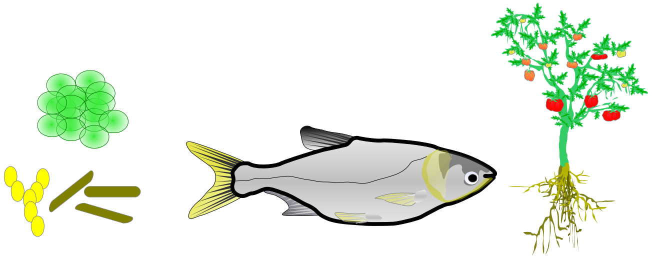
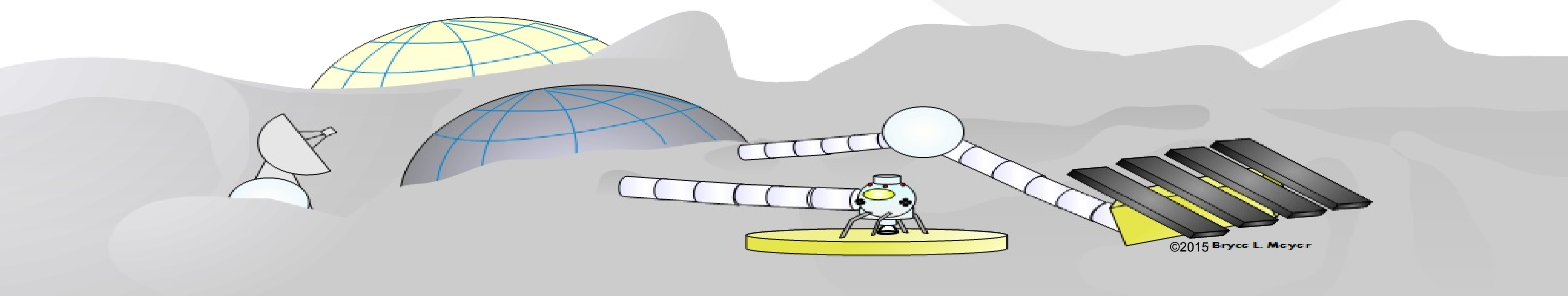


Of Fruits and Fishes: A Space Farm and Recycling Concept

Bryce L. Meyer

SPACE 2015, 31 August – 02 September 2015, Pasadena, CA, USA



Overview

- Purpose and Goals, Assumptions
- Mass Balances & Simplified Chemistry
- Pseudo Ecosystem
- Habitat, Stages and Species
- Population Sizes, Masses, and Volumes

Purpose and Goals

- Develop the key principles and mechanisms and simplified system design of a space farm that can feed, and recycle the air, water, wastes, from 100 colonists, efficiently, using crop plants and animals.
- Understand sizing, initial requirements, and combination of in situ vs. shipped in mass.
- Quantify where additional work should focus to add reality.

Assumed Conditions

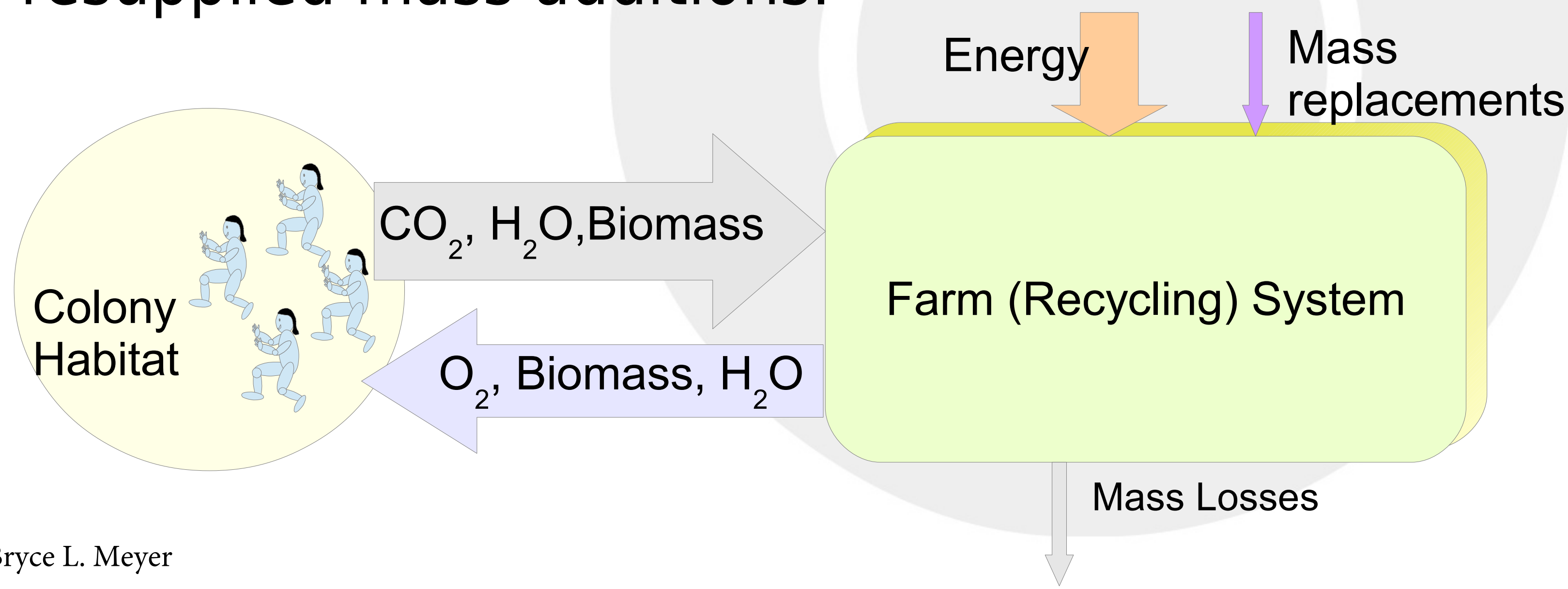
- 100 unchanging humans, who eat 2,000 kcals per day, split between vegetables and animals. The habitat itself is not part of the analysis.
- Infinite energy as needed, including electricity and warmth.
- Simplified chemistry and partial pressures...i.e. concern is what changes. Ideal reactions.
- Optimal conditions for all living things.
- Assume gases, liquids, and solids can be moved ideally where needed.

Mass Balance

- Mass is conserved in individuals, populations, and stages
- Mass is chemically converted, then either passed or retained in growth (to be passed along later).
  - Chemical conversions determined from common chemical reactions.
- If the farm has no losses, mass is conserved in the farm.

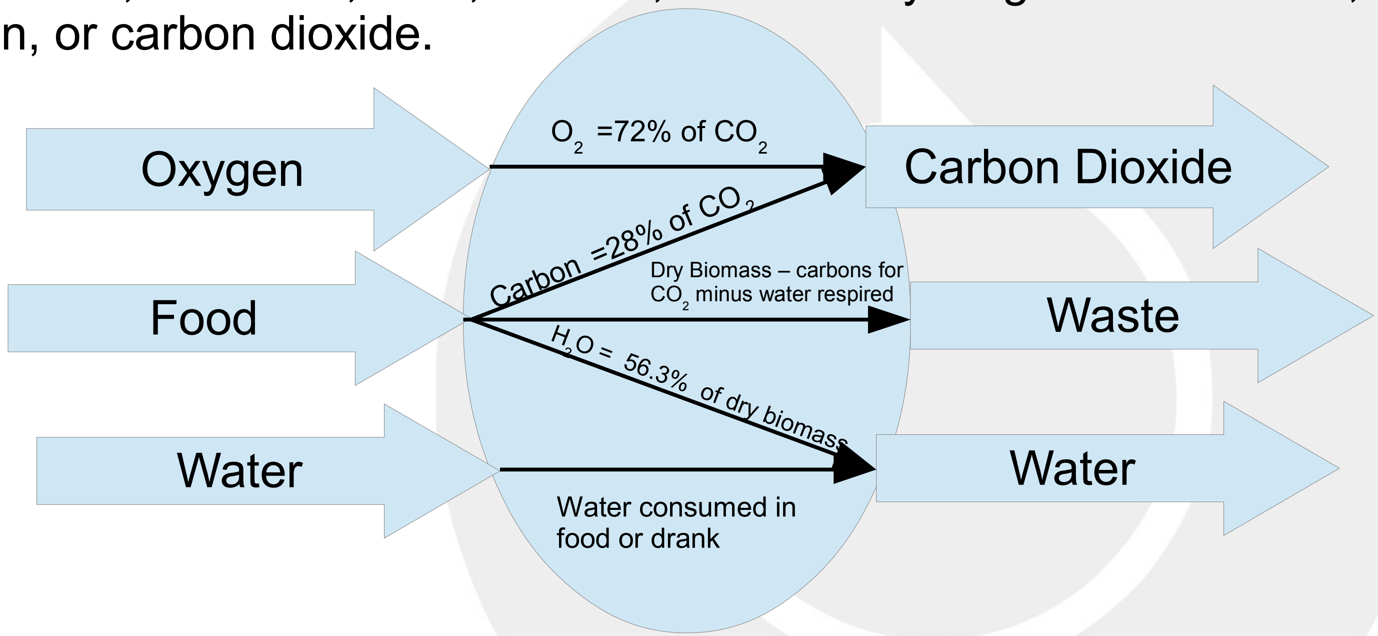
Space Farm as a Black Box

- Habitat exchanges mass in carbon dioxide, water, and biological wastes for oxygen, water, and biological foods
- Once stable, the farm takes in energy, then exchanges any losses due to inefficiency or other losses for resupplied mass additions.



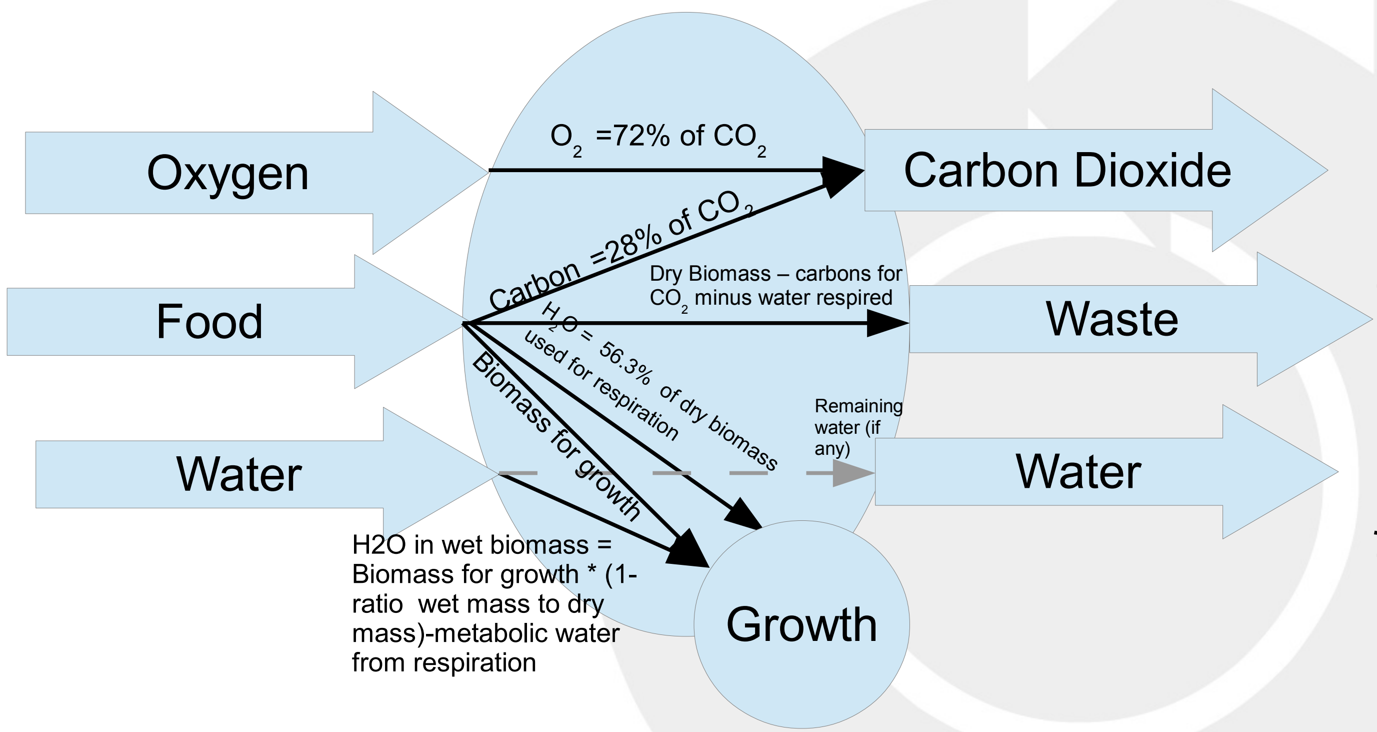
Living Systems: Not growing, Aerobic (i.e. People Stage)

Food, growth, and wastes are all called **biomass** in this presentation. Biomass includes sugars, proteins/amino acids, fats, other organic compounds, ammonia, urea, nitrates, etc. i.e. Anything that isn't water, oxygen, or carbon dioxide.



Biomass is either dry or wet.
Biomass as in living or formerly living tissue, or in biological waste, is wet biomass.
Dry biomass is the fraction of wet biomass if all the water is removed.
The ratio of wet biomass to dry biomass by mass is important, called 'X'
Animals (inc. People) eat wet biomass, and excrete wet biomass.

Living Systems: Growing, Aerobic (i.e. Aquatic Stage)



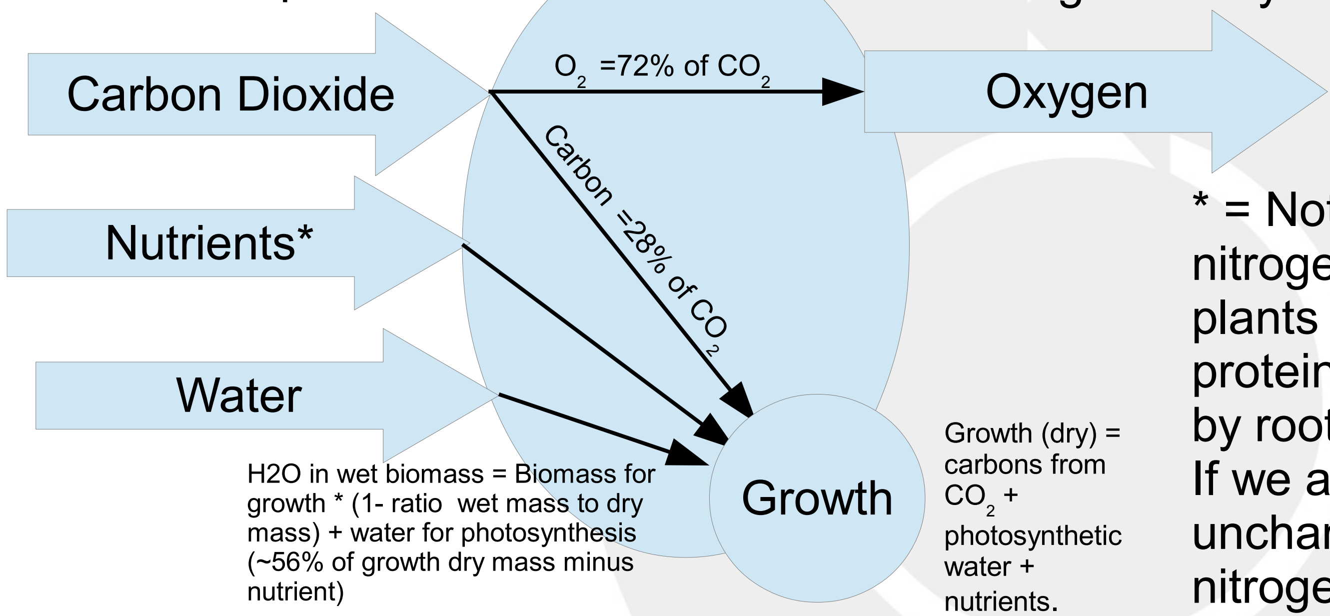
for animals, (I.e. Aquatic Stage fish) growth will be in both individuals in the crop, and in non-crop individuals, i.e breeders and juveniles for the next crop.

Growth is incorporation of organic compounds, water, and gases into living tissue, i.e. wet biomass. Dry biomass from chemical reactions is combined with water inputs to make the wet biomass.

Living Systems: Growing, Photosynthetic
(i.e. Algae Reactor and Hydroponic Stages)

Growth can be extracted as a crop.

Water is needed to form wet biomass, but also to covert carbons into sugars in dry biomass.



* = Note: In air, nitrogen is fixed by plants to make proteins, or absorbed by roots from the soil. If we assume an unchanging amount of nitrogen in the air/water surrounding the plant, then all the needed nitrogen comes from the nutrients.

For algae, growth is in new algae cells.
For vascular plants (Hydroponic Stage), the growth is split into more plant (called vegetative growth in this paper) or reproduction in the form of fruits (or grains).
For plans like carrots and chard, all growth is crop growth.

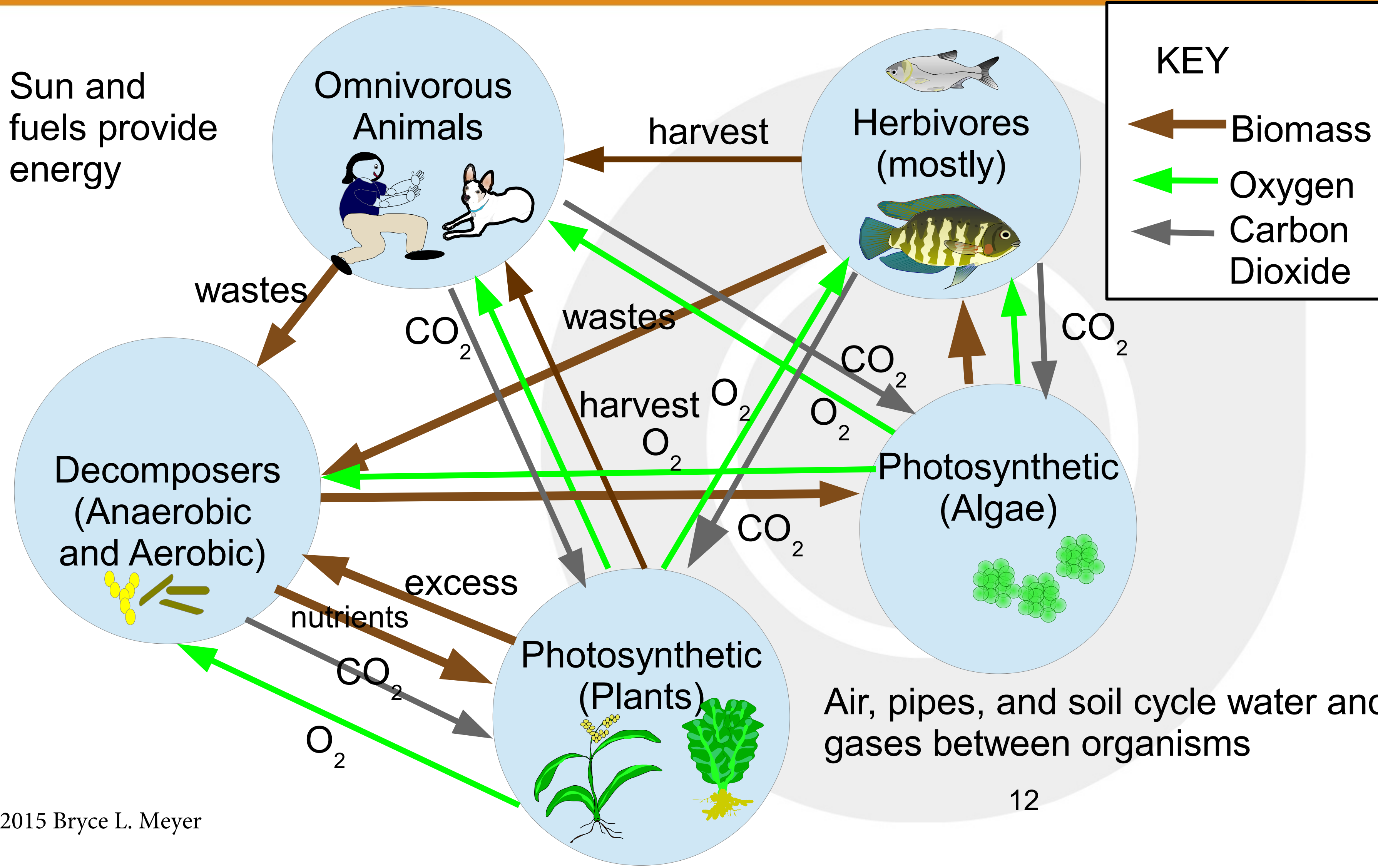
Individuals vs. Populations

- Populations are combinations of individuals of the same species.
- Assume a linear relationship between mass-equivalent size of the population, and averaged per-capita (i.e. individual) values.
- Two population values: Mass-equivalent (N), and count of individuals (T).
  - Use ratios to find each stage's N and T
- Per capita values are shown per day per mass-equivalent individual
- Stage values are per year for the whole mass equivalent population, i.e. N*365.25* per capita

Pseudo Ecosystem vs Natural Ecosystem

- Natural ecosystems are very efficient at recycling
- Pseudo Ecosystems use combinations of biological systems (stages) need to fill chemical process niches in a controlled manor, combined with machinery and controls to shift materials between major systems.
- Each stage contains tanks, pumps, ultraviolet sterilizers, and separators to recirculate products, and to buffer flows from other stages.

Simplified Earth Ecosystem



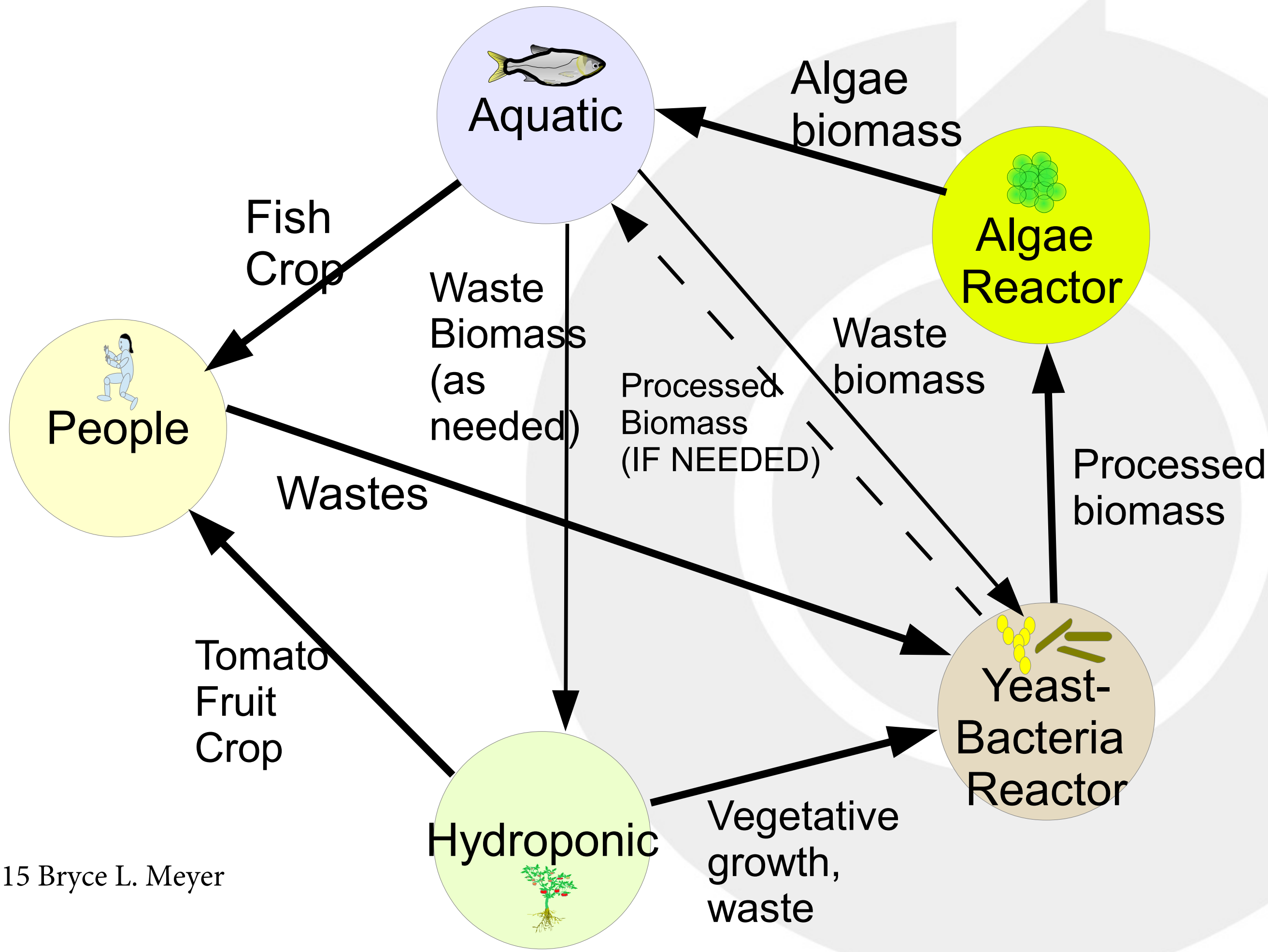
The Five Stage Farm Model

- The Space Farm has five stages:
- People Stage: i.e. the human population in the habitat
- Aquatic Stage: Aquatic animals with machinery and controls to optimize growth. A one year harvest occurs to provide a food crop for the People Stage. Silver Carp are used for this analysis.
- Hydroponic Stage: A fully controlled hydroponic garden, with optimized lighting, carbon dioxide rich atmosphere, oxygen infused and nutrient rich wet root-bed. Fruits are harvested continuously, vegetative growth is provided to the Yeast-Bacteria reactor as biomass. Tomatoes are used for analysis.

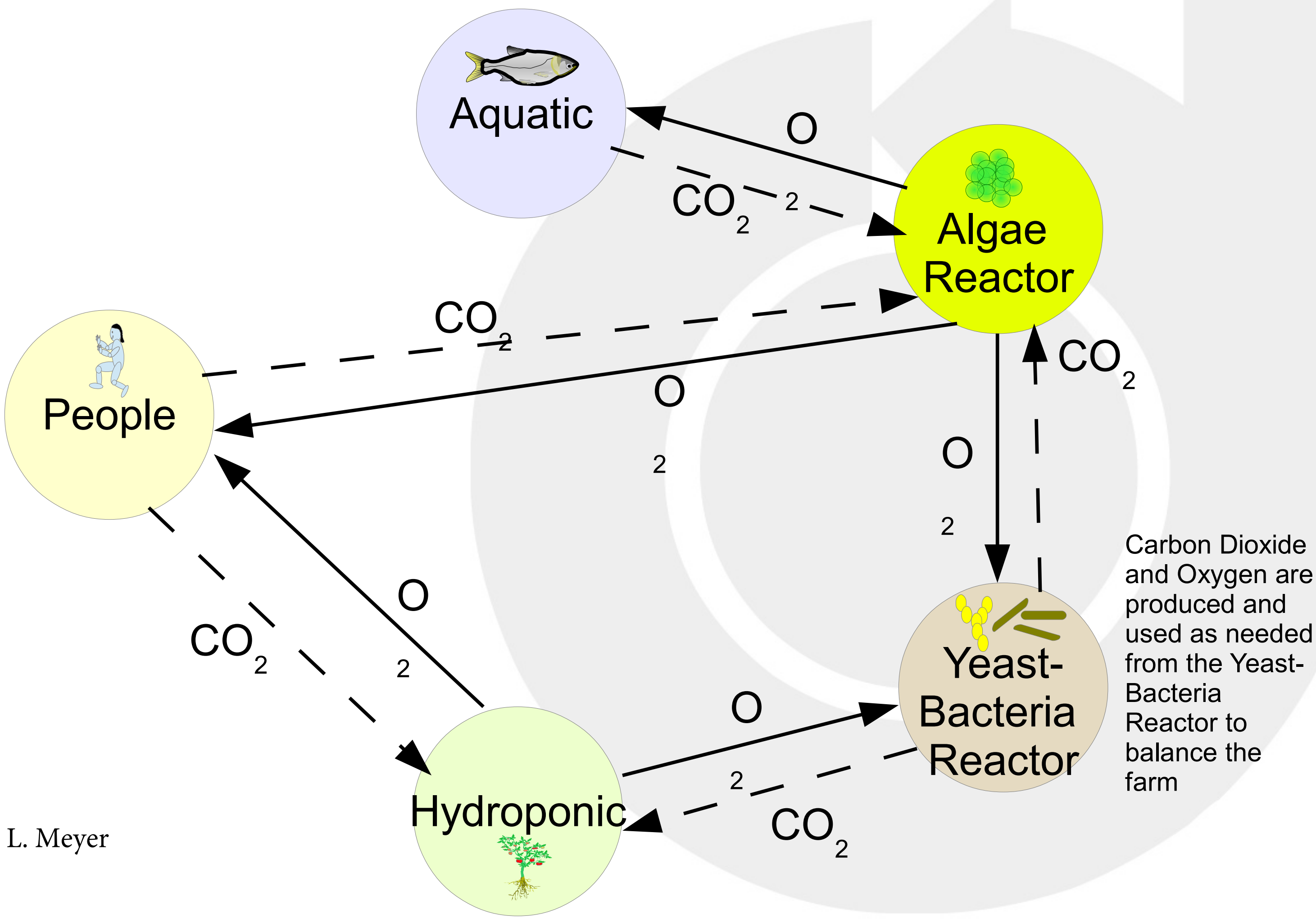
The Five Stage Farm Model continued

- Algae Reactor Stage: Has a membrane bio-reactor seeded with green algae with optimized lighting and gas control. All growth goes to biomass for the aquatic stage, though may be used at times to feed people.
- Yeast-Bacteria Reactor Stage: Has a complex membrane bio-reactor seeded with yeasts and bacteria to mediate a wide variety of reactions. This stage is the mass balance to the rest of the stages. It can also produce hydrogen gas if required.

Biomass Cycling in the Farm



Oxygen-Carbon Dioxide Cycling in the Farm



Human Diet

- 2000 kcal consumption
- 1000 kcal of silver carp, if 769 kcal/kg wet mass of whole fish meal results in 1.3kg of raw fish meal and fillets. This is realistic if the fish meal is mixed into dishes like curries and soups.
- 1000 kcal of tomatoes, is similarly 5.56kg wet mass. I.e a large salad bowl of raw tomatoes per day. Ugh!
- While this diet is not very realistic, it is not impossible given very good chefs who can convert the raw biomass to a variety of cooked and dried products.
- It is assumed water removed in cooking, etc. is re-introduced as liquid drinking water, or water in recipes
- In a real colony, a greater variety of crops would be needed…

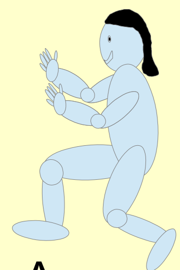
Source	kcal/day/ person consumed (k)	kcal/ kg wet mass (k_l)	kcal/ kg dry mass	kg dry mass /day consumed (b_l)	Ratio wet mass to dry mass (X)	kg raw wet biomass consumed pp per day	kg water in food consumed	Units per day to provide kcal	Unit	Crop population for all People, per year
Silver Carp	1000	769	3314.62	0.3	4.31	1.3	1	1.28	Crop fish	46589
Tomatoes	1000	180	1260	0.79	7	5.56	4.76	0.44	plants for fruit	16046
TOTALS	2000	0	0	1.1	0	6.86	5.76			
Drinking water	4.24	kg/pp/pd		= liters per person per day						

People Stage: Per Capita

Biomass: 1000kcal of fish,
1000kcal of tomatoes
1.09kg dry mass total

Oxygen Gas: 0.84kg
[Jones, 2003]

Water: 10 kg in drinking
and wet biomass from food.



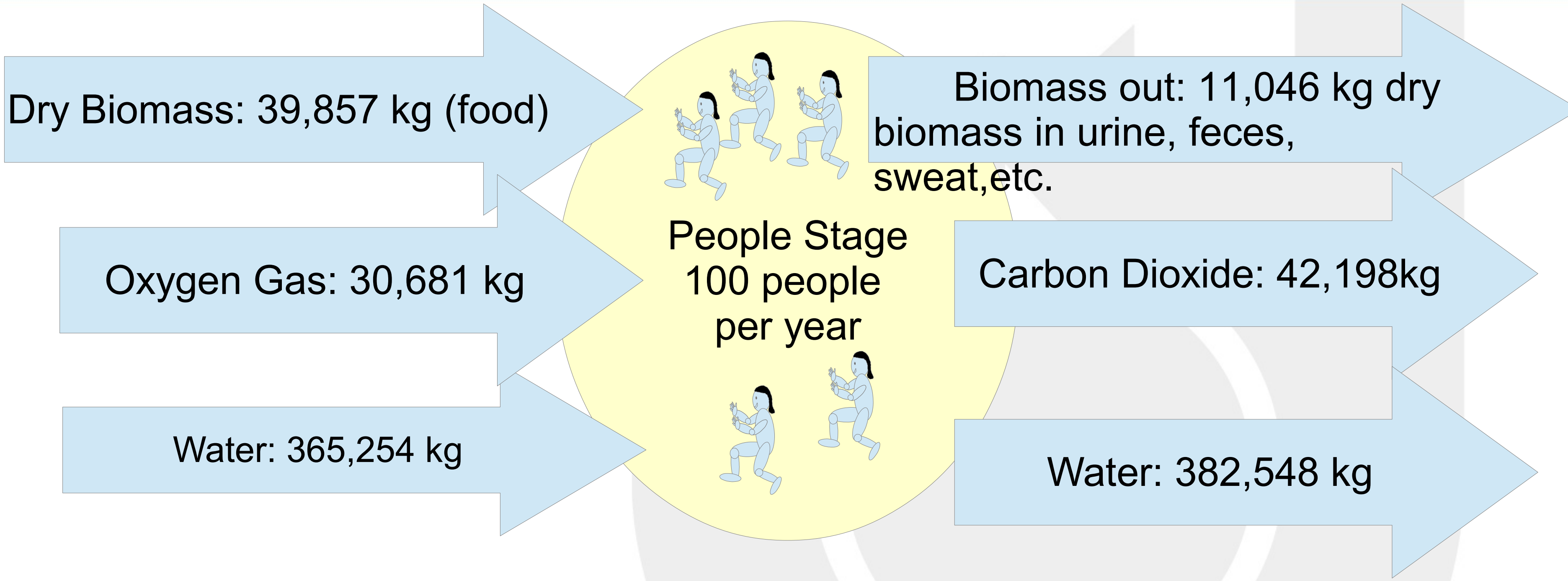
A person
per day

Biomass out: 0.30 kg dry
biomass in urine, feces, sweat,etc.

Carbon Dioxide: 1.16kg
(~0.84kg/72%)

Water: 10.47 kg
(urine, feces, etc.)

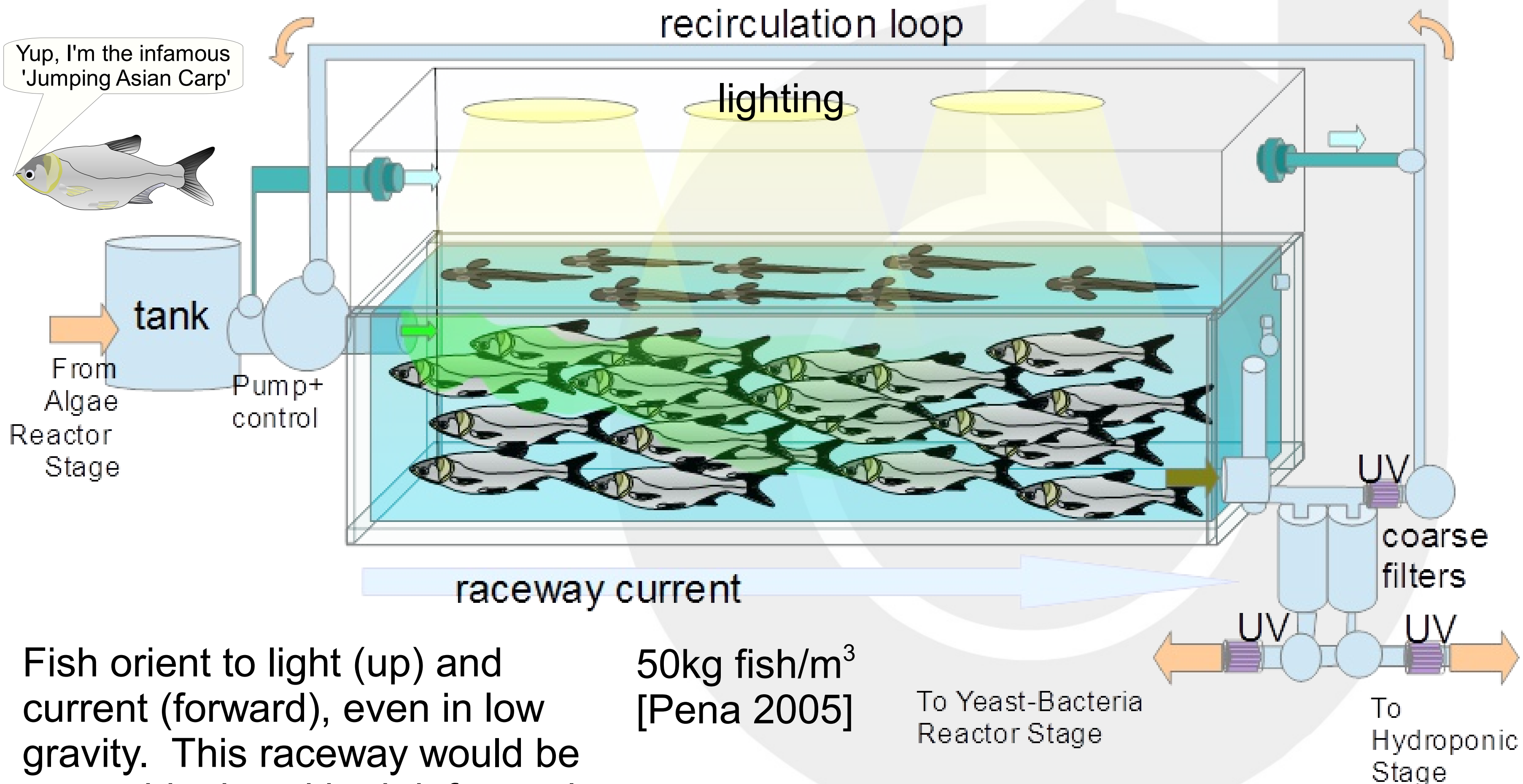
People Stage: Overall, 1 year



Population:
100 (mass-equivalent)

Note: Water out is 'black' water, i.e. sewage.
'gray' water, such as water from washing, dehumidifiers, etc. can be filtered, sterilized, and reused directly...any biomass from that added to the sewage.

Aquatic Stage Basics



Fish orient to light (up) and current (forward), even in low gravity. This raceway would be an ovoid tube with air infusers in 0 g.

50kg fish/m^3 [Pena 2005]

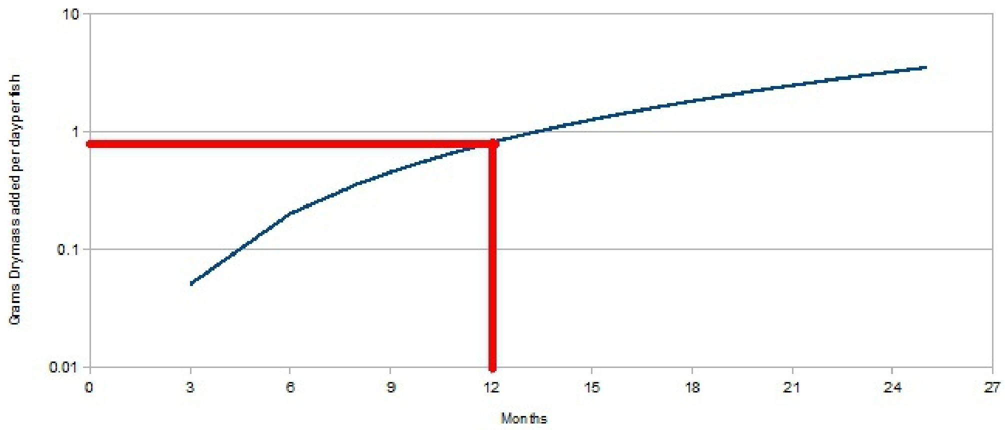
Aquatic Stage

Silver Carp (Hypophthalmichthys molitrix, i.e. Asian Carp) used for Aquatic Stage analysis

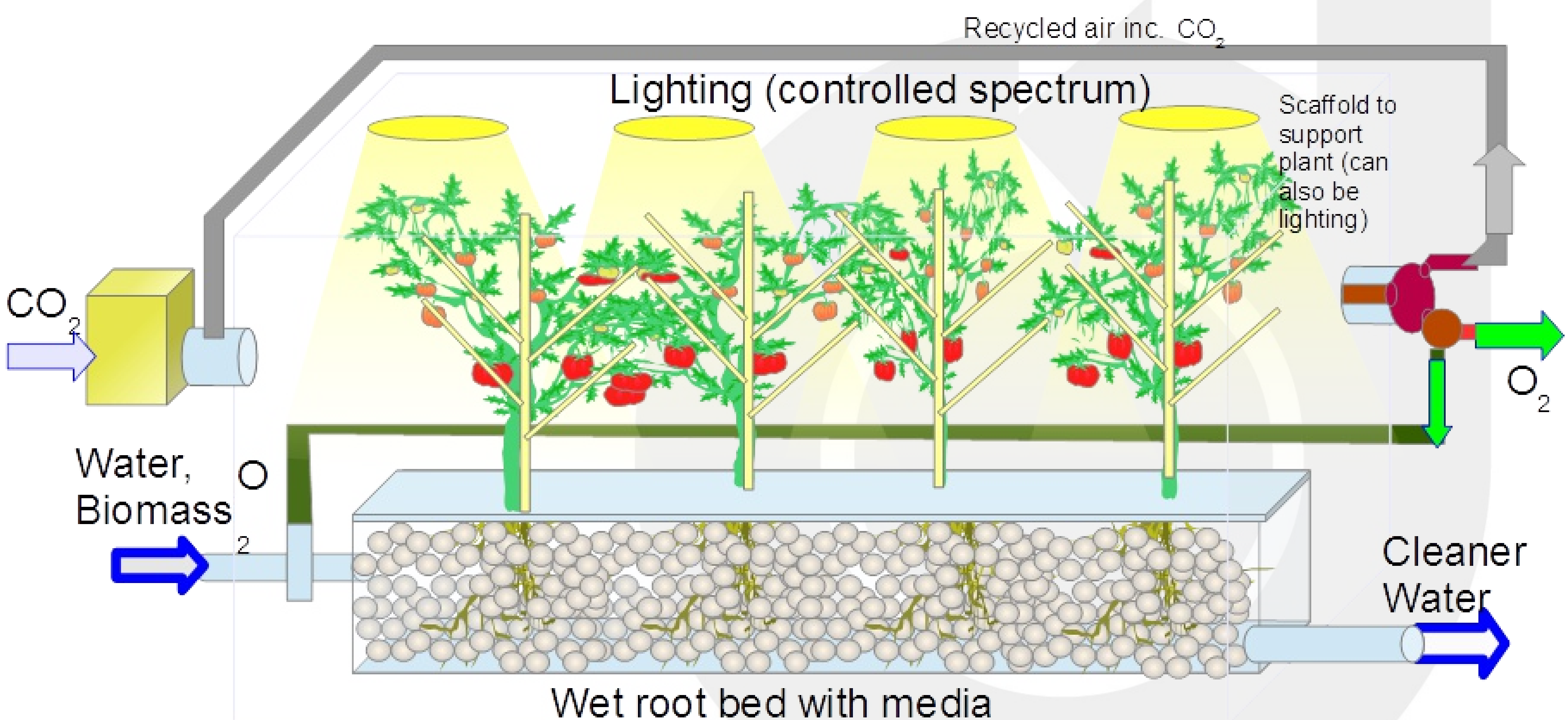
- Very tough, very fast growing, good filters
- Assumed harvest at 1 year, 1.02 kg wet mass, 1 foot (305 mm), not too far past wild growth in MS River Basin.
- Assume 1.04 mass- equivalent population ratio, though a total population ratio of 4.46

Per fish per day		
dry biomass in	0.018480	kg dry mass
water in (net value)	0.000519	kg
oxygen in	0.003840	kg
biomass out	0.014880	kg dry mass
-- biomass is waste	0.014070	kg dry mass
--biomass in growth	0.000810	kg dry mass
carobon dioxide out	0.005281	kg
water in wet biomass growth	0.00268100	kg

Used data from [Ref 6] and [Ref 7] and personal observations to find per capita dry biomass intake.



Hydroponic Stage Basics



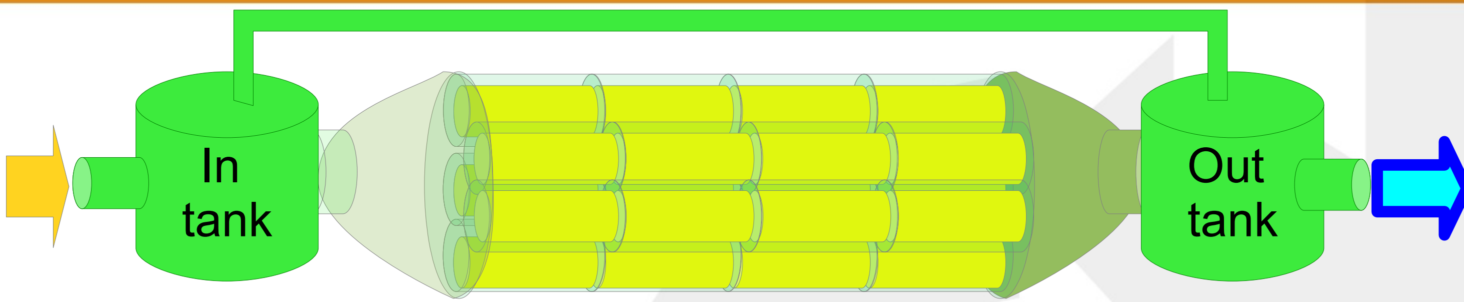
Assume long-lived indeterminate vine engineered tomatoes, 1 kg dry mass, 2 m tall (w/o root), occupying $1.2m^3$. Ratio fruit to vegetative growth is 65%

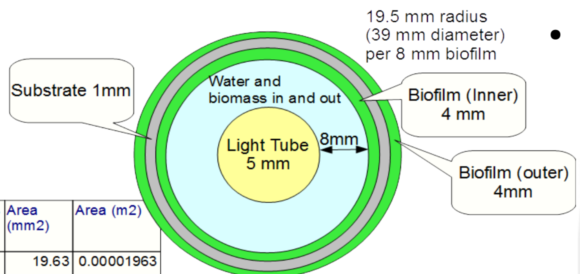
Hydroponic Stage

- 120 days to full production
- Used 7:1 ratio of wet biomass to dry biomass for both fruits and vegetative parts. This very dense for fruit.
- Assumed 1.1 both mass-equivalent and total plant population ratios.
- Nutrients are from Aquatic wastes
- Some oxygen from photosynthesis is infused into the root bed water to maximize production.

Per capita values for the Hydroponic Stage		
mass per plant per day		
Dry biomass in Nutrients	0.00010	kg dry mass
Total Water Input	0.04868	kg
-- Water used to make wet biomass	0.04431	kg
-- Water used in photsynthesis	0.00437	kg
Carbon Dioxide Input	0.01067	kg
Total dry biomass in growth	0.00753	kg dry mass
--dry biomass in vegetative growth	0.00258	kg dry mass
--dry biomass in fruit growth	0.00495	kg dry mass
kcal in fruit per day per plant	6.23	kcal
(days per avg. Each med Tomato fruit)	3.5	days
Oxygen out (Net)	0.00761	kg
--oxygen produced but sent to rootbed	0.00015	kg
--total oxygen produced	0.00776	kg
Water out in wet biomass	0.04431	kg

Algae Reactor Stage Basics





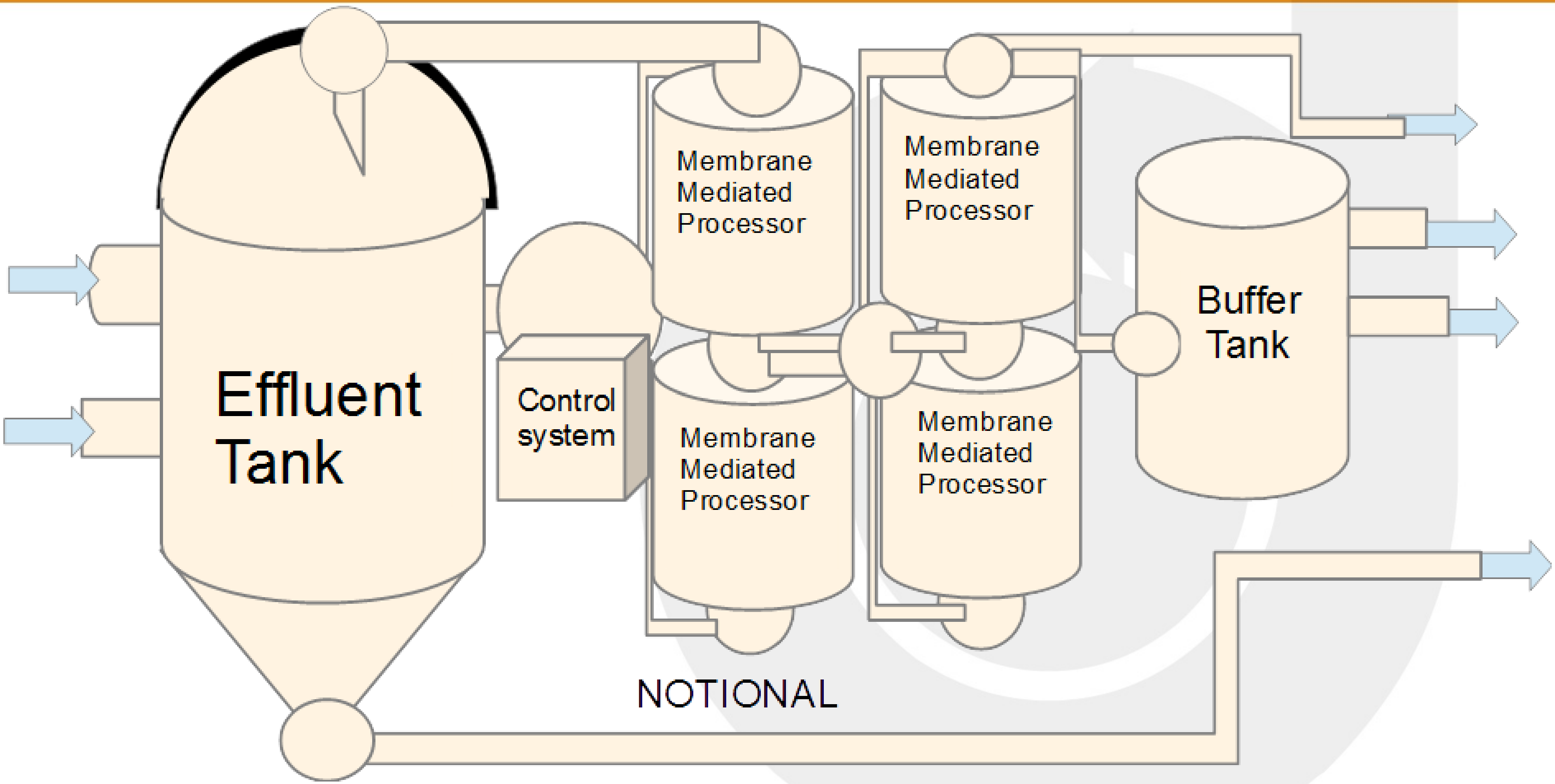
Areas	Outer dia. (mm)	Thickness (mm)	Area (mm2)	Area (m2)
Light tube	5		19.63	0.00001963
water sleave	21	8	326.73	0.00032673
Biofilm inner	29	4	333.79	0.00033379
sustrate	31	1	420.97	0.00042097
Biofilm-Outer	39	4	773.62	0.00077362

- Arrangements of algae substrates and light sources to maximize oxygen production, and nutrient consumption in a volume of water.
- Flow will send algae clumps and oxygen into the Aquatic Stage (to be eaten by shrimp or fish), along with unused detritus.
- The reactor maximizes the surface area of algae exposed to nutrients and light

Per capita values for the Algae Reactor Stage		
mass per kg algae dry mass per day		
Nutrients (biomass) in	0.006970	kg dry mass
Water in (total)	0.117372	kg
– Water in for photsynthesis	0.054645	kg
– water for grown wet mass	0.062727	kg
Carbon Dioxide in	0.133333	kg
Biomass out in growth	0.098004	kg dry mass
Oxygen gas out	0.096944	kg
water out in wet biomass (growth)	0.062727	kg
unit = 1 kg dry mass algae		

Productivity per unit = 289.88 kg processed per kg dry biomass (assumed and calculated from [Ref. 12])
Efficiency assumed is 70% by dry mass (for sizing)

Yeast Bacteria Reactor Stage Basics



Productivity per unit = 289.88 kg processed per kg dry biomass
(same as algae reactor)
Efficiency assumed is 70% by dry mass (for sizing)

Aquatic and Hydroponic Stage Populations and Sizes

People Stage food inputs (see slide 19) determine populations for Aquatic and Hydroponic Stages:

For the Aquatic Stage Overall		
Population of crop	46,589	crop fish
Ratio total to crop by mass	1.04	
Total Stage Pop (mass equivelents)	48,366	equivelent fish if sized as crop
Ratio total to crop	4.31	
Total Population of fish	200,813	fish
Population unit	1	1.02 kg wet mass fish
For the Aquatic Stage for the Year		
Biomass in	326,465	kg dry mass
Water in	9,169	kg
Oxygen in	67,837	kg
Biomass out total	262,868	kg dry mass
-- Biomass out wastes	248,559	kg dry mass
-- Biomass out growth	14,309	kg dry mass
--- Biomass out growth for just the crop	13,784	kg dry mass
--- Biomass in growth for non- crop fish	526	kg dry mass
Carbon Dioxide out	93,293	kg
Water out in wet biomass growth	47,362	kg
--Water out in wet biomass growth, non-crop fish	1,740	kg
--Water out in wet biomass growth, crop fish	45,622	kg

Total Values for the Hydroponic Stage for a Year		
mass total stage		
Population of crop	16,046	plants
Total Stage Pop (mass or total)	17,651	plants
Ratio total to crop by mass (and total)	**1.1**	
unit	**1**	Plant @ 1 kg dry
Nutrients in (biomass)	646	kg dry mass
Water in	313,850	kg
--water in for wet mass in growth	285,659	kg
--water in for photosynthesis	28,190	kg
Carbon Dioxide in	68,785	kg
Biomass out (all in growth)	48,551	kg dry mass
Biomass out (vegetative growth)	16,664	kg dry mass
Biomass out (fruit growth)	31,887	kg dry mass
Oxygen out (net production)	49,068	kg
--Oxygen taken from production for roots	938	kg
--total Oxygen out from photosynthesis	50,006	kg
Water out (in wet mass growth)	285,659	kg

Algae Reactor Stage and Yeast Bacteria Stage Totals

Algae Reactor Stage is sized to meet biomass in for Aquatic Stage (which is greater then for all stage oxygen requirements)

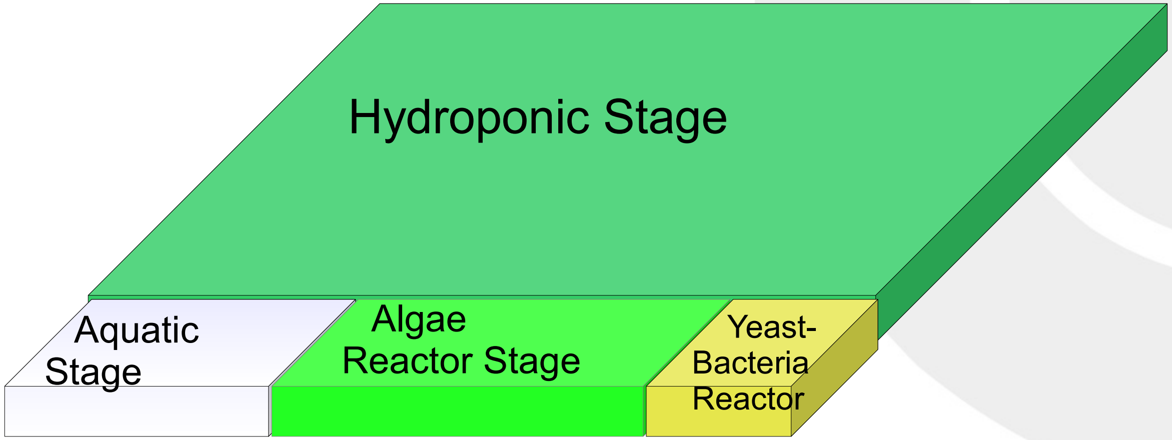
Total Values for the Algae Reactor Stage for a Year		
Total Stage Population (effective)	9,120	kg dry mass
Total Stage Population (total)	13,029	kg dry mass
mass total stage		
Nutrients in (biomass)	23,217	kg dry mass
Water in	390,983	kg
--water in for wet mass in growth	182,030	kg
--water in for photosynthesis	208,953	kg
Carbon Dioxide in	444,152	kg
Biomass out (all in growth)	326,465	kg dry mass
Oxygen out	322,934	kg
Water out (in wet mass growth)	208,953	kg

Yeast-Bacteria Reactor Stage in this case is sized to balance the farm to process remaining biomass wastes and produce carbon dioxide for Algae Reactor and Hydroponic Stage, produce water, and consume excess oxygen from the Algae Reactor Stage. In other scenarios it may have other products and inputs.

Total Values for the Yeast-Bacteria Reactor Stage for a Year		
Total Stage Population (effective)	1836	kg dry mass
Total Stage Population (total)	2,623	kg dry mass
mass total stage		
Biomass in	258,744	kg dry
Oxygen in	273,482	kg
Carbon Dioxide out	377,444	kg
Water out	154,731	kg

How Big is the Space Farm?

STAGE	Volume (m3)	Floor Area (hectares)	Height (m)	Total Mass (kg)	Minimum Ship Mass (kg)	Time to Operation
Aquatic	2,031	0.07	3	1,086,784	78,933	366 days
Hydroponic	28,356	0.95	3	685,710	32,653	120 days
Algae Reactor	391	0.13	3	244,288	74,101	35 days
Yeast Bacteria Reactor	139	0.05	3	207,910	78,700	35 days
TOTAL	**30,917**	**1.19**	**12**	**2,224,692**	**264,387**	

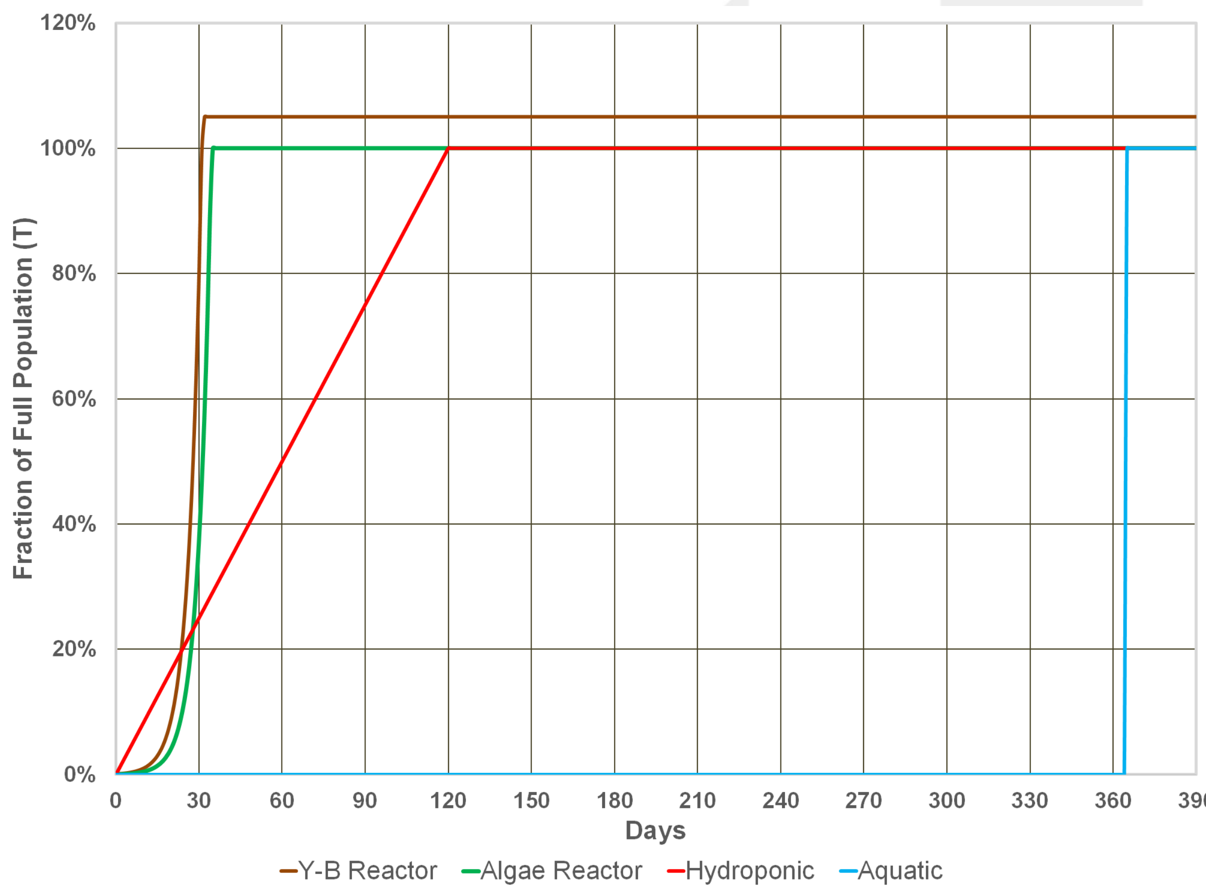


1.19 hectares = 2.94 acres

- Bio-reactors have complex equipment that is likely to be built on Earth.
- Other stages have significant portions that can be built with on site using in situ materials
- Minimum 6 trips on Falcon Heavy to LEO, 4 on Block 2 SLS. Then a larger vehicle to send to destination.
- Farm requires 1,745 metric tons of water found in situ.

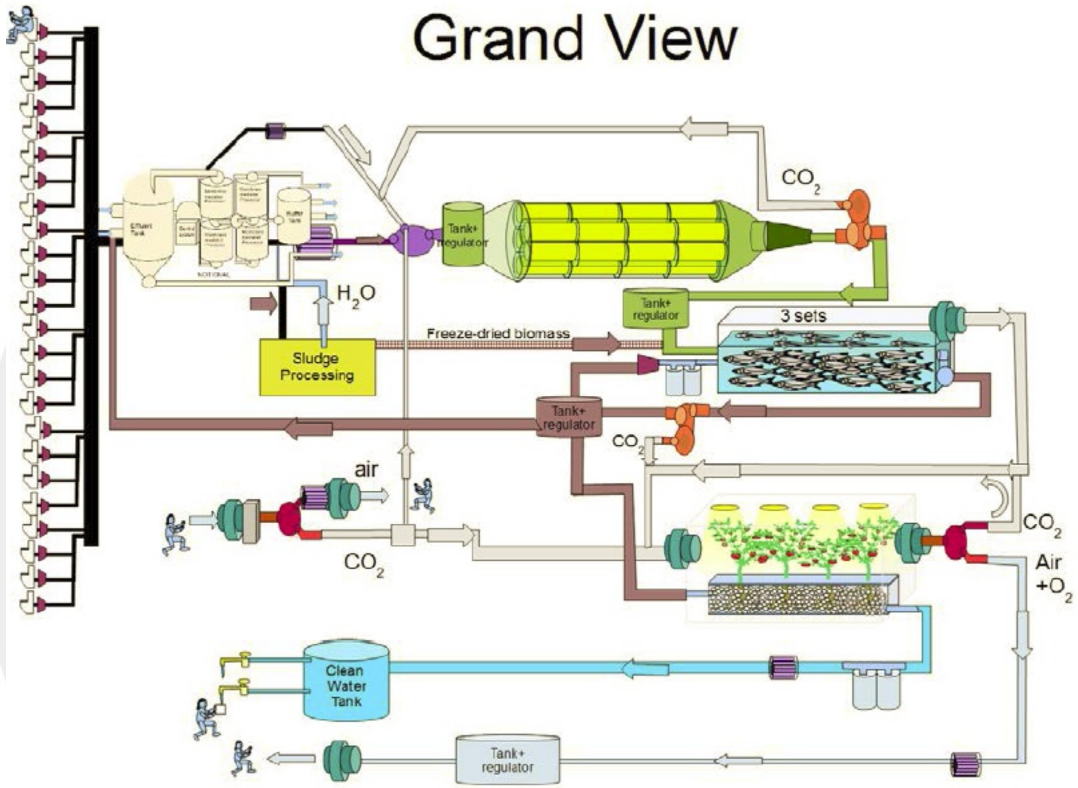
Time to Start, First 40 Days

- It will take 366 days to full production however:
- Running the Yeast-Bacteria Reactor at 105% and Algae Reactor at 100% can provide the needed People Stage inputs until the Hydroponic Stage is up at 4 months. Resizing the Y-B reactor costs 10 metric tons in total stage mass.



CONCLUSIONS/FUTURE WORK

- Five Stage Space Farm study shows the basic dynamics of the pseudo ecosystem, even if idealized
- More detailed models should account for efficiencies, losses, and population time dynamics



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Extra: What do Silver Carp look like in the Wild?

Feeding Silver and Bighead Carp below Lake Carlyle Dam, Kaskaskia River, Carlyle IL

Jumping Silver Carp (Sandy Slough, Winfield, MO)

Juvenile Silver Carp (Mississippi River, St. Louis MO)

Roughly 1 year old Silver Carp (Mississippi River, St. Louis MO)

Roughly 5 year old Silver Carp (Mississippi River, Hannibal, MO)

Solution method overview

- Assumptions and givens
- Simplified biochemistry
- Basic connections between stages
- Calculate per capita
- Use People Stage food need to drive Aquatic and Hydroponic
- Find worse of (Oxygen for Aquatic+People, Food for Aquatic) for Algae Stage
- Use remainders for Yeast-Bacteria stage
- Use population sizes to find volumes and masses