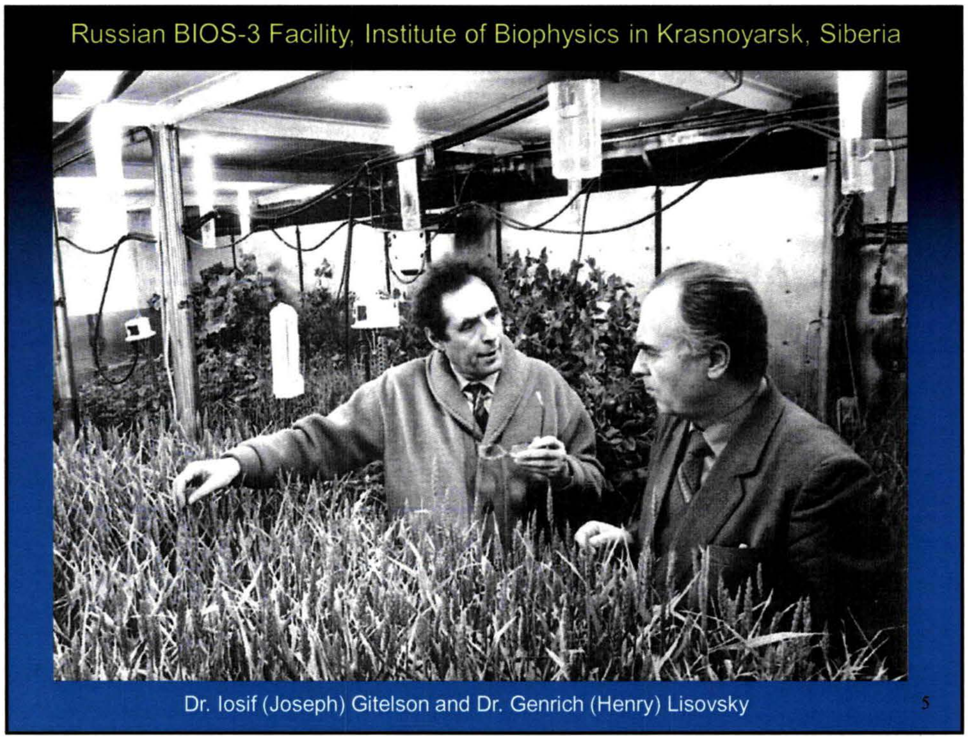
*Source: NASA SPP 30262 Space Station ECLSS Architectural Control Document*
*Food assumed to be dry except for chemically-bound water.*



Plants for "Bioregenerative" Life Support
HUMANS
Metabolic Energy
food
$(CH_2O) + O_2 \rightarrow CO_2 + H_2O$
Clean Water → Waste Water
Light
food
$(CH_2O) + O_2^* + H_2O \leftarrow CO_2 + 2H_2O^*$
Clean Water ← Waste Water
PLANTS

Bioregenerative Life Support Testing around the World
1960
1980
2000
US Military
USSR Military
Inst. for Biomedical Problems–IMPB (Moscow)
Inst. of Biophysics–IBP (Krasnoyarsk, Siberia)
NASA
NASA (CELSS)
NASA (ALS)
Aerosp. Lab (Tokyo); Inst. Env. Sci. (IES)
Cadarache, FR
MELISSA / ESA
Univ. Guelph / CSA
University Studies (US, Europe, Japan, Canada, Asia)
Chinese Natl. Space Agency


Russian BIOS-3 Facility, Institute of Biophysics in Krasnoyarsk, Siberia
Dr. Iosif (Joseph) Gitelson and Dr. Genrich (Henry) Lisovsky
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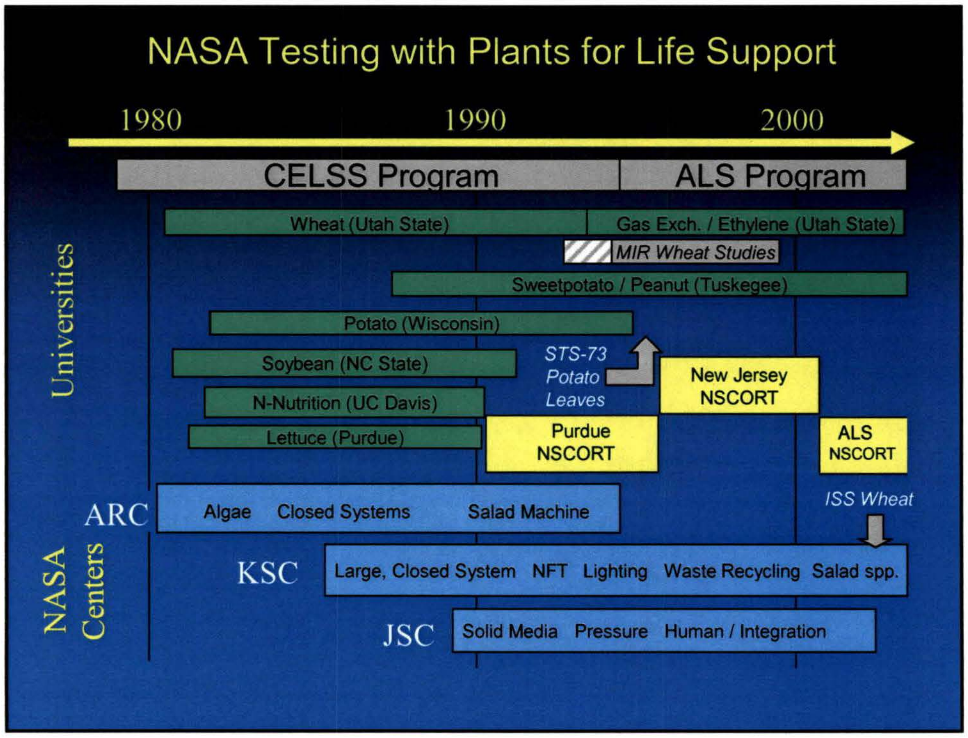

NASA Testing with Plants for Life Support
1980
1990
2000
CELSS Program
ALS Program
Universities
Wheat (Utah State)
Gas Exch. / Ethylene (Utah State)
MIR Wheat Studies
Sweetpotato / Peanut (Tuskegee)
Potato (Wisconsin)
Soybean (NC State)
STS-73 Potato Leaves
New Jersey NSCORT
N-Nutrition (UC Davis)
Lettuce (Purdue)
Purdue NSCORT
ALS NSCORT
NASA Centers
ARC
Algae
Closed Systems
Salad Machine
ISS Wheat
KSC
Large, Closed System
NFT
Lighting
Waste Recycling
Salad spp.
JSC
Solid Media
Pressure
Human / Integration

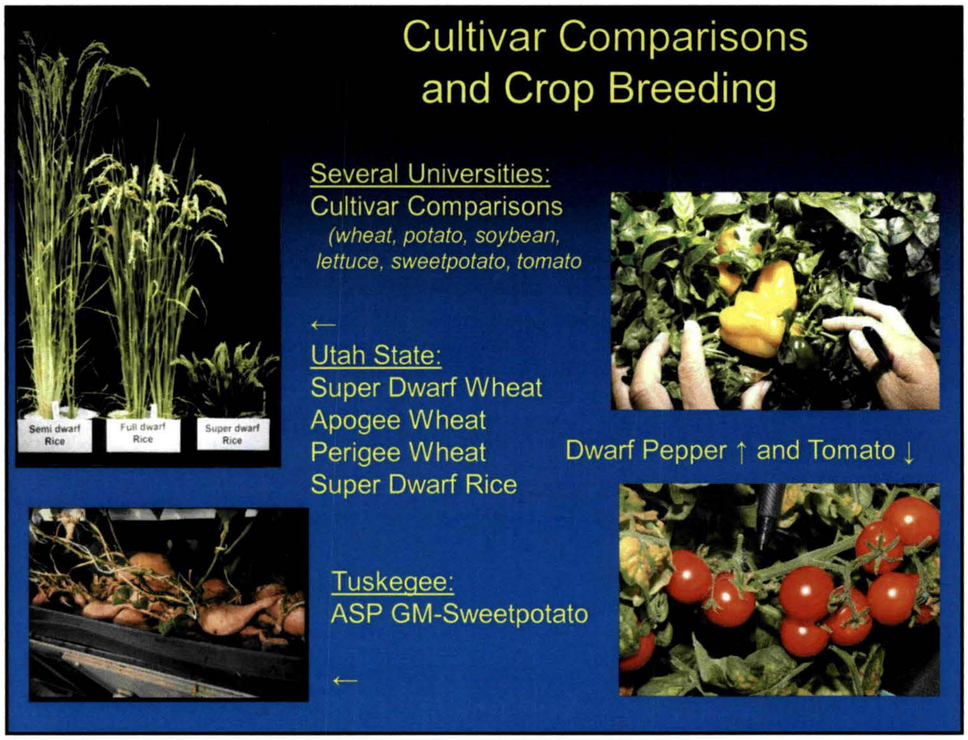
## Crops Needed for Space

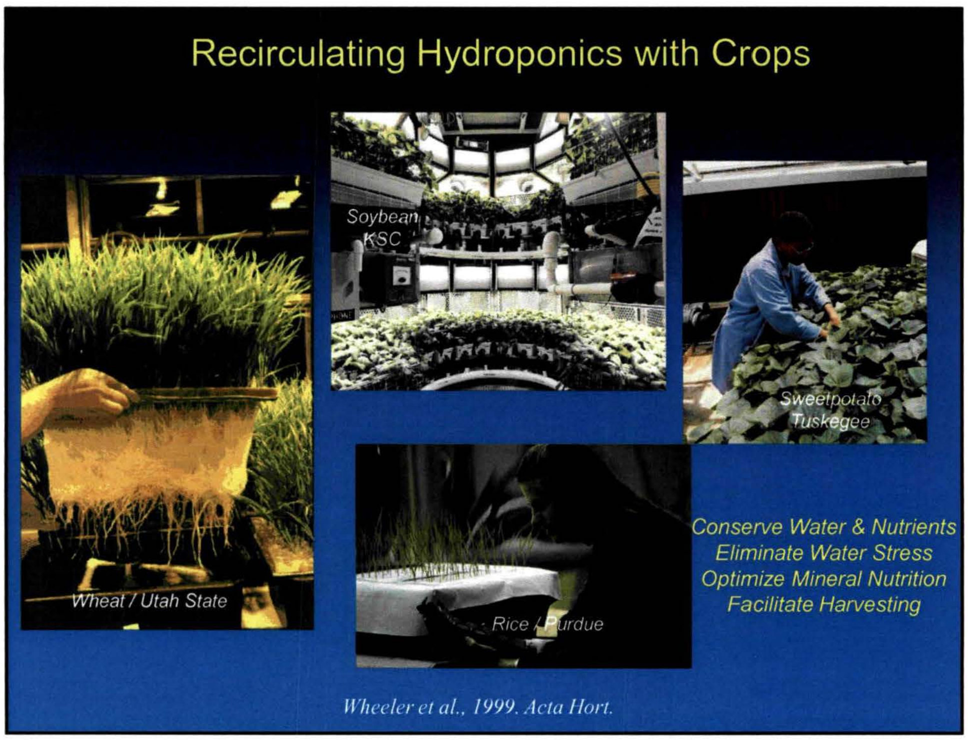
- High yielding and nutritious
- High harvest index (edible / total biomass)
- Horticultural considerations
  - planting, harvesting, pollination, propagation
- Environmental considerations
  - photoperiod, temperature, mineral nutrition
- Processing requirements
- Dwarf or low growing types

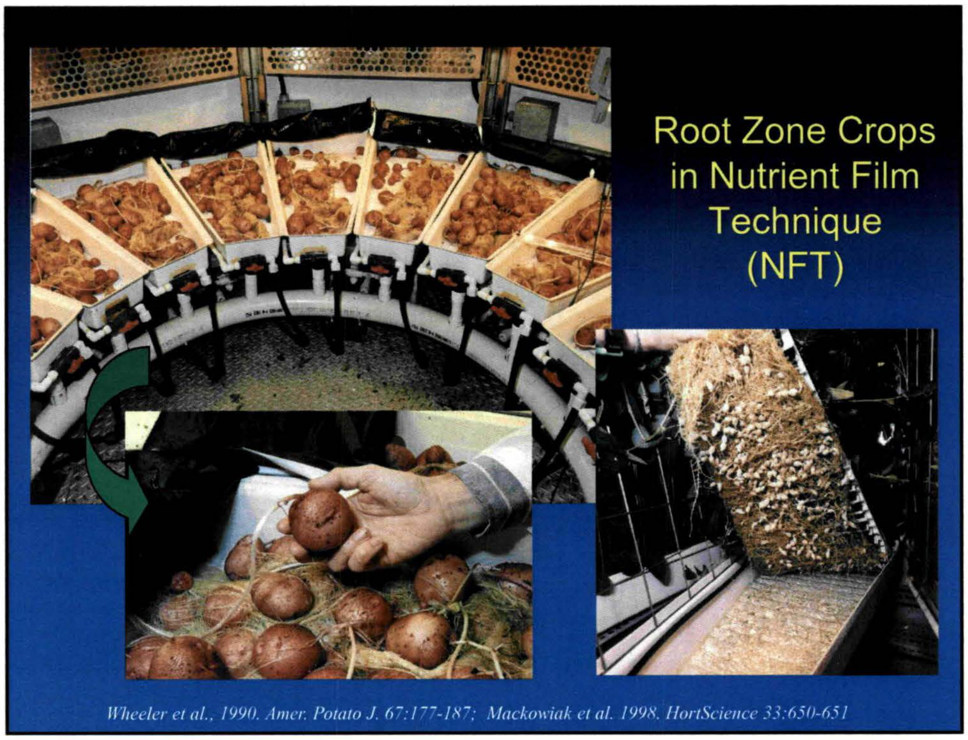
## Some Crops for Life Support

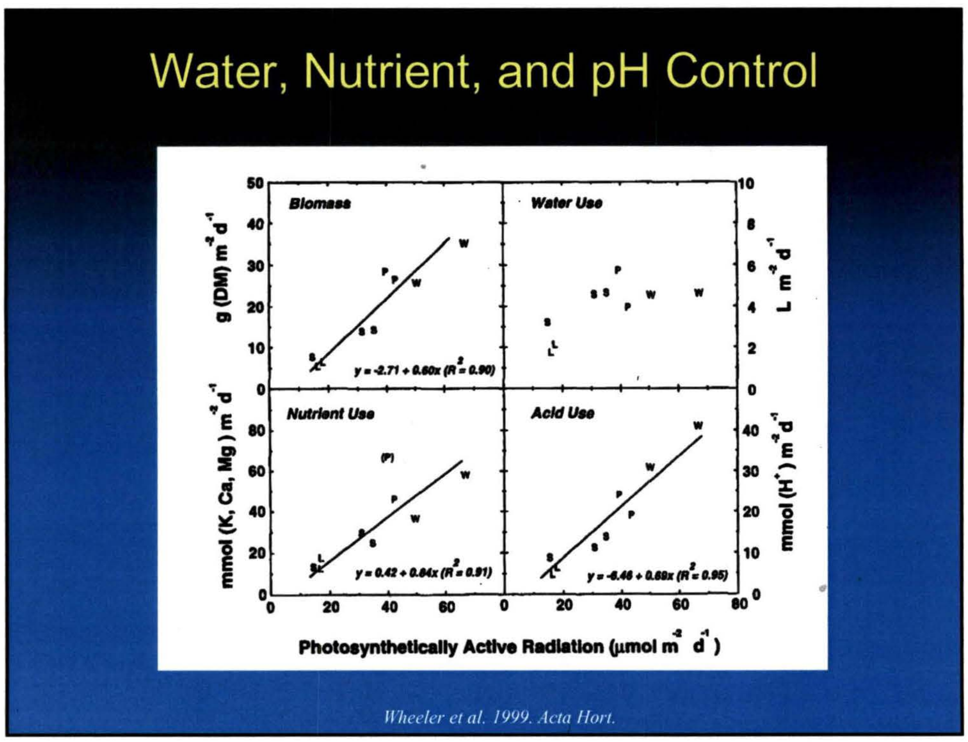
| Tibbitts and Alford [a] | Hoff, Howe, and Mitchell [b] | Salisbury and Clark [c] | Crops Used in BIOS-3 Testing [d] |
|---|---|---|---|
| Wheat | Wheat | Wheat | Wheat |
| Soybean | Potato | Rice | Potato |
| Potato | Soybean | Sweetpotato | Carrot |
| Lettuce | Rice | Broccoli | Radish |
| Sweetpotato | 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.*

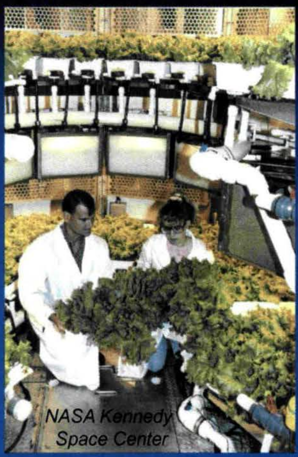

Cultivar Comparisons
and Crop Breeding
Several Universities:
Cultivar Comparisons
(wheat, potato, soybean,
lettuce, sweetpotato, tomato
←
Utah State:
Super Dwarf Wheat
Apogee Wheat
Perigee Wheat
Super Dwarf Rice
Semi dwarf Rice
Full dwarf Rice
Super dwarf Rice
Dwarf Pepper ↑ and Tomato ↓
Tuskegee:
ASP GM-Sweetpotato
←


Recirculating Hydroponics with Crops
Soybean
KSC
Sweetpotato
Tuskegee
Wheat / Utah State
Rice / Purdue
Conserve Water & Nutrients
Eliminate Water Stress
Optimize Mineral Nutrition
Facilitate Harvesting
Wheeler et al., 1999. Acta Hort.

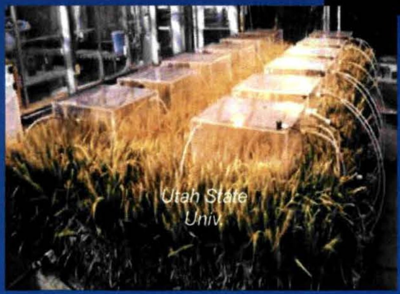

Root Zone Crops
in Nutrient Film
Technique
(NFT)
Wheeler et al., 1990. Amer. Potato J. 67:177-187; Mackowiak et al. 1998. HortScience 33:650-651


Water, Nutrient, and pH Control
Biomass
Water Use
Nutrient Use
Acid Use
g (DM) m-2 d-1
L m-2 d-1
mmol (K, Ca, Mg) m-2 d-1
mmol (H+) m-2 d-1
y = -2.71 + 0.60x (R2 = 0.90)
y = 0.42 + 0.84x (R2 = 0.91)
y = -6.46 + 0.68x (R2 = 0.95)
Photosynthetically Active Radiation (µmol m-2 d-1)
Wheeler et al. 1999. Acta Hort.

## 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 for 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] 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) |

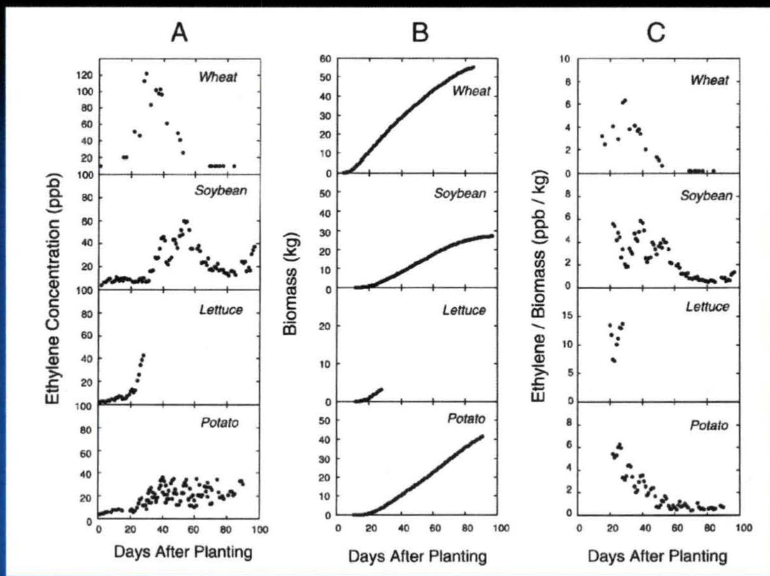
CEA NASA Studies

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

[1] *From D.O. Hall. 1976. FEBS Letters*
[2] *Original data based on total solar irradiance; table data reflect efficiency based on PAR (400-700 nm)*
[2] *Estimated from O. Monje and B.Bugbee. 1998. Plant Cell Environment*
[3] *From R. Wheeler, 2006. Potato Res. (assumes transplanting to increase PAR absorption).*

## Closed Systems: An Issue for Space but not as Much for Earth

## Canopy / Stand Ethylene Production

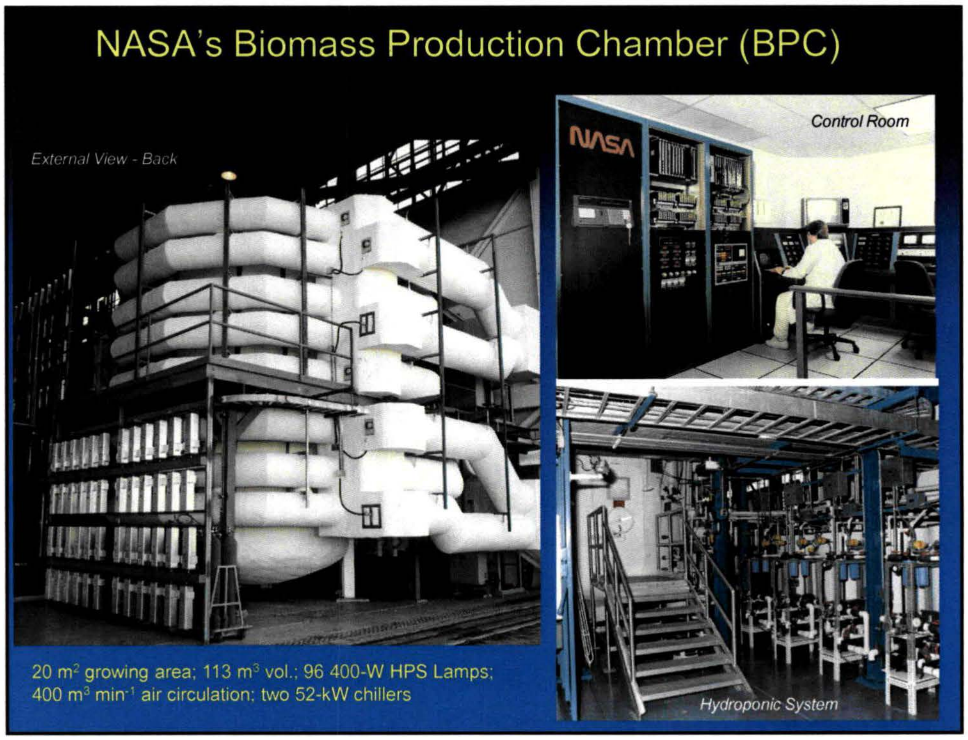



Wheeler et al. 2004. HortScience 39:1541-1545.

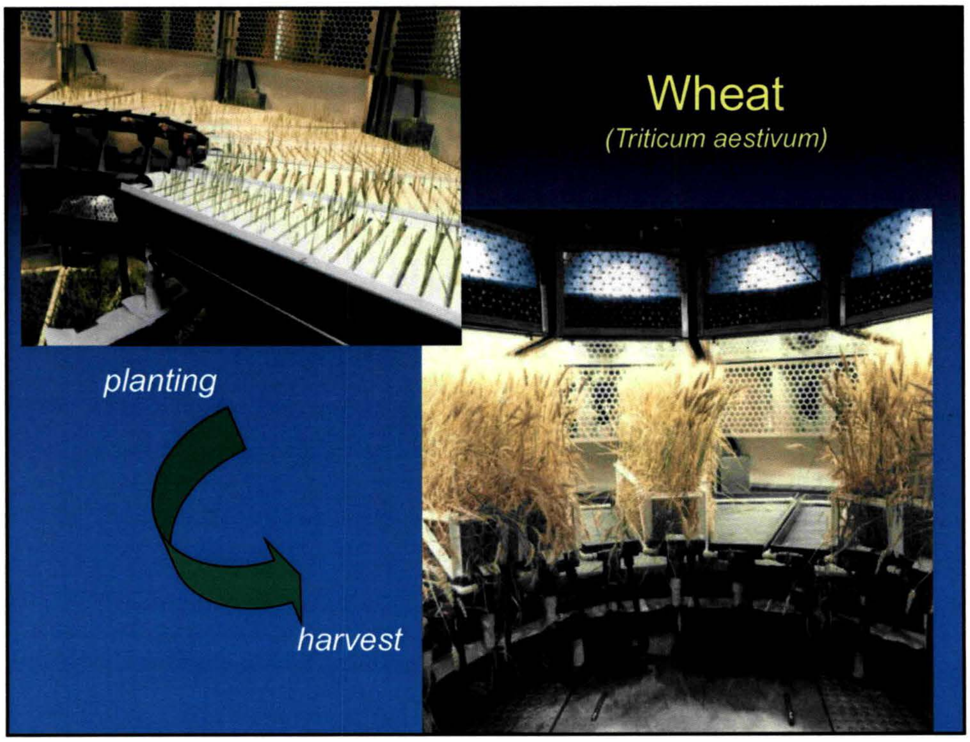
## Ethylene in Closed Systems

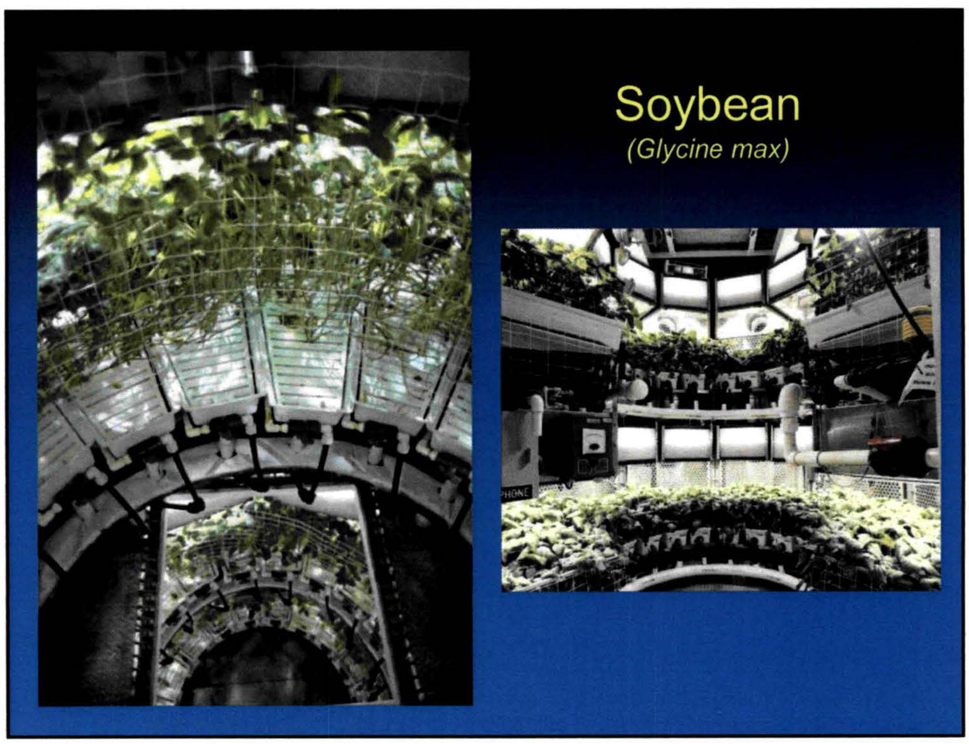
Epinastic
Wheat Leaves
at ~120 ppb

Epinastic
Potato Leaves
at ~40 ppb

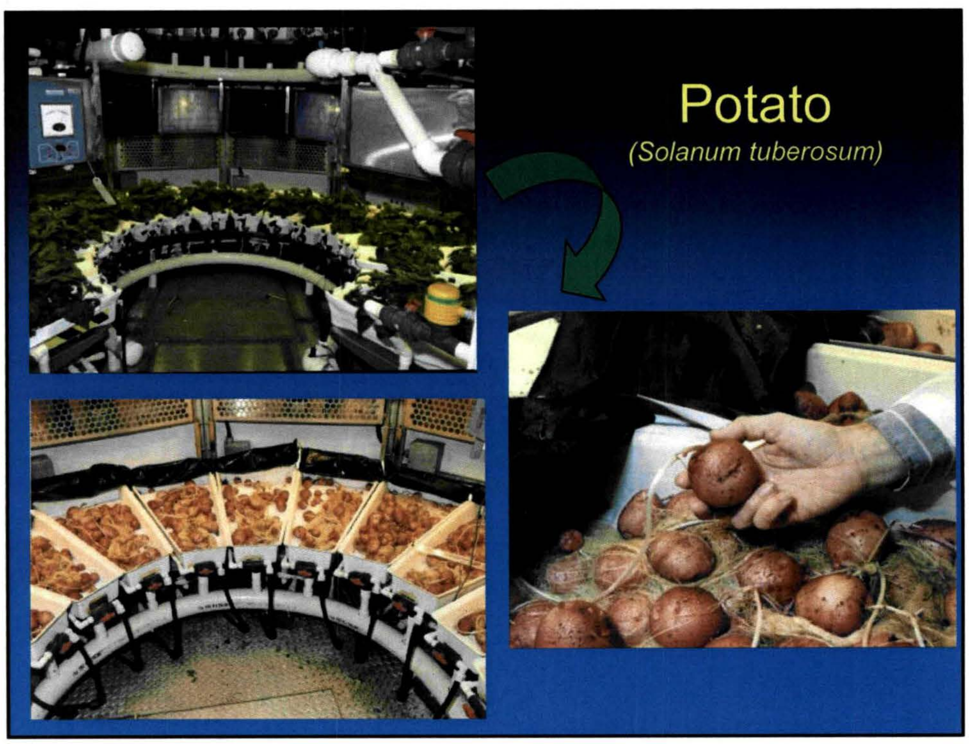

NASA's Biomass Production Chamber (BPC)
External View - Back
Control Room
20 m² growing area; 113 m³ vol.; 96 400-W HPS Lamps; 400 m³ min⁻¹ air circulation; two 52-kW chillers
Hydroponic System


NASA's Biomass Production Chamber (BPC)

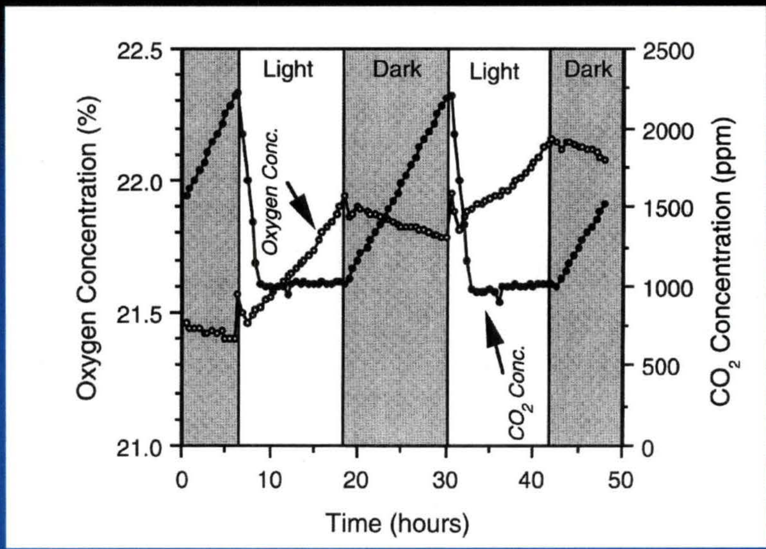

Wheat
(Triticum aestivum)
planting
harvest


Soybean
(Glycine max)


Lettuce
(Lactuca sativa)

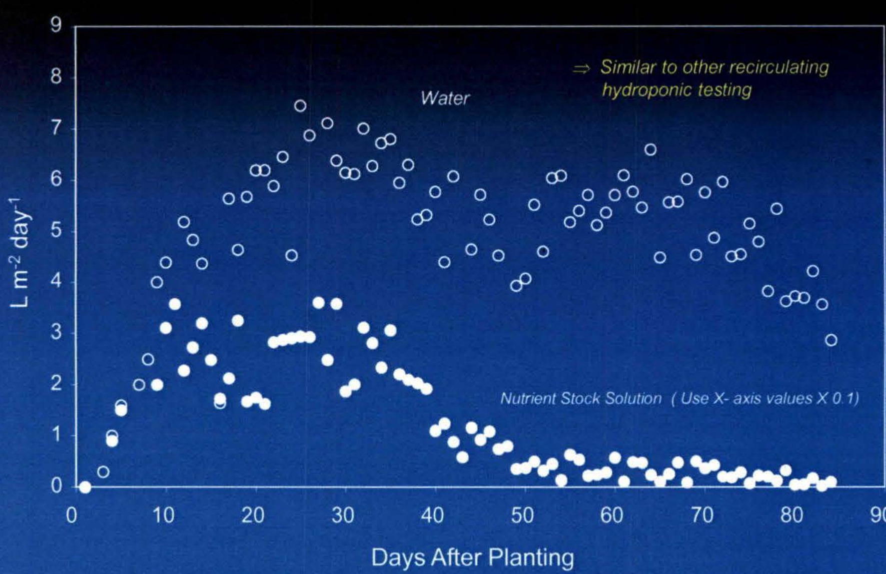

Potato
(Solanum tuberosum)

## Canopy $CO_2$ Uptake / $O_2$ Production
*(20 m² Soybean Stand)*

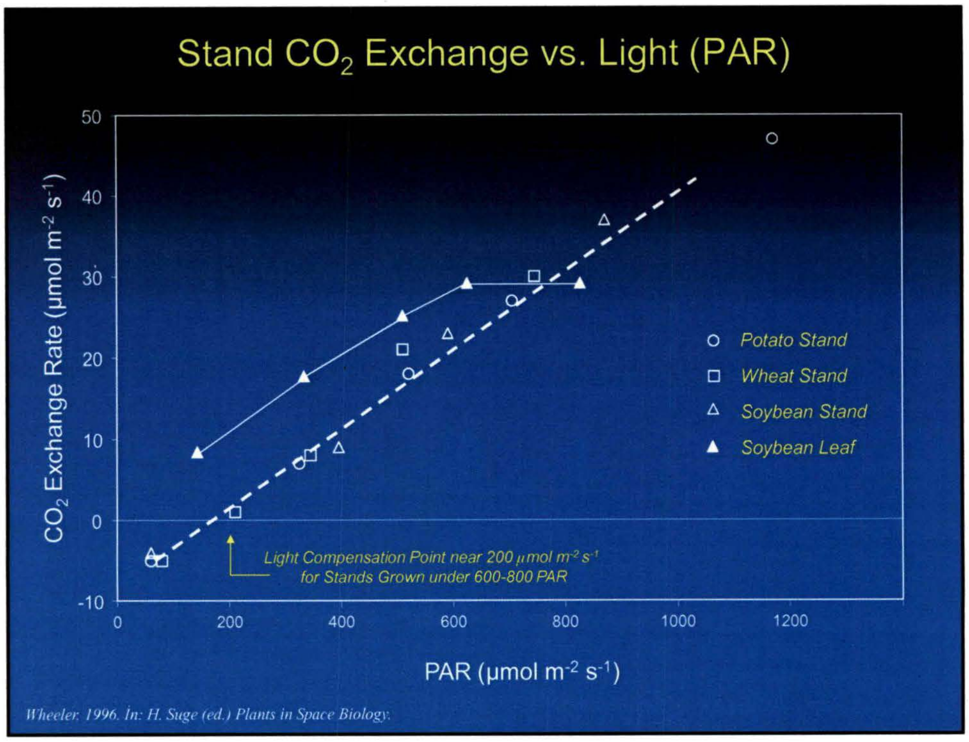



Wheeler. 1996. *In:* H. Suge (*ed.*) Plants in Space Biology.

## Closed Nutrient and Water Cycles ( 20 m² *wheat*)




*Wheeler et al. 1993. J. Plant Nutrition 16:1881-1915.*

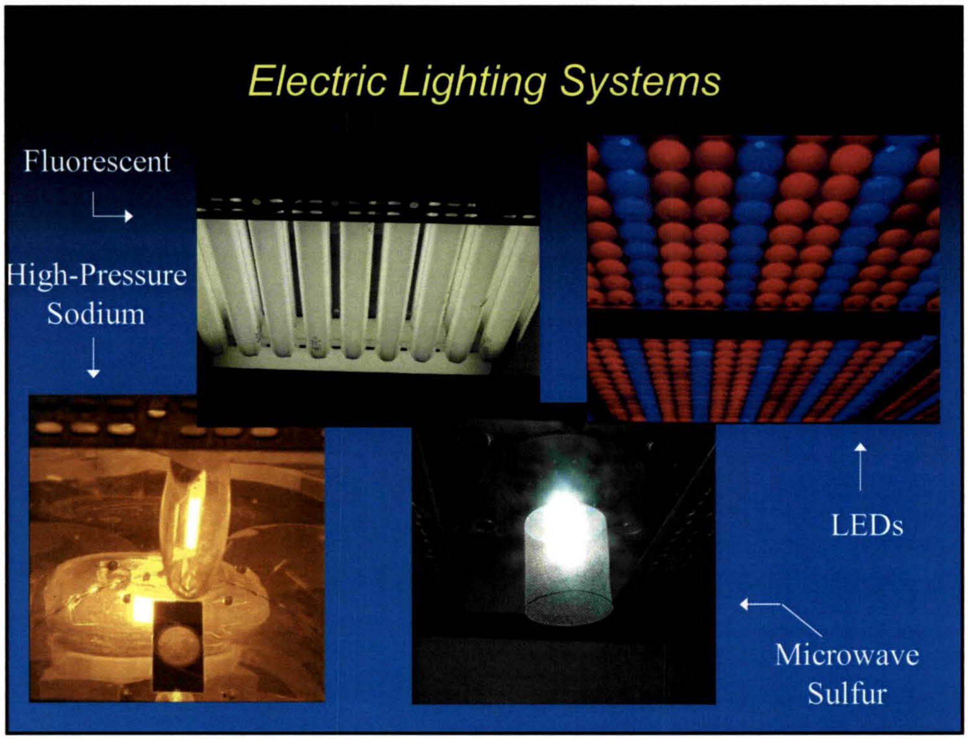


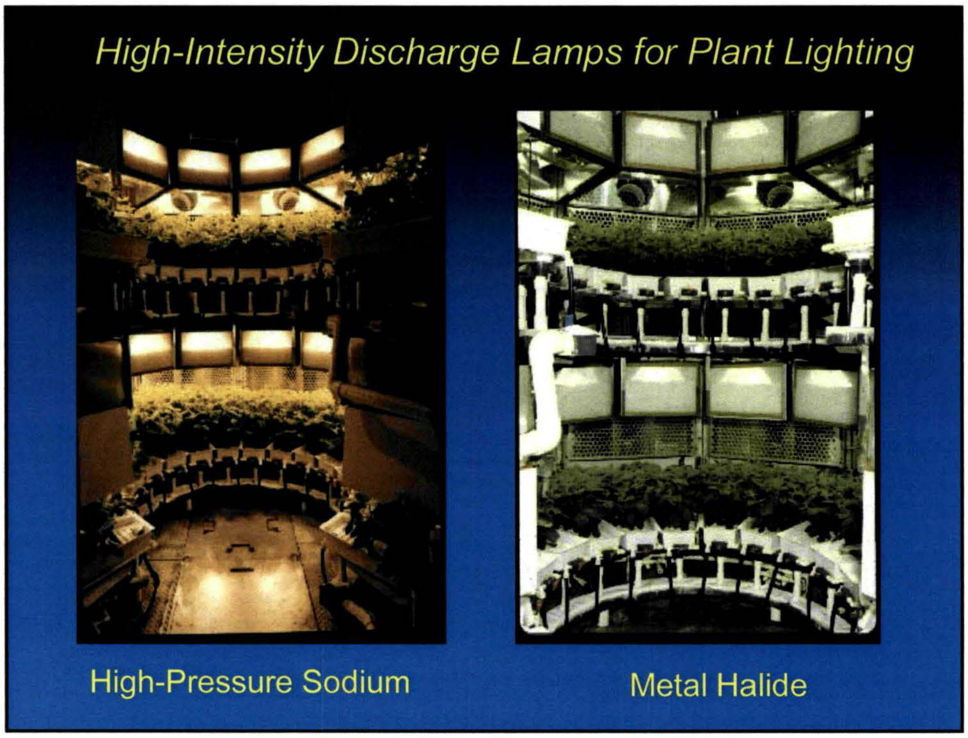

## The Importance of Lighting

*--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 |

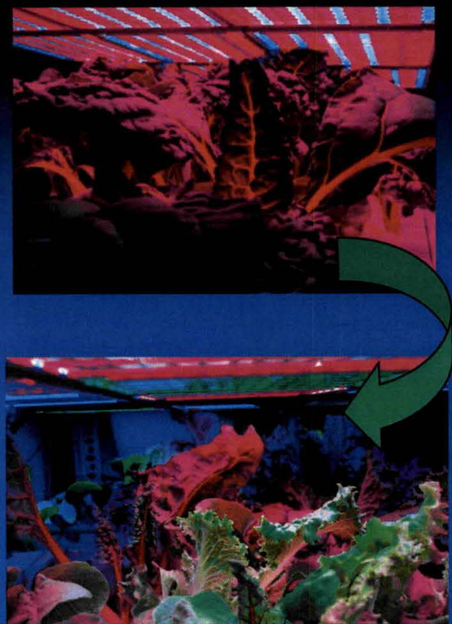
* *Approximate values.*
** *Tungsten halogen lamps have broader spectrum.*
*** *For VHO lamps; lower power lamps with electronic ballasts last up to ~20,000 hrs.*
**** *State-of-Art Blue and Red LEDs most efficient.*


Electric Lighting Systems
Fluorescent
High-Pressure Sodium
LEDs
Microwave Sulfur


High-Intensity Discharge Lamps for Plant Lighting
High-Pressure Sodium
Metal Halide

## *LED Studies*

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



*Some References:*

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

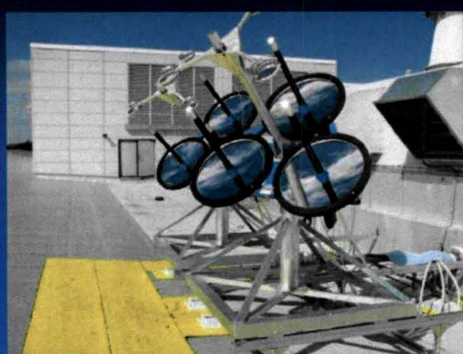
Barta et al. 1992. Adv. Space Res. 12(5):141-149.

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.

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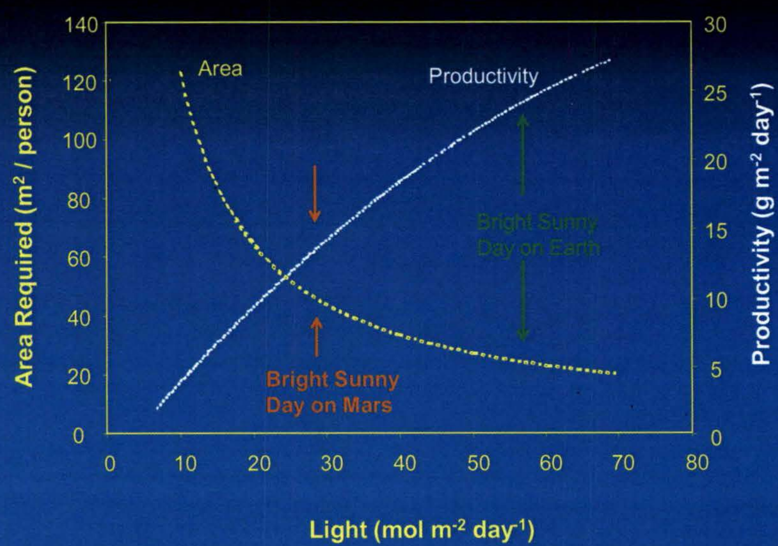
## Light, Productivity, and Crop Area Requirements

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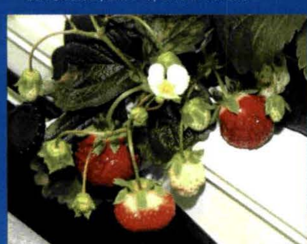
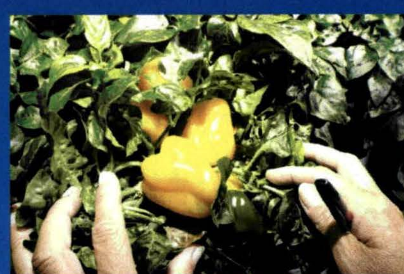
## Recent Testing with "Salad" Crops

*Cultivar Comparisons:*

- Lettuce: Waldmanns' Green, Ostinata, Flandria, (Red Sails, Eruption, Outredgeous)
- Onion: Kinka, Kruncho, Choho, Choetsu, Guardsman, Pacific Pearl, Evergreen Hardy White, Deep Purple
- Radish: Cabernet, Fireball, Cherriette, Giant White Glove, Cherry Belle, Sora, Cherry Bomb II, Vintage
- Tomato: MicroTina, Florida Petite, Red Robin
- Pepper: Triton, Hanging Fruit Basket, False Alarm
- Strawberry: Tristar, Tribute, Whitney, Cavendish, Evie-3, and Everest.





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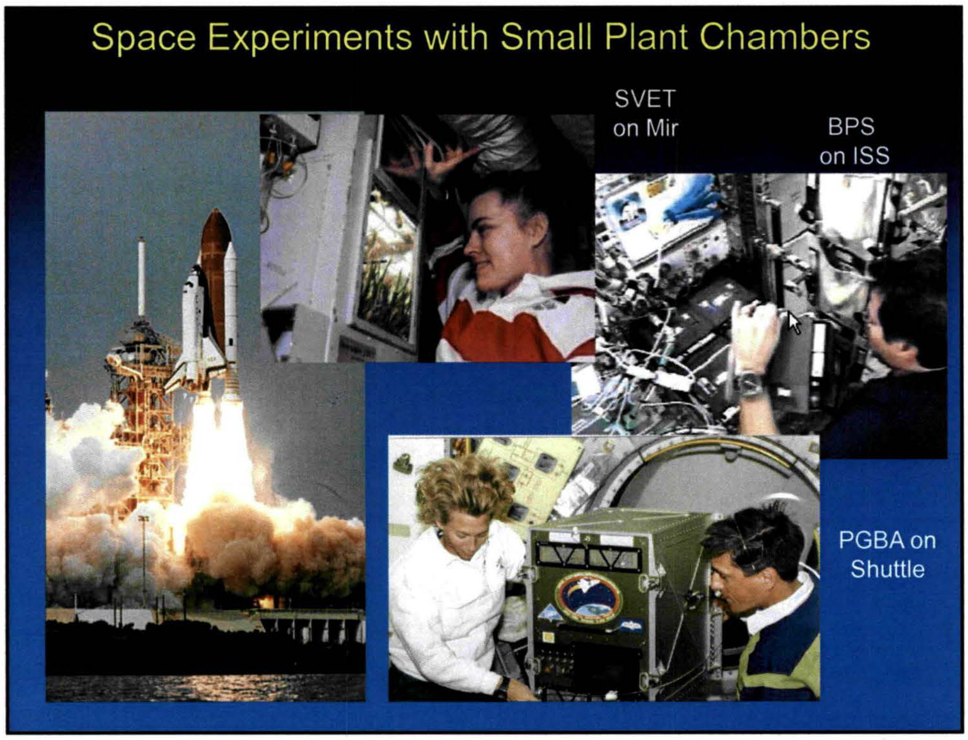
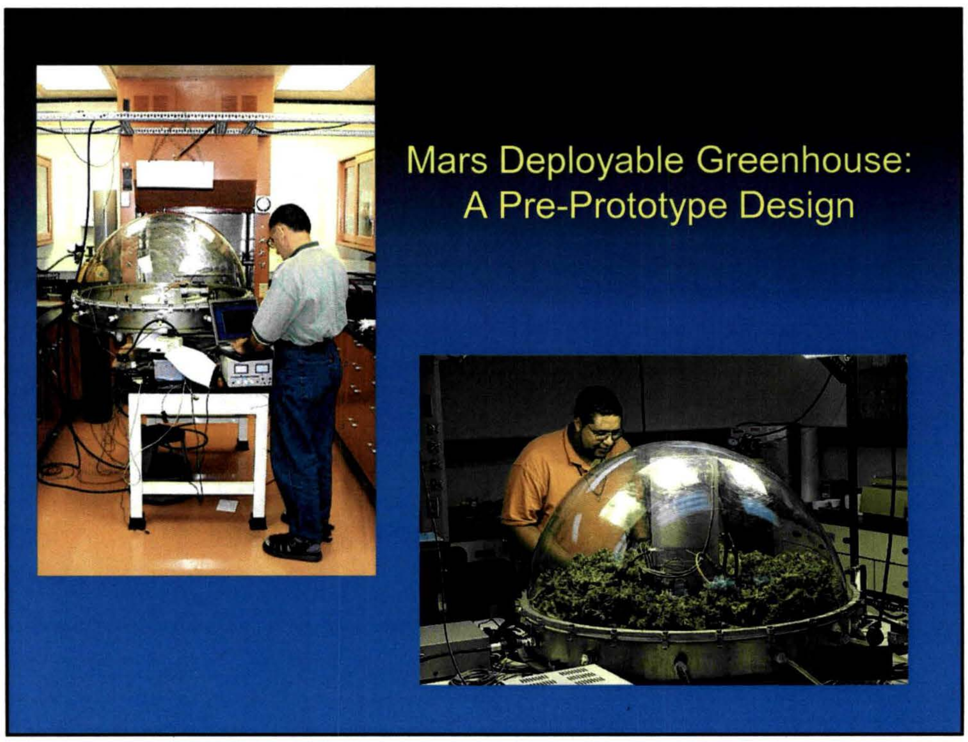
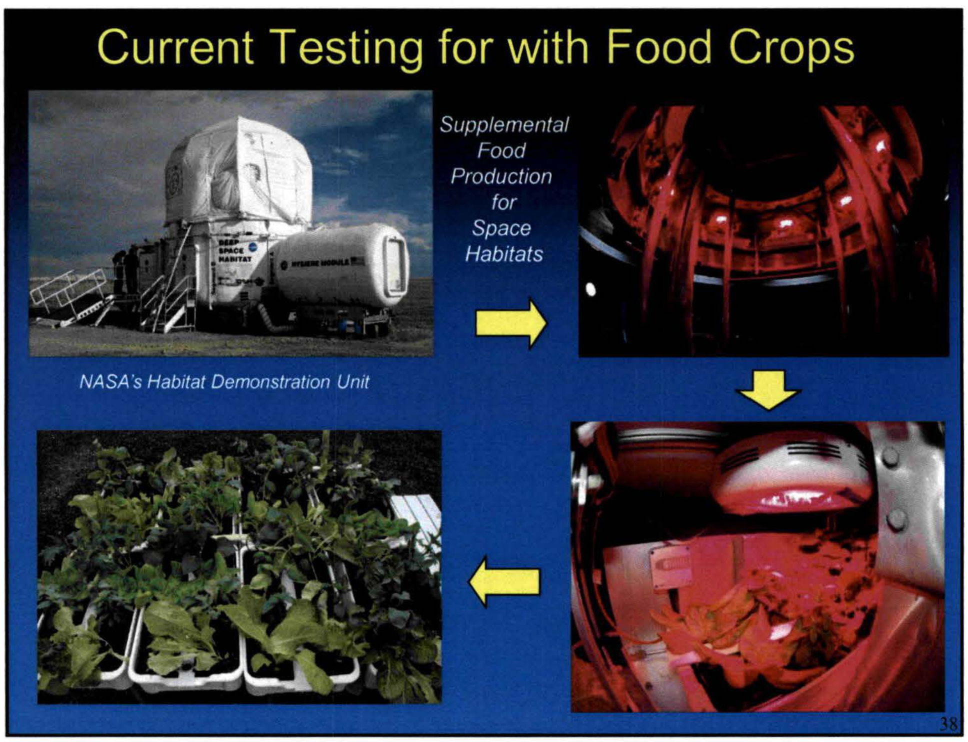

Space Experiments with Small Plant Chambers
SVET
on Mir
BPS
on ISS
PGBA on
Shuttle


Mars Deployable Greenhouse:
A Pre-Prototype Design


One Human and 11 m2 of Wheat !


Current Testing for with Food Crops
Supplemental Food Production for Space Habitats
NASA's Habitat Demonstration Unit
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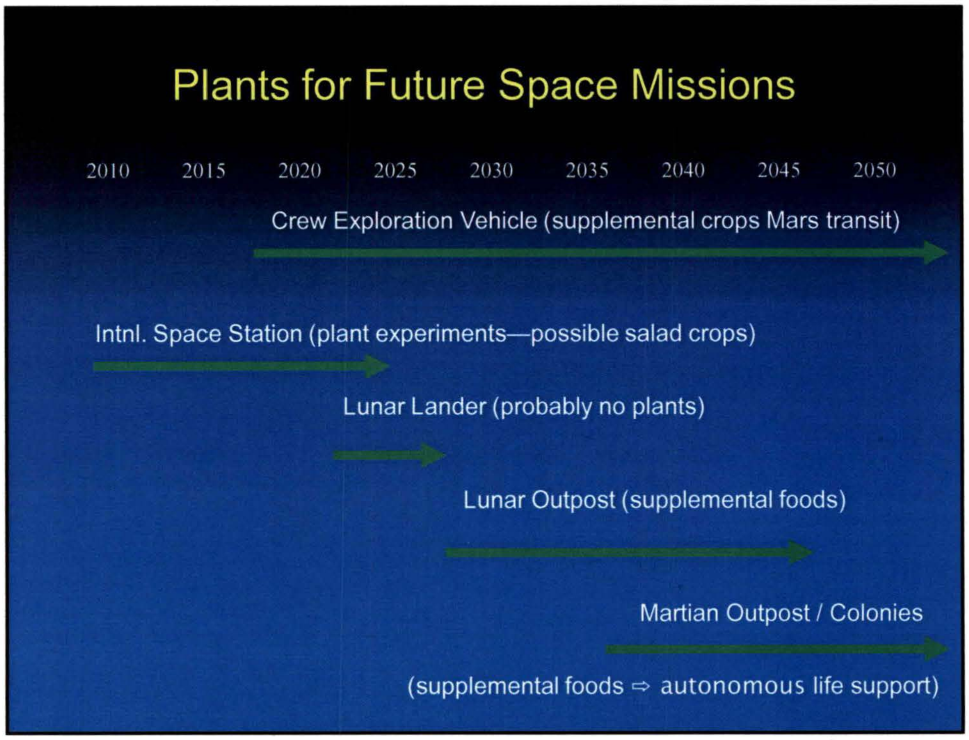
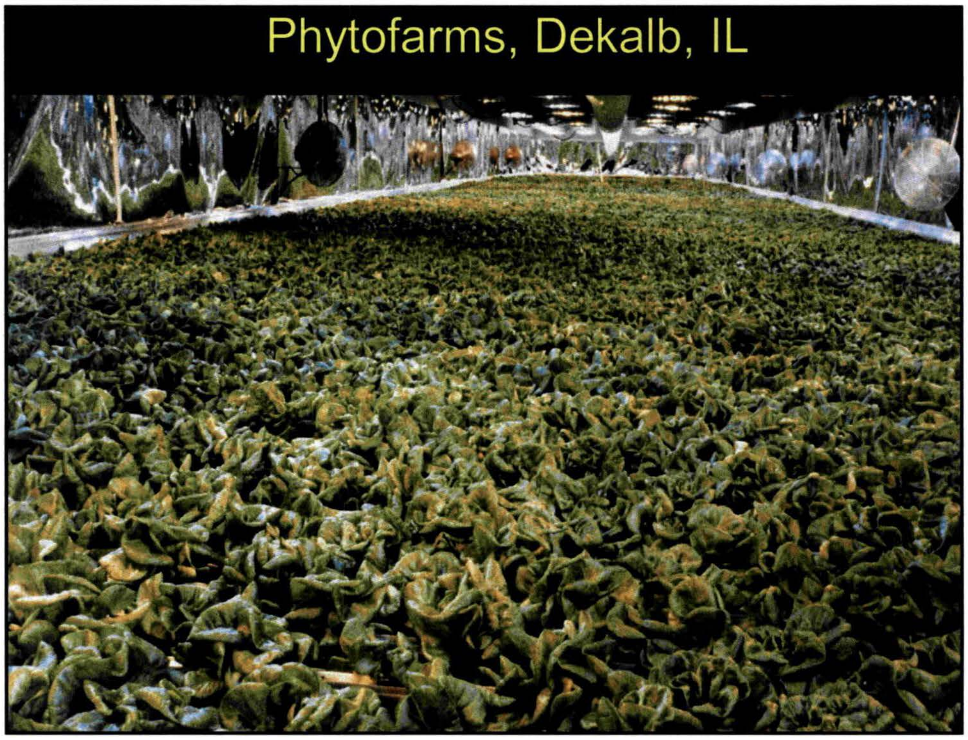
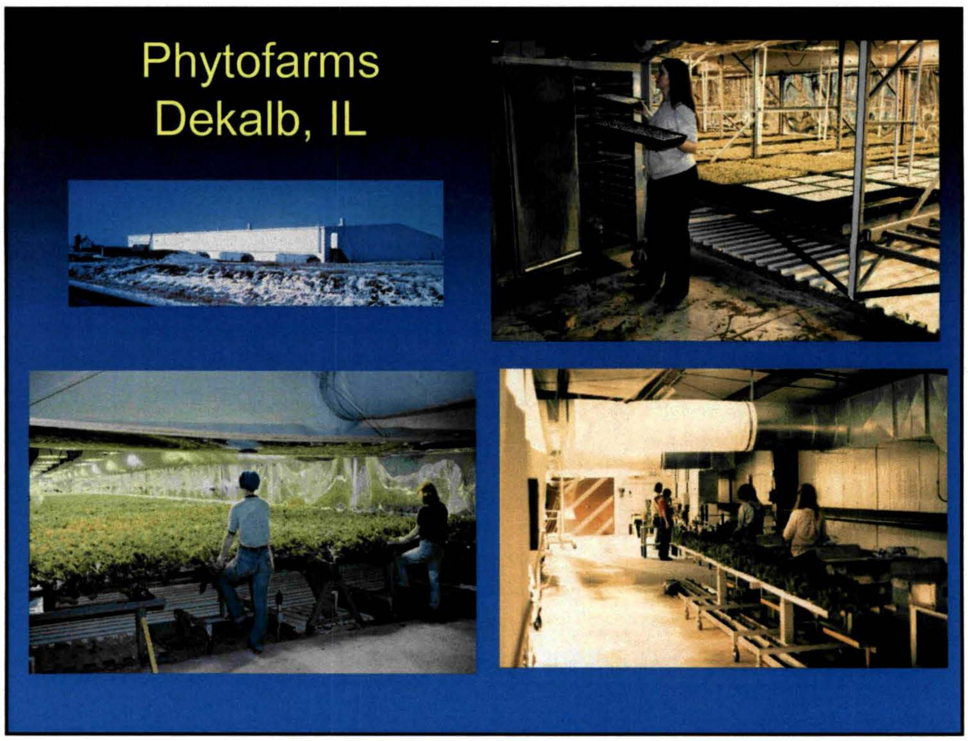



## Phytofarms: A Pioneering Effort at CEA and Vertical Agriculture

- 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 its demand to off-peak hours.


Phytofarms, Dekalb, IL


Phytofarms
Dekalb, IL


Phytofarms
Dekalb, IL
SALAD TREASURES
LEAF LETTUCE
BIBB LETTUCE
SALAD SPINACH
FRESH HERBS


KSC Advanced Life Support Team, Hangar L, KSC 1994