A Multi-Stage Space Farm Model

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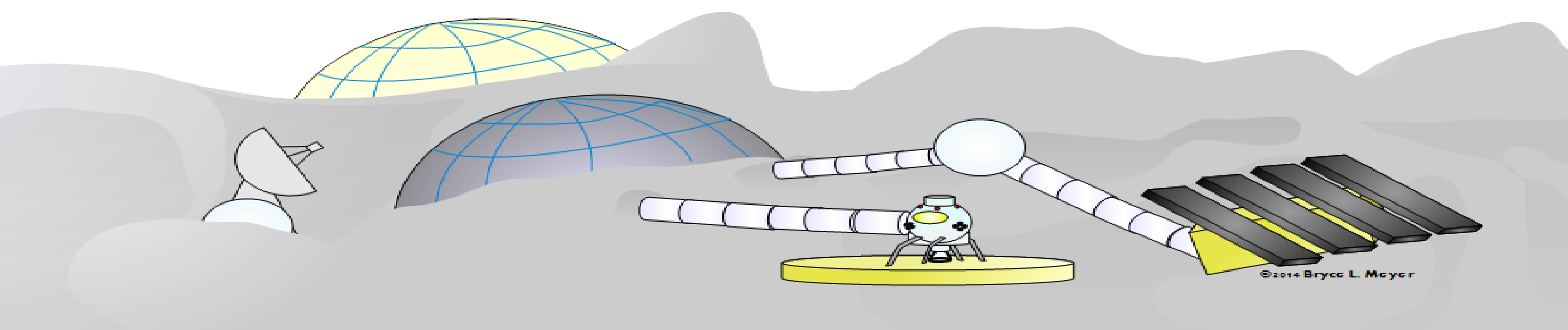
14 October 2015

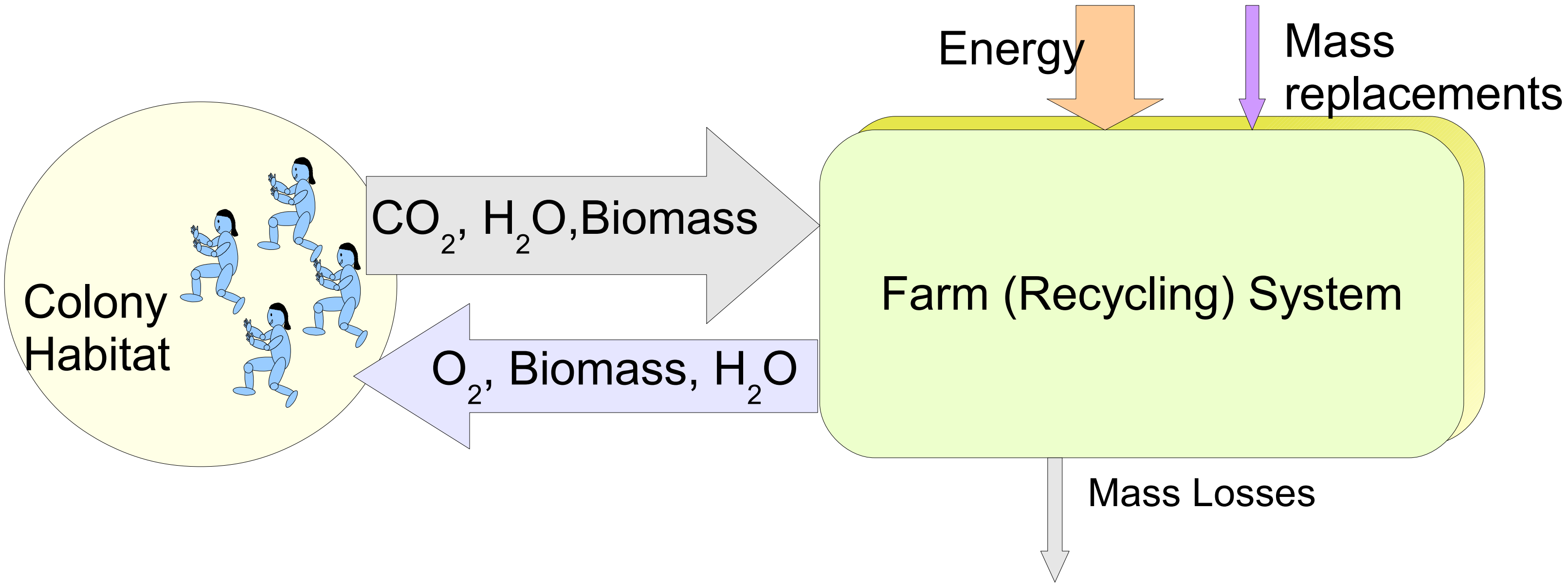


Overview

- A Space Farm Concept
- V1/AIAA SPACE 2015 Paper
- V2: PERL/XML Improved Model
  - Files and Data Structures
  - XML schema
  - Perl constructs
  - Using GD Graph
- Grand Plan

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.

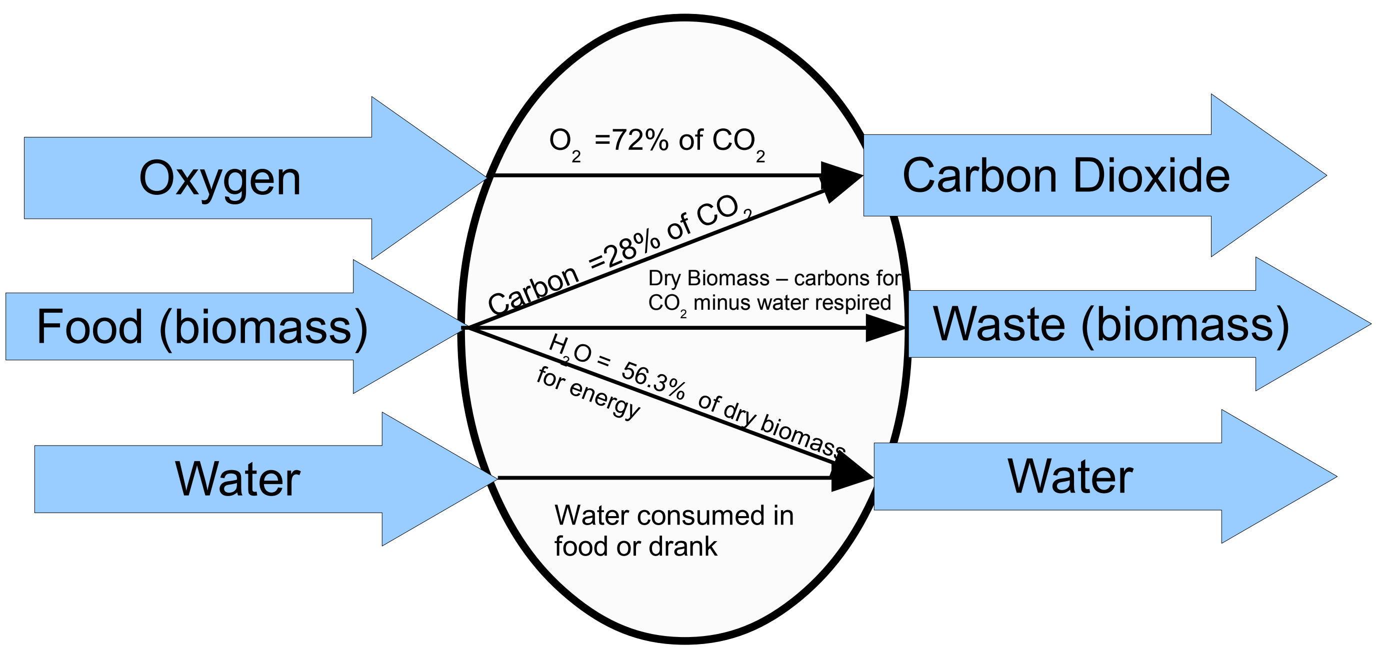


Biomass

- 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 usually 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.
- Animals (inc. People) eat wet biomass, and excrete wet biomass.

Living Systems: Aerobic Respiration

- Animals and Fungi (and many other kinds of life) convert Oxygen and Food into Chemical energy, a bit of water, and Carbon Dioxide.
- Water is a mediator of many reactions



Living Systems: Growth

Growth is incorporation of organic compounds, water, and gases into living tissue, i.e. wet biomass.

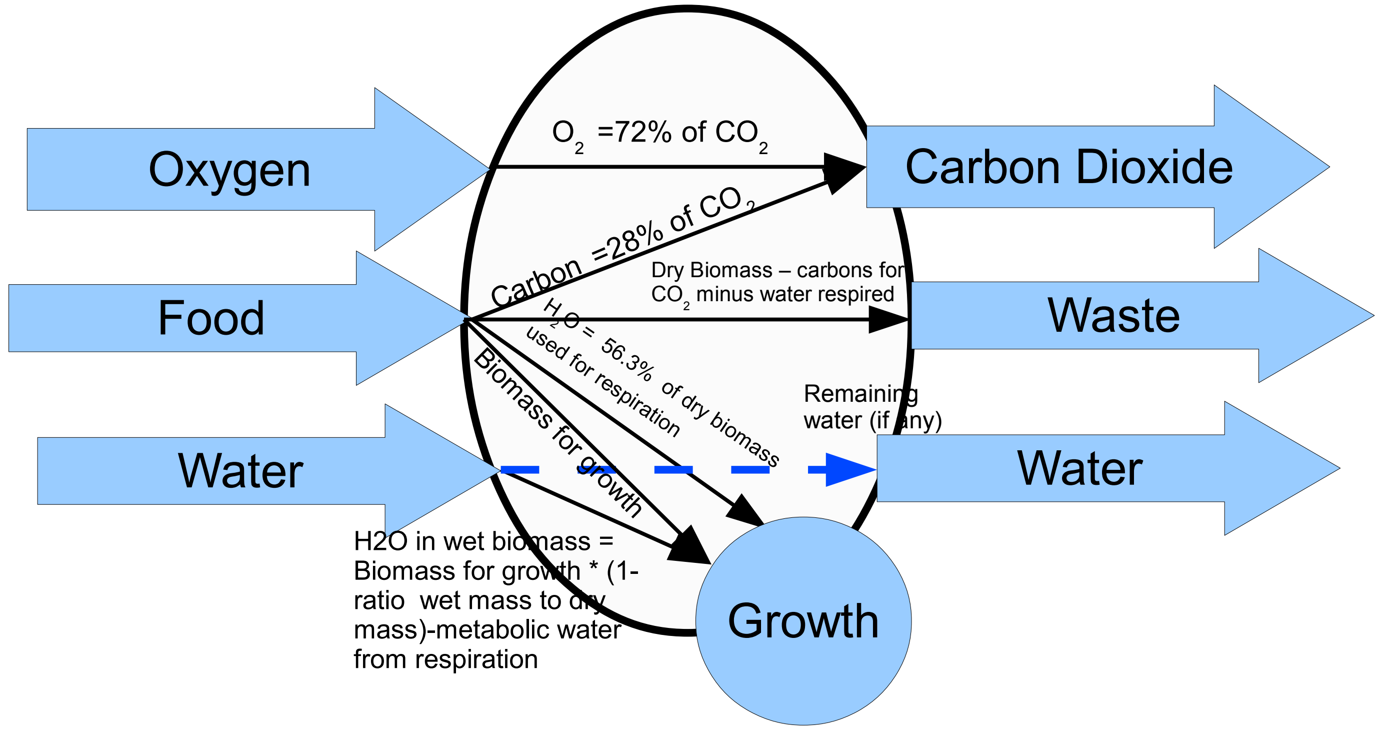
Dry biomass from chemical reactions is combined with water to make wet biomass.

In the case of Animals and Plants, growth is an incress in the wet biomass of the organism

In the case of microorganisms like bacteria, yeast, and algae, growth is in new cells/individuals.

Aerobic Growth Simplified

- Material from food is combined with water to grow
- Organisms budget between energy and growth



Note they also budget between growth and reproduction...

Photosynthetic Growth Simplified

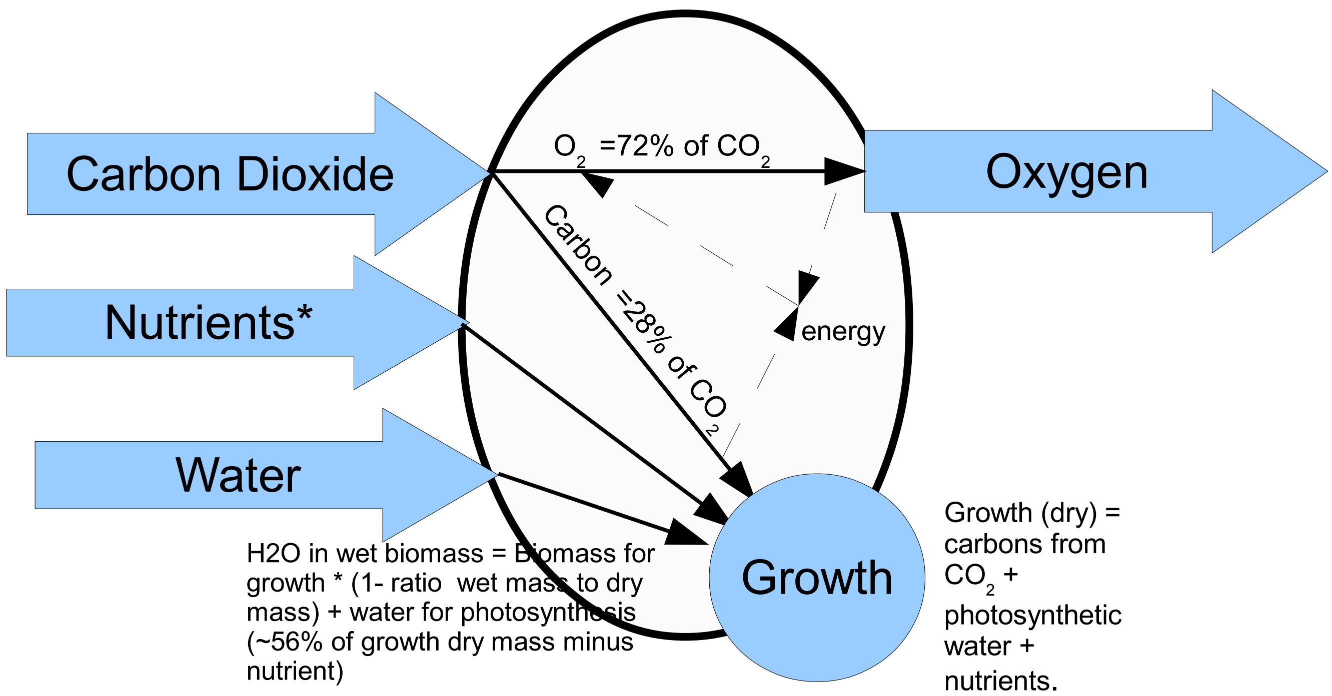
Photosynthetic organism capture carbon dioxide and water to produce sugars.

Some sugars are aerobically consumed by the plant

The rest are stored in wet biomass in growth

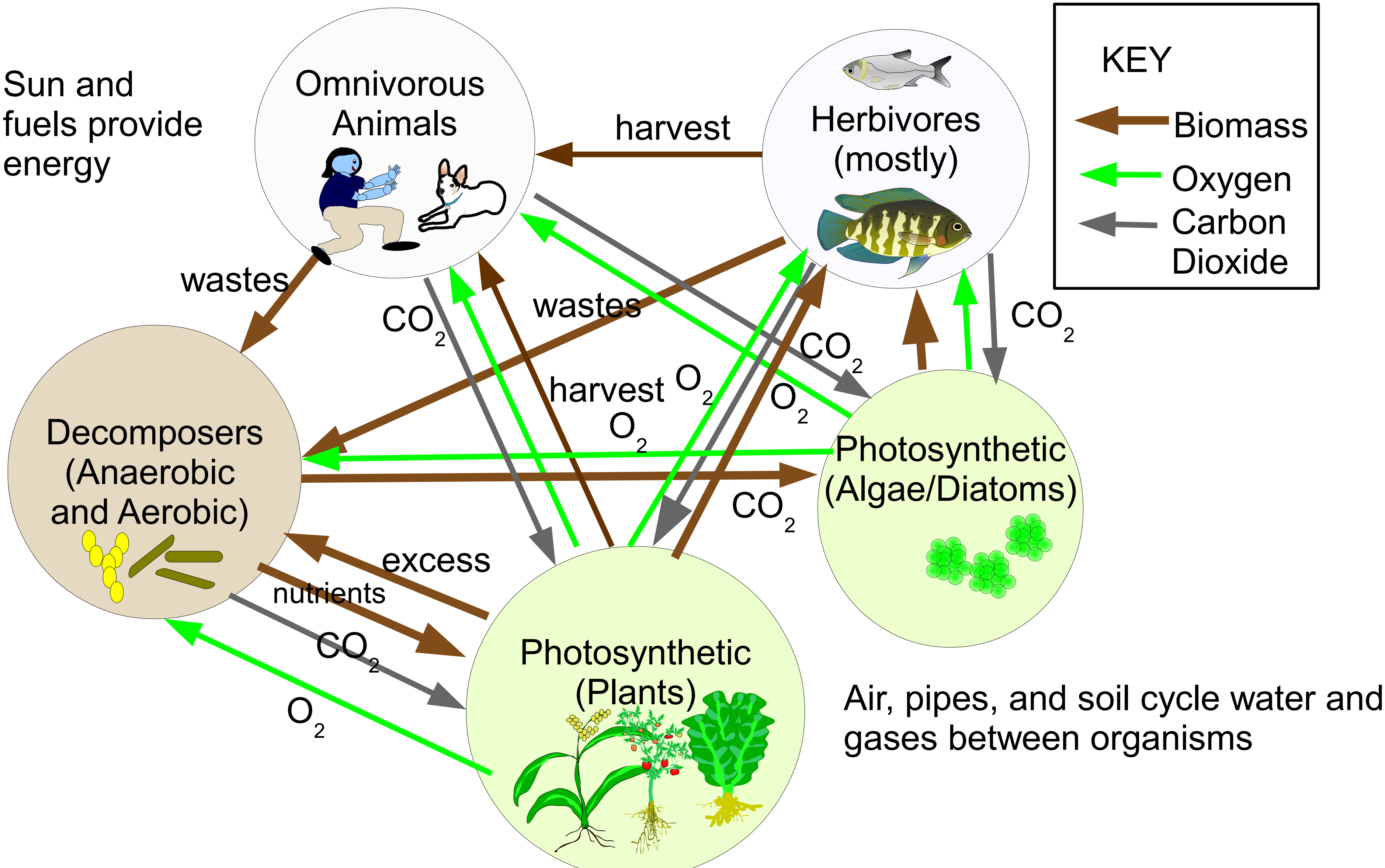
Some growth in fruiting plants or grain goes into the grain/fruit (called here, fruit or crop growth)

The rest goes into leaves, roots, stems including stored sugars (inc. cellulose)(called here vegitative growth)



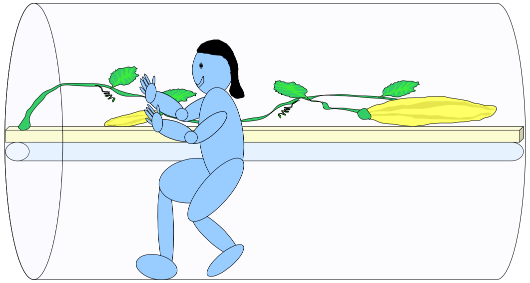
Note: In air, nitrogen is fixed by plants to make proteins, or absorbed by roots from the soil. If we assume an unchanging amount of nitrogen in the air/water surrounding the plant, then all the needed nitrogen comes from the nutrients.

An Earth Farm Example Pseudo Ecosystem



Pseudo Ecosystems

- 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.



Space Farm vs Earth Farm/Ecosystem

- Space Farms are very mass limited, space limited or not, and maybe energy limited or not.
- Species must be carefully selected, and are of limited availability (since they get shipped too).
- All mass is either shipped in and resupplied at very high cost, or collected on-site (i.e. In situ)
  - Sites like Mars, or the Moon, have gravity and access to water, minerals, building materials.
  - Water can be cracked into rocket fuel, or can be made by extracting oxygen and hydrogen then combining it again at a cost.
  - Comets, Asteroids can provide carbonates and carbon dioxde ice at a cost.

Space Farm Differences (Continued)

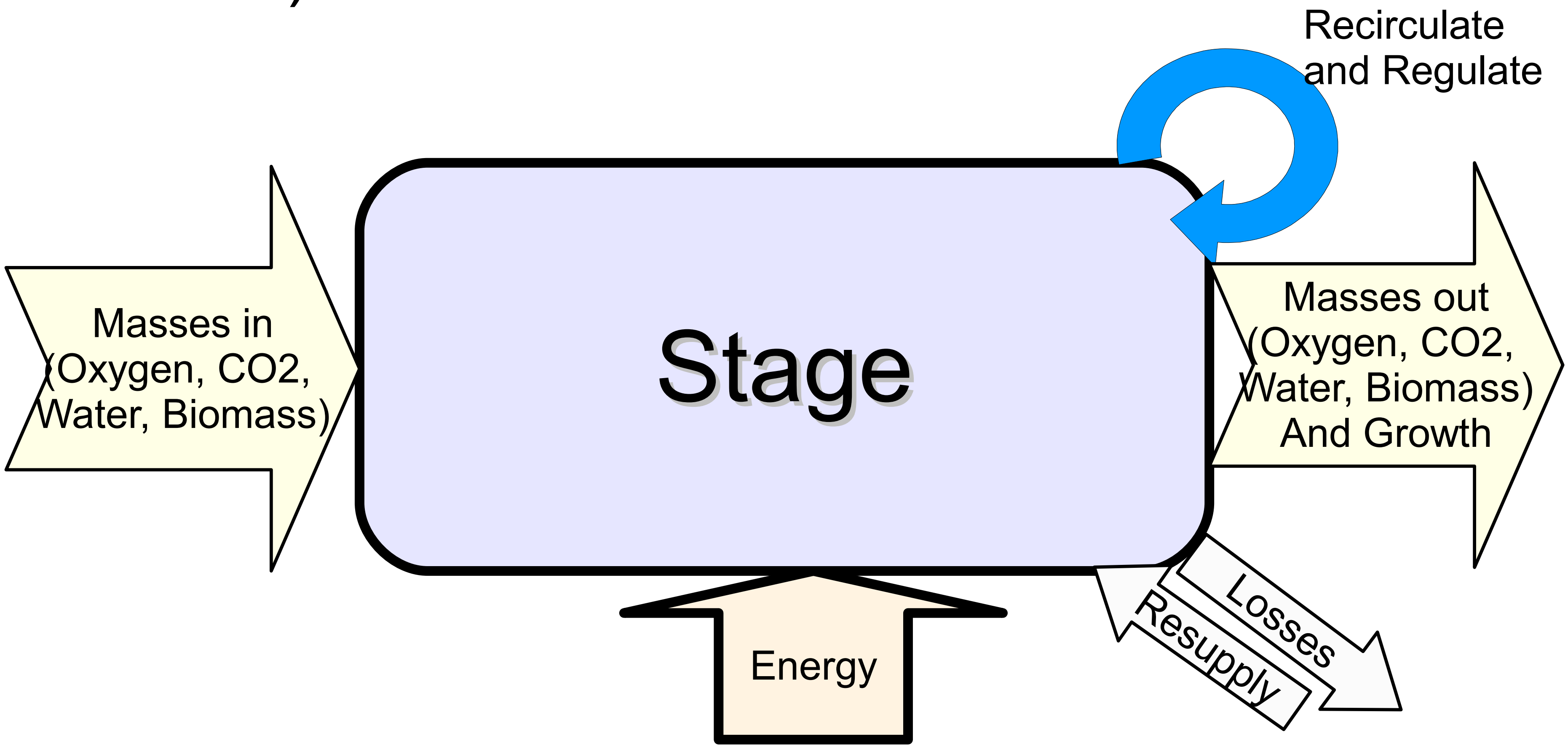
- Solar energy is available, nuclear can be as well, but fuel cells or geothermal might be options energy during dark periods.
- Air is not a given, so gases must be efficiently recycled and conserved.
- Water can boil off in a vaccum, or be contaminated, so it is also precious as well.
- Thermal control and Radiation protection are important for living things.
- Space Farms Therefore must track and tightly control:
  - Water
  - Air (and it composition, Oxygen, CO_2, inerts)
  - Food +Wastes

Stage Concept

- In a stage in this model, only the things needed, or sent on, are tracked.
- It is assumed that machinery ideally recirculates remaining masses at healthy levels for the animals/plants
- Crops growing are sent on eventually, when harvested
- There are 4 stage types: Aquatic, Hydroponic, Algae Reactor, and Yeast-Bacteria Reactor
  - Yeast Bacteria Reactor in the intial model was an ideal balancer...i.e. It made all the numbers balance out. In v2, it is not so magical.
- Over time the stage should be mass-balanced

Mass Balance

- Combination of the Masses of Inputs = Combination of Masses of Outputs (inc. Growth)

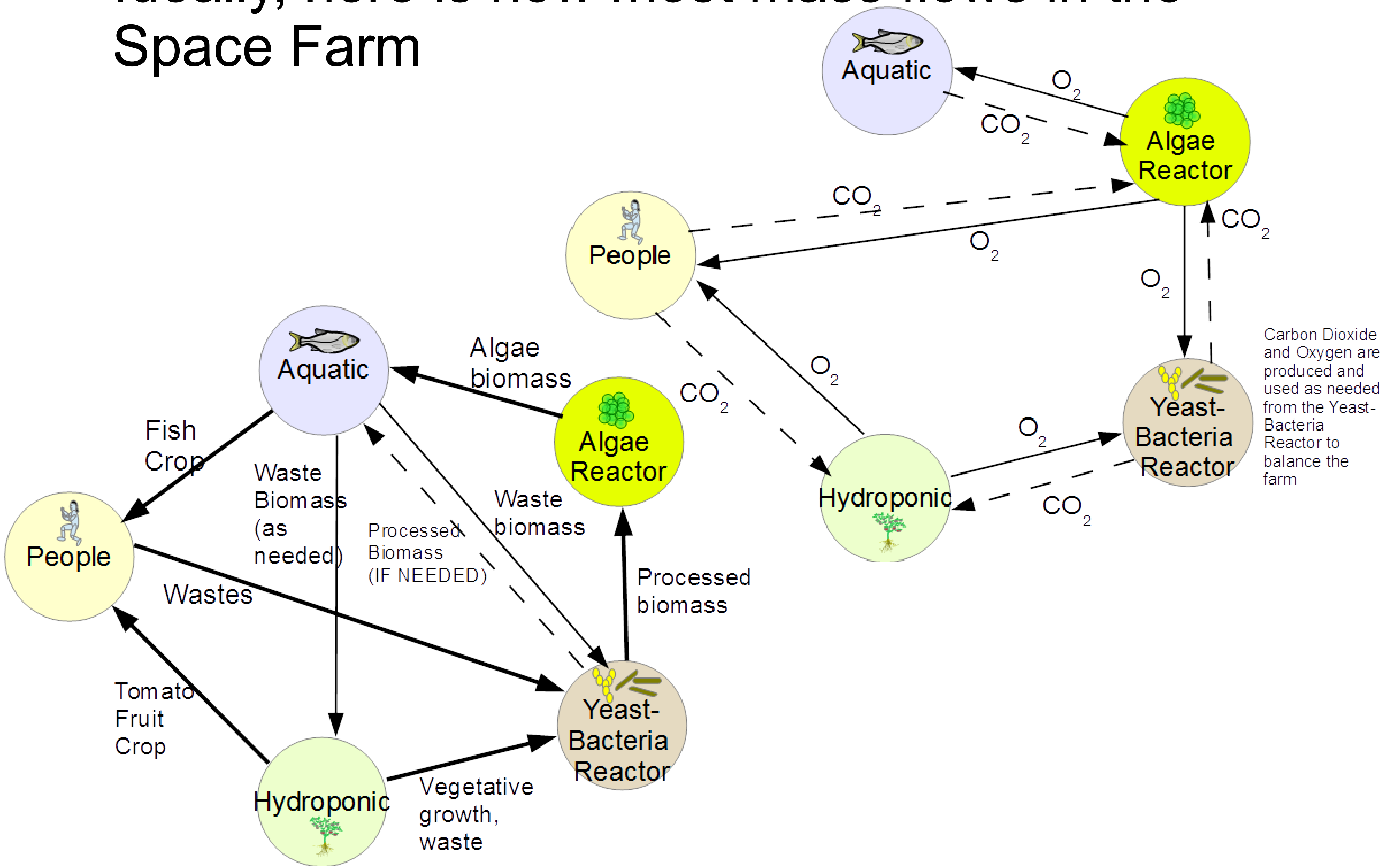


Populations vs Per Capita

- Populations are assumed in v1 to be linear combinations of mass equivelent individuals
- So far, the same in the v2 model.
- Per Capita Values are values for 1 mass-equivelent unit of life in the stage, for 1 Earth Day
  - In v1, there are two population type: individuals and mass-equivelents.
  - In v2 this is 1 kg wet mass of living plant/animal/microorganisms, and a factor is used to calculate extras
  - People(habitat) are assumed an average ungrowing mass.

Primary Flow

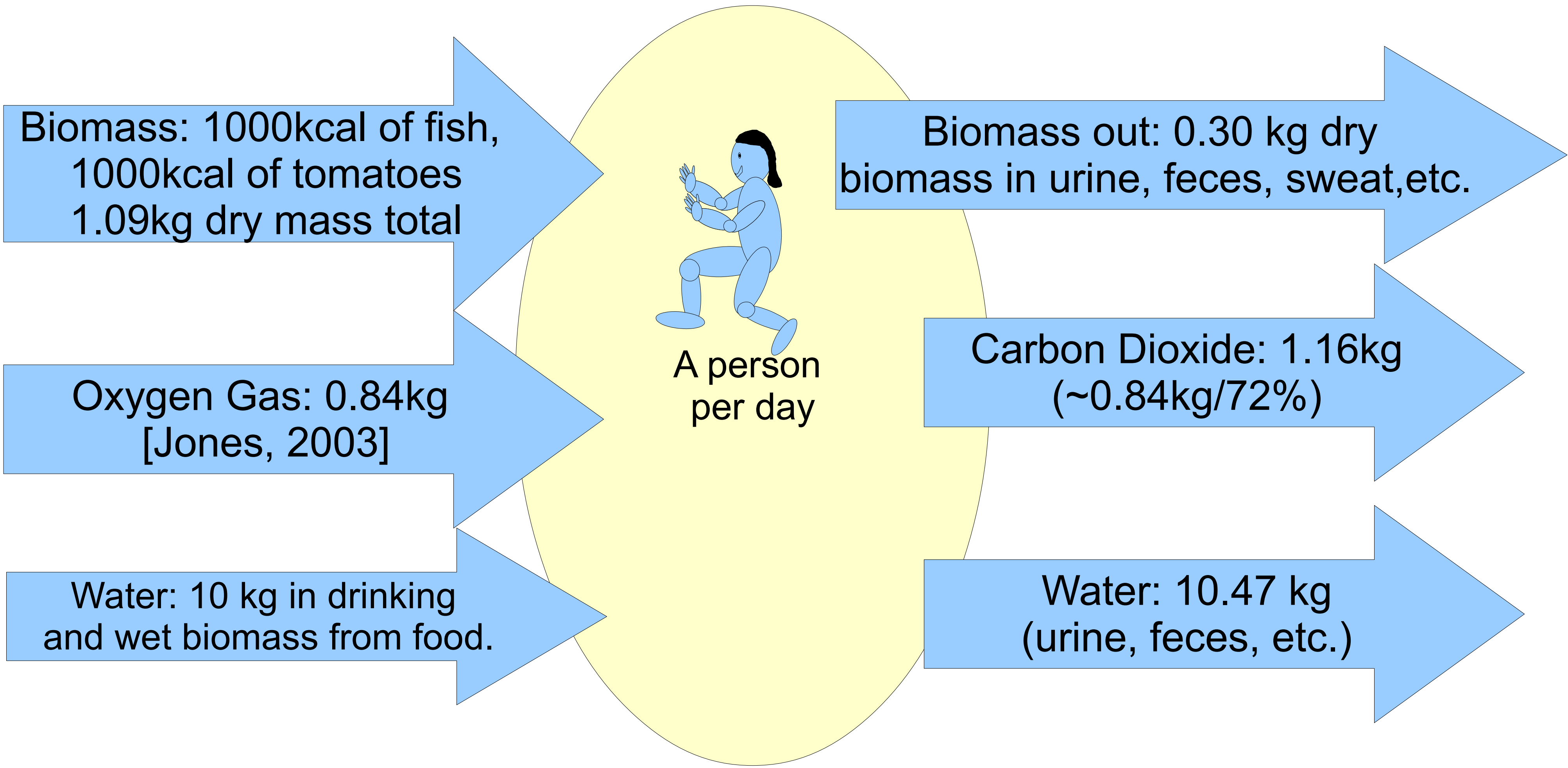
- Ideally, here is how most mass flows in the Space Farm



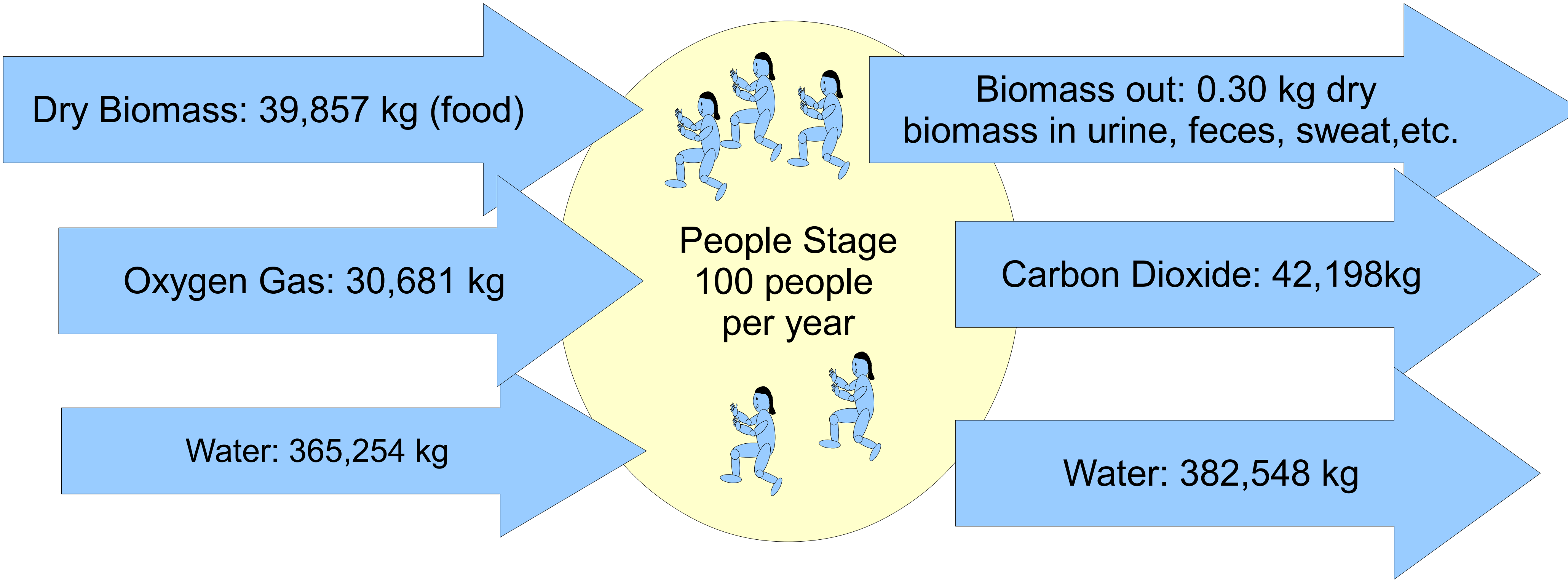
v1

- Published and Presented at AIAA SPACE 2015
- Initial Model Assumed:
  - 5 Stages:
    - People
    - Aquatic with Silver Carp in Raceways
    - Hydroponic with Tomatoes
    - Algae Reactor
    - Yeast Bacteria Reactor
  - No Losses
  - Ideal Reactions
  - Calculated in Open Office Spreadsheets...very cumbersome, but good enough to resolve equations.

People Stage: Per Capita



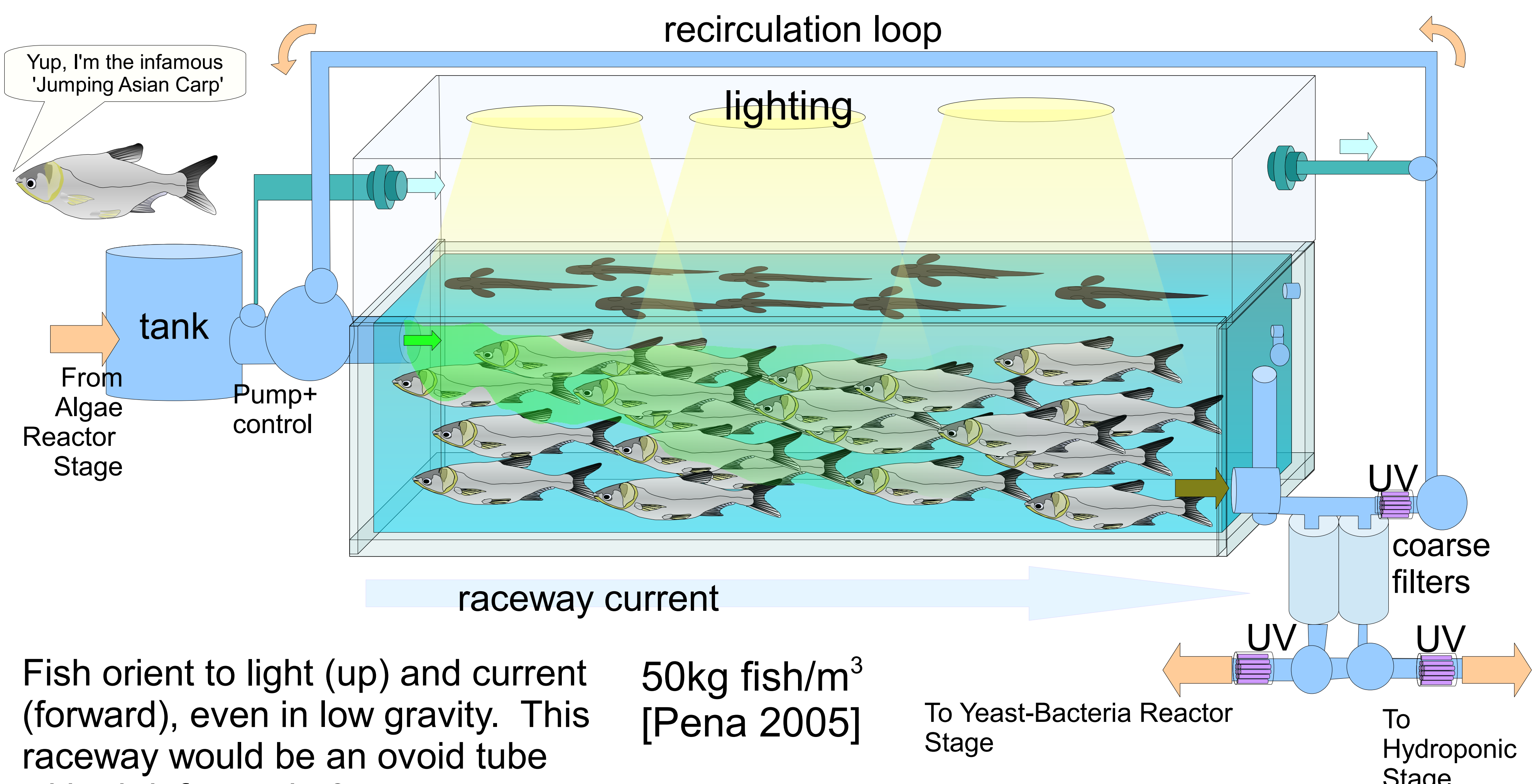
People Stage: Overall, 1 year



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.
Multiple raceways for juvenilles and Breeders

50kg fish/m^3
[Pena 2005]

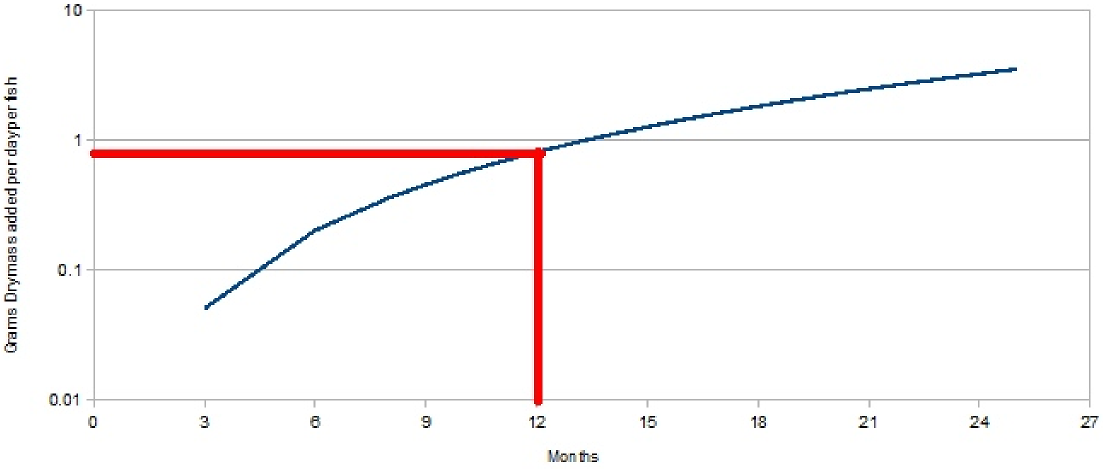
Aquatic Stage

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

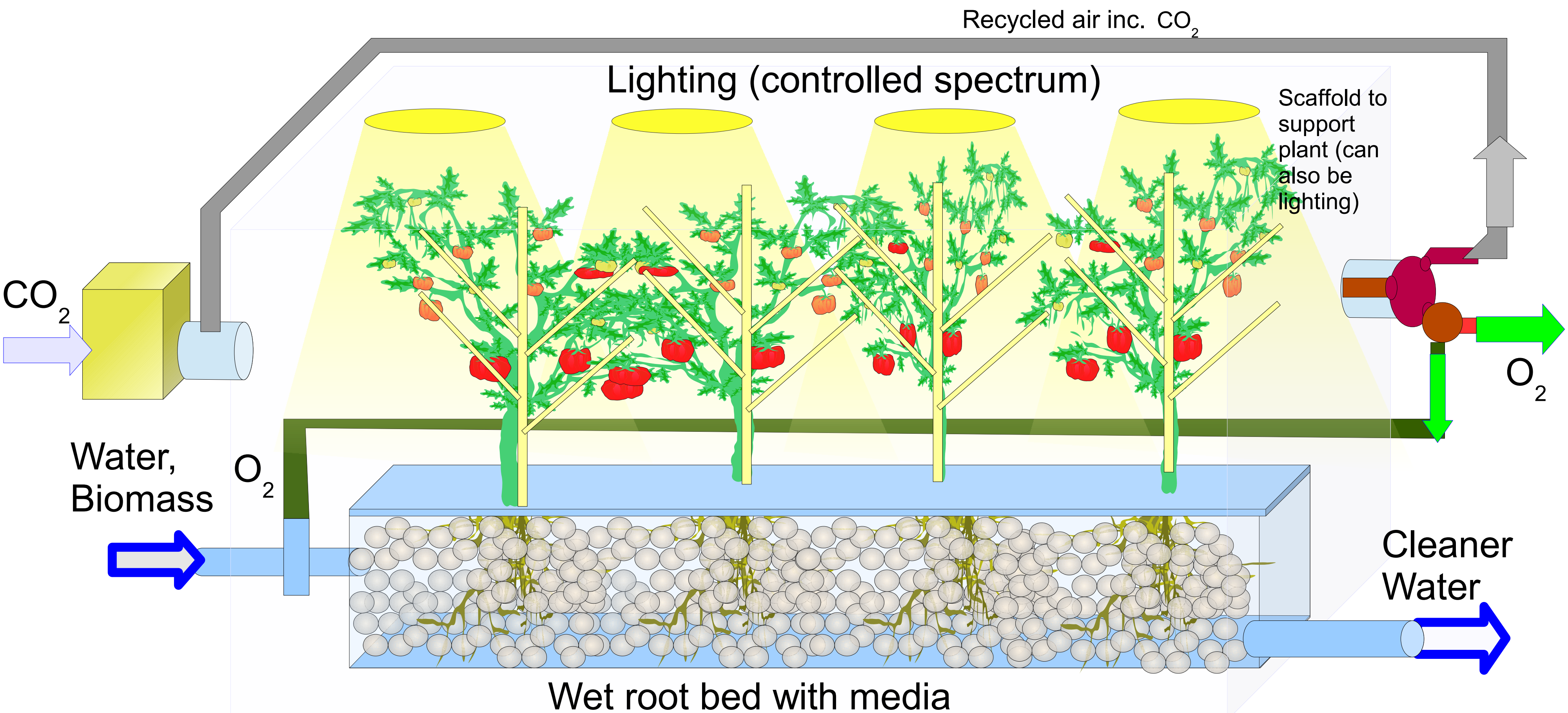
- Very tough, very fast growing, good filters
- Assumed harvest at 1 year, 1.02 kg wet mass, 1 foot (305 mm), not too far past wild growth in MS River Basin.
- Assume 1.04 mass- equivalent population ratio, though a total population ratio of 4.46

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



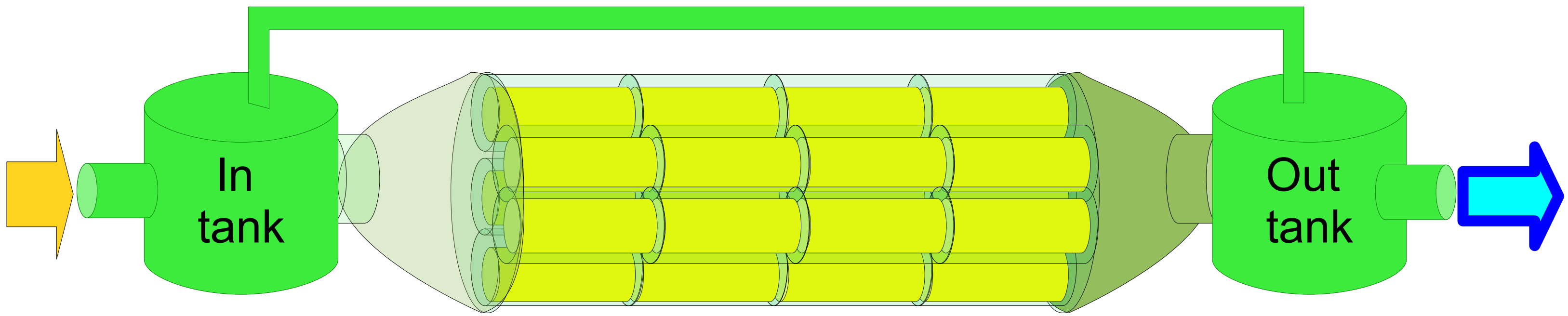
Assume long-lived indeterminate vine engineered tomatoes, 1 kg dry mass, 2 m tall (w/o root), occupying 1.2m^3. Ratio fruit to vegetative growth is 65%

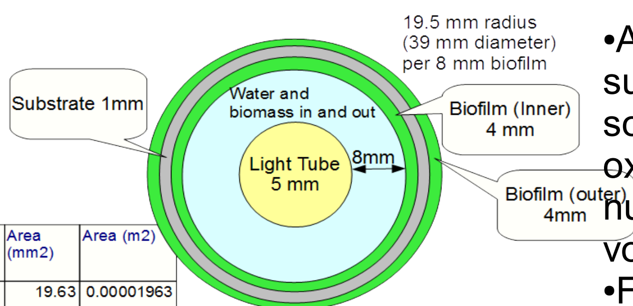
Hydroponic Stage

- 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





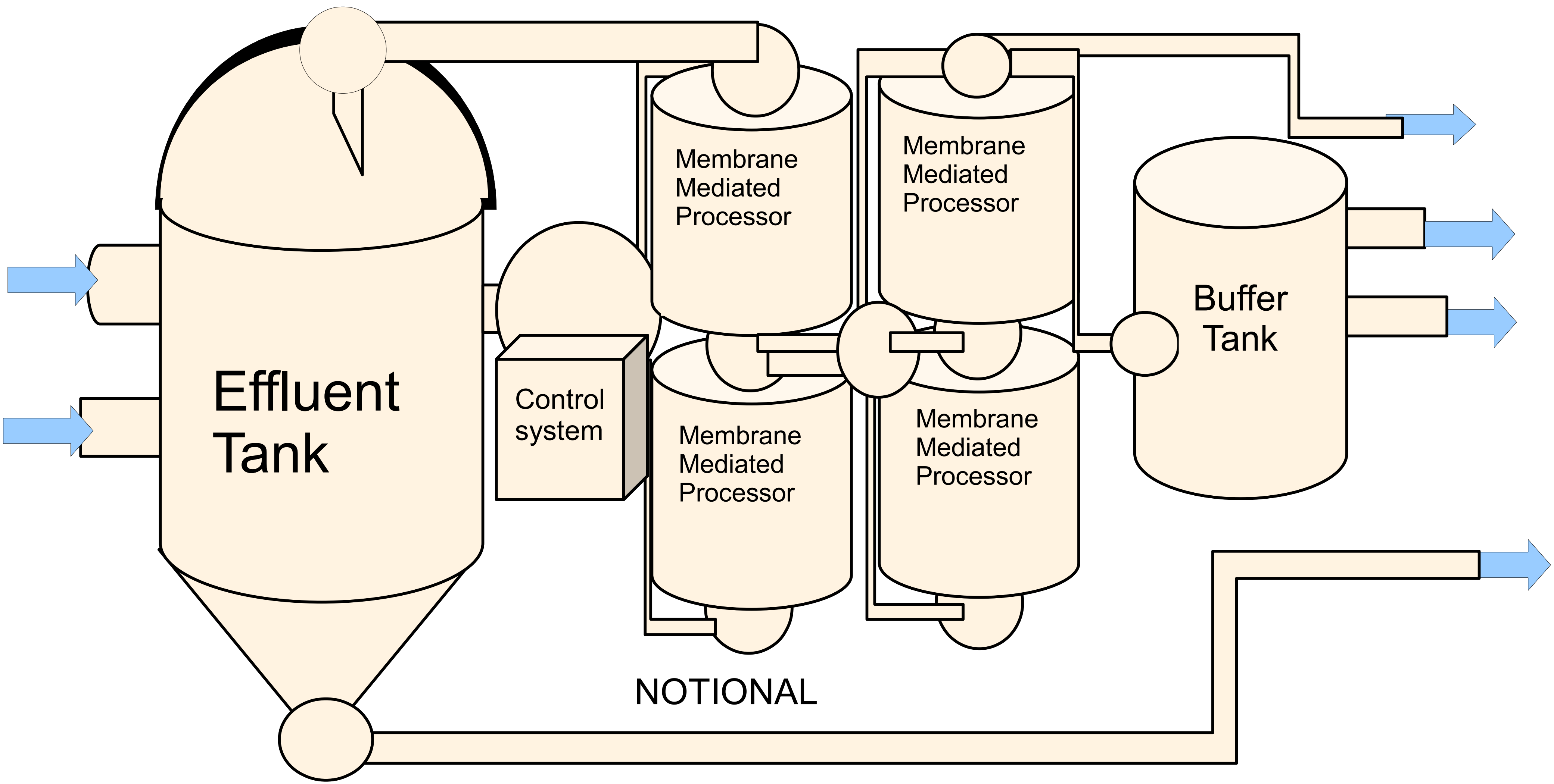
Areas	Outer dia. (mm)	Thickness (mm)	Area (mm2)	Area (m2)
Light tube	5		19.63	0.00001963
water sleave	21	8	326.73	0.00032673
Biofilm inner	29	4	333.79	0.00033379
sustrate	31	1	420.97	0.00042097
Biofilm-Outer	39	4	773.62	0.00077362

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)

- 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		

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)

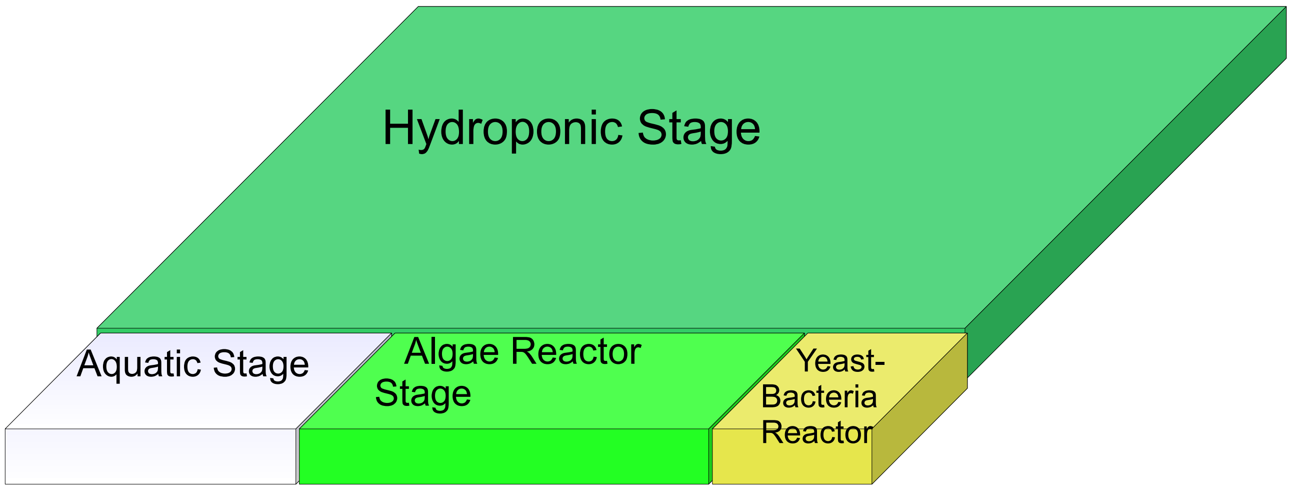
Total Values for the Algae Reactor Stage for a Year		
Total Stage Population (effective)	9,120	kg dry mass
Total Stage Population (total)	13,029	kg dry mass
mass total stage		
Nutrients in (biomass)	23,217	kg dry mass
Water in	390,983	kg
--water in for wet mass in growth	182,030	kg
--water in for photosynthesis	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.

V2: Why?

- Coding a sim allows better examination of:
  - More Species: Multiple Hydroponic Stages, Multiple Aquatic Stages
  - Any Number of Stages
  - Changes over time
  - Inefficiencies and Losses
  - More complexity: Nutrients, Nitrates, sizing
  - Tighter Granularity
  - Easier to switch datasets
  - Prototyping control systems
- V2 is adaptable and expandable

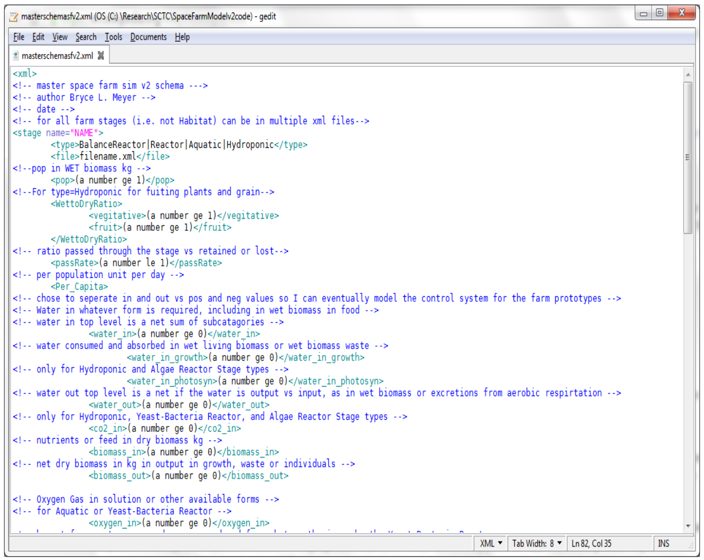
v2

- Files and Data Structures
- XML schema
- Perl constructs
- Using GD Graph
- Outputiing to RRDtool
- Volumes, In-Situ, and Lofting Requirements
- Things to do soon....

XML Scheme

- Adaptable and easily human readable
- Already have a light PERL parser, XML to Hashes
- Joins data types accross files
- Downside: Heavy for large data types
- V2 uses a central schema that spans so far two types:
  - Overall Farm Description
  - Stage Descriptions
  - (TBD—other data)

Overall XML Scheme so far



```
masterschemasfv2.xml (OS (C:) \Research\SCTC\SpaceFarmModelv2code) - gedit
File Edit View Search Tools Documents Help
masterschemasfv2.xml
<xml>
<!-- master space farm sim v2 schema --->
<!-- author Bryce L. Meyer -->
<!-- date -->
<!-- for all farm stages (i.e. not Habitat) can be in multiple xml files-->
<stage name="NAME">
        <type>BalanceReactor|Reactor|Aquatic|Hydroponic</type>
        <file>filename.xml</file>
<!--pop in WET biomass kg -->
        <pop>(a number ge 1)</pop>
<!--For type=Hydroponic for fuiting plants and grain-->
        <WettoDryRatio>
                <vegitative>(a number ge 1)</vegitative>
                <fruit>(a number ge 1)</fruit>
        </WettoDryRatio>
<!-- ratio passed through the stage vs retained or lost-->
        <passRate>(a number le 1)</passRate>
<!-- per population unit per day -->
        <Per_Capita>
<!-- chose to seperate in and out vs pos and neg values so I can eventually model the control system for the farm prototypes -->
<!-- Water in whatever form is required, including in wet biomass in food -->
<!-- water in top level is a net sum of subcatagories -->
                <water_in>(a number ge 0)</water_in>
<!-- water consumed and absorbed in wet living biomass or wet biomass waste -->
                        <water_in_growth>(a number ge 0)</water_in_growth>
<!-- only for Hydroponic and Algae Reactor Stage types -->
                        <water_in_photosyn>(a number ge 0)</water_in_photosyn>
<!-- water out top level is a net if the water is output vs input, as in wet biomass or excretions from aerobic respirtation -->
                <water_out>(a number ge 0)</water_out>
<!-- only for Hydroponic, Yeast-Bacteria Reactor, and Algae Reactor Stage types -->
                <co2_in>(a number ge 0)</co2_in>
<!-- nutrients or feed in dry biomass kg -->
                <biomass_in>(a number ge 0)</biomass_in>
<!-- net dry biomass in kg in output in growth, waste or individuals -->
                <biomass_out>(a number ge 0)</biomass_out>

<!-- Oxygen Gas in solution or other available forms -->
<!-- for Aquatic or Yeast-Bacteria Reactor -->
                <oxygen_in>(a number ge 0)</oxygen_in>
XML   Tab Width: 8   Ln 82, Col 35   INS
```

Likely flesh out growth model as multi-factor and footprint calculator ratios next

(XML which is for the whole farm): Farm data

Stage

Name (used many places)
Type (eventually to do growth)
File (location of stage data file)
Pop(ulation) in mass-equivelent wet biomass kg
Wet to Dry Biomass

Per Capita: Biomass, Water, Oxygen, CO2

Crop: Harvest data

Nutrition: Fat, Carbo, Moisture, Protein, etc.

Footprint:
Volume and Mass Ratios:
How big is the farm,
how much mass total,
initial resources
Launches to LEO

Habitat: Habitat level Data, Population

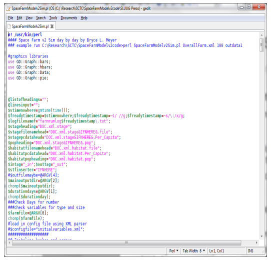
Per Capita: Biomass, Water, Oxygen, CO2

Diet: Fat, Carbo, Moisture, Protein, etc.

Where to get Per-Capita Data?

- Lots of internet searches
  - http://ndb.nal.usda.gov/ndb/search/list
- Use the Aerobic and Photosynthetic Models shown previously (i.e. Convert inputs to outputs using efficencies and rates of growth vs energy)
- Best Guess
- Eventually these will be a variable set from a to be written calculator that loads the stage.xml.

PERL Constructs



- Command line calls overal farm file and determines output location and duration of sim
- XML to Hash...then use the data from the hashes
- Accumulators are hashes of stage names, stage names in array
- Day by Day iterator and calculator
  - For now just gets a mass balance for the whole farm + habitat by summing Per Diem hashes by day then accumulating.
  - Soon will do nutrition and footprint calcs
- Use list of lists to feed graphers
  - Tried Clicker, et, al. Settled on GD:Graph via CPAN but I modified Graph.pm...may mod further
  - Created std subroutines to make common graphic types
- Running on Strawberry PERL, but is std for any platform once libs are loaded.

GD Graph

- Chosen for ease of install from CPAN and use

My subroutine to make the graph, adapted from GD Grapher example 11:

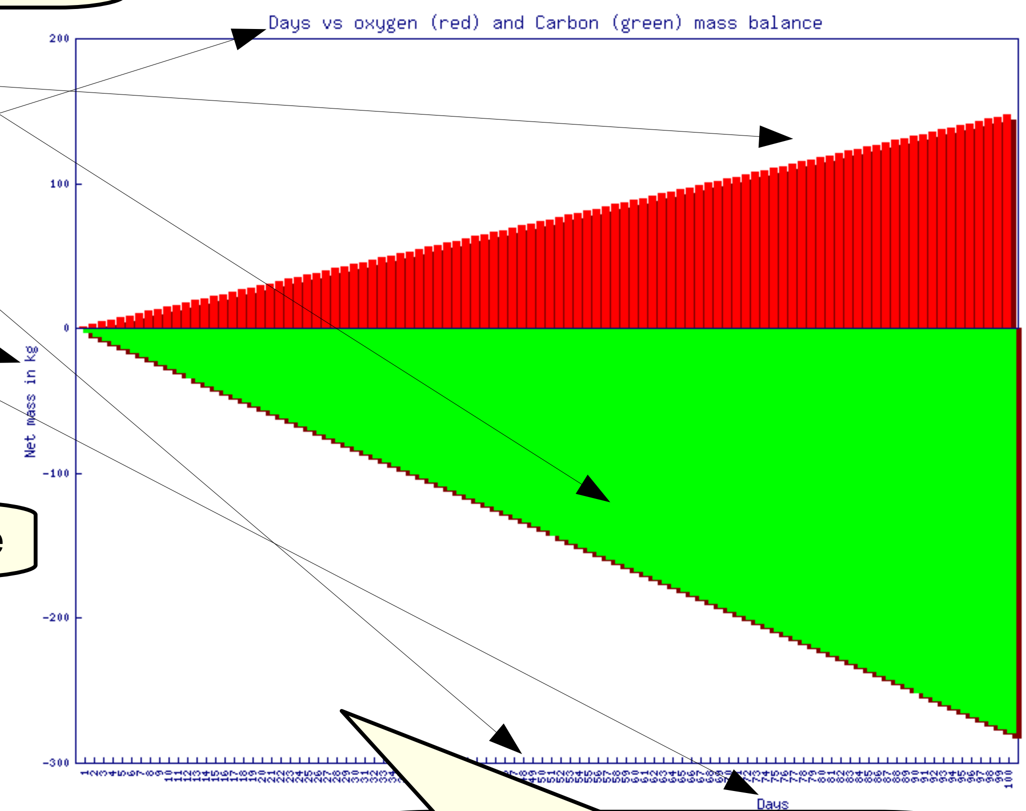
```
sub threepgraph{
my $dataforgh = GD::Graph::Data->new([[@x1],[@y1],[@y2]]);
$my_graph = GD::Graph::bars->new;
$my_graph->set(
        x_label        => $xlabelhere,
        y_label        => $ylabelhere,
        title          => $titleghere,
        #y_max_value     => 8,
        #y_tick_number   => 8,
        #y_label_skip    => 10,
        x_labels_vertical => 10,
        # shadows
        bar_spacing     => 8,
        shadow_depth    => 4,
        shadowclr       => 'dred',
        transparent     => 0,
    )
    or warn $my_graph->error;
$my_graph->plot($dataforgh) or die $my_graph->error;
save_chart($my_graph, $nameheregraph);


##end sub threepgraph
}
```

List of Lists for data

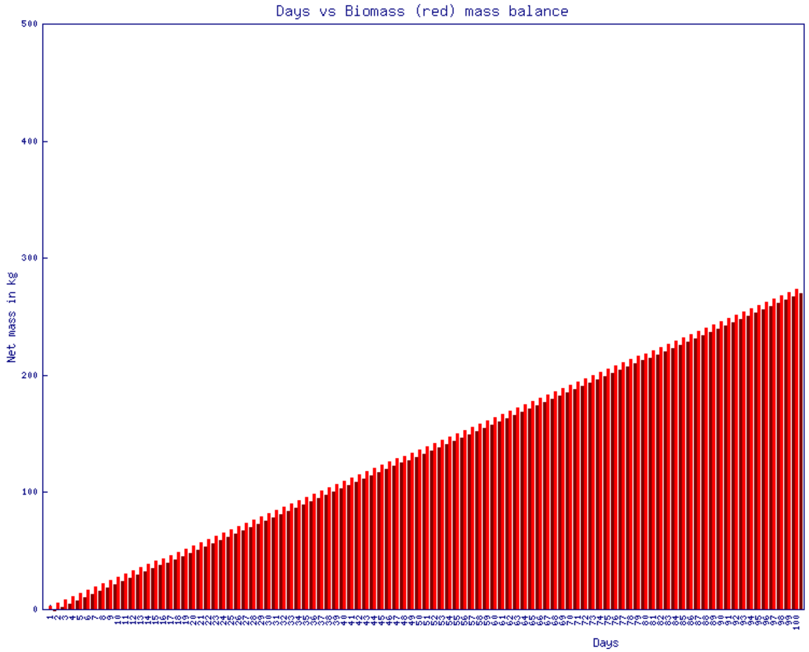
Plots graph structure

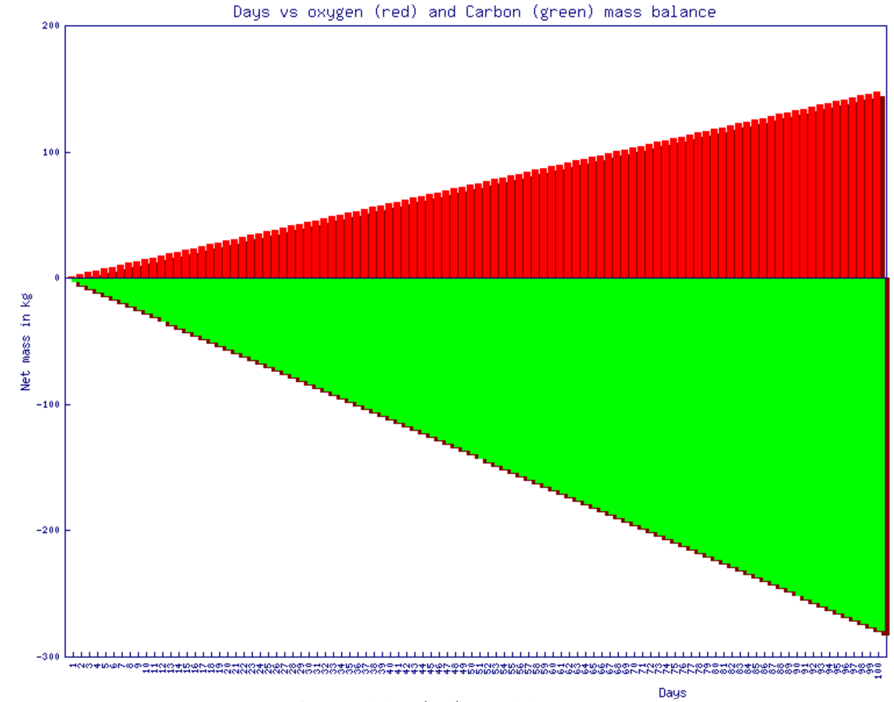
Chart is GIF default

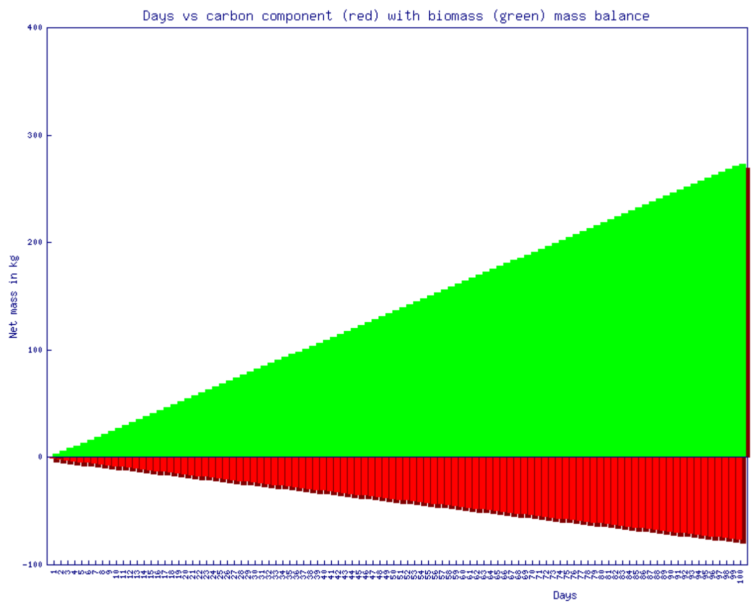


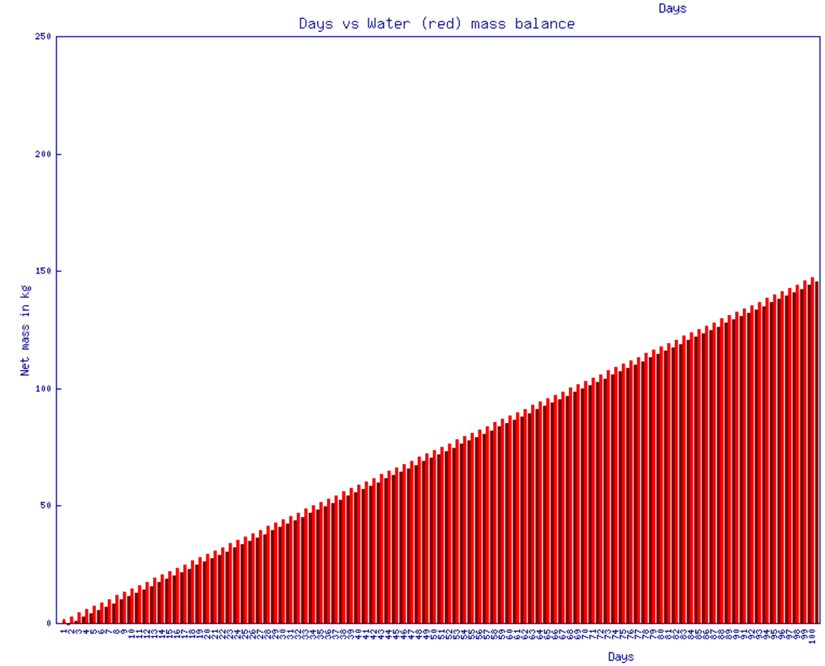
Was read only at 400 x 300, modded .pm to make it 800 x 600

GD Graphs

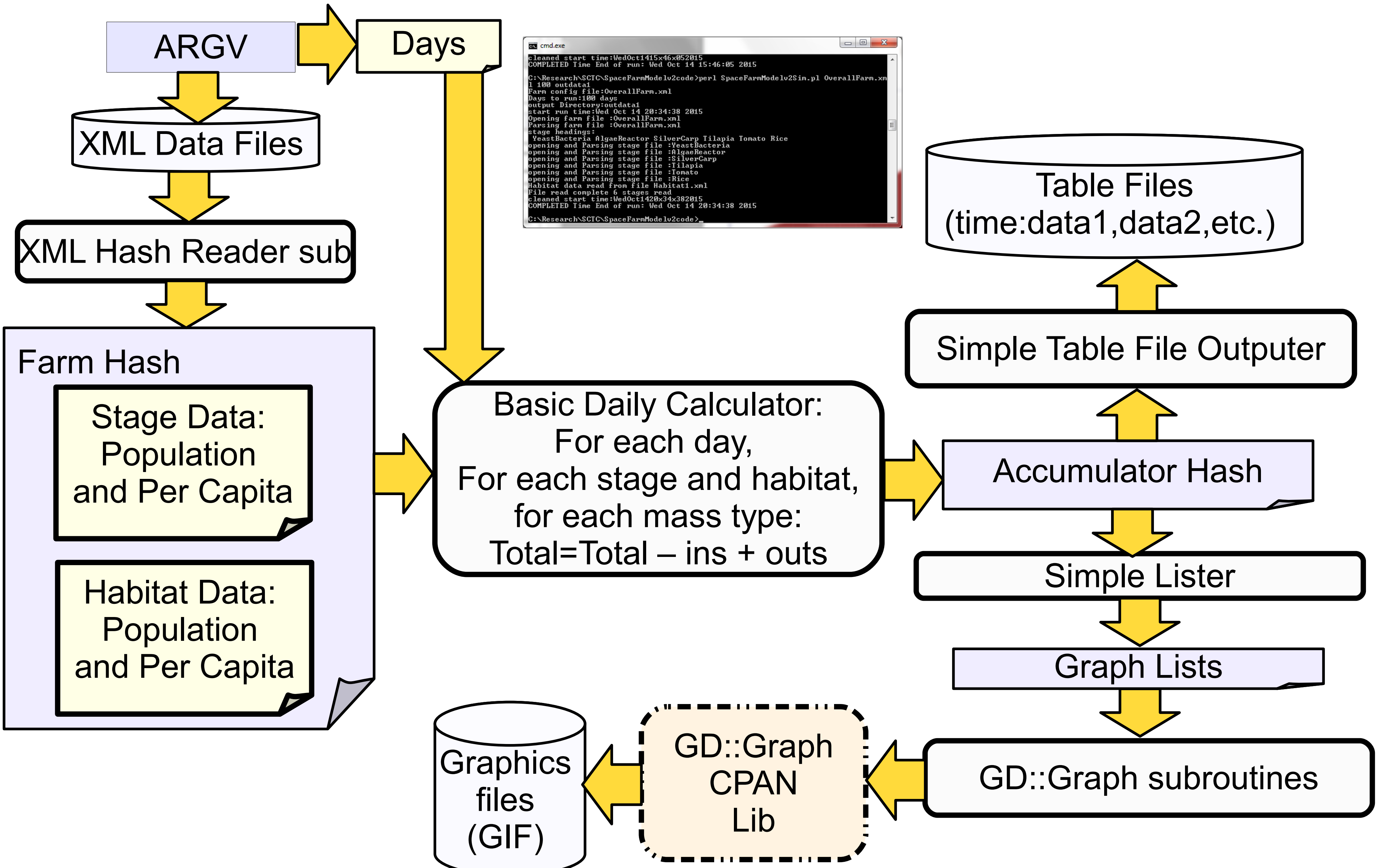

Days vs Biomass (red) mass balance
Net mass in kg
500
400
300
200
100
0
Days


Days vs oxygen (red) and Carbon (green) mass balance
Net mass in kg
200
100
0
-100
-200
-300
Days

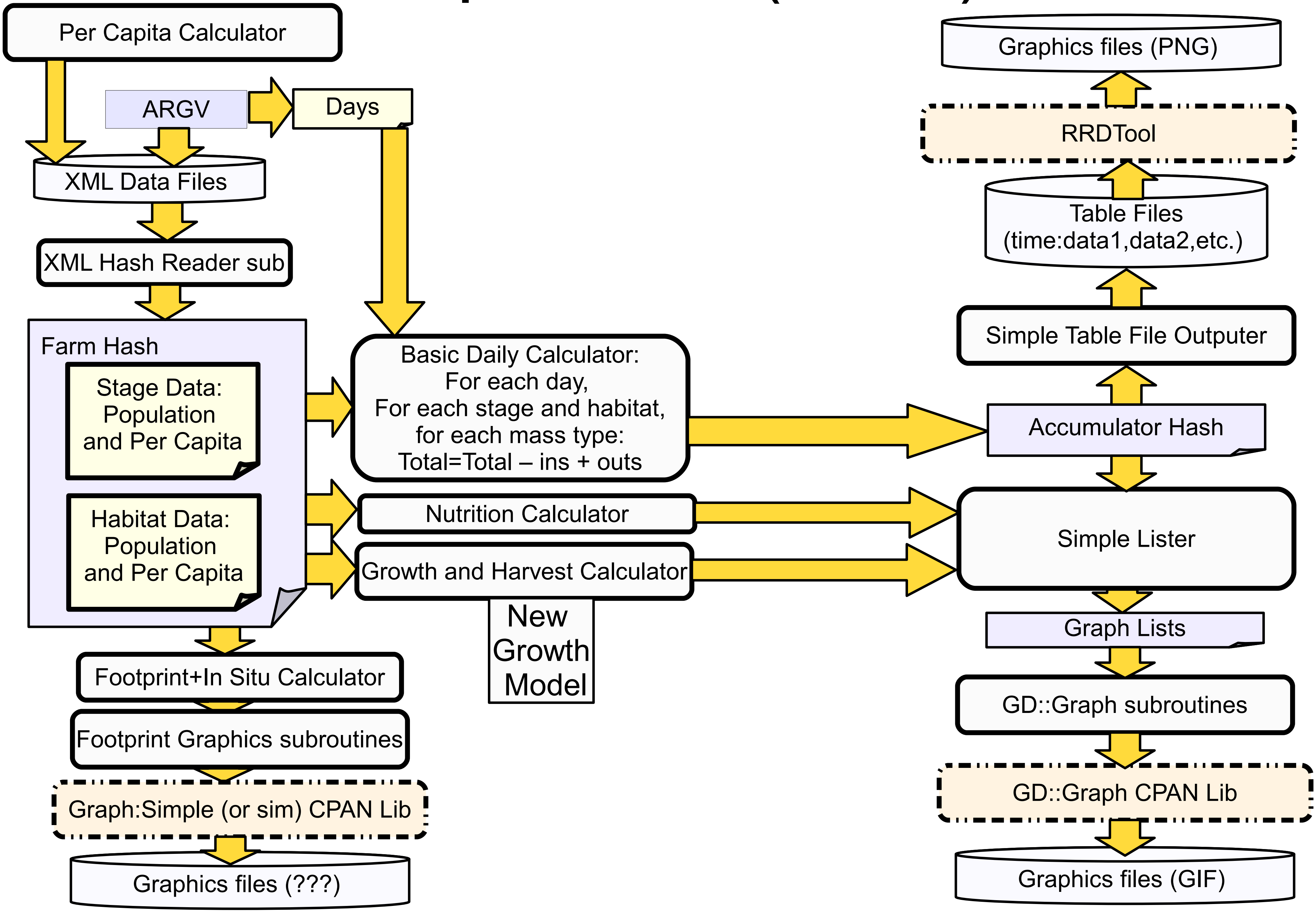

Days vs carbon component (red) with biomass (green) mass balance
Net mass in kg
400
300
200
100
0
-100
Days


Days vs Water (red) mass balance
Net mass in kg
250
200
150
100
50
0
Days

Simple Flow (Current, Daily)



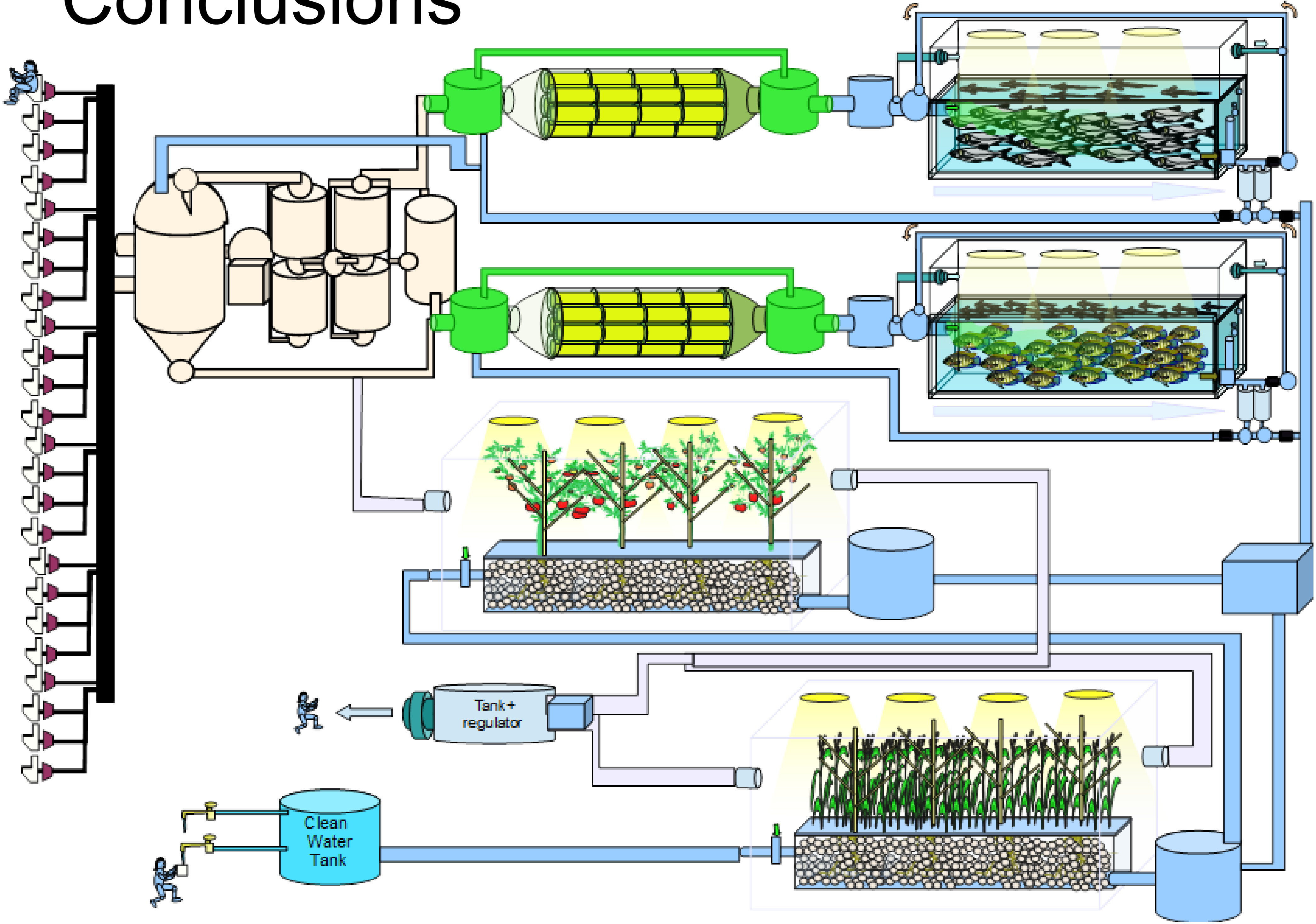
Simple Flow (Soon)



Grand Plan

- 1) Duplicate with minor mods v1, adding graphs
- 2) increase growth model fidelity, add footprint calcs and graphics, calculate basic nutrition
- 3) add in-stage models and allow randomized perturbations
- 4) begin control system sims
- 5) physical prototypes for some components, better inputs
- 6) Prototype control sim, improve biochemical models, build scale farm.

Conclusions



backups

SLUUG Abstract

Main Event 10/14/2015

The main presentation will be A Multi-Stage Space Farm Model by Bryce Meyer

(note the inial theory is here: http://www.combat-fishing.com/animationspace/AIAA_Presentation_SPACE2015bImfltWEB.pdf though the presentation will be more computer focused)

Long term colonization of space, the moon, and Mars, will require not only recycling of core resources such as water, oxygen-carbon dioxide, and biomass, but the long term efficient production of foods of various types. In this model, the People Stage (i.e. The human habitat) exchanges black water, carbon dioxide, and wastes with a farm composed of an Algae Reactor Stage, a Yeast-Bacteria Reactor Stage, a Hydroponic Stage, and an Aquatic Stage. The initial version presented at AIAA SPACE 2015 was modeled roughly using Open Office Spreadsheets, and was restricted to a single species in the Hydroponic Bed, and single species in the Aquatic Stage, and a one year averaged time frame. A more complex model was needed to better examine the result using different species and more fine grained time frames. As a result a XML structure is used to store the model data such as species per-capita chemistry, and the farm's structure, and code in PERL is used to process the XML by day into *RRDTool readable tables*. The talk will not only talk about the dynamics of space farms, but the problems encountered in modelling, and long term projects beyond the initial effort.

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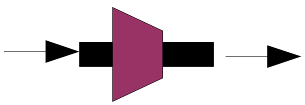
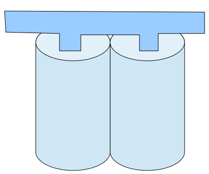
Interesting parts we need

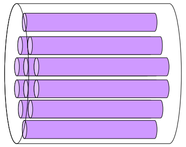
- There are several parts we would need to make this or any space farm work optimally. All need energy to work. These parts exist now, but I assume they will be more advanced in the near future.:



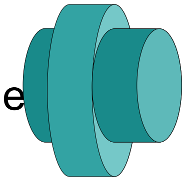
Macerating Pump and flow regulator
These are common in marine applications, they chop any solids in a liquid and push/pull liquids



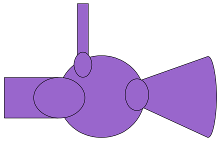
In-Line Filter:
For filtering and cleaning water



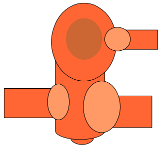
UV (Ultraviolet) Sterilizers
Common in aquaculture. Used to kill bacteria, viruses, and other microorganisms in gases or liquids. Stops the spread of diseases or contamination from one area to another.



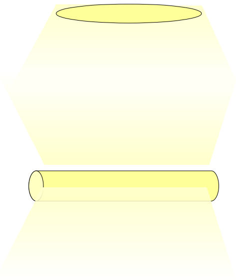
Air Pump and flow regulator



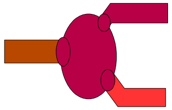
Infuser: Pushes a gas into solution in a liquid (common in aquaculture)



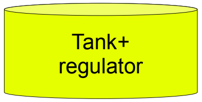
Extractor: Pulls a gas from a liquid.



Controllable multi-spectrum light sources



Gas Separator: Separates gases from a mix of gasses.



Tank and controlling valves to control liquid or gas flow.

There are many more, like pipes, ducts, sensors, valves, thermostats, condensers, humidifiers, etc.