Controlled Environment Horticulture for Space and Earth

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Why horticulture for 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.

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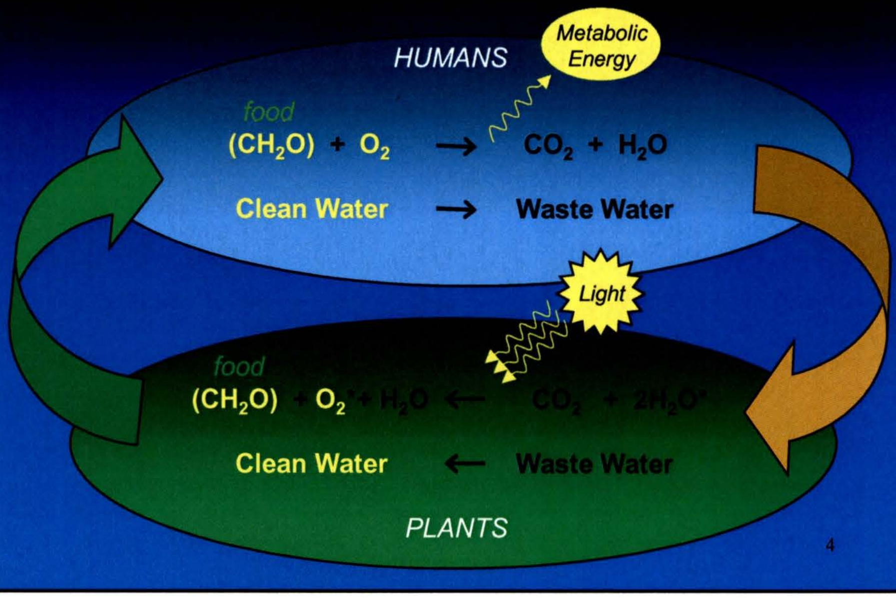
Plants and "Bioregenerative" Life Support



4

Space habitats for humans will require protected, controlled environments.
The same will be true for plants.

→ To grow crops in space would also require a controlled environment approach

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Controlled Environment Considerations for Space

Similar for Earth ↑

- Temperature
- Humidity
- Air Circulation
- Lighting
  - Electric Sources
  - Solar
- Carbon Dioxide

Unique for Space ↓

- Atmospheric Closure
  - Super-elevated CO_2, pO_2, Volatile Organic Compounds (VOCs)
- Gravity
  - μ-g Orbiting or Transit, 1/3 g (Mars), 1/6 g (Moon)
- Radiation
  - Shielding for solar events, cosmic rays

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If plants and are used for life support, they must be measured against competing options, such as stowage / resupply or physico-chemical technologies.

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Key Factors for Choosing Life Support Technologies

- Mass
- Power Requirements
- Volume
- Stowage and Deployment
- Ease of Integration
- Reliability / Risk of Failure

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Some Drivers for Space Horticulture and Life Support:

→ *Maximize yields to reduce system mass and volume*

→ *Select nutritious and easily managed crops*

→ *Consider dwarf and high harvest index crops*

→ *Energy efficient lighting*

→ *Develop reliable support hardware to reduce failures*

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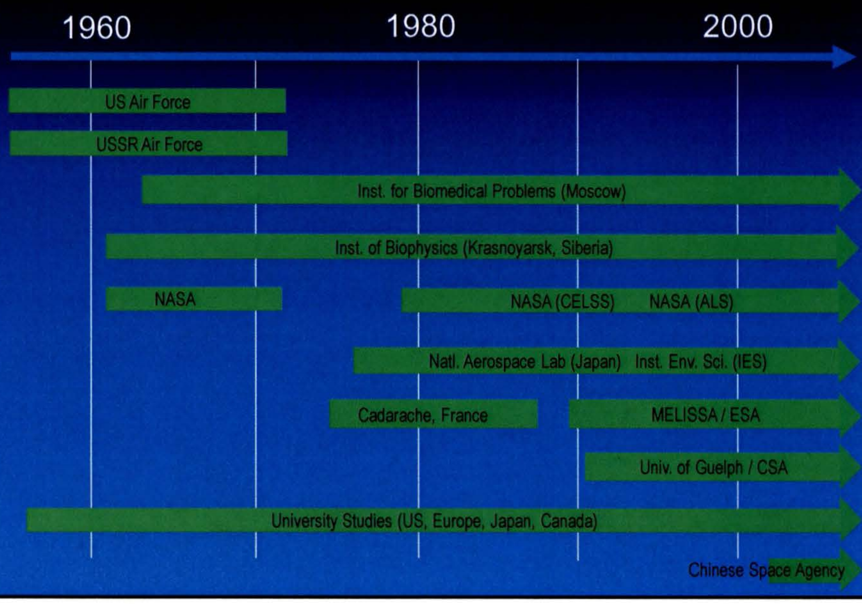
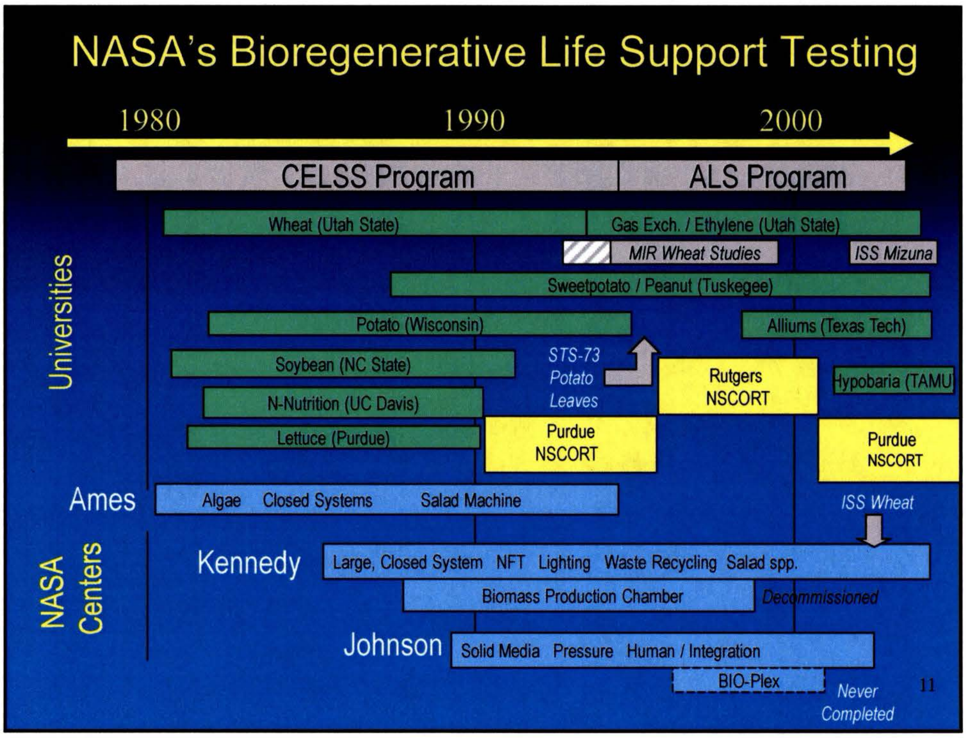
Bioregenerative Life Support Testing around the World



10



Potential 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.*

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Some Observations from NASA-Sponsored Controlled Environment Horticulture

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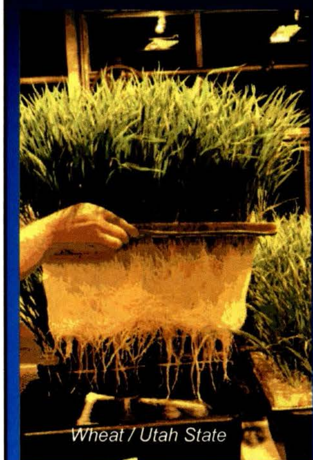
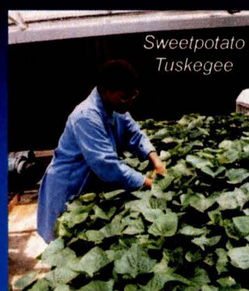
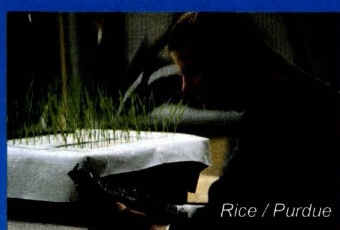
Use of Recirculating Hydroponics







Conserves Water & Nutrients
Optimizes Growth
Reduces System Mass

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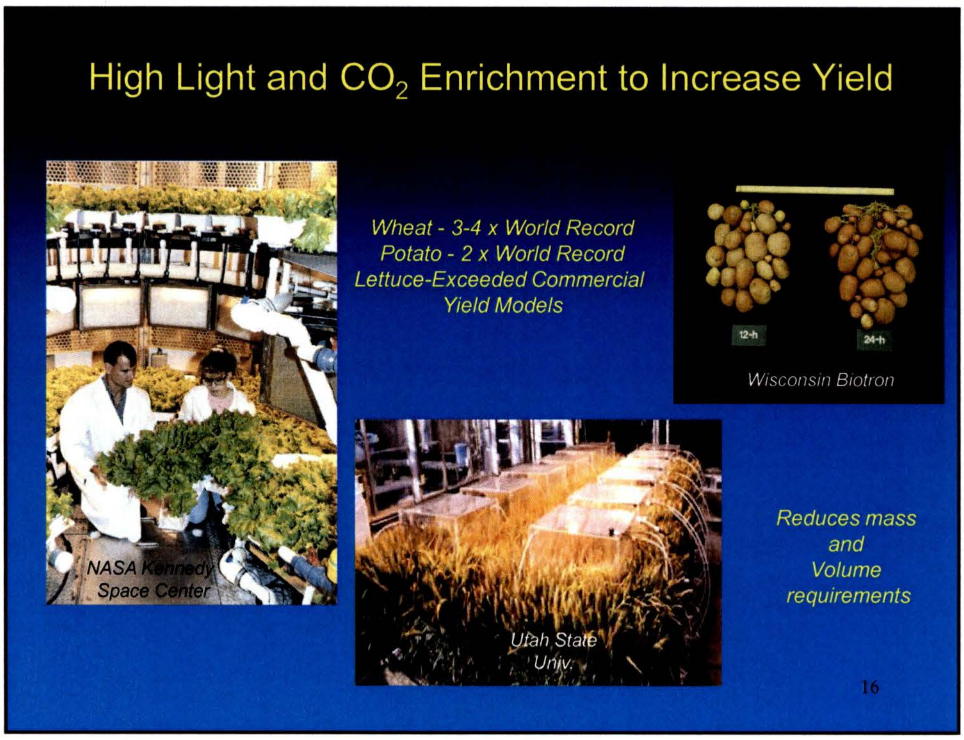
Including Root Zone Crops in Nutrient Film Technique
Peanut
Potato
Wheeler et al., 1990. Amer. Potato J. 67:177-187; Mackowiak et al. 1998. HortScience 33:650-651
15


High Light and CO_2 Enrichment to Increase Yield
Wheat - 3-4 x World Record
Potato - 2 x World Record
Lettuce-Exceeded Commercial Yield Models
12-h
24-h
Wisconsin Biotron
NASA Kennedy Space Center
Utah State Univ.
Reduces mass and Volume requirements
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Understanding Atmospherically Closed Systems
NASA Ames Research Center
Purdue Univ.
NASA Johnson Space Center
NASA KSC
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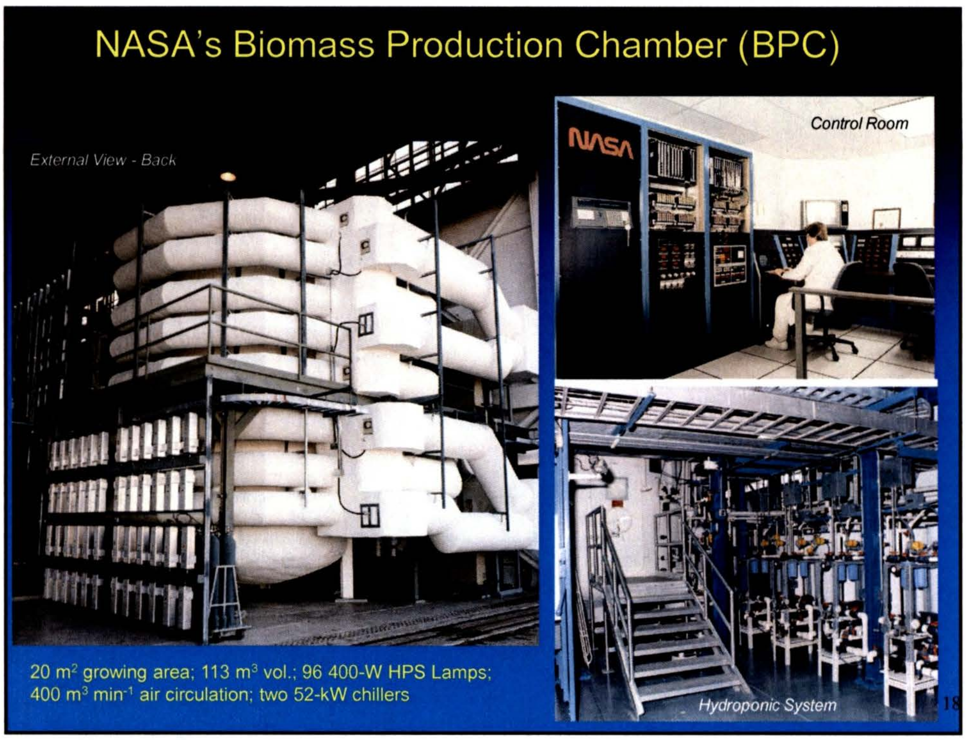
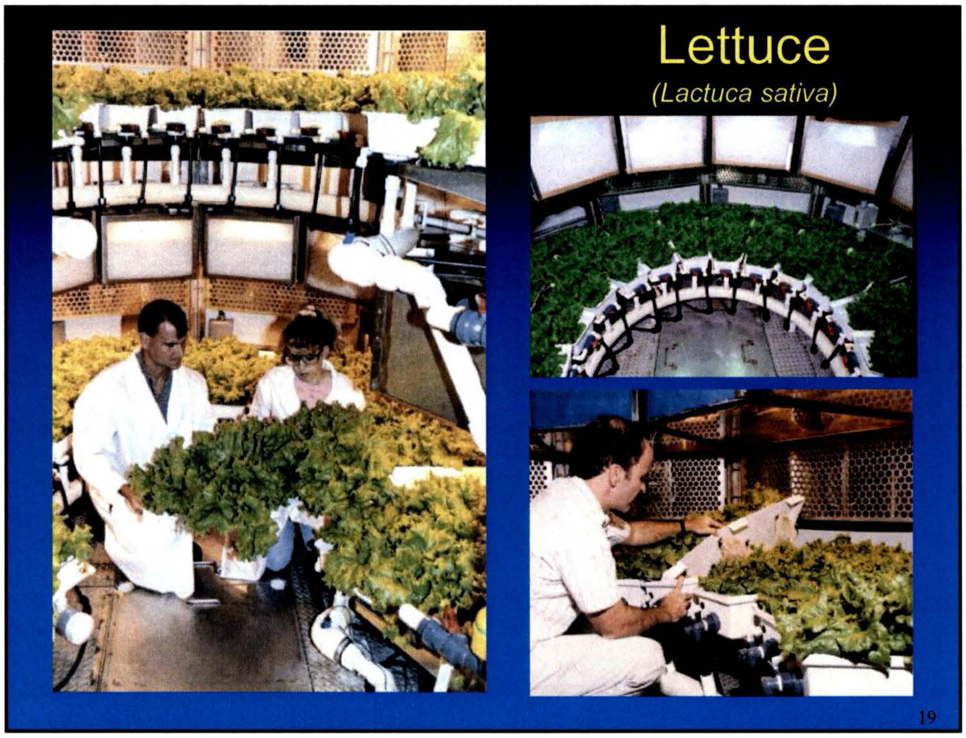
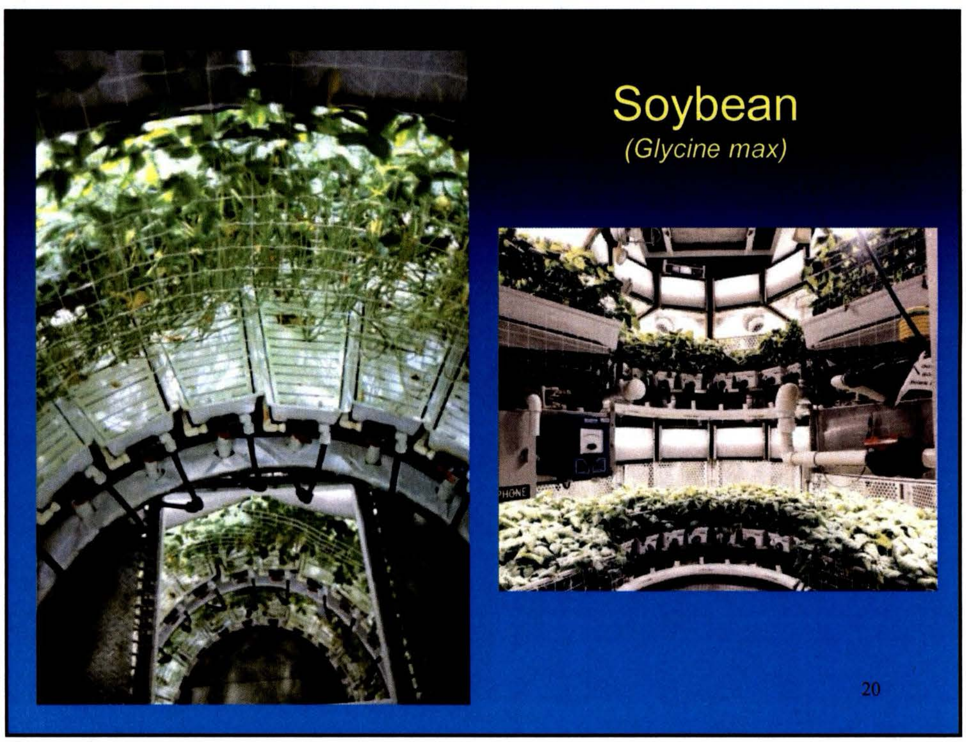
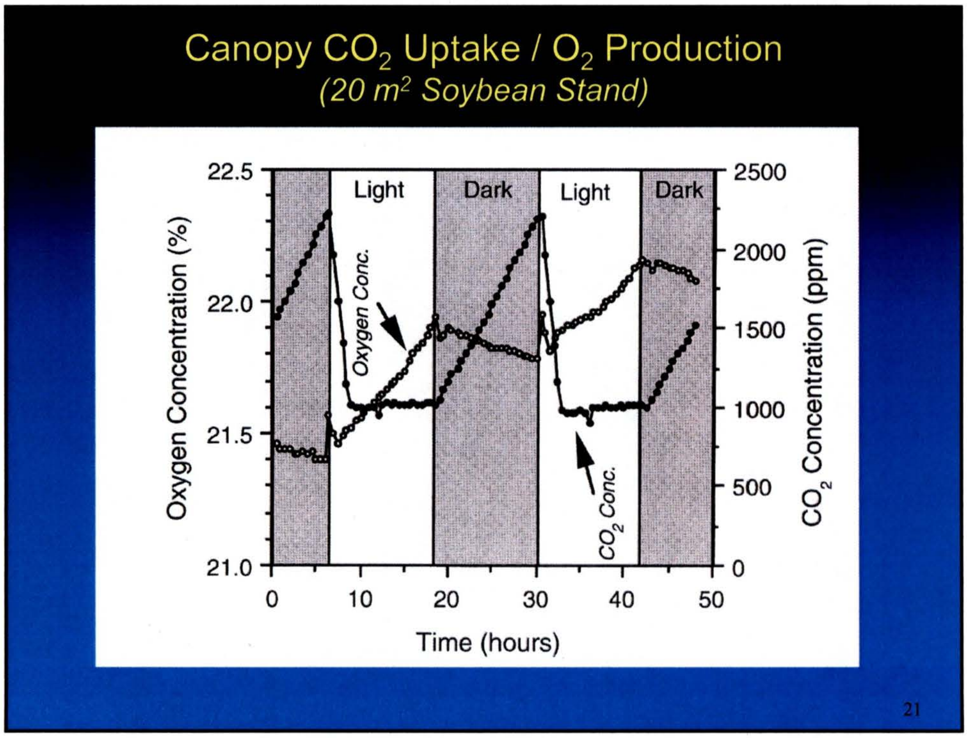
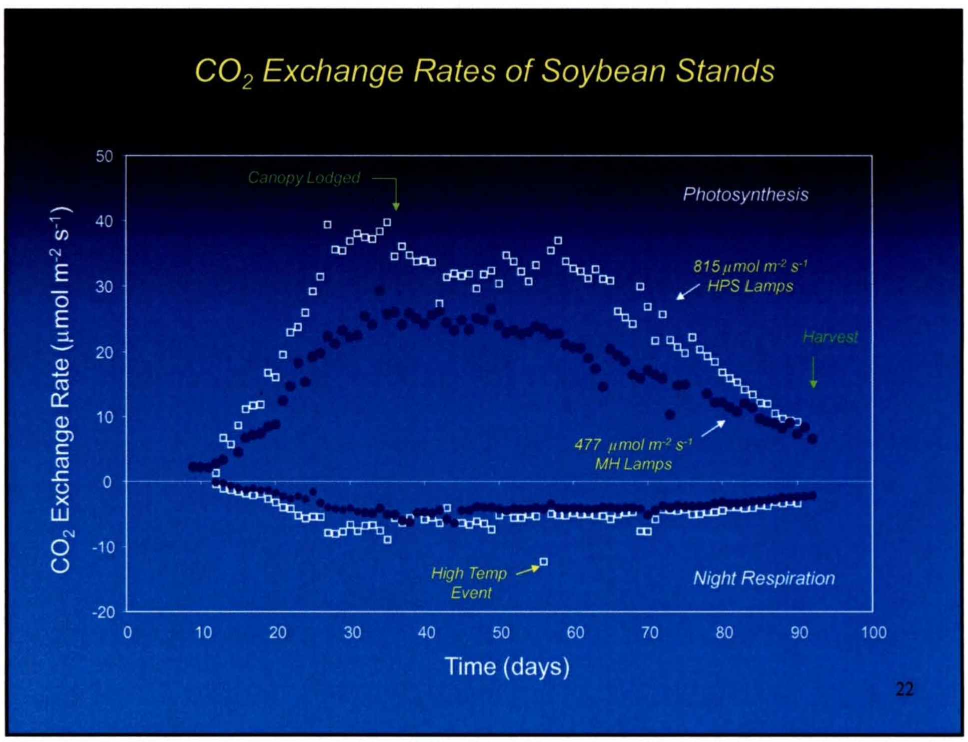
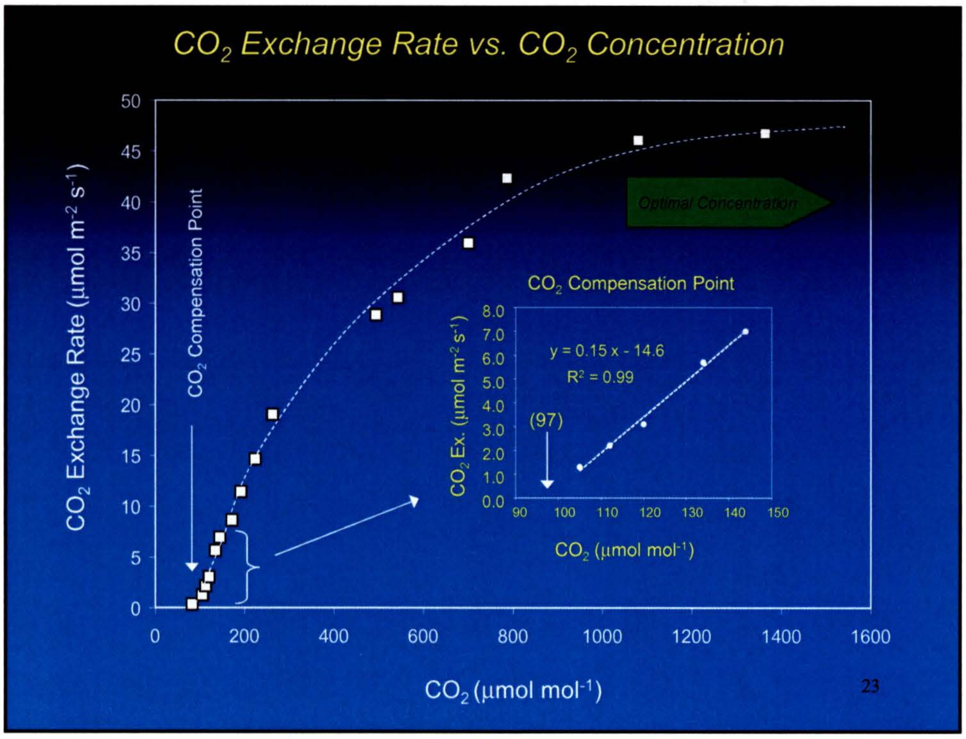

NASA's Biomass Production Chamber (BPC)
External View - Back
Control Room
NASA
Hydroponic System
20 m² growing area; 113 m³ vol.; 96 400-W HPS Lamps; 400 m³ min⁻¹ air circulation; two 52-kW chillers
18


Lettuce
(Lactuca sativa)
19


Soybean
(Glycine max)
20


Canopy CO2 Uptake / O2 Production
(20 m2 Soybean Stand)
Light
Dark
Light
Dark
Oxygen Conc.
CO2 Conc.
Oxygen Concentration (%)
CO2 Concentration (ppm)
22.5
22.0
21.5
21.0
2500
2000
1500
1000
500
0
0
10
20
30
40
50
Time (hours)
21


CO2 Exchange Rates of Soybean Stands
Canopy Lodged
Photosynthesis
815 μmol m-2 s-1
HPS Lamps
Harvest
477 μmol m-2 s-1
MH Lamps
High Temp
Event
Night Respiration
CO2 Exchange Rate (μmol m-2 s-1)
50
40
30
20
10
0
-10
-20
0
10
20
30
40
50
60
70
80
90
100
Time (days)
22



Some Volatile Organic Compounds in Closed Systems

Humans	Plants
acetaldehyde	benzaldehyde
acetone	2-butanone
ammonia	carbon disulfide
n-butyl alcohol	ethylene
carbon monoxide	2-ethyl-1-hexanol
caprylic acid	heptanal
ethanol	hexanal
ethyl mercaptan	2-hexen-1-ol acetate
hydrogen	isoprene
hydrogen sulfide	limonene
indole	2-methylfuran
methanol	nonanal
methane	ocimene
methyl mercaptan	α-pinene
propyl mercaptan	β-pinene
pyruvic acid	α-terpinene
skatole	tetrahydrofuran
valeraldehyde	tetramethylurea
valeric acid	thiobismethane

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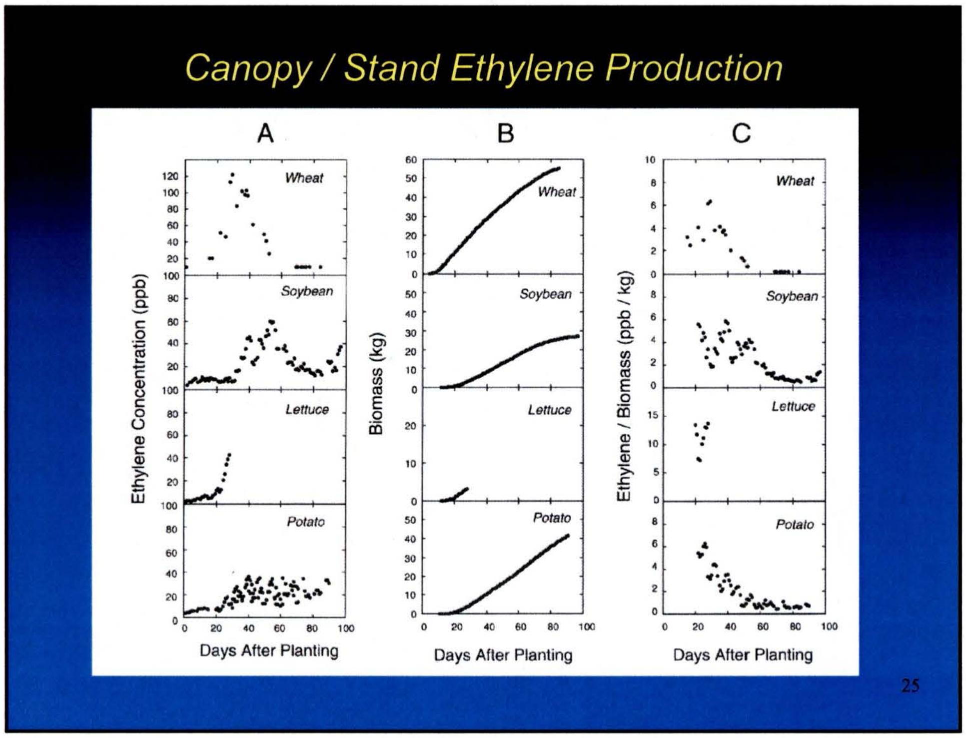
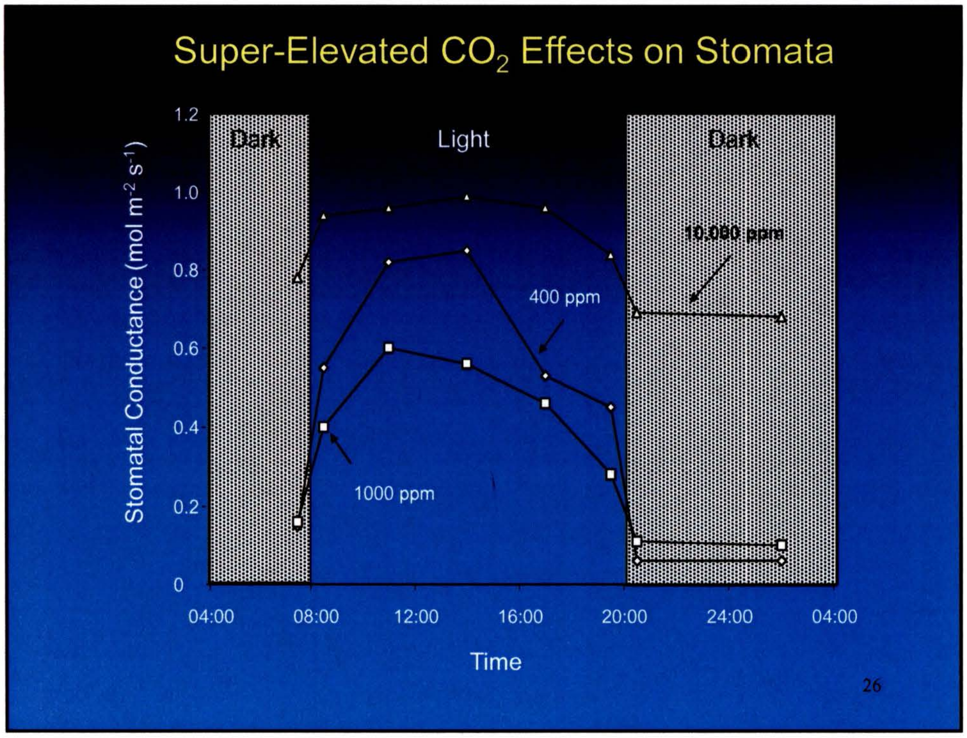

Canopy / Stand Ethylene Production
A
B
C
Ethylene Concentration (ppb)
Biomass (kg)
Ethylene / Biomass (ppb / kg)
Wheat
Soybean
Lettuce
Potato
Days After Planting
25


Super-Elevated CO_2 Effects on Stomata
Dark
Light
Dark
10,000 ppm
400 ppm
1000 ppm
Stomatal Conductance (mol m^{-2} s^{-1})
Time
04:00
08:00
12:00
16:00
20:00
24:00
04:00
26

Physiological Disorders in Controlled Environments

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Leaf Tipburn

Lettuce cv. Flandria

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Long Photoperiod Intolerance

Potato cv. Denali

Note: Upright, chlorotic leaves

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Oedema or Intumescence

Potato
cv. Denali

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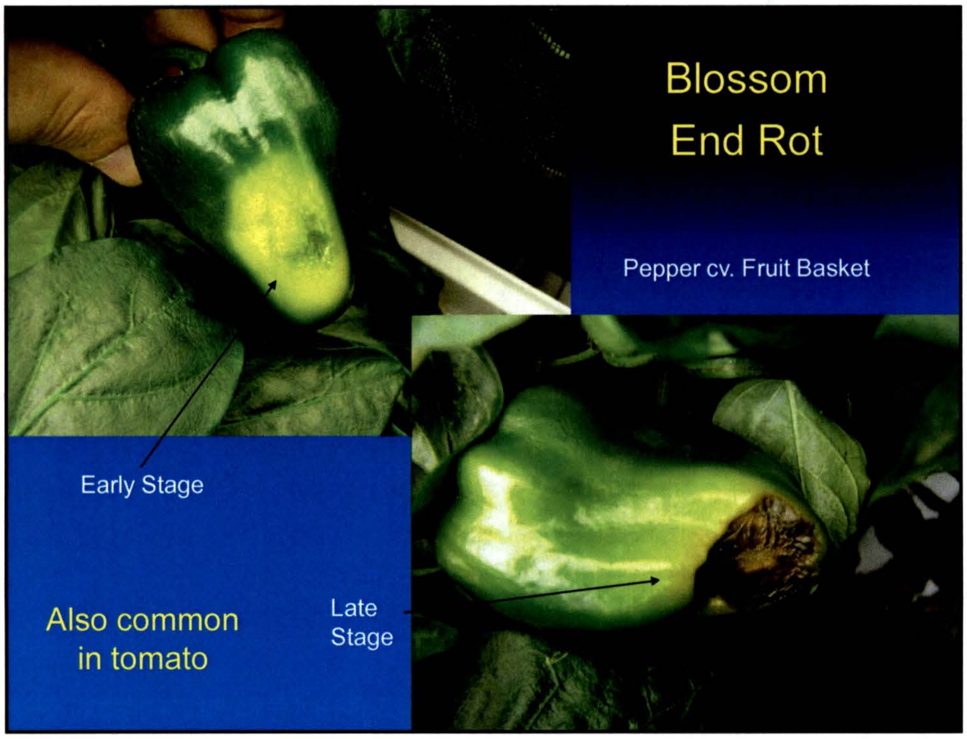
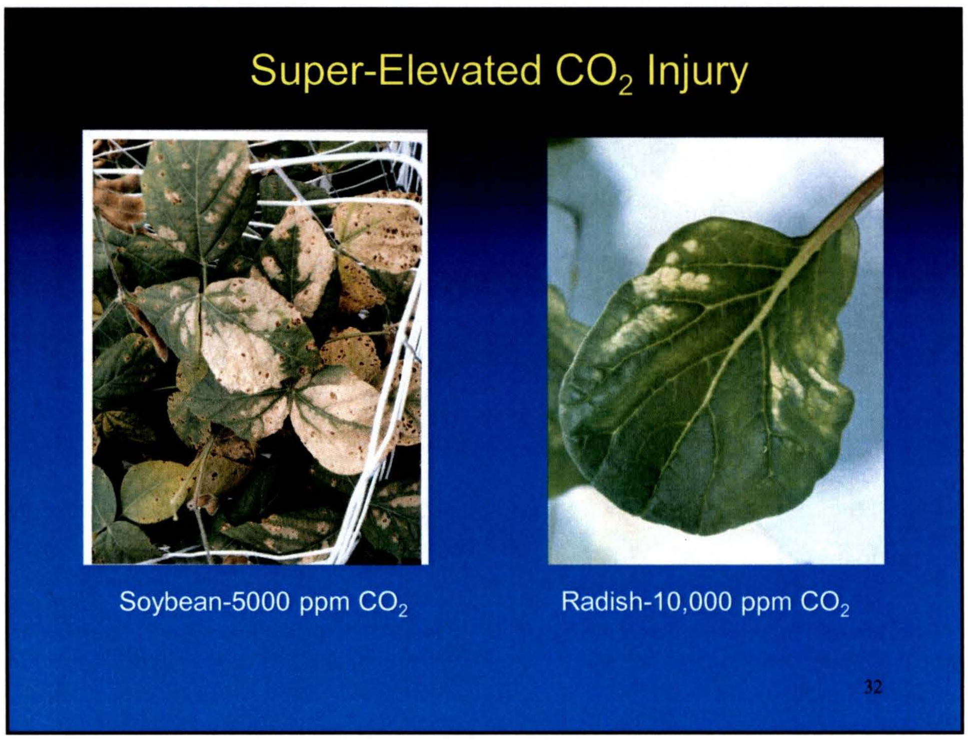

Blossom
End Rot
Pepper cv. Fruit Basket
Early Stage
Also common
in tomato
Late
Stage


Super-Elevated CO_2 Injury
Soybean-5000 ppm CO_2
Radish-10,000 ppm CO_2
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Leaf Epinasty from Ethylene

Potato cv. Denali

Wheat cv. Yecora Rojo

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The Importance of Lighting

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Electric Light 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.*
**** *Green LEDs ~10-15% efficient; state-of-art white LEDs ~ 20-25% efficient,*

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LEDs for Growing Plants

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

John Sager, KSC, Testing Prototype Flight Plant Chambers with LEDs

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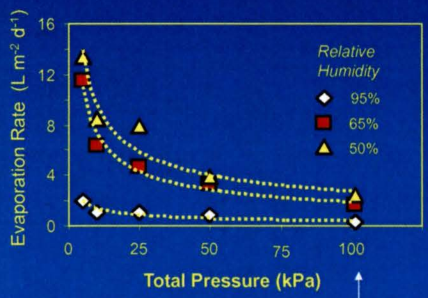
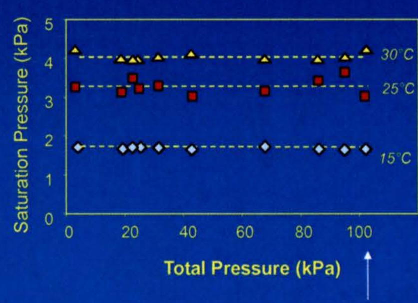
Atmospheric Pressures Considerations

Advantages of low pressure:

- *Reduced structural mass*
- *Reduced gas leakage (and resupply)*
- *More possibilities for transparent materials*





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Low Pressure, Deployable Greenhouse Concepts

→ Inflatable, low mass, easy stowage
→ Low pressure to reduce leakage
→ Might be covered at night

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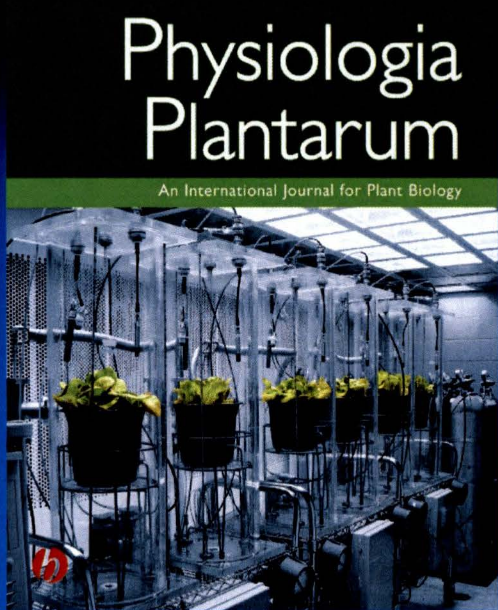

Hypobaric
Chambers
Texas A&M
University

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How Can Controlled Environment Horticulture for Space Relate to Earth ?

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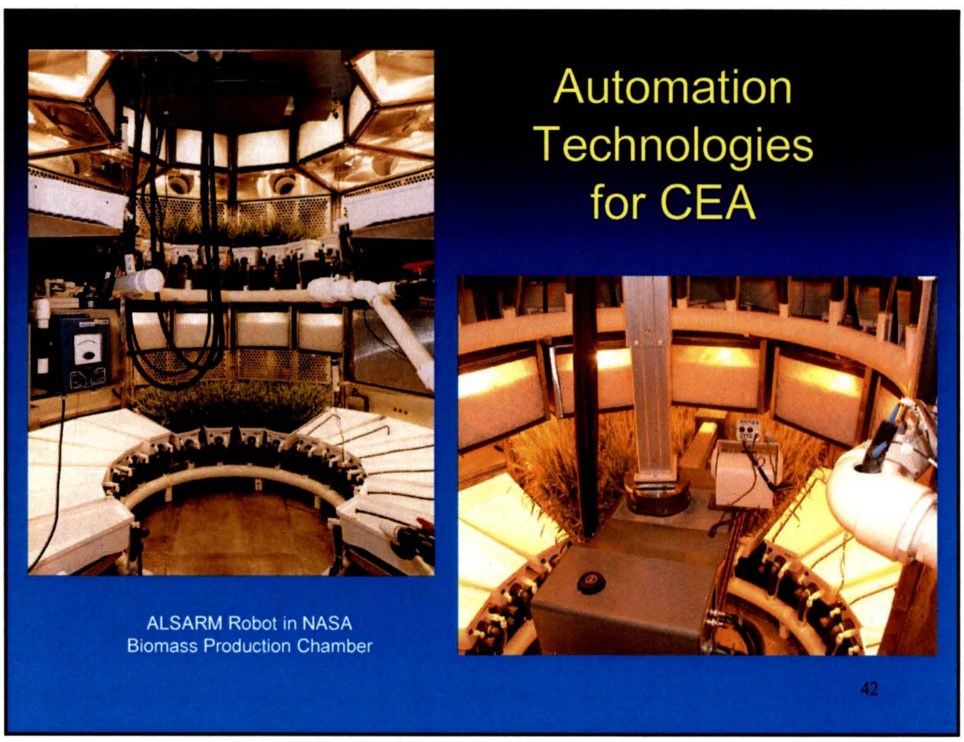
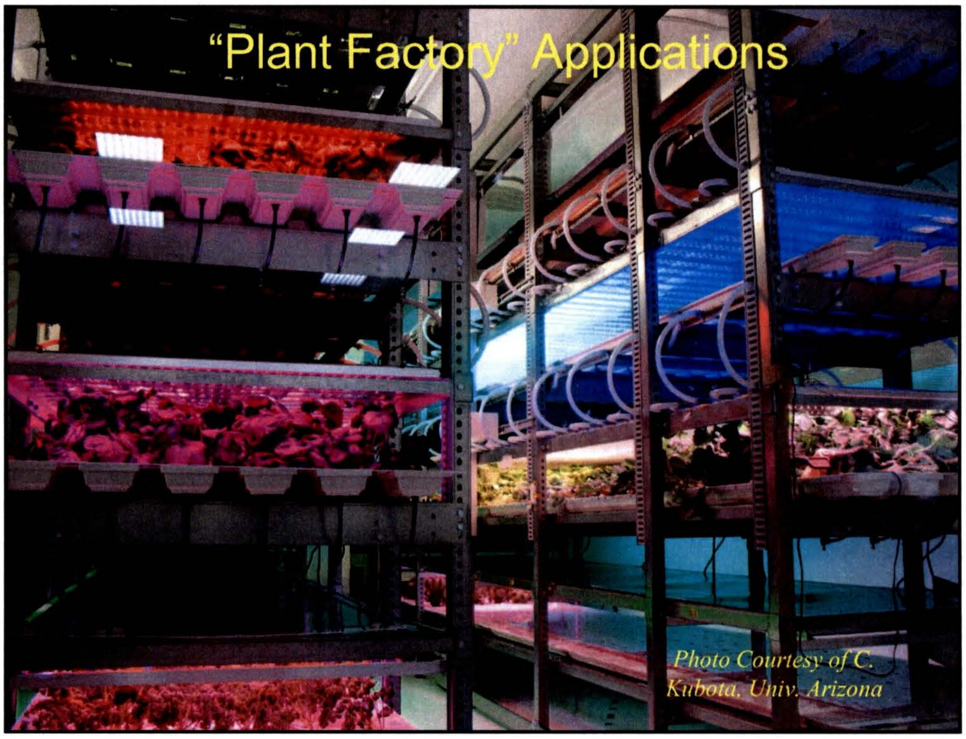
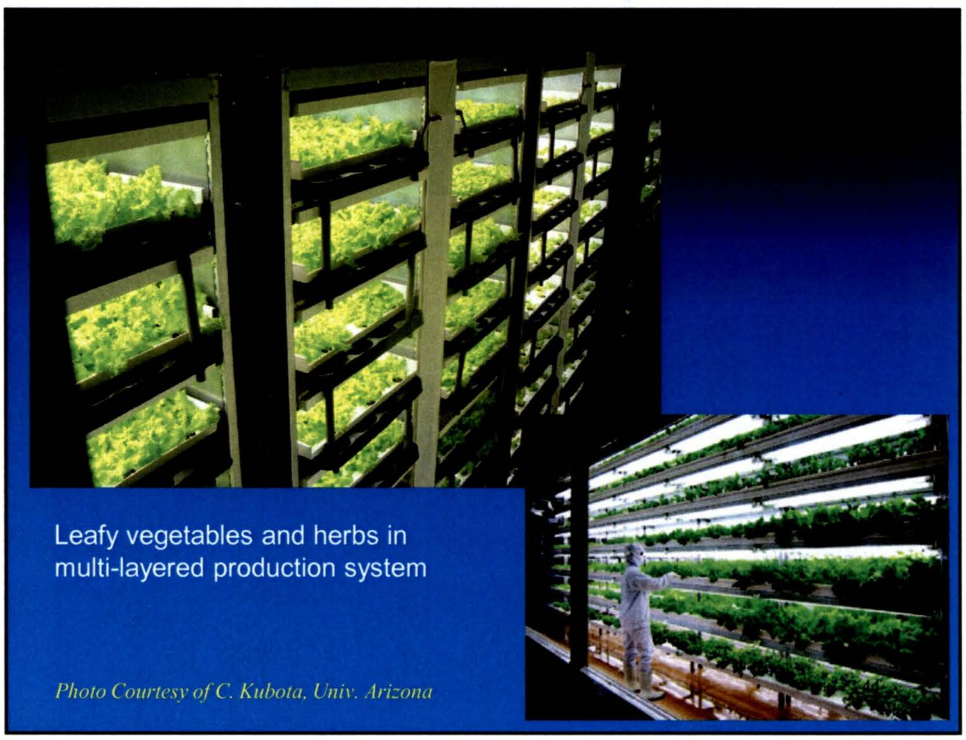
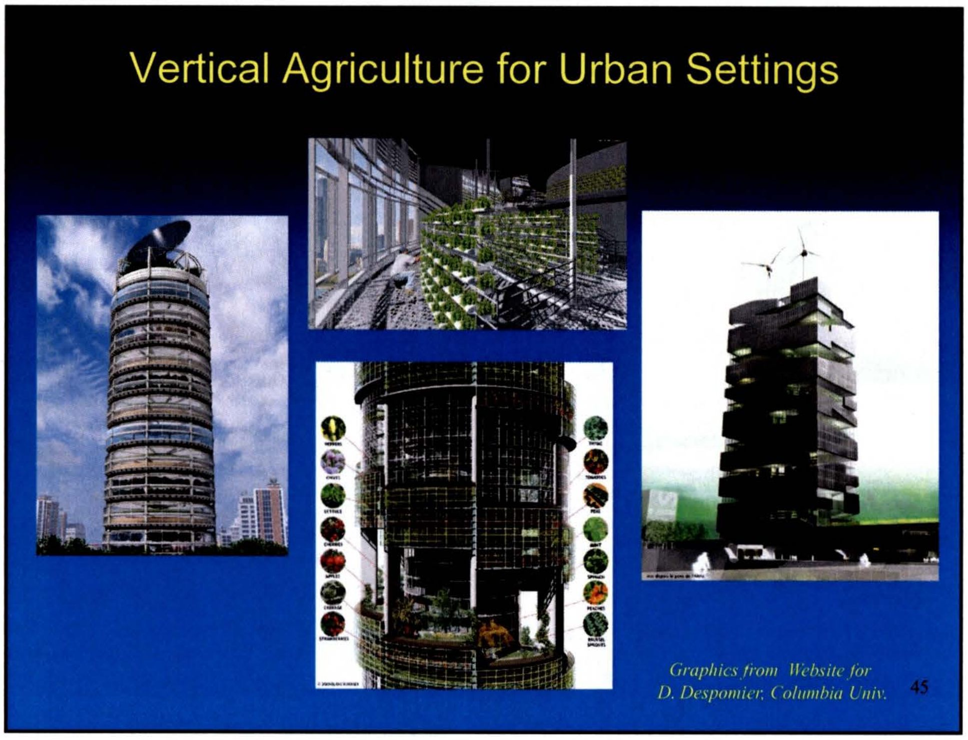
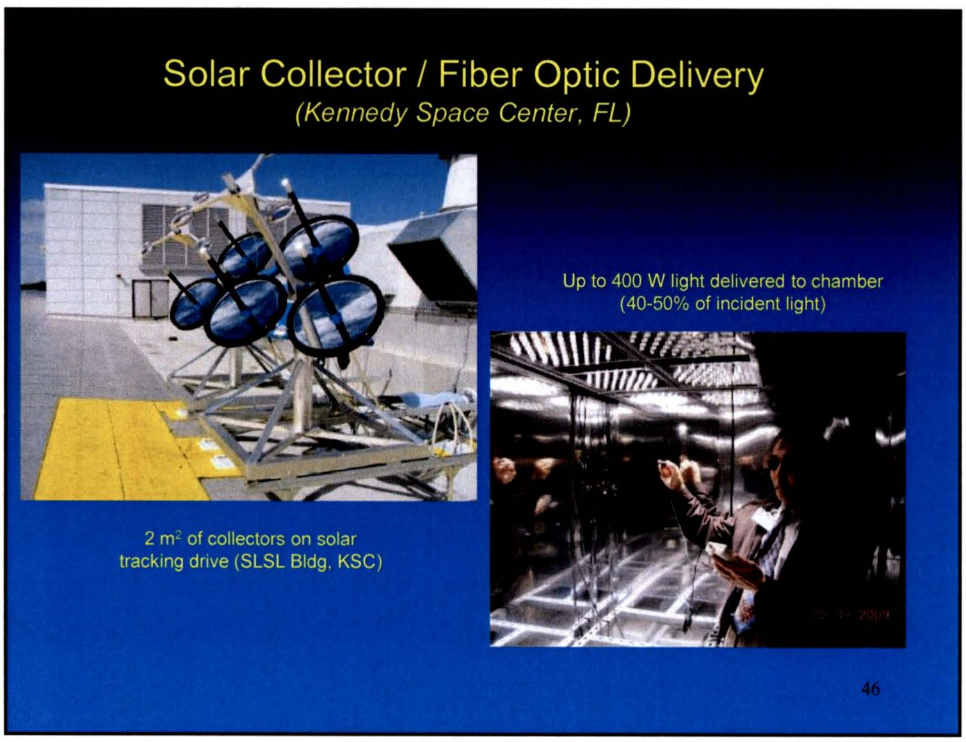
Help Improve :
Hydroponic Techniques
Monitoring and Control Technologies
Automation
Electric Lighting Efficiency
Explore New Crops, Develop New Cvs.
Hydroponic Lettuce, Ithaca NY


Automation
Technologies
for CEA
ALSARM Robot in NASA
Biomass Production Chamber
42


"Plant Factory" Applications
Photo Courtesy of C. Kubota, Univ. Arizona


Leafy vegetables and herbs in multi-layered production system
Photo Courtesy of C. Kubota, Univ. Arizona


Vertical Agriculture for Urban Settings
Graphics from Website for
D. Despomier, Columbia Univ.
45


Solar Collector / Fiber Optic Delivery
(Kennedy Space Center, FL)
Up to 400 W light delivered to chamber
(40-50% of incident light)
2 m2 of collectors on solar
tracking drive (SLSL Bldg, KSC)
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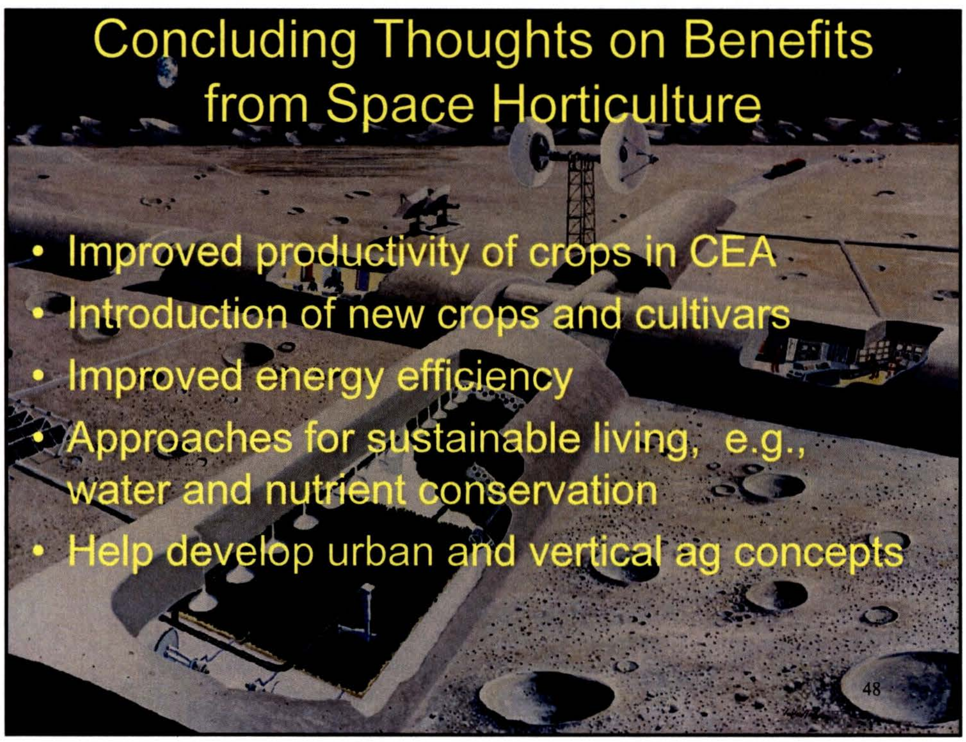
Vertical
Farming
Happening
Right Now
Texas Plant-Expressed
Vaccine Consortium
Photos Courtesy of Illumitex
Austin, TX
47


Concluding Thoughts on Benefits from Space Horticulture
• Improved productivity of crops in CEA
• Introduction of new crops and cultivars
• Improved energy efficiency
• Approaches for sustainable living, e.g., water and nutrient conservation
• Help develop urban and vertical ag concepts
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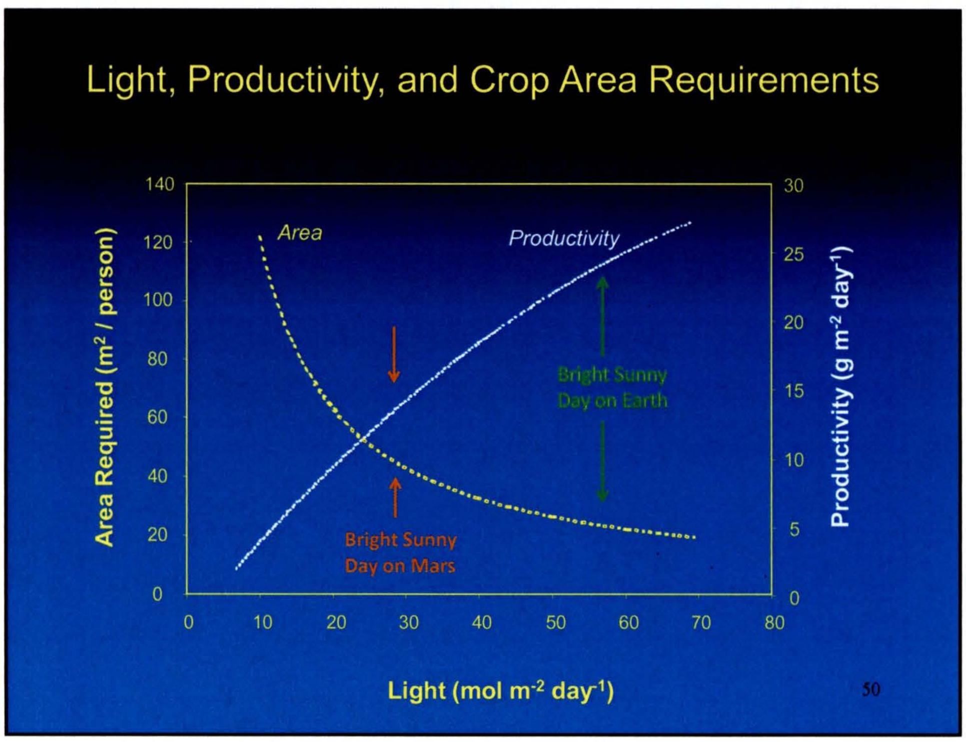
Kennedy Space Center Advanced Life Support Team


Light, Productivity, and Crop Area Requirements
Area
Productivity
Bright Sunny Day on Earth
Bright Sunny Day on Mars
Area Required (m2 / person)
Productivity (g m-2 day-1)
Light (mol m-2 day-1)
0
20
40
60
80
100
120
140
0
5
10
15
20
25
30
0
10
20
30
40
50
60
70
80
50