Nutrient Balance and Nitrogen Cycling In a Multistage, Multispecies Space Farm

AIAA SPACE 2016

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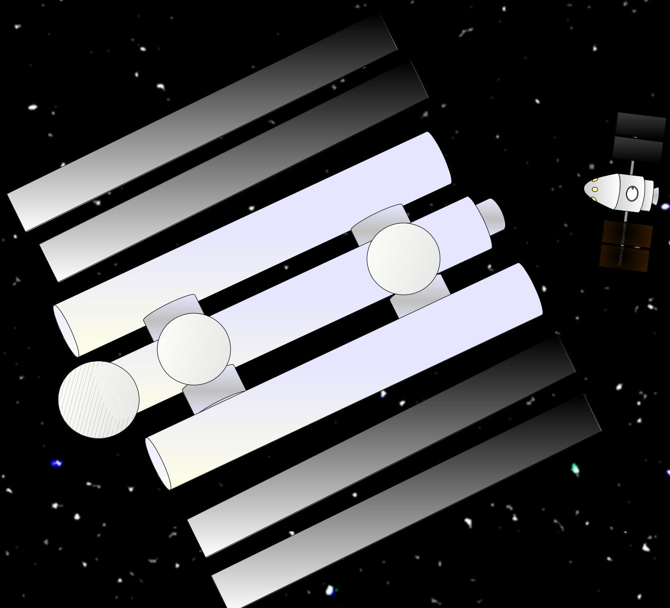

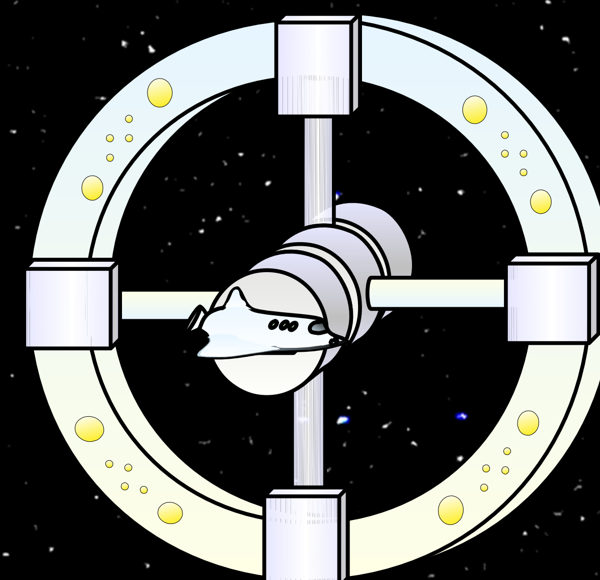

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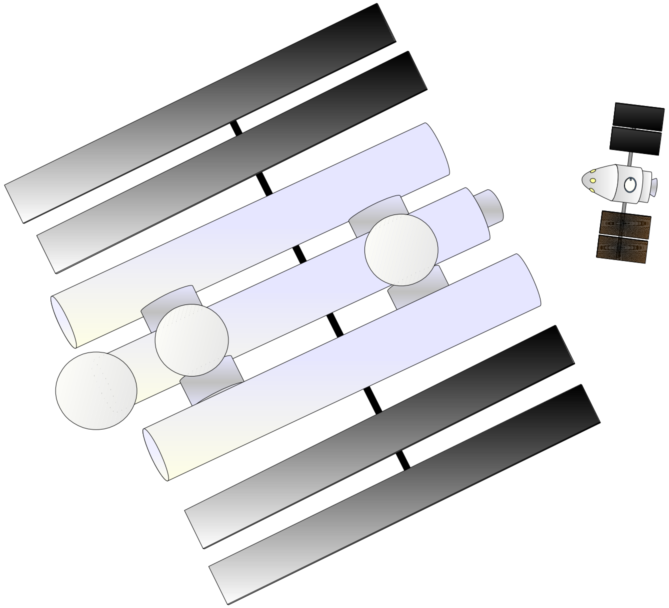
Overview

- Space Farm Basics
- Assumptions
- Mass Balances
- Habitat Needs
- Nitrogen in the Farm
- Methods
  - Simulator
- Results
  - Masses
  - Footprint

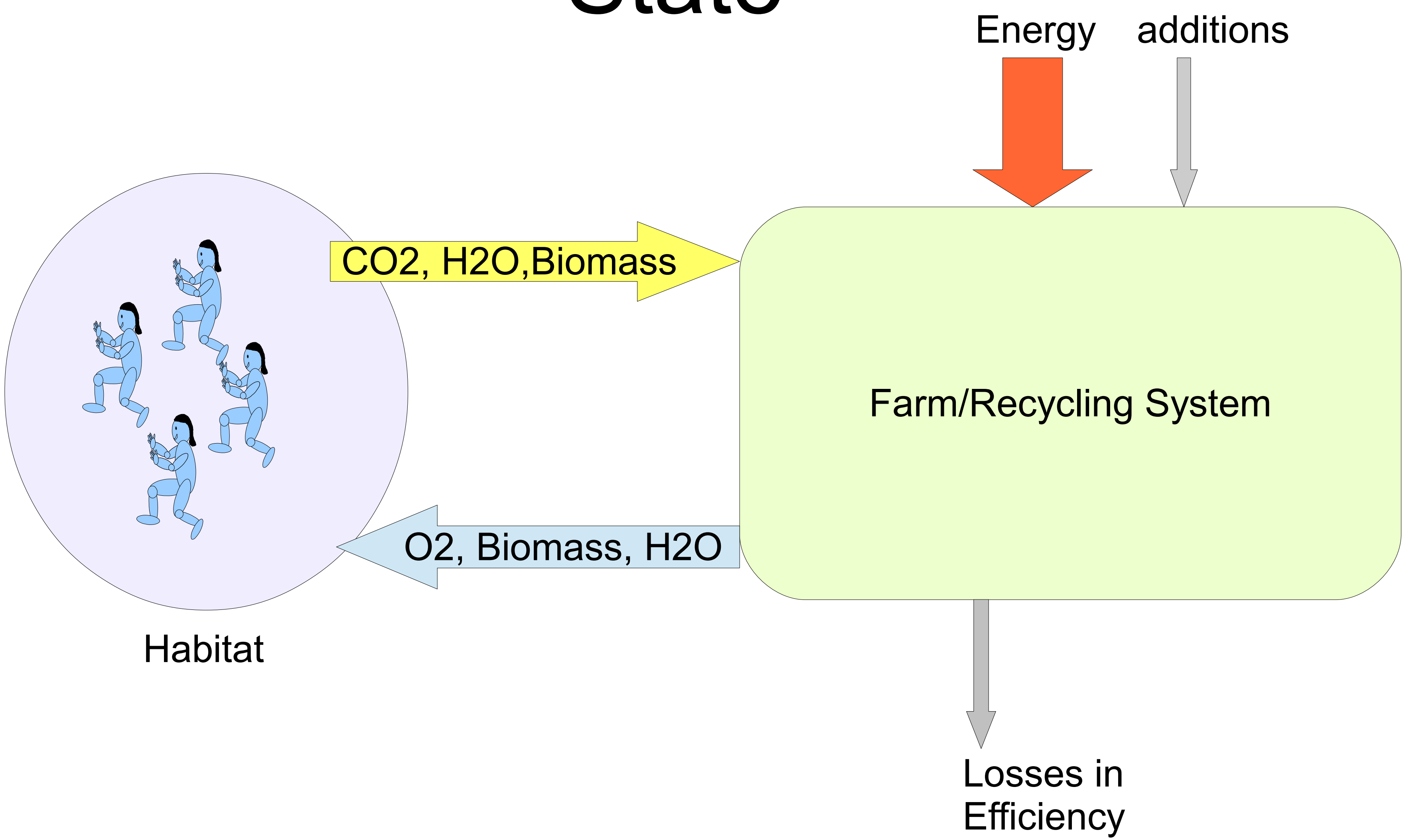


Space Farm 101

- The Closer a Space Farm and Habitat together emulate a psuedo-ecosystem, the more efficient it will be.
- Four Stage Types in this farm concept:
  - Hydroponic: Grains, Legumes, Vegitables, Fruits
  - Aquatic: Fish, Shrimp, Molluscs, other Crustaceans
  - Yeast-Bacteria Reactor: Film and Tank Bioreactor
  - Algae Reactor: High efficiency algae growth reactor

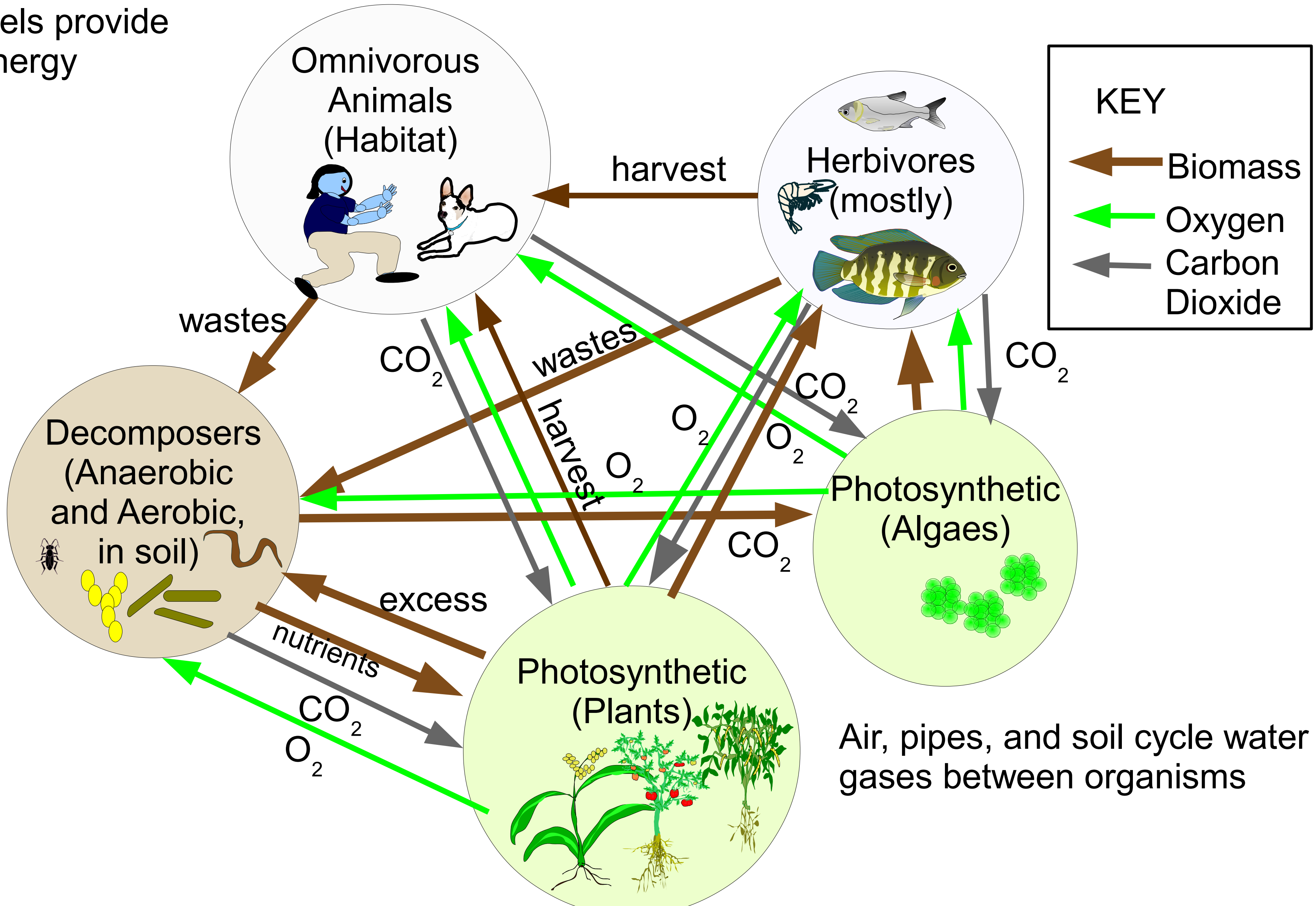
Driving Question: What combinations of species, meet the nutritional needs of the habitat, AND recycle gasses and water for mass balance, especially Nitrogen balance

Overall System Balance at Steady State



An Earth Farm Example Pseudo Ecosystem

Sun and fuels provide energy

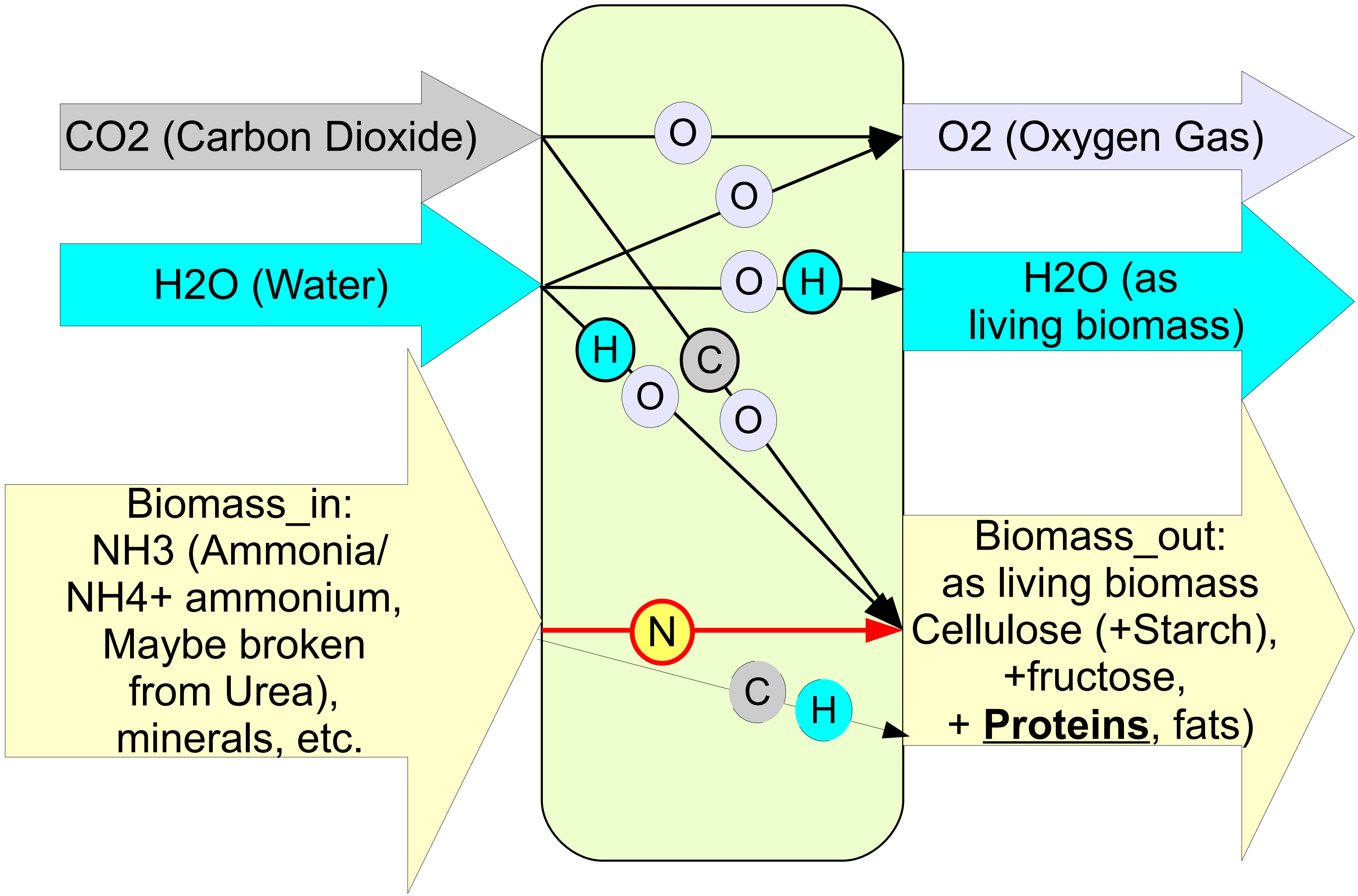


Air, pipes, and soil cycle water and gases between organisms

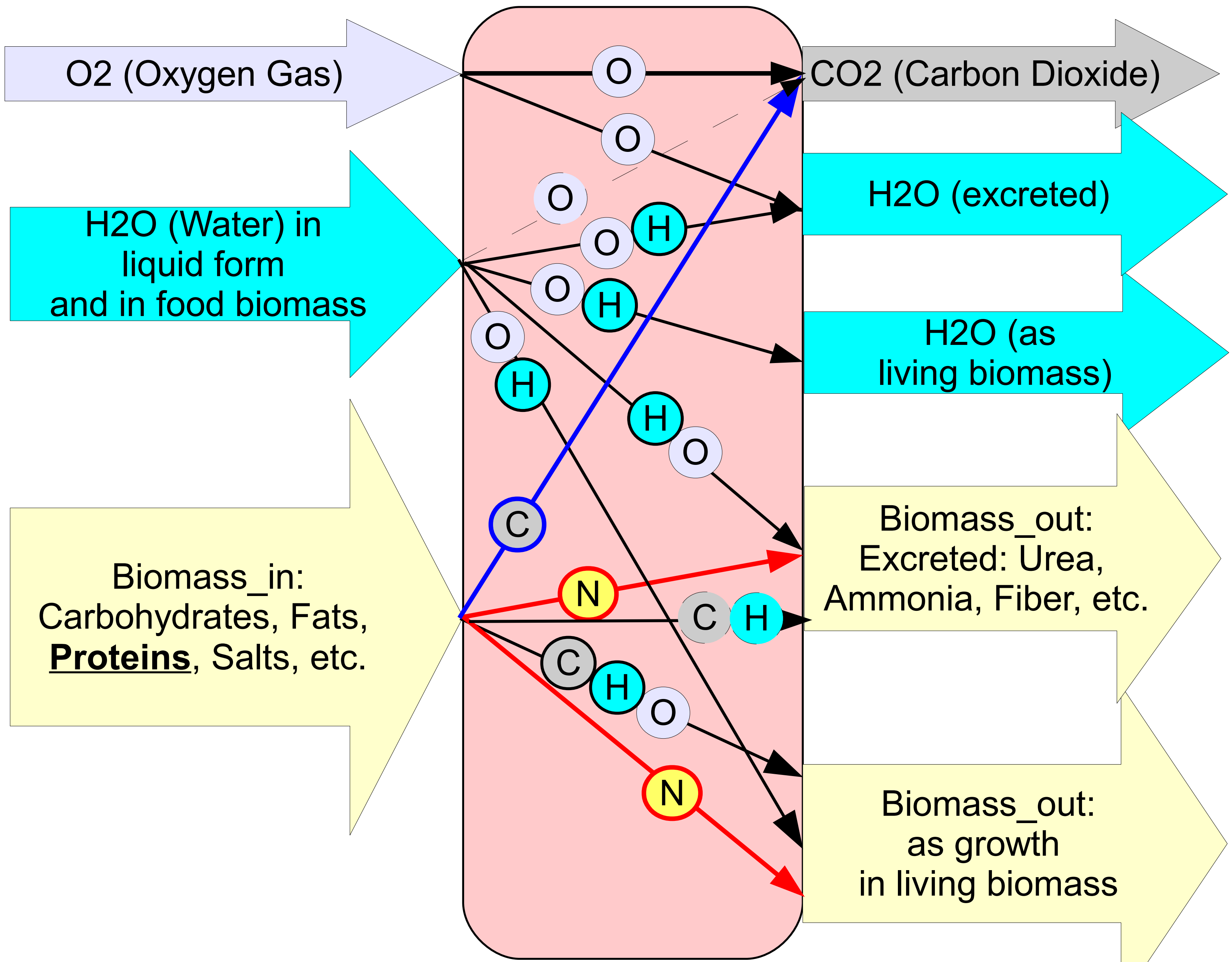
Assumptions

- Inifinite heat and electrical energy
- Gases and liquids are ideally shunted where needed by a control system
- Harvest and replacement is continuous to remove periodic nature of production.
  - Unit of examination is per living biomass
- Algae and Animals are consumed completely (for now) = all edible biomass in crop.
- Each stage maintains ideal conditions (or as noted) for each organism
- Inedible Biomass (from Hydroponic crops) can be consumed by either Yeast-Bacteria Reactor or Aquatic Organisms
  - Note only the Yeast-Bacteria Reactor can metabolize cellulose into other compounds
- Excreted biomass from animals (inc. People) can be only used by Hydroponic or Algae Reactor crops.

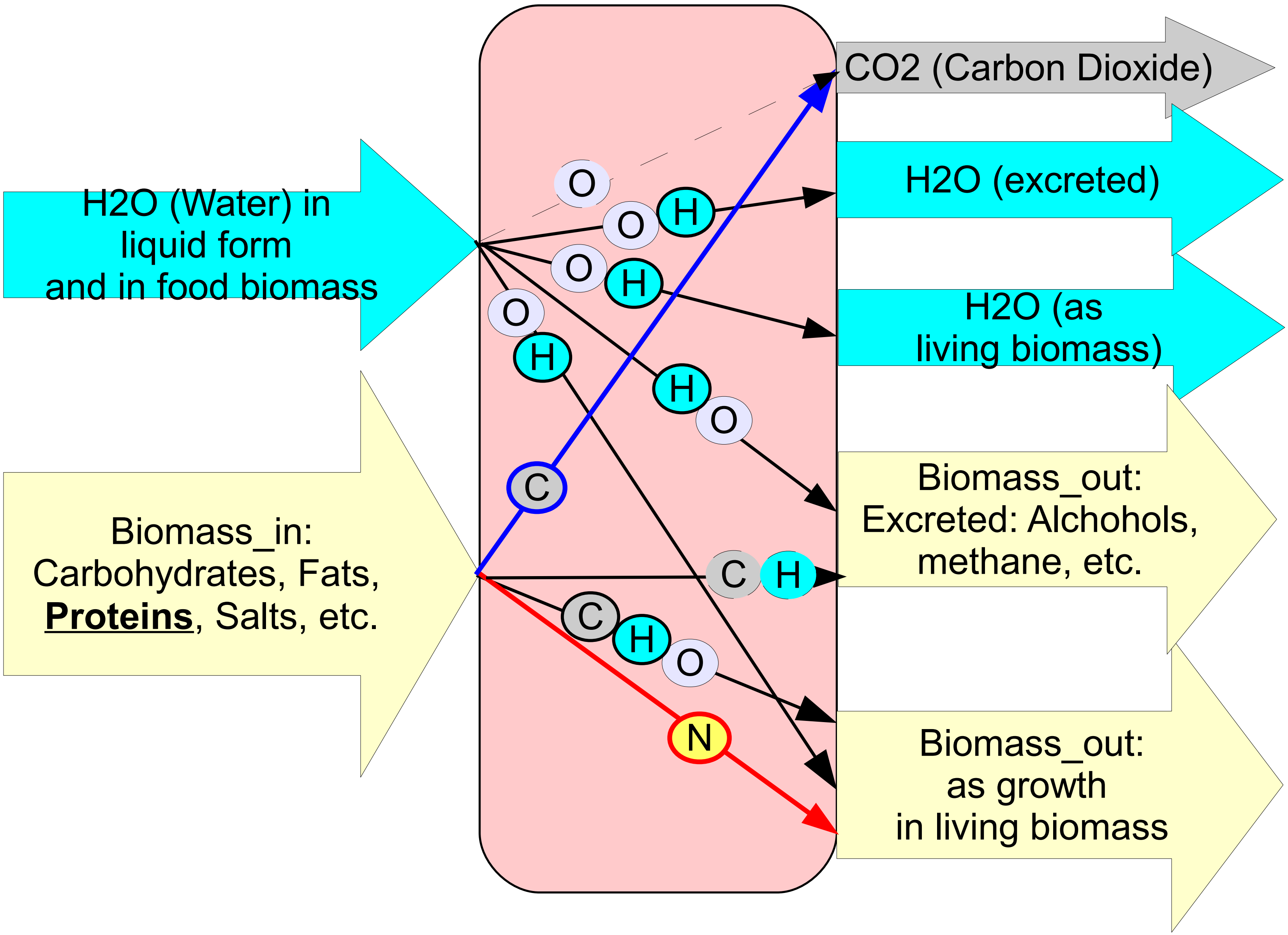
Mass Balance in Photosynthetic Organisms (i.e. Algae and Hydroponics)



Mass Balance in Aerobic Organisms
(i.e. Yeast-Bacteria Reactor in Aerobic Mode, and Aquatics)



Mass Balance in Anerobic Metabolism (i.e. Yeast-Bacteria Reactor in Anerobic Mode)



Common Biological Molocules

			Atoms in Formula					Relative mass by Element				
Name	**Formula**	**Molecular Weight[Ref]**	**C**	**O**	**H**	**N**	**S**	**C**	**O**	**H**	**N**	**S**
Elemental Carbon	**C**	12.01	**1**					100%	0%	0%	0%	0%
Elemental Oxygen	**O**	16		**1**				0%	100%	0%	0%	0%
Elemental Hydrogen	**H**	1.01			**1**			0%	0%	100%	0%	0%
Elemental Nitrogen	**N**	14.01				**1**		0%	0%	0%	100%	0%
Elemental Sulfur	**S**	32.06					**1**	0%	0%	0%	0%	100%
Carbon Dioxide	**CO2**	44.01	**1**	**2**				27%	73%	0%	0%	0%
Oxygen gas	**O2**	32		**2**				0%	100%	0%	0%	0%
Water	**H2O**	18.01		**1**	**2**			0%	89%	11%	0%	0%
Fructose (and most dietary Carbohydrates once hydrated)	**C6H12O6**	180.15	**6**	**6**	**12**			40%	53%	7%	0%	0%
Cellulose	**C6H10O5**	162.14	**6**	**5**	**10**			44%	49%	6%	0%	0%
Starch (i.e. Chains of unhydrated monosaccarides)	**(C6H10O5)n**	162.14 x n	**6**	**5**	**10**			44%	49%	6%	0%	0%
Ethanol	**C2H5OH**	46.07						52%	35%	13%	0%	0%
Cholesterol (a fat)	**C27H46O**	386.66	**27**	**1**	**46**			84%	4%	12%	0%	0%
Fat Trigliceride (most fats)	**C55H98O6**	855.37	**55**	**6**	**98**			77%	11%	12%	0%	0%
Methane	**CH3**	15.03	**1**		**3**			80%	0%	20%	0%	0%
Urea	**CH4N2O**	60.06	**1**	**1**	**4**	**2**		20%	27%	7%	47%	0%
Ammonia	**NH3**	17.03			**3**	**1**		0%	0%	18%	82%	0%
Ammonium	**NH4+**	18.04			**4**	**1**		0%	0%	22%	78%	0%
Alanine	**C3H7NO2**	89.09	**3**	**2**	**7**	**1**		40%	36%	8%	16%	0%
Arginine	**C6H14N4O2**	174.2	**6**	**2**	**14**	**4**		41%	18%	8%	32%	0%
Asparagine	**C4H8N2O3**	132.12	**4**	**3**	**8**	**2**		36%	36%	6%	21%	0%
Aspartic acid	**C4H7NO4**	133.1	**4**	**4**	**7**	**1**		36%	48%	5%	11%	0%
Cysteine	**C3H7NO2S**	121.15	**3**	**2**	**7**	**1**	**1**	30%	26%	6%	12%	26%
Glutamic acid	**C5H9NO4**	147.13	**5**	**4**	**9**	**1**		41%	43%	6%	10%	0%
Glutamine	**C5H10N2O3**	146.15	**5**	**3**	**10**	**2**		41%	33%	7%	19%	0%
Glycine	**C2H5NO2**	75.07	**2**	**2**	**5**	**1**		32%	43%	7%	19%	0%
Histidine	**C6H9N3O2**	155.16	**6**	**2**	**9**	**3**		46%	21%	6%	27%	0%
isolucine	**C6H13NO2**	131.17	**6**	**2**	**13**	**1**		55%	24%	10%	11%	0%
Leucine	**C6H13NO2**	131.18	**6**	**2**	**13**	**1**		55%	24%	10%	11%	0%
lycine	**C6H14N2O2**	146.19	**6**	**2**	**14**	**2**		49%	22%	10%	19%	0%
Methinonine	**C5H11NO2S**	149.21	**5**	**2**	**11**	**1**	**1**	40%	21%	7%	9%	21%
Phenylalanine	**C9H11NO2**	165.19	**9**	**2**	**11**	**1**		65%	19%	7%	8%	0%
Proline	**C5H9NO2**	115.13	**5**	**2**	**9**	**1**		52%	28%	8%	12%	0%
Serine	**C3H7NO3**	105.09	**3**	**3**	**7**	**1**		34%	46%	7%	13%	0%
Threonine	**C4H9NO3**	119.12	**4**	**3**	**9**	**1**		40%	40%	8%	12%	0%
Tryptophan	**C11H12N2O2**	204.23	**11**	**2**	**12**	**2**		65%	16%	6%	14%	0%
Tyrosine	**C9H11NO3**	181.19	**9**	**3**	**11**	**1**		60%	26%	6%	8%	0%
Valine	**C5H11NO2**	117.15	**5**	**2**	**11**	**1**		51%	27%	9%	12%	0%
Amino Acid Average			**5.35**	**2.45**	**9.85**	**1.45**	**1**	***46%***	***30%***	***7%***	***15%***	***2%***

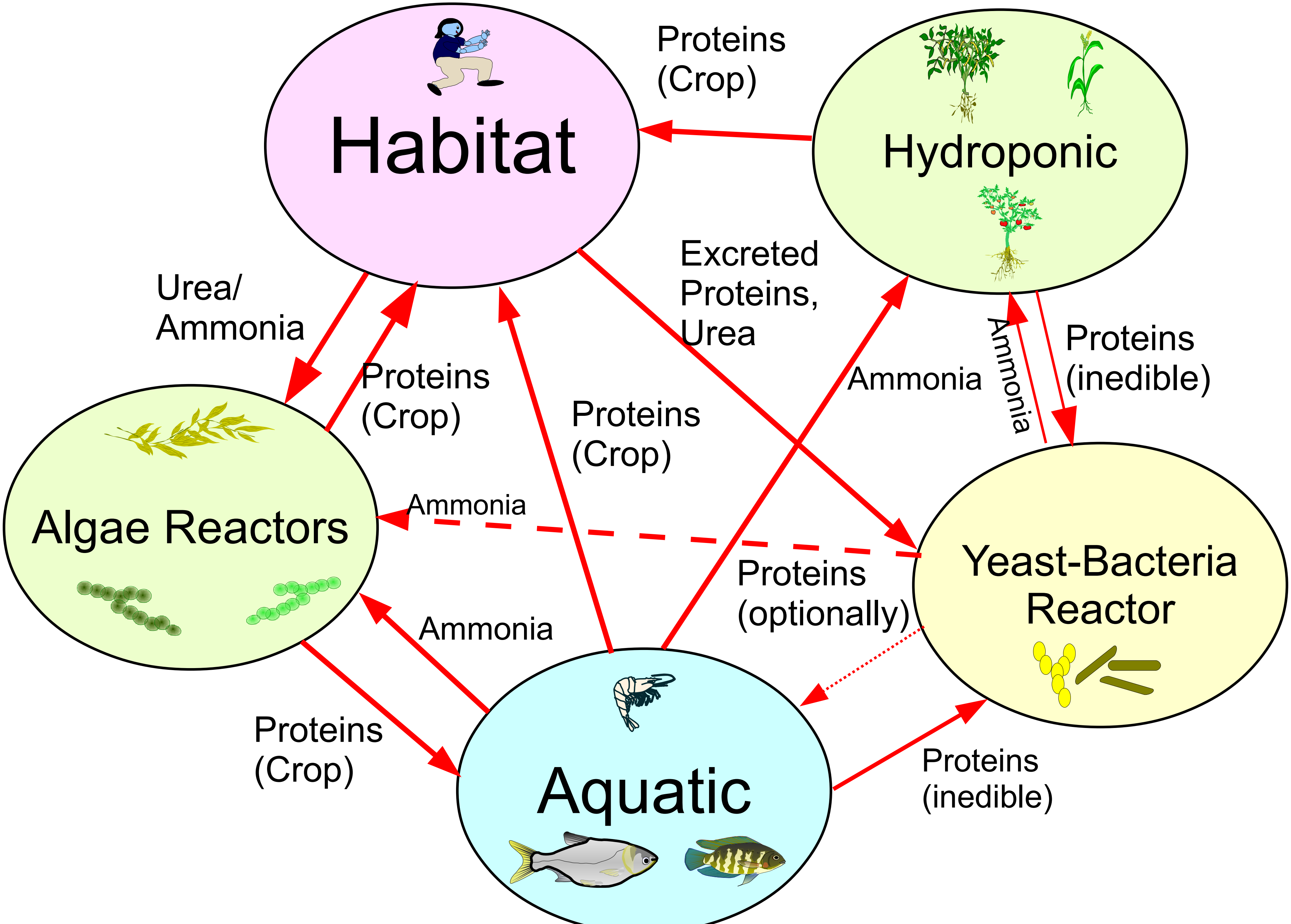
What Does a Person Need?

Inputs per person per day: 5kg Water in food and drink, 0.59 kg Oxygen, and at least .07 kg Fats, 0.32 Carbohydrates, 0.025 kg Fiber, 0.05 kg Proteins, and 2,000 kcal.

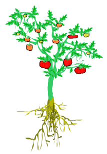
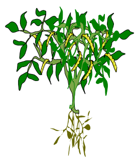
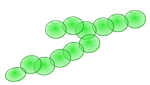
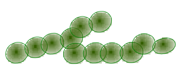
Outputs per person per day: 0.034 kg Dry biomass (Excreted), 0.81 kg CO_2, 5.2 kg Water

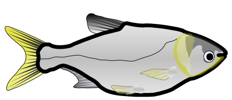
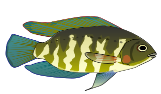
Human inputs per person		**%% by mass**				**kg mass**			
Nutrient (Dry Biomass in)	**kg/person/day**	**C**	**O**	**H**	**N**	**C**	**O**	**H**	**N**
Lipids+Cholesterol	0.0703	**83.87%**	4.14%	11.99%	0.00%	0.059	0.003	0.008	0.000
Carbohydrates	0.3240	**42.11%**	51.41%	6.48%	0.00%	0.136	0.167	0.021	0.000
Cellulose (Fiber)	*0.0250*	*44.45%*	*49.34%*	*6.22%*	*0.00%*	*0.011*	*0.012*	*0.002*	*0.000*
Proteins	0.0500	**45.28%**	30.11%	7.20%	14.88%	0.023	0.015	0.004	0.007
NET Oxygen in**	0.5900	0	100.00%	0	0	0.000	0.590	0.000	0.000
Water in*	5.0000	0.00%	88.81%	11.19%	0.00%	0.000	4.441	0.559	0.000
NET INPUT	**6.059**					**0.229**	**5.227**	**0.594**	**0.007**
USABLE INPUT (i.e. Input -cellulose)	6.034					0.22	5.22	0.59	0.01
Excrete (Dry Biomass out)	0.034					0.008	0.007	0.011	0.007
Carbon Dioxide	0.811	27.29%	72.71%	0.00%	0.00%	0.221	0.590	0.000	0.000
Water out	5.214	0.00%	88.81%	11.19%	0.00%	0.000	4.631	0.583	0.000
NET OUTPUT	**6.059**					**0.229**	**5.227**	**0.594**	**0.007**
** = Includes water in wet biomass from foods, assumes 3 liters drink, and 2 liters in food*									
*** = NET Oxygen in is Oxygen inhaled – minus Oxygen exhaled*									

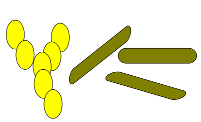
NASA guidance[3], and US Recommended Daily Allowance for a 2,000 kcal diet[4]


Habitat
Proteins (Crop)
Hydroponic
Excreted Proteins, Urea
Urea/ Ammonia
Proteins (Crop)
Proteins (Crop)
Ammonia
Ammonia
Proteins (inedible)
Algae Reactors
Ammonia
Yeast-Bacteria Reactor
Proteins (optionally)
Ammonia
Proteins (Crop)
Aquatic
Proteins (inedible)

Species Examined



SPECIES	Scientific Name	Dietary Source	Metabolic Sources	Assumptions
Rice	*Oryza sp. (hybrids)*	USDA NDD #20088[7]	8,9,*10,11,12*	Efficiency is equal or greater than field production, entire plant is harvested, including roots. Planting and growth is staggerd for continuous production
Tomato	*Solanum lycopersicum (hybrids)*	USDA NDD #11529[7]	1,24,25,26	Plants are picked for fruit, and trimmed to stay the same size continuously
Soybeans	*Glycine max (hybrids)*	USDA NDD #11450[7]	13,14,15	Efficiency is equal or greater than field production, entire plant is harvested, including roots. Planting and growth is staggerd for continuous production
Chlorophyta	*Chlorophyta sp.*	Ref 30, Nutrtion facts, compared to Ref 29	28,29,30,31,32	Doubled biomass is consumed as edible biomass by humans or animals
Spirulina	*Spirulina sp.*	USDA NDD #11666[7]	22	Doubled biomass is consumed as edible biomass by humans or animals
Kelp	*Macrocystis sp.*	USDA NDD #11445[7]	21	All plant is edible. Growth is continuously trimmed to provide edible biomass
Silver Carp	*Hypophthalmichthys molitrix*	USDA NDD #15008[7]	16	Entire mature organism is consumed. Breeders and small juvenilles are a very small mass relative to crop. Crop is staggered to allow continuous harvest and replacement.
Tilapia	*Oreochromis sp.*	USDA NDD #15261[7]	17,18	Entire mature organism is consumed. Breeders and small juvenilles are a very small mass relative to crop. Crop is staggered to allow continuous harvest and replacement.
Shrimp	*Litopenaeus sp. Or Macrobrachum sp.*	USDA NDD #15270[7]	19,20,21	Entire mature organism is consumed. Breeders and small juvenilles are a very small mass relative to crop. Crop is staggered to allow continuous harvest and replacement. Growth is at least as good as pond rearing.
Yeast-Bacteria Reactor	Many species on film and in tanks	USDA NDD #18375[7]	27	Excretes produced only from protein aerobic or anerobic respiration, edible biomass only produced as needed if the system is lacking biomass

Method

- Determine mass balance per living kg per organism per day
  - Include Nitrogen balance
- Given Habitat needs per person, run a Monte Carlo Analysis using a simulator written in PERL/XML to get at least one solution where:
  - Meets all human nutrition and habitat mass balance requirements (i.e. Oxygen, water in, CO_2, excretes out).
  - Mass Balances across farm and habitat
    - Balances Nitrogen and Biomass Types
  - Minimum total mass of living organisms in farm
- Use solution with estimate factors to get size.

Mass Balance
per living kg per day

	kg per kg live mass per day productive							
	Inputs				Outputs			
Crop	CO_2	H_2O	O_2	Biomass_in (total)	CO_2	H_2O	O_2	Biomass out (total)
Rice	0.01214	0.00507	0	0.00024	0	0.00062	0.00908	0.00776
Tomato	0.02349	0.140137	*0*	0.00156	*0*	0.13052	0.01923	0.01543
Soybeans	0.01841	0.020902	*0*	0.00243	*0*	0.01397	0.01090	0.01688
Chlorophyta	0.01557	0.83397	*0*	0.00176	*0*	0.82800	0.01409	0.00920
Spirulina	0.00873	0.05260	*0*	0.00075	*0*	0.05206	0.00443	0.00559
Kelp	0.00398	0.017634	*0*	0.00136	*0*	0.01614	0.00298	0.00386
Silver Carp	*0*	0.002079	0.003840	0.00446	0.005281	0.00424	*0*	0.00086
Tilapia	*0*	0.004723	0.001466	0.10000	0.002016	0.00474	*0*	0.09944
Shrimp	*0*	0.006519	0.009600	0.01506	0.013204	0.00652	0	0.01145

These estimates were the core inputs for the simulator.
Loaded into an XML file per species.

Mass Balance (total and nitrogen) per live kg per species per day

	Mass (kg) dry biomass per kg live mass per day productive							
	TOTAL				Nitrogen			
Crop	Biomass in	Biomass out excrete	Biomass out growth edible	Biomass out growth inedible	Biomass in	Biomass out excrete	Biomass out growth edible	Biomass out growth inedible
Rice	0.00024	0	0.003374	0.004387	0.000111	0	0.00006898	0.0000417
Tomato	0.00156	0	0.004800	0.01063	0.000614	0	0.00007353	0.0005403
Soybeans	0.00243	0	0.003780	0.01310	0.000794	0	0.00006896	0.0007251
Chlorophyta	0.00176	0	0.009200	0	0.000610	0	0.0006099	0
Spirulina	0.00075106	0	0.005589	0	0.000494	0	0.0004944	0
Kelp	0.00136	0	0.003861	0	0.000042	0	0.0000418	0
Silver Carp	0.00446	0.000198	0.000661	0	0.000089	0.0000205	0.000068	0
Tilapia	0.10000	0.098061	0.001375	0	0.004319	0.0041445	0.000175	0
Shrimp	0.01506	0.009639	0.001815	0	0.000820	0.0005741	0.000246	0

These estimates were also inputs for the simulator.
Loaded into the species' XML file.

Human Edible Crop assay per crop kg per live kg per species per day

	kg per kg live biomass per day Human Usable					
Crop	**Kcal**	**Carbohydrate**	**Fats**	**Proteins**	**Fiber**	**N**
Rice	13.00	0.0025861	0.0000373	0.0004842	0.0002141	0.000068981
Tomato	13.14	0.0028058	0.0001443	0.0006239	0.00086553	0.000073532
Soybeans	15.89	0.0011382	0.0007004	0.0013339	0.0004326	0.000068959
Chlorophyta	3.77	0.0018400	0.0018400	0.0041400	0.0004600	0.0006099
Spirulina	14.99	0.0013894	0.0002239	0.0034015	0.000229654	0.00049435
Kelp	8.6	0.0018931	0.00011078	0.00029034	0.000257163	0.0000417932
Silver Carp	3.48	0.0000000	0.0001526	0.0004686	0.0000000	0.0000683
Tilapia	5.87	0.0000000	0.0001039	0.0012140	0.0000000	0.0001748
Shrimp	7.08	0.0000000	0.0000424	0.0016702	0.0000000	0.0002461

Ex: 1 kg of living rice plant produces 13 kcal per day on average.

These estimates were also inputs for the simulator.
Loaded into the species' XML file.

Pre-Sim Calculations: How much live organism assuming 1 species, for each habitat need.

kg living mass to meet Habitat Needs for each person per day per category (no overgrowth)		
Crop	**Habitat O2 in**	**Habitat CO2 out**
Rice	65.007	66.816
Tomato	30.678	34.549
Soybeans	54.104	44.066
Chlorophyta	41.863	52.127
Spirulina	133.114	93.004
Kelp	198.275	203.866

Ex: It would take ~65 kg of live rice plant to produce enough oxygen for a person to breathe, but 66 kg of live rice plant to use a person's CO_2.

This is lower than dietary requirements....see next slide

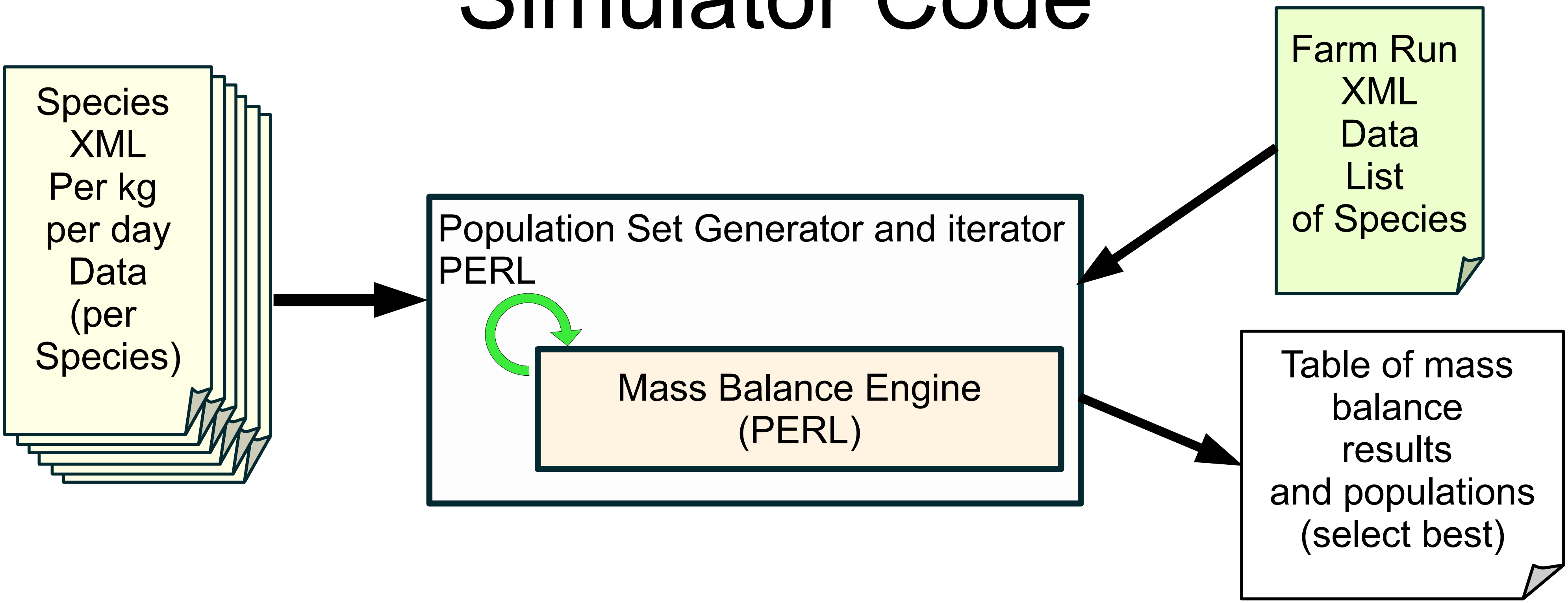
Pre-Sim Calculations:

How much live organism assuming 1 species, to produce enough for each dietary habitat need.

	kg living mass to meet Habitat Needs for each person per category (no overgrowth)						Maximum Pop (living kg)
Crop	**Kcal**	**Carbohydrate**	**Fats**	**Proteins**	**Fiber**	**N**	
Rice	153.81	125.29	1885.27	103.26	116.79	106.79	**1885.27**
Tomato	152.26	115.48	487.33	80.14	28.88	100.18	**487.33**
Soybeans	125.88	284.65	100.37	37.48	57.79	106.82	**284.65**
Chlorophyta	530.22	176.09	38.21	12.08	54.35	12.08	**530.22**
Spirulina	133.44	233.19	313.96	14.7	108.86	14.9	**313.96**
Kelp	232.57	171.15	634.6	172.21	97.21	176.25	**634.6**
Silver Carp	574.8	N/A	460.82	106.71	N/A	107.86	**574.8**
Tilapia	340.91	N/A	676.68	41.19	N/A	42.14	**676.68**
Shrimp	282.35	N/A	1658.91	29.94	N/A	29.94	**1658.91**

Ex: It would take ~154 kg of live rice plant to produce enough grain to get 2000 kcal per day, but 1,885 kg of live rice plant to produce enough grain to get enough fat. The fat value drives a maximum population of rice plants of 1885 kg.

Simulator Code



1) Maximum Population was initial seed to random number generator

2) tightened range as runs progressed around populations that got close to goals

Near Solution after 130,000 runs (took <10mins for all)

Best Solution from 130k runs
(per person)

Crop	Live kg of total organism	kg of food to Habitat per person (raw wet mass)	% kcal	Nitrogen in Food (kg)
Rice	2	0.01	1.30%	0.0001380
Tomato	2	0.15	1.31%	0.0001471
Soybeans	193	0.39	38.19%	0.0033149
Chlorophyta	5	0.51	0.94%	0.0030496
Spirulina	5	0.29	3.75%	0.0024718
Kelp	2	0.04	0.86%	0.0000836
Silver Carp	71	0.19	12.35%	0.0048490
Tilapia	25	0.15	7.33%	0.0043698
Shrimp	385	0.8	33.96%	0.0235946
Yeast-Bacteria Reactor	24.3			

i.e. Menu-wise, lots of options. Cooked, this is roughly a ¼ cup of rice, 2 tomatoes, 2 cups of soybeans, a big plate of shrimp, a patty of fish, a leaf of kelp, and a ¼ cup of other algae (though more likely a few tablespoons of dry powder).

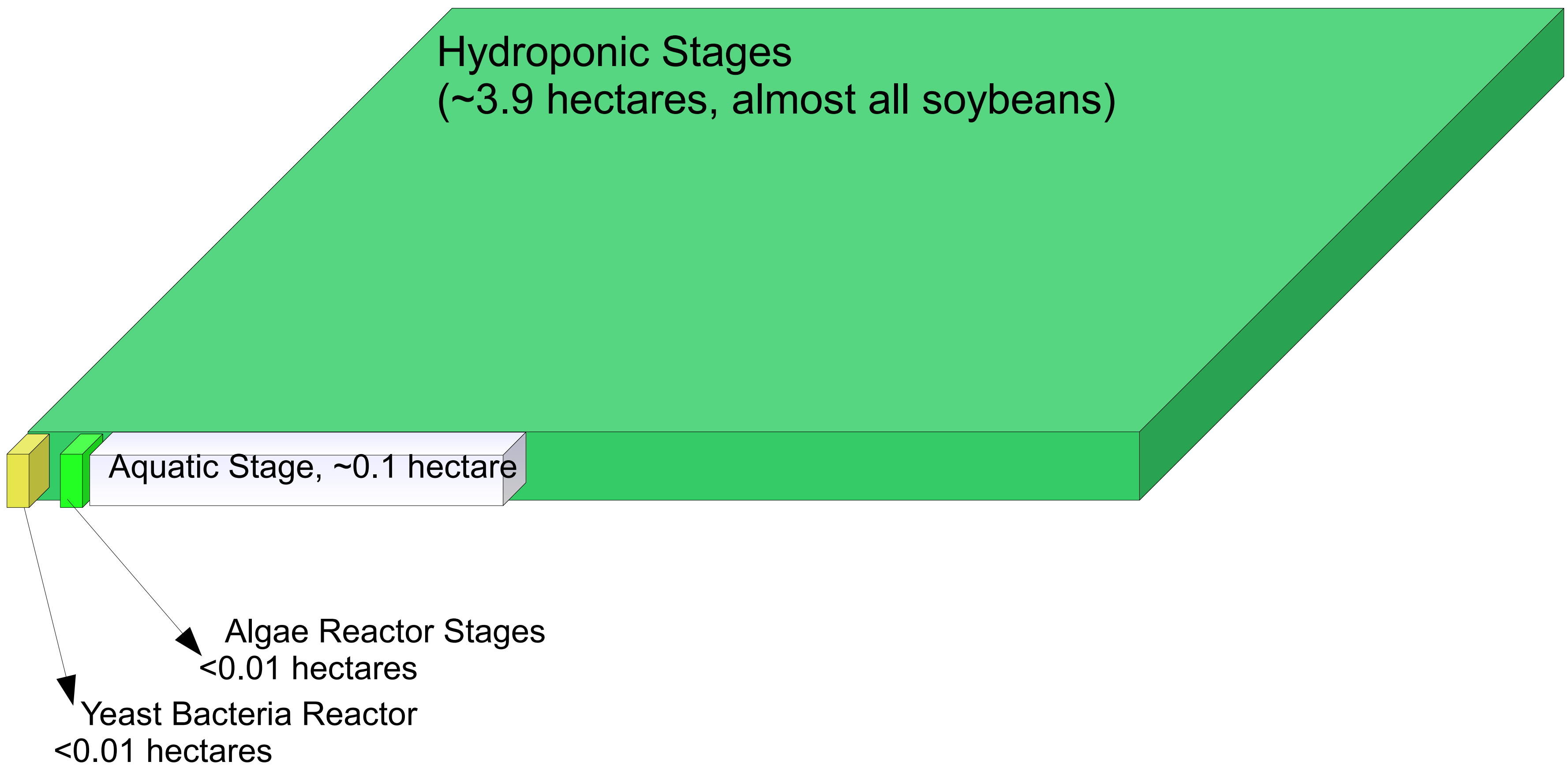
How Big is the Farm-Solution to Balance 100 people?

•Many 'guesses' at volumes and machinery masses, results in 6 hecares, 3 meters high

Crop	living kg	space ratio in living kg/m^3	m^3 for this living kg	multiplier for structure (total size of stage per living m^3)	stage volume in m^3	height (m)	Footprint (m^2)	Footprint (hectares)	Footprint (acres)
Rice	200	0.9	222.22	3	666.67	3	222.22	0.02	0.05
Tomato	200	0.5	400	3	1200	3	400	0.04	0.1
Soybeans	19300	0.5	38600	3	115800	3	38600	3.86	9.54
Chlorophyta	500	500	1	2	2	3	0.67	0.00	0.000165
Spirulina	500	500	1	2	2	3	0.67	0.00	0.000165
Kelp	200	10	20	2	40	3	13.33	0.00	0.003295
Silver Carp	7100	50	142	2.5	355	2	118.33	0.01	0.029241
Tilapia	2500	50	50	2.5	125	2	41.67	0.00	0.010296
Shrimp	38500	50	770	2.5	1925	2	641.67	0.06	0.158559
Yeast-Bacteria Reactor	2429.69	500	4.86	2	9.72	3	3.24	0.00	0.000801
Subtotal					*120,125*		*40,042*	*4*	*10*
Multiplier for between stages							*1.5*		
TOTAL SIZE					**180,188**		**60,063**	**6.01**	**14.84**

Note: would need >22 metric tons to start, assuming a year to buildout and heavy use of in situ materials, to get 211 metric tons of farm.

Relative Farm Solution Footprint



Conclusions/Future Work

- Soybeans in this solution drive a large footprint
  - Soybeans are very loose for beans produced!
  - Might be possible to increase crop density w/scaffolds and genetics
- MANY OTHER SOLUTIONS POSSIBLE!
  - Removing soybeans may force a smaller footprint farm, or a different set of runs might arrive at a different solution.
- Future Work:
  - Examine other solutions
  - Examine construction of bioreactors

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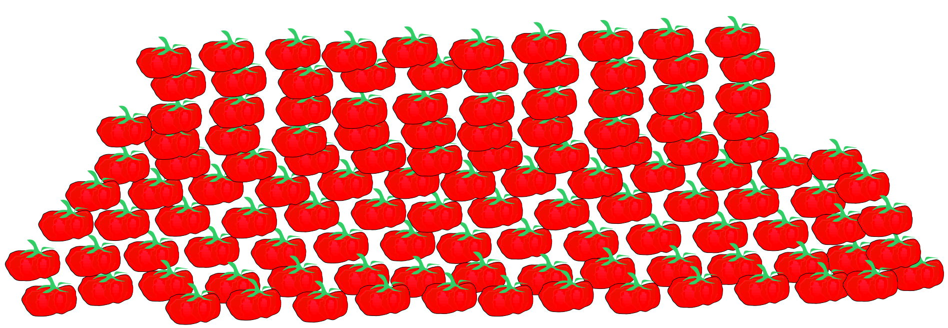
Pre-Sim Calculations:
How much edible biomass (Food) assuming 1 species, to get 2000 kcal

That is A LOT of Tomatoes to eat (ugh!) A small tomato is around 90g, 122 small tomatoes = 2000 kcals.

Crop	kg of food (raw wet mass) to meet dietary kcal	kg of food (raw wet mass) to meet Nitrogen needs
Rice	0.56	0.39
Tomato	11.11	7.31
Soybeans	1.03	0.87
Chlorophyta	53.66	1.22
Spirulina	7.69	0.86
Kelp	4.65	3.52
Silver Carp	1.57	0.30
Tilapia	2.08	0.26
Shrimp	2.35	0.25



For 100 people, how massive is the farm?

Crop	living kg	Dry or Seed kg	Dry biomass inputs for 1 yr for this living mass (kg)	Total 1 year initial supply (kg)
Rice	200	87	5	292
Tomato	200	2	31	233
Soybeans	19300	193	4,697	24,190
Chlorophyta	500	5	88	593
Spirulina	500	5	38	543
Kelp	200	2	27	229
Silver Carp	7100	71	3,168	10,339
Tilapia	2500	25	25,000	27,525
Shrimp	38500	39	57,971	96,510
Yeast-Bacteria Reactor	2429.69	24	100	2,554
Subtotal				*163,008*
Add Structure	*(Assume 0.3 multiplier)*			48,902
TOTAL INITIAL MASS (kg)				**211,910**