Of Fruits and Fishes: A Space Farm and Recycling Concept

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This paper will outline the core system principles, design concepts, and cyclical dynamics of a multi-stage system that combines four stages: Aquatic (Fish), Hydroponic, Algae Reactor, and Yeast-Bacteria Reactor to balance the needs for one hundred colonists, scalable to much larger sizes. The concept calculates balances for Calories, Dry Mass, Water, Oxygen, and Carbon Dioxide, and the paper will lay out how the mass balances dictate volume and sizing. It is assumed that energy in electrical and heat form are readily available, and that structures are transported to site or created in situ. An initial stage, a Yeast-Bacteria membrane reactor capitalize on septic tank concepts to produce nutrient-rich water, high protein feed, and carbon-dioxide gas for later stages, using human and other wastes. An algae membrane reactor concept uses high surface area to light ratios to produce oxygenated water and excess algae for the aquatic animal stages. Aquatic animal species used are robust organisms, such as Silver Carp (*Hypophthalmichthys molitrix*), which produce high protein food efficiently while filtering water. A later stage uses hydroponic beds and greenhouses to produce vegetables including tomatoes. This paper used a combination of sources to assess the human population as a black-box as well. A 2,000 kcal diet is used as a baseline, and modeled 50% of calories from animal sources. At each stage the paper shows the types of machines required and species core characteristics used to model each stage as a black box for system models. Analysis to date shows that since multiple year classes are required for fish, additional side stages will be required for rearing, this is also similar to a seedling house for vegetables. Core to the systematic balance is the conversion rate of inputs to outputs, in growing and pre-harvest states. For animal stages, an annual harvest requires the ability to store each harvest for up to a year. Silver Carp were selected for examination due to their ability to filter sewage, crowd, and grow swiftly to harvest in a year at over 1 kg fish. Due to the needs for 365 days a year feeding, one estimate shows a crop need of 48,366 fish. Complete population tables and sizing tables for all four stages are included, as is a table for sizing and footprint of the whole farm.

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Nomenclature

Primary Mass Components (Capitalized for a whole stage. lowercase for per capita values.):

B = Dry Biomass.
C = Carbon Dioxide (CO2) by dry mass
O = Oxygen Gas (O2) by dry mass
W = Water (H2O) by mass
N = population in mass equivalent units of a stage
T = Total population of organisms
K = Human edible Kilocalories
L = Wet Biomass

Ratios (Capitalized only):

M = Mass fraction of oxygen in carbon dioxide, set to 72.7%. (1-M) is the mass fraction of carbons in carbon dioxide, or 27.3%.
D = Mass ratio of water to carbon dioxide in simple photosynthesis of fructose, set to 2.44.
R = Ratio of mass equivalent population to crop size.
Q = Ratio of Water out to Oxygen gas input by mass in aerobic respiration. Set to 56.3%.

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V = Volume per unit.
X = Ratio wet mass to dry mass of an organism (greater than 1).
Z = Efficiency of a bioreactor (less than 1). Used to determine the size of the bioreactor such that Ideal Size divided by Z is the actual minimum size for volume and mass.
P = Reactor productivity, mass input for dry biomass per year.
U = Ratio total population to crop population.

Subscripts (lowercase only), these can be chained, separated by commas:
i = in to the per capita unit or Stage
o = out from the per capita unit or Stage
g = growth
m = metabolic
c = crop
w = passed along, or wasted
v = vegetative (including roots, vines, stems)
j = juvenile or breeder organisms not part of the crop
l = wet biomass vs dry biomass

These subscripts are used when referring to multiple stages:
h = People (Habitat) Stage
y = Yeast-Bacteria Reactor Stage
a = Algae Reactor Stage
t = Hydroponic ('Tomato') Stage
f = Aquatic ('Fish') Stage

I. Introduction

While it is possible to directly synthesize food via bioreactors and accumulative manufacturing, humans need to see growing things. On Earth, our current only home, it is difficult to find a set of happy workers who don't have at least a plant, or fish tank, or pet nearby. We do the same in our homes. We enjoy going outside (or inside) and rarely notice the plethora of growing plants and animals that influence our subconscious at a very basic level. As we expand humanity forth beyond the giant bioreactor that is Earth, we will miss this subtext of growing life, and crave its replacement. Further, we like foods that are fresh, a known product of growth. Our bodies need the fiber, nutrients, and complex structures from organisms. Organisms, in turn, are finely honed for making the foods we need, and recycling the wastes we breathe or excrete. Every ecosystem is a series of interlinked recycling chains that capture energy to convert mass to and from organisms. Therefore, the closer an artificial ecosystem, i.e. a (space) farm, approaches the complexity of a natural ecosystem, the more likely it will be efficient. See Figure 1. Both food and recycling aspects are key for vacuum environment systems where every gas and liquid is precious, as for Lunar or Martian colonies. In this paper, a simplified five stage space farm system design and model is proposed, one that replicates the mass cycle of a very simplified ecosystem, and is a fusion of natural and artificial means. The five stages include: People Stage (that is the human habitat), a Yeast-Bacteria Reactor Stage, an Algae Reactor Stage, an Aquatic Stage, and a Hydroponic Stage. In particular, this paper will focus on the system dynamics of the proposed model, and minimal animal and plant population and sizing concerns including farm volume and mass, targeted at a human population of 100 adults, eating a 2,000 kilocalorie diet split evenly by calories between silver carp, and tomatoes.

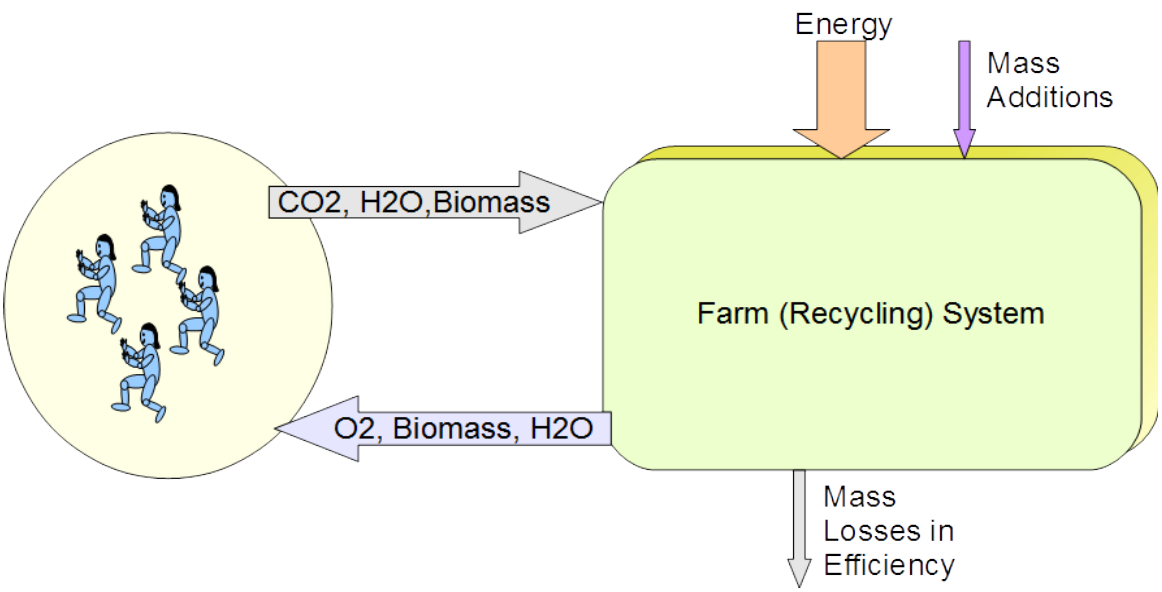

Figure 1. High Level linkage of the Space Farm to the People Stage (Habitat)

II. Assumptions

This paper is focused on the initial sizing and shape of the proposed space farm concept. As such this paper makes many assumptions that will need resolution in later work.

1. This paper assumes that energy is both abundant and provided as needed ideally. This may not be a fanciful assumption for planetary or lunar based locations, as energy in the form of nuclear reactors combined with solar arrays could provide the needed power sources. While the Yeast-Bacteria stage provides some heat for some reactions, it is assumed that this is just part of the larger thermal management of the overall farm.
2. It is assumed that each stage will be maintained at ideal environmental conditions, including protection from radiation or leakage.
3. It is assumed that food can be stored for over 366 days without loss in nutrition.
4. It is assumed that the human chefs are very good at turning the limited crops into a delightful and nutritious array of foods.
5. It is assumed that metabolisms as an aggregate are near ideal in efficiency, that any unused products are used elsewhere in the stage.
6. First calculations will be provided for a snapshot of the farm at a point just before Aquatic harvest.
7. It is assumed the humans are stable (for now) in population and biomass sum. Any weight gain in one person is compensated on average by weight loss in another, so that no additional biomass is retained by the human population as a whole. People will need food and supplies to last long enough for the first crops to mature, though some crops can be started in route. It is also assumed that in-situ resources will be used to constructs the farm at full scale and provide initial masses. In situ or resupply will be required to replace inefficiencies.
8. It is assumed that the Yeast-Bacteria Reactor is far more efficient than current similar reactors, and that its yeasts and bacteria have been engineered or bred to work together in the reactor.
9. Several devices that work better than current counterparts will be available, including gas separators, and can be manufactured on-site or brought in components.
10. Linear modeling of uptake, consumption, efficiency, and production are assumed for this paper, as is linear multiplication of individual organisms (or units thereof) to the stage population. As a result per capita values (lowercase) can be multiplied by N and by days in a year to get stage level values (uppercase).
11. Partial gas pressures and chemical concentrations are largely ignored, as chemistry is assumed to be maintained as ideal, to focus on mass balances across stages to get sizes. Real life systems will rely on complex balances maintained by complex machinery, control systems, and software. As respiration and photosynthesis is non-deal, this also means that unused oxygen exhaled, carbon dioxide unused, and water exhaled is recirculated until consumed.

12. I assume in each stage of the farm machinery exists to ideally distribute water, gases, and biomass or nutrients per capita. I also focus on what is needed to make initial calculations.

II. Simplified Biochemistry

A. Basic Atoms

Nearly all biologically key modules are made from combinations of Hydrogen (chemical symbol 'H'), Oxygen (chemical symbol 'O'), Carbon (chemical symbol 'C'), and Nitrogen (chemical symbol 'N'). In addition, many trace elements such as sulfur, phosphorous, iron, chlorine, potassium, and many others are used. These are combined to make biological molecules.

B. Basic Biological Molecules

This paper heavily focuses on the key molecules below. Atomic weights are drawn from the Periodic Table of the Elements[1], then added together for a simplified molecular mass in compounds:

Table 1. Key Molecular Weights Used in this Paper

Molecule	Molecular Mass	Name	Variable in this paper*
CO2	44.01	carbon dioxide	***C, c***
O2	32.00	oxygen gas	***O, o***
H2O	18.01	water	***W, w***
H2	2.02	Hydrogen gas	***n/a***
CH4	16.04	methane	***B, b***
NH3	17.03	ammonia	***B, b***
C6H12O6	180.15	fructose	***B, b***
C6H10O5	162.14	cellulose	***B, b***
C6H13O2N1	131.17	example amino acid	***B, b***
C6H14N2O2	146.19	example amino acid	***B, b***
* = *UPPERCASE:* for a whole stage, *lowercase*: per capita			

C. Conservation of Mass and Aggregate Mass Balances.

The equations in this paper assumes mass is conserved in all equations, as in Lavoisier's Law of Conservation of Mass, such that mass injected into a stage, where each unit of the stage is a living system, is either released out, or retained in growth.

In real life, populations of animals and plants vary in mass, due to age or other growth reasons. As a result, mass balances require a mass-equivalent population size. For example, in a fish farm, I will have juvenile fish that might be 20% of the size of the harvest crop sized fish, and breeders that might be three times the size of a crop sized fish by mass. For example, if I have 1,000 juveniles at 20% mass, 5,000 crop sized fish, and 100 breeders at triple mass, the mass-equivalent size of the fish population may be 1,000*20% + 5,000 + 100*3 = 5,500, even though the actual organism count is 6,100 fish.

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D. What is Biomass in this Paper?

Biomass in this paper is the dry mass combination of all organic and life-related compounds, including: carbohydrates, lipids, proteins, organic molecules, ammonia and other nitrates, and minerals. It is symbolized by the capital or lowercase letter '*B*'. Dry mass is real life for an organism is found by dehydrating a dead organism (or in the case of viruses, bacteria, and some others, live upon wetting), and weighing the result. The similar process is used for non-living materials such as fruit, or excrement.

E. Wet Biomass and Dry Biomass

'Wet Biomass' refers to the combination of Dry Biomass and water in a living or formerly living organism. Given the ratio X for an organism (or mass-equivalent population), wet mass (l) is X times dry mass (b).

$$l = b * X \tag{1}$$

To find water input in consumed wet mass, we use X as defined above:

$$w_{i,l} = b_i * (X - 1) \tag{2}$$

Where k_l = per kg wet mass kcal content:

$$b_i = k/[k_l * X] \tag{3}$$

F. Basic Ideal Aerobic Metabolism

Aerobic metabolism is used by animals, plants, bacteria, and fungi to convert sugars to chemical energy. In short, sugars are combined with oxygen gas to extract energy and producing carbon dioxide and water. An example reaction, very simplified, is for fructose: C6H12O6 + 6O2 → 6H2O + 6CO2 + energy. This paper uses this equation in part for all animals, including people, to fill in missing mass values. Not everything animals eat is sugar (thankfully), so some of the chemicals from food must be excreted after use. Using the nomenclature above, food containing sugar and other chemicals for one animal is b_i. The chemicals not used for energy are excreted or used in growth as b_o. Animals also take in water to mediate chemical reactions and to add to wet biomass, w_i. This results in these equations:

$$b_i + w_i + o_i = b_o + c_o + w_o \tag{4}$$

If the oxygen in carbon dioxide is from the oxygen gas inhaled, we can use the ratio defined above, M, to calculate c_o given o_i.

$$c_o = o_i / M \tag{5}$$

$$w_{o,m} = o_i * Q \tag{6}$$

G. Basic Ideal Photosynthesis

In photosynthesis, plants or algae convert carbon dioxide and water, using light energy, into sugars and oxygen. An example simplified chemical reaction is 6CO2 + 6H2O + light energy → 6O2 + C6H12O6. You should note this is the reverse of the Aerobic Respiration chemical equation above. Carbon atoms in the fructose come from the carbon dioxide, while the hydrogen come from the water. In short, this farm (and Earth's ecosystems) depends on cycling of Photosynthesis and Aerobic Respiration to move mass and energy between organisms. A space farm will likely depend on artificial light in a spectrum optimal for photosynthesis in lieu of direct sunlight. As plants and algae also respire, mass balances in photosynthetic stages will be a net production of biomass and oxygen gas, where any use of oxygen and sugar is deducted for each per capita unit from photosynthesis. As photosynthesis and plant growth in reality consume a small fraction of biomass, there will be some inbound biomass provided. Plants also allocate growth to cellulose in lieu of sugars, and intake more water to add to this added biomass, which gets captured in growth biomass (which is biomass out). Using the nomenclature above the chemical equation and other factors noted above result in the following per capita equations:

$$b_i + c_i + w_i = b_o + w_o + o_o \tag{7}$$

$$w_i = w_{i,m} + w_{o,g,w} \tag{8}$$

If all the water excreted is in plant growth:

$$w_o = w_{o,g} \tag{9}$$

$$w_{i,m} = c_i / D \tag{10}$$

$$c_i = (b_o - b_i) / (1 - M + 1/D) \tag{11}$$

$$o_{o,m} = M * c_i \tag{12}$$

H. Sample Reactions Mediated in the Yeast-Bacteria Reactor

The Yeast-Bacteria Reactor will have a controllable set of reactions, designed to balance out the overall space farm. Some reactions consume oxygen, others release oxygen, and others control methane, ammonia, alcohol, or hydrogen gas. Here are the example set of chemical reactions assumed to generate mass balances across the Yeast-Bacteria stage, more on this stage follows in sections below:

Table 2. Example Chemical Reactions

C6H12O6+6O2 → 6CO2 + 6H2O
C6H10O5 +6O2 → 6 CO2+ 5 H2O
2C2H5OH + 6O2 → 4 CO2+ 6 H2O
6CH4 + 6O2 → C6H12O6 + 6H2O
2C6H10O5 + 2NH3 → 2C6H13O2N1+3 O2
C6H10O5 + 2NH3 → C6H14N2O2 + H2O +O2
5C6H10O5 + 4NH3 → 6 CO2+ 5 H2O +4C6H13O2N1
7 C6H10O5 +12 NH3 → 6 C6H14N2O2 + 11 H2O+6 CO2
2H2 + O2 → 2H2O
5C6H12O6 + 4NH3 → 6 CO2+ 10 H2O +4C6H13O2N1
6CH4 + 6H2O → C6H12O6 +12H2
C6H12O6 → 2 C2H5OH + 2 CO2
C6H12O6 +6H2O → 6CO2+ 12 H2
3C2H5OH + 3H2O → C6H12O6 + 6H2
C6H10O5 + 7H2O → 6CO2+ 12 H2
C6H10O5 + 7H2O → 6CH4 + 6O2
C6H10O5 + H2O → C6H12O6

I. Energy versus Growth

Every organism budgets between metabolic use of chemicals for energy, and growth. Animals consume food and oxygen, and either use the food with oxygen for energy resulting in water and carbon dioxide, or transform the food and water into wet biomass in growth. Managing this budget is important for maximizing crop yields. Similarly, plants budget between using and producing chemical energy, and between growing wet mass for leaves, roots and stems to capture light for energy, against securing the next generation by growing wet mass in seeds and fruits. For algae here, growth is simply more algae cells, which become biomass food for other stages.

III. Characteristics and Systems of Each Stage

Each stage has a population of organisms or dry mass units, and features used to feed other stages. This paper begins with the People Stage which has given characteristics, then defines the per capita values for the remaining stages. For per capita values, the general mass balance is like so:

$$b_i + c_i + w_i + o_i = b_o + c_o + w_o + o_o \tag{13}$$

Or for a whole stage:

$$B_i + C_i + W_i + O_i = B_o + C_o + W_o + O_o \tag{14}$$

Aerobic stages, People and Aquatic primarily, do not take in carbon dioxide, and as an aggregate population (assuming recirculation and gas separation) do not exhale oxygen, therefore (as in the Aerobic discussion above), using Eq. (4) for a whole stage:

$$B_i + W_i + O_i = B_o + C_o + W_o \tag{15}$$

Similarly, Photosynthetic stages, i.e the Hydroponic Stage and Algae Reactor Stage, produce oxygen and intake carbon dioxide, using Eq. (7) above, for a whole stage:

$$B_i + C_i + W_i = B_o + W_o + O_o \tag{16}$$

The Yeast-Bacteria Reactor Stage can do all the above in this paper and uses Eq. (13) and Eq. (14), based on what the farm needs overall to achieve balance.

A. People Stage

Our people live in a sealed habitat that seeks to limit resupply needs, from either other colonies such as Earth, or from missions to collect resources away from our colony. Complex machines and control systems maintain environmental conditions, and buffer inputs to the habitat from the space farm. Water in the air is partially locally recycled from condensers and humidifiers. Grey water sources from showers, wash basins, or similar sources is also collected and partially recycled. Urine and feces are collected, macerated, sterillized, and partially separated, before entering the farm. Water is overall tanked and released as needed by the human population and the space farm. Meals must use many portions of food optimally, to prevent waste that has to be processed by the space farm. Fish meal is used in addition to fillets, to better utilize the fats and proteins from consumed fish. Tomatoes are processed in many ways to again use the most of the tomato fruits. Fish and some tomatoes are stored ideally for up to 366 days, since fish harvest is annual, not continuous. The human population, assumed to be 100 adults, aerobically respires like any other mammal, using the per capita Eq. (4), Eq. (5), and Eq. (6). Using data from Table 2 in Ref. 2, and simple observations, we assume that humans consume roughly 10 liters (10 kg) of water per day between drinking water and wet mass, and breathe in 0.84 kg of oxygen gas per day, given the proposed 2000 kilocalorie diet. Ignoring the water for now, this reference provides a value for o_i. Using Eq. (5) (and on aggregate, assuming very good respiration efficiency) we can calculate c_o to be approximately 1.16 kg. The carbons in carbon dioxide come from b_i, though b_i has more than just carbons.

Given 2,000 kcal per person per day, and assuming a human diet of 1,000 kcal fish, and 1,000 kcal tomatoes, we can use Eq. (1), Eq. (2) , Eq. (3) and values of X and k, to create Table 3. The values X_f estimated from Fig. 5 in Ref. 3, adjusted for higher nutrition engineered silver carp in raceways to be 4.31 (or 76.8% moisture, would be a 1 meter wild fish in the reference), and $k_{f,\,l}$ of 769 kcal per wet mass kilogram assuming whole fish meal (or a conservative 61% of the 127 kcal/100 grams from Ref. 4), to calculate the table values below. Using the same equations, setting X_t at 7 (same for fruits and stems, though this value is very conservative given X=18 calculated from Ref. 5), and 180 kcal/kg wet mass per Ref. 5 we can fill in Table 3 for tomatoes also.

Table 3. Daily Diet per Person

Source	kcal/day/ person consumed (k)	kcal/ kg wet mass (k_i)	kcal/ kg dry mass	kg dry mass /day consumed (b_i)	Ratio wet mass to dry mass (X)	kg raw wet biomass consumed pp per day	kg water in food consumed
Silver Carp	1000	769	3315	0.3017	4.31	1.300	0.999
Tomatoes	1000	180	1260	0.7937	7	5.556	4.762
TOTALS	**2000**			**1.0953**		**6.856**	**5.761**

Given Table 3, total per person per day, or b_i is equal to 1.0953 kg/person/day. Given the water in wet mass from Table 4 above, and the 10 kg combined from food and drinking water, this leads to each person drinking 10-5.761 = 4.24 kg water (i.e. ~4.2 liters) per day. As this seems fairly reasonable, w_i is set to 10 kg/day/person. Water in, is usually water out, but as this paper uses an ideal set of conditions, metabolism produces water from aerobic respiration as in Eq. (6), which is $w_{o,m}$ = 56.3% * 0.84kg = 0.473 kg. Therefore knowing no wet mass in growth is occurring in people: $w_o = w_i + w_{o,m}$ =10 kg + 0.473 kg = 10.473 kg/person/day. Given no growth, biomass out will be biomass in minus mass in carbons lost to carbon dioxide and minus metabolic water which is assumed to come from the dry biomass as well (since the equations assume the oxygen in is used completely for the carbon dioxide). Mass of carbons lost to carbon dioxide is $c_o * (1\text{-}M)$. Therefore, for people $b_o = b_i - Q{*}o_i + c_o * (1\text{-}M)$ = 0.3024 kg/person/day. These calculations lead to the per capita values in Table 4 below:

Table 4. Per Capita People Stage Values

	mass per person per day	
b_i	1.0912	kg dry mass
w_i	10.0000	kg
o_i	0.8400	kg
b_o	0.3024	kg dry mass
w_o	10.4735	kg
c_o	1.1553	kg

These per capita values are multiplied by the population (100 people) and days in an Earth year (~365 days) to calculate Table 5 below:

Table 5. People Stage Total per Year Values

B_i	39857	kg dry mass
W_i	365254	kg
O_i	30681	kg
B_o	11046	kg dry mass
W_o	382548	kg
C_o	42198	kg

The people consume 73,050,800 kcal total for the population for the year, as in the following, as part of B_{i}:

Table 6. Annual People Stage Caloric Consumption

Diet	total	person/day
K_f	36,525,400	1000
K_t	36,525,400	1000
K (total)	73,050,800	2000

Outputs from the People Stage represent inputs to the farm, and inputs to the People stage are outputs from the farm, to keep steady state and conserve mass.

B. Aquatic Stage

The Aquatic Stage consists of a series of raceways and tanks, circulating pumps, course filters, chemical control systems, and gas separators designed to keep the animals in the raceways optimally growing. Such raceways, as depicted in Fig. 2, will have optimal feed rates, with water at optimal dissolved oxygen levels, and at ideal temperatures. There are a series of tanks that grow out larval animals, a series of raceways to grow larval to juvenile forms, a set to grow breeder organisms to produce larvae, and a final set to grow out the harvest-able crop. Therefore inputs will need to take into account the total population beyond the crop. While the animals could be mollusks, crustaceans, or fish, for initial analysis, this paper assumes a hybrid of the Silver Carp (*Hypophthalmichthys molitrix*). Pictures of the wild type are in Fig. 3 and Fig. 4 below. We assume that the carp is modified genetically to consume both solid and suspended filter foods, be behaviorally stable, and grow swiftly. This modification would only be a very minor modification from those carp already populating the Mississippi River System on Earth. Data for these fish was assembled from many sources including the author's own observations. This fish is very tough, and breeds readily and in abundance in open water as long as conditions are favorable, and as a result has colonized the Mississippi River System and tributaries in a few decades.

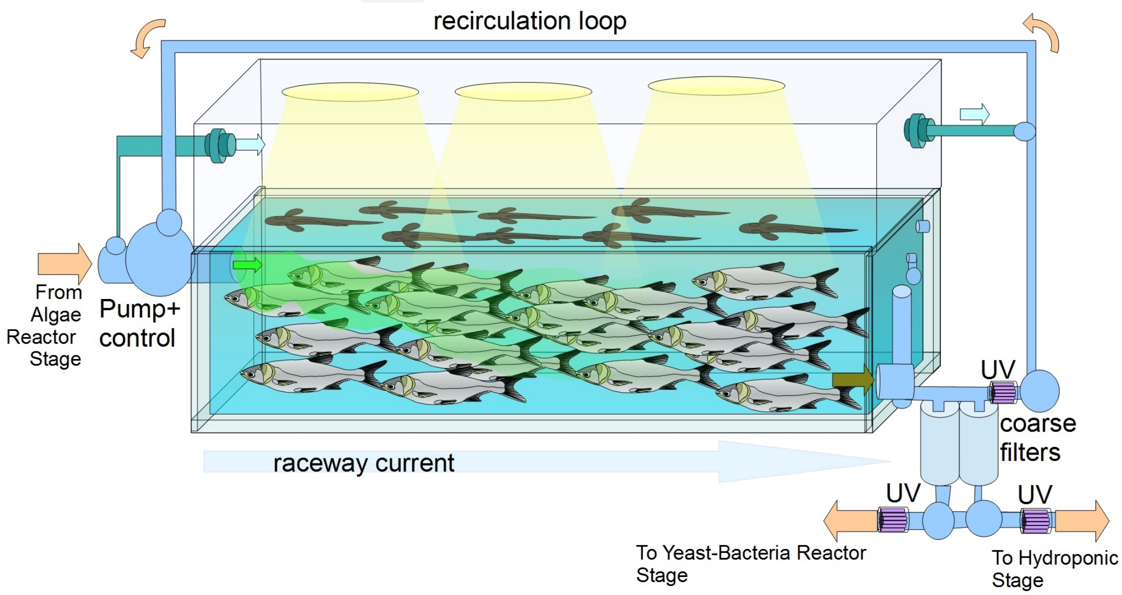


Figure 2. Aqutic Stage Raceway Notional Layout

Figure 3. Silver Carp Juvenile from the Mississippi River in Missouri, USA (Author Photo)

Figure 4. Wild Silver Carp at Roughly One Year from the Mississippi River in Missouri, USA (Author Photo)

The core equation for aerobic organisms is Eqn. (4). From Fig. 1 in Ref. 6, and calculations, intake of oxygen can be set roughly at 160 micrograms per fish gram per hour for a 1 kg fish. Given a near harvest 1 kg wet mass carp, this is 3.84 grams per fish per day or o_i = .00384 kg/fish/day. Using Eq. (5) above, c_o = 0.00384/72.7% = 0.00528 kg/fish/day. The mass of carbons in the carbon dioxide come from biomass used for metabolism = $(1-M)*c_o$ = 27.3%*.00528 = .00144 kg/fish/day. This is combined with the mass of water excreted from metabolism, which must be from the biomass in = o_i /Q = 0.00384/56.3% = 0.00216. As a result, $b_{i,m} = o_i *((1-M)/M)+1/Q)$= 0.00144 +0.00216 = 0.00360 kg/fish/day.

Next, using data from Ref. 7 it can be deduced that the growth rate of silver carp in ideal conditions is 1 inch (25.4 mm) per month. Using data for mass to length for other cyprinids, in table 17.1 and equations in Ref. 8: Log_{10} (wet mass, grams) = -4.44245 + 3.0 * Log_{10} (length in mm)[8], in combination with the 25.4 mm/month growth rate. The following graph, Fig. 5, illustrates the biomass incorporation:

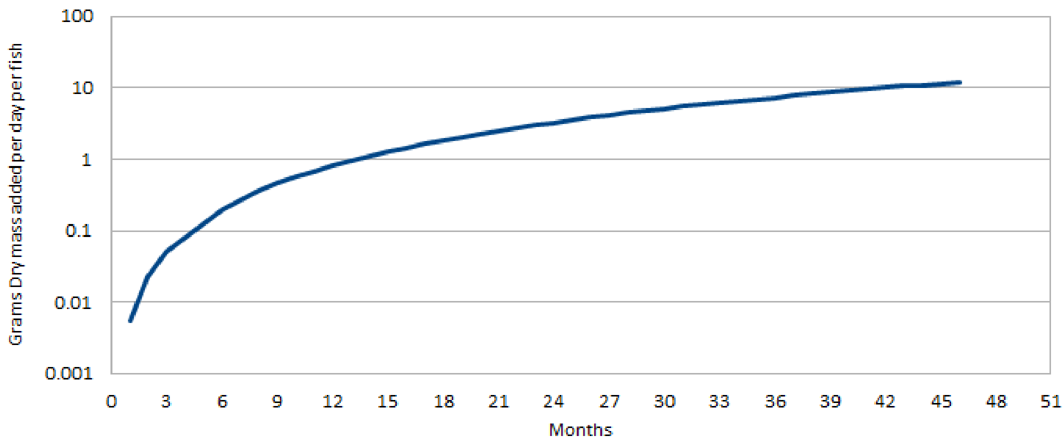


Figure 5. Silver Carp Mass Incorporation over Time

The graph calculations show a wet mass of 1.02 kg at 305 mm (1 ft.) at one year. The dry mass incorporated per day for this growth on average from larvae size is $b_{o,g}$ = 0.0008102 kg/day/fish. This paper assumes a one year harvest cycle, though breeder fish will take three years to produce, but can be gathered from the crop initially.

Next, carp are not ideal systems, in that much of what is consumed is excreted as feces or urine. From the right hand graphs from Fig. 4 in Ref. 6, it can very roughly be determined that approximately 770 micrograms/gram fish/hr. for growing fish (bighead carp are a very close relative to silver carp) is consumed. This results in b_i = 0.01848 kg/fish/day consumed. Therefore $b_{o,w} = b_i - b_{o,g} - b_{i,m}$ = 0.01848 – 0.0008102 - 0.00360 = 0.01407 kg/fish/day. Overall biomass out, $b_o = b_{o,w} + b_{o,g}$ = 0.01407 + 0.0008102 = 0.014880 kg/fish/day.

Water is also required to turn dry mass in growth into wet, living, mass. If growth from above is $b_{o,g}$ = 0.0008102 kg/day/fish then wet mass in growth = $X * b_{o,g}$ = 0.0008102 * 4.3103 kg/day/fish. Water to add to get this wet biomass is therefore = $X * b_{o,g} - b_{o,g} = (X-1) * b_{o,g}$ = (4.3103 – 1) * 0.0008102 = 0.002681 kg/fish/day. Since the water from metabolism reduces the need for water for biomass, w_i is a net value = $(X-1) * b_{o,g} - o_i /Q$ = 0.002681 - 0.00216 = 0.0005194 kg/fish/day. In reality the raceway will recirculate water in a larger volume than this net, but the net water requirement per fish is useful for sizing the stage itself.

The resulting minimal per capita values per day per fish are as follows in Table 7:

Table 7. Per Capita Values for the Aquatic Stage

	mass per fish per day	
b_I	0.018480	kg dry mass
w_I (net value)	0.000519	kg
o_I	0.003840	kg
b_o	0.014880	kg dry mass
-- $b_{o,w}$	0.014070	kg dry mass
-- $b_{o,g}$	0.000810	kg dry mass
c_o	0.005281	kg
$w_{o,g}$	0.002681	kg

These values will be used in sections below to size the Aquatic Stage. The fish are the long pole in the tent of yield, as they will take a year to mature each crop, and other stages will take less time to produce biomass. Note that this mass balance is transient, as the crop will be growing, then be removed before the next crop is grown. Additional tanks to buffer water and gasses will be require into and out of the stage, and a separator will be required to shunt excess biomass out to the Yeast-Bacteria Reactor Stage. In micro-gravity conditions, tanks will be round (ovoid) tubes where fish are oriented based upon light and current, and gas infusion and removal will be critical. It should also be noted that cleaning of the tanks can be the function of a few snails and amphipods, which should be trivial in the overall balance. Algae fed to the carp should be live, and therefore they will try to colonize light facing areas of tanks. In gravity locations, such as the Earth and the Moon, the tanks can be left open to a larger area for the stage, as long as seals prevent mass loss.

Population of the carp should be mixed at a ratio of many times crop size due to mortality at early larval stages. Breeders should be at least two years old, and are selected from the best 1/1000th of the crop. Crop size is also subject to mortality, though at a very low rate, of around 1 in 200 or less. Three year old fish eat nine times the average rate of a one year old fish, with one month old fish eat 0.7% of a year old as per calculations from Fig. 4. Accounting for all these leaves a biomass averaged population multiplier, R_f = 3.45*.007+.001*9 + 1+ (1/200) = 1.04 to crop size by mass, though a fish count U_f = 3.45+.001+1+(1/200) = 4.46 times crop size. Note as each crop fish has a wet mass of 1.02 kg, there are 784 kcal/fish.

Volumes needed in tanks are roughly V_f = 50 kg fish per m^3 of raceway[9], mass averaged for the population. This size should allow adequate growth room, and avoid crowding.

C. Hydroponic Stage

In the Hydroponic Stage, vascular plants are used to produce food biomass from fruit, and vegetative growth, using photosynthesis. Tomatoes were selected initially due to data availability, and due to successes in studies in hydroponic environments. For tomatoes and similar fruiting plants, biomass is split between vine/stem growth and fruit production. Tomato plants in this paper are more like trees then traditional garden plants. They are indeterminate vines grown in structures that optimize light and fruit production by limiting the need for the tomato to build support structure. Tomato production favors low gravity environments, and tomatoes can even be grown inverted. Increasing carbon dioxide in the hydroponic air component increases biomass yield, and it is assumed that genetics are used to favor fruit over current varieties. The roots are bathed in nutrient rich water output from the Aquatic Stage, and water exiting the Hydroponic Stage is cleaner then when it entered, though lower in oxygen. A rough sketch of the hydroponic bed is shown in Fig. 6 below. Note that light is distributed for optimal production, and scaffolding allows the tomato plant to focus on fruit production. We assumed a future tomato variety would exist, that in the environment of the space farm would devote 65% of growth to fruit versus vegetative growth in leaf, stem, and roots. I also assumed a large mature plant, which may take 120 days to begin steady production at a consistent rate.

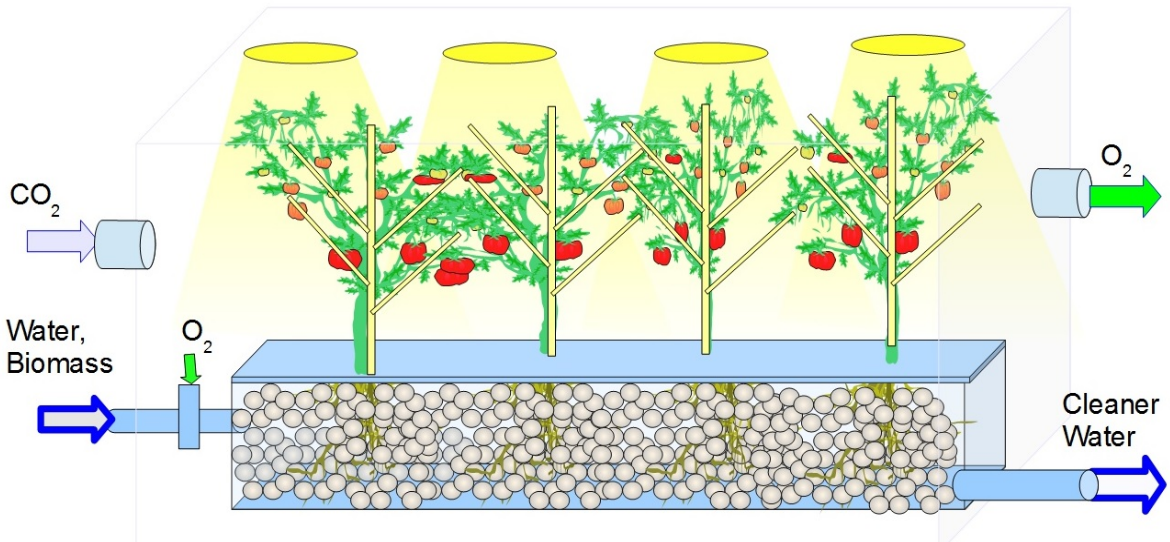


Figure 6. Hydroponic Bed Notional Layout

To calculate per capita rates, as in Eqs. (7-12) above, a series of calculation and derivations from Ref. 9 and Ref. 10 were used. Note the X_t was set as a dry mass to wet mass ratio for fruit and stem and leaves. From Ref. 10, yield is roughly 27 lbs. per mature plant per year. Converting to metrics, and applying X above, this is 1.7532 kg dry mass of fruit/plant/year or $b_{o,g,c}$ = 0.0048001 kg/plant/day. The 65% fruit to vegetation growth budget is very different from the leaf to fruit partitioning in Ref. 11, but assumed to be reflective of a mature genetically modified vine. The fruit to vegetation ratio results in $b_{o,g} = b_{o,g,c}$ / 65% = 0.0073847 kg dry mass total growth per plant per day. Therefore $b_{o,g,v} = b_{o,g} - b_{o,g,c}$ = 0.0073847 - 0.0048001 = 0.0025847 kg dry mass in vegetative growth per plant per day.

Next, a calculation was made using nutrient uptake amounts and area from the Aquaponics-Tomato line in Table 2 in Ref. 10, and counting plants from Fig. 2 in Ref. 10 to roughly estimate a nutrient uptake (b_i) per plant, of b_i = 0.0001002 kg/plant/day. It is assumed that any excess nutrient is passed out from the hydroponic bed to a coarse filter that sends it to the Yeast-Bacteria reactor for processing. For the paper's purposes, the focus is on what is used. As a result $b_o = b_{o,g}$. Using $b_{o,g}$ (dry mass) is therefore a combination of carbon fixed from carbon dioxide, nutrients, and water used in metabolism, largely for sugars including fructose and cellulose. Using Eq. (11) above, c_i = (0.0073847 - 0.00010022) /(1-72.7% +1/ 2.44)) = 0.010668 kg/plant/day.

Water required and used is a series of ratio calculations from c_i and $b_{o,g}$. Water required for metabolic use can be calculated from Eq. (10) above: $w_{i,m}$ = 0.010669 / 2.44 = 0.004373 kg/plant/day. Water required for wet mass production is a multiple of X-1 of $b_{o,g}$: $w_{o,g}$ = (7-1) * 0.0073847 = 0.04431 kg/plant/day. Together, $w_i = w_{o,g} + w_{i,m}$ = 0.04431 + 0.004373 = 0.048683 kg/plant/day.

Oxygen is a bit more complex. Assuming that nutrients are ammonia heavy (from animals like the silver carp) and are used to synthesize proteins, we assume a reaction that requires approximately 14.5% oxygen for nutrient mass (derived from oxygen mass in amino acid reactions), and additional ratio of 10 to 1 for oxygen for aerobic respiration in the plant to nutrient uptake. The resulting equation for dissolved oxygen input to the plant, o_i, is 14.5% * 10 * 0.0001003 = 0.0001455 kg/plant/day. Using mechanisms in the hydroponic system, such as an oxygen gas separator from the air in the hydroponic chamber, and oxygenator for the wet portion of the system, this dissolved oxygen is subtracted from the much larger photosynthetic (metabolic) output from the plant, $o_{o,m}$ via Eq. (12) above for a net o_o: $o_o = M^* c_i - o_i$ = 72.7% * 0.010669 - 0.000145493 = 0.007608 kg/plant/day, where $o_{o,m} = M *$ 0.010669 = 0.00775.

For mass balance, root oxygen mass goes into the crop's end mass (justified, due to ripening) such that $b_{o,g,c}$ =$b_{o,g,c}$ + o_i, such that $b_{o,g,c}$ = 0.004800 + 0.010669 = 0.004946 kg/plant/day.

The resulting minimal per capita values per day per plant are as follows:

Table 8. Per Capita Values for the Hydroponic Stage

	mass per plant per day	
b_i	0.0001002	kg dry mass
w_i total	0.048681	kg
-- $w_{i,g}$	0.044308	kg
-- $w_{i,m}$	0.004373	kg
c_i	0.010669	kg
b_o	0.007531	kg dry mass
--$b_{o,g,v}$	0.002585	kg dry mass
--$b_{o,g,c}$	0.004946	kg dry mass
o_o (net production)	0.007611	kg
--o_i (roots)	0.0001455	kg
--$o_{o,m}$	0.007756	kg
w_o	0.044308	kg
-- $w_{o,g}$	0.044308	kg

As for the Aquatic Stage, the Hydroponic Stage per capita values are used below for sizing the farm.

It should be noted that the 'air' in the Hydroponic Stage will not be breathable by humans, as it will be over concentrated in carbon dioxide. The plants are assumed to be 1 kg in dry mass, with a height of 2 m, and using a volume of roughly 1.2 m^3.

The tomato trees are assumed to need a very small number of replacements, which are assumed not to contribute to the crop, by mass an additional 10%, or a multiplier of R_t=1.1. Plants are considered roughly of similar mass, so U_t = R_t = 1.1.

In Table 3 above, tomatoes produce 1260 kcal/kg dry mass. Given $b_{o,g,c}$ above, each plant produces k_t = 1260 * 0.004946 = 6.23 kcal per plant per day.

D. Algae Reactor Stage

In this stage, the paper assumes a very sophisticated apparatus with membranes seeded with green algae (*Chlorophyta*) that produces oxygen and biomass from photosynthesis, consuming water and dissolved carbon dioxide and biomass inputs including minerals, ammonia and urea. The reactor, while tube-based, is sized in tube length to optimize carbon dioxide distribution and oxygen removal, and allow biomass, composed of all the growth of the algae, to be removed by pulsing pumps or other means.

To achieve very high levels of efficiency, the reactor will use highly distributed lighting to place light source tubes in proximity to growth membranes. Each membrane will have a thin coating of algae exposed to light and water. See Fig. 7 and Fig. 8 below.

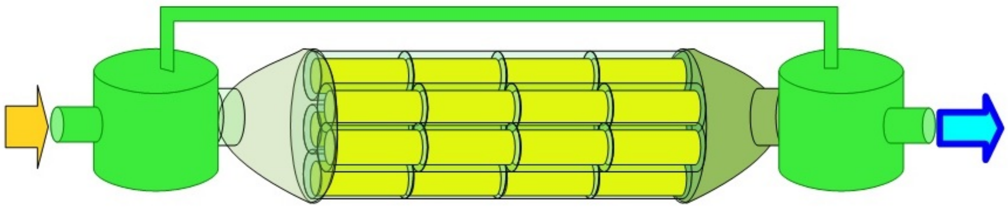
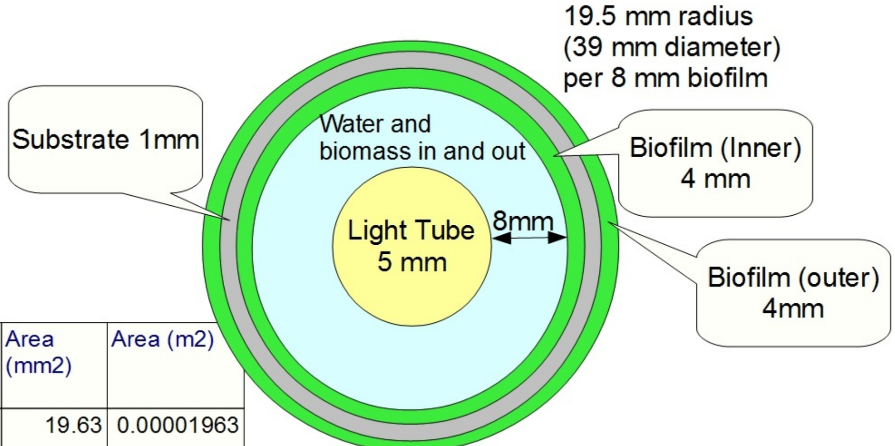


Figure 7. Notional Algae Reactor High Level



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

Figure 8. Algae Reactor Notional Tube Cross Section

The stage will have tanks, separators, and gas infusers, for each input from People, Yeast-Bacteria, and Aquatic stages. As for other stages, ultraviolet (UV) sterilizers will be stationed on each input to prevent contamination. The largest consumer of outputs will be the Aquatic Stage, though during spin-up of the farm, algae can be dried and consumed by people. To address inefficiency, the reactor will be oversized to meet minimum product and carbon dioxide inputs for an assumed reactor efficiency of Z_a = 70%.

To find per capita values, this paper uses carbon to biomass to dry biomass ratios for a reactor from Ref. 12. The reference reactor's dry biomass can be calculated to be 33 kg from volume (55 m^2 * 6mm bio-film thickness = 330,000 ml of wet biomass volume, 330 kg wet biomass assuming a density near 1 kg/liter) and a wet mass to dry mass ratio of 10 to 1. This dry biomass produces 4.4 kg carbon dioxide and 1 kg dry biomass in algae per day[12], using 0.23 kg in nutrients. Carbon dioxide per kilogram algae dry mass out in this paper's reactor is therefore c_i = 4.4/33 = 0.1333 kg/kg algae/day. Biomass in (i.e. nutrients) is likewise computable: b_i = 0.23/33 = 0.00697 kg/kg algae/day. This paper assumes a far greater efficiency approaching photosynthetic ideals, then that suggested in the reference, due to the light placement and gas efficiency (this efficiency is recaptured to 70% of ideal in sizing the reactor's volume). Oxygen out per mass is calculated using Eq. (12), o_i = 0.096944 kg/kg algae/day. Water for metabolic needs is calculated by using Eq. (10), $w_{i,m}$ = 0.05463 kg/kg algae/day. Biomass out (which is also biomass in growth) is the sum of biomass in, carbons fixed from carbon dioxide, and water for metabolism, which is b_o = 0.00697 + 0.1333*27.3% + 0.05463 = 0.09799 kg/kg algae/day. Given X, wet biomass out is from Eq. (1), therefore $w_{i,g} = w_{o,g} = b_o * (X-1)$ = 0.06273 kg/kg algae/day.

The above calculations lead to these per capita values:

Table 9. Per Capita Values for the Algae Reactor per day, per kg dry Biomass

	mass per kg algae dry mass per day	
b_i	0.006970	kg dry mass
w_i	0.117372	kg
– $w_{i,m}$	0.054645	kg
– $w_{i,g}$	0.062727	kg
c_i	0.133333	kg
b_o	0.098004	kg dry mass
– $b_{o,g}$	0.098004	kg dry mass
o_o	0.096944	kg
w_o	0.062727	kg
– $w_{o,g}$	0.062727	kg

Summing the inputs (or outputs) results in the productivity of the algae biomass: $b_i + w_i + c_i$ = 0.006970 + 0.117372 + 0.133333 = 0.2577 kg processed per kg dry biomass in the reactor per day, or P_a = 289.88 kg processed per kg dry biomass in the reactor per year.

E. Yeast-Bacteria Reactor Stage

The Yeast-Bacteria Reactor Stage consists of a very complex array of membranes holding yeast and bacteria in various elements to control a series of reactions to balance the space farm overall, including producing biomass and carbon dioxide from biomass and if required, oxygen, and water. The reactor is preceded by a per-digestion and holding tank that is fed by waste from food processing, the Aquatic Stage, and excrement and urine from the People Stage. In each case the waste is macerated then sterilized using UV or heat to prevent contamination of the reactor before being fed into the holding and pre-digestion tank. From the tank, the material, including water, gases, and solids is fed into the reactor in dissolved form. Any solids are added to the solid products from the reactor. Alternatively, the reactor can be controlled to release hydrogen gas, which can be used for fuel or burned for energy to create water. The figure below shows a notional layout.

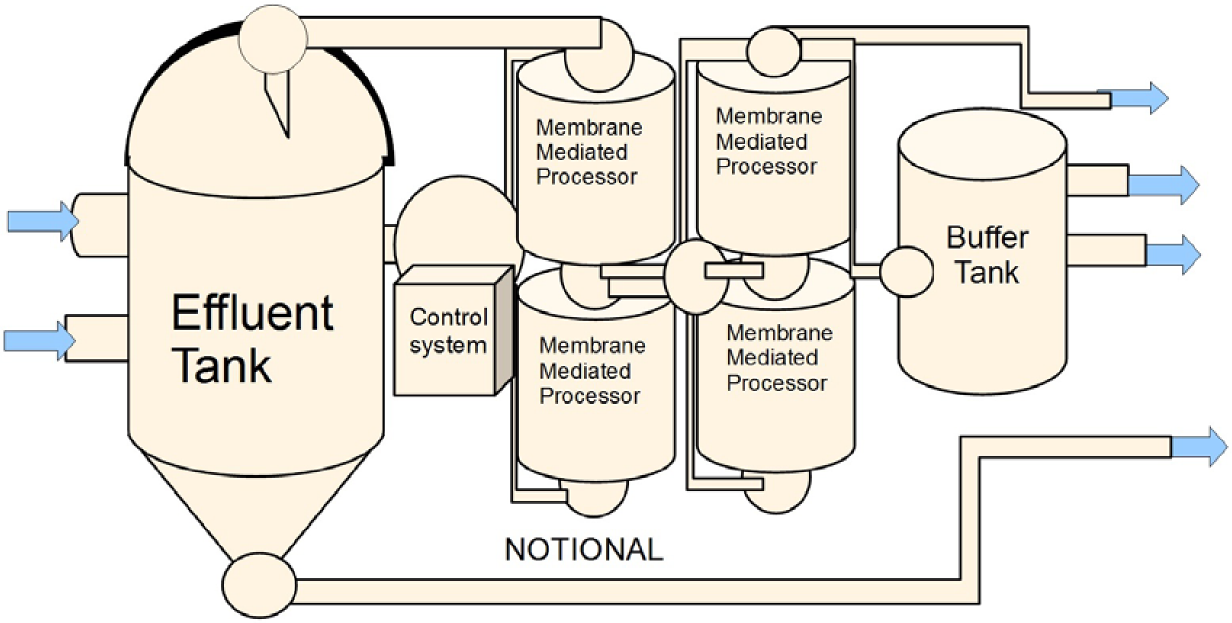


Figure 9. A Notional Schematic for the Yeast-Bacteria Reactor

To calculate per capita inputs, a model uses the relative molecular masses of each reaction, then a percentage is chosen to tailor outputs from the reactor. It is assumed that software will balance the sample reactions to achieve the needed balances at a per capita basis near ideally.

Productivity for the Yeast-Bacteria Reactor is set here to the productivity of the Algae Stage per capita, $P_y = P_a = 289.88$ kilogram processed input per kilogram dry biomass per year. Ideal efficiency of the reactor is assumed to be $Z_y = 70\%$.

IV. Connecting the Stages and Determining Populations of Each Stage

The space farm must balance the needs of the People Stage, and in the farm must balance the totals of carbon dioxide, oxygen, water, and biomass. As a result this paper goes through a sequence of balances to arrive at the populations for each stage. First, the populations of the Aquatic and Hydroponic stages are computed from the People stage Biomass input needs (see Fig. 10 below). Next, oxygen and carbon dioxide are used to find a population for the Algae Reactor Stage (see Fig. 11 below). The population is adjusted up if need be for biomass to the Aquatic Stage as well. Next, the Yeast-Bacteria Reactor Stage is used as a grand balancer, to even out biomass, oxygen, water, and carbon dioxide.

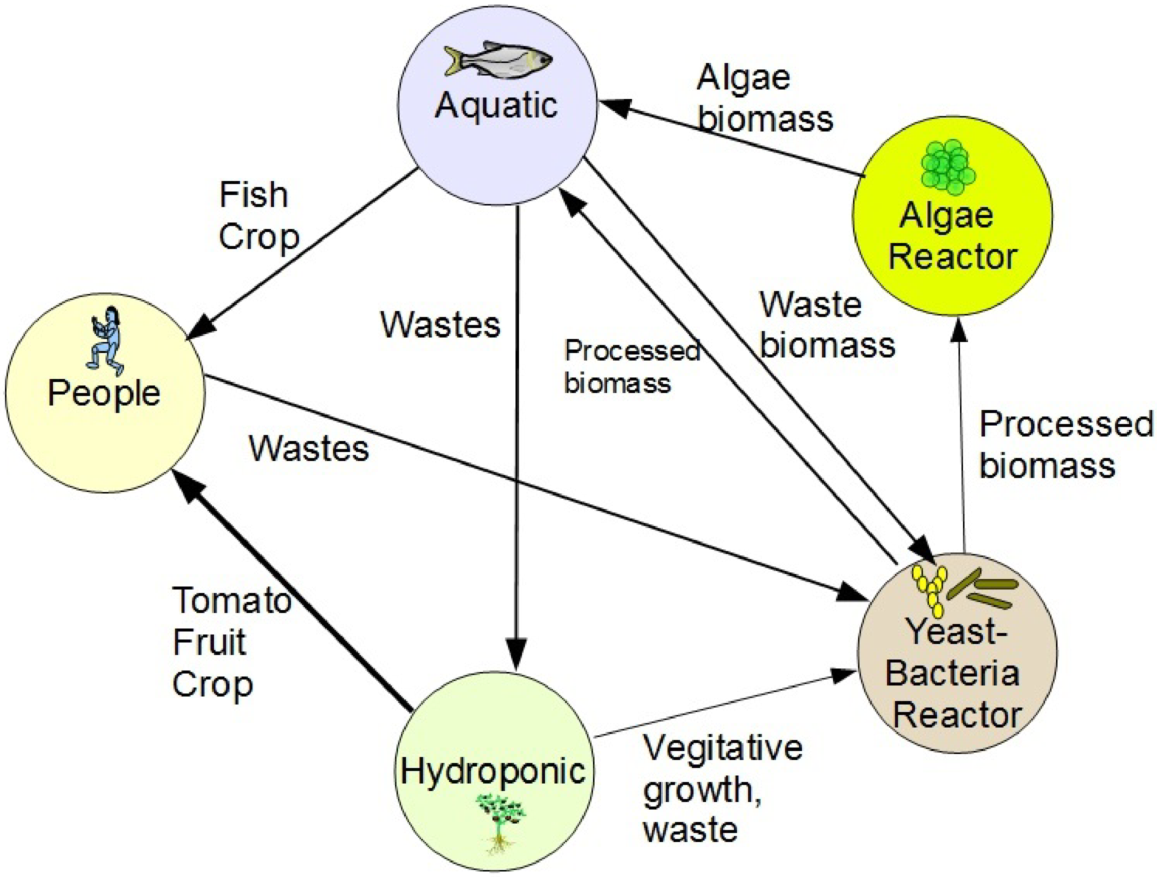


Figure 10. Biomass Relationships between Stages

Note from Fig. 10 that the flow of biomass will require management to be optimal. From the Aquatic Stage flows crop fish as wet biomass, while from the Hydroponic Stage flows tomato fruit as wet biomass. Any processed biomass, and (not shown) biomass flows from People Stage and Aquatic Stage provide the minimal Algae biomass inputs (especially for ammonia), but carbon dioxide converted to wet algae biomass is a major flow to the Aquatic Stage. Some Aquatic Stage excreted waste flows to the Hydroponic Stage for the whetted roots. All excess wastes, food processing wastes, fish that die before harvest, and trimmed vegetative tomato growth go into the Yeast-Bacteria Stage.

Note from Fig. 11 that the biomass flows are somewhat matched by carbon dioxide and oxygen flows. A gas management system for the farm as a whole is assume to balance flows for carbon dioxide and oxygen to keep safe levels for each organism in the farm. As discussed before, the capture of carbon from carbon dioxide into biomass, and the chemical reactions to convert biomass and oxygen into carbon dioxide, define the cycle of the farm's pseudo-ecosystem.

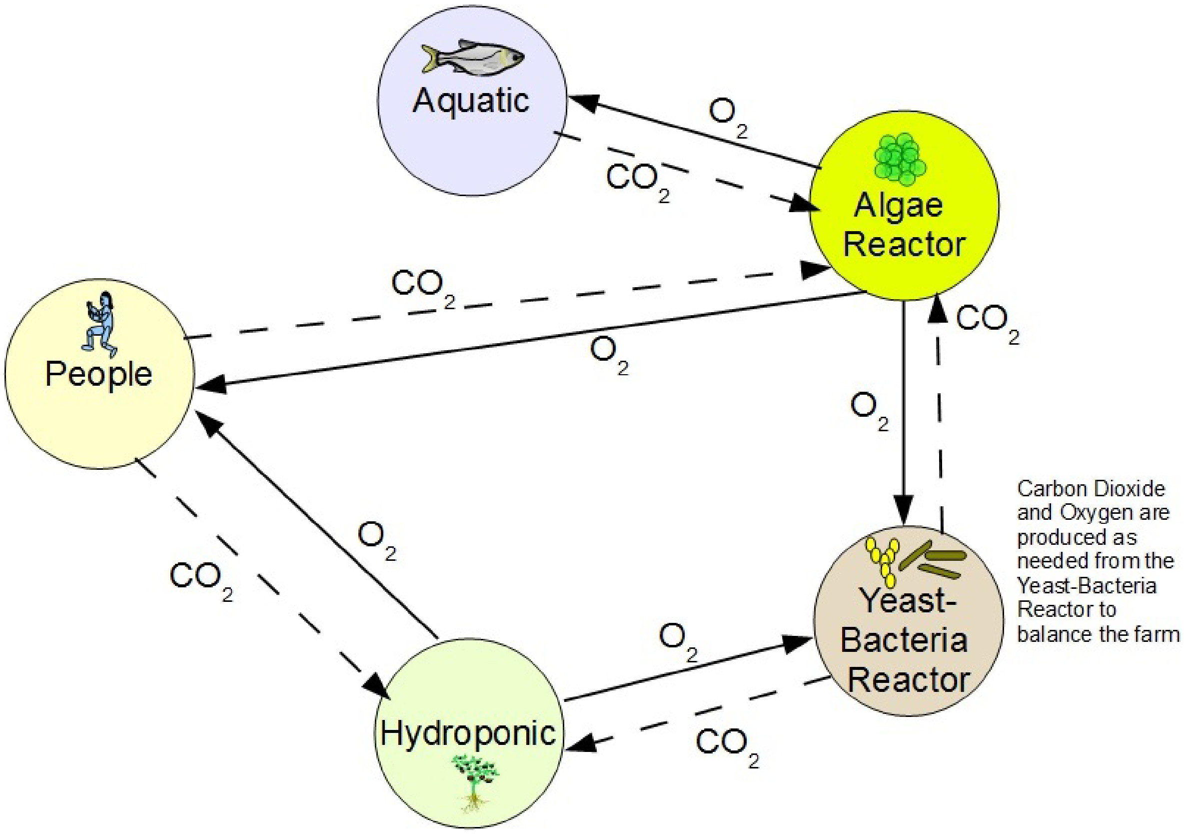


Figure 11. Oxygen-Carbon Dioxide Flows between Stages

People Stage caloric needs dictate minimum populations for Aquatic and Hydroponic stages, which in turn can be used to find minimal values for Algae and Yeast-Bacteria Stages. However, oxygen requirements for Aquatic and People stages also determine minimal size for Algae and Hydroponic stages.

To determine population of Aquatic and Hydroponic stages, the following equation is used:

$$N = R * \frac{K}{k} = R * \boldsymbol{N_c} \qquad \textbf{(17)}$$

From above, processed crop fish have k_f = 784 kcal/fish. Given the need for 36,525,400 kcal from the Aquatic Stage crop per year, this leads to a minimum crop of $N_{f,c}$ = 36,525,400 kcal / 784 kcal/fish = 46,589 fish. From the Aquatic Stage discussion above, R_f = 1.04, therefore $N_f = R_f * N_{f,c}$ = 1.04* 46,589 fish = 48,366 mass averaged minimum fish population. Given this we can use the results from Table 8 above, multiplying by N_f * days per year to complete the table below (and showing the split between non-crop and crop fish for water using R_f):

Table 10. Aquatic Stage Values (for the Stage per Year)

N_f	48366	Mass Averaged Population
$N_{f,c}$	46589	Population of Crop
T_f	207601	TOTAL FISH POP
R_f	1.04	Ratio mass averaged total pop. To crop
X_f	4.31	Ratio wet/dry biomass
U_f	4.46	Ratio total population to crop
B_i	326465	kg dry mass
W_i	9169	kg
O_i	67837	kg
B_o	262868	kg dry mass
-- $B_{o,w}$	248559	kg dry mass
-- $B_{o,g}$	14309	kg dry mass
--- $B_{o,g,c}$	13784	kg dry mass
--- $B_{o,g,j}$	526	kg dry mass
C_o	93293	kg
$W_{o,g}$	47362	kg
--$W_{o,g,j}$	1740	kg
--$W_{o,g,c}$	45622	kg

Similarly, the caloric needs of the People Stage drive the plant population in the Hydroponic Stage. From above, k_t = 6.23 kcal per crop plant per day. Given the need for 36,525,400 kcal from the Hydroponic Stage per year, $N_{t,c}$ = 36,525,400/ (6.23 * 365.25) = 16,046 crop plants. From above, ratio of crop size to total population mass-equivalent size is R_t = 1.1, therefore $N_t = R_t * N_{t,c}$ = 1.1 * 16,046 = 17,651 mass averaged minimum plant population. Given this population we can use the results from Table 9 above, multiplying by N_t * days per year to complete the table below.

Table 11. Hydroponic Stage Values for a Year

	mass total stage	
B_i	646	kg dry mass
W_i	313850	kg
-- $W_{i,g}$	285659	kg
-- $W_{i,m}$	28190	kg
C_i	68785	kg
B_o	48551	kg dry mass
--$B_{o,g,v}$	16664	kg dry mass
--$B_{o,g,c}$	31887	kg dry mass
O_o (net production)	49068	kg
--O_i	938	kg
--$O_{o,m}$	50006	kg
W_o	285659	kg
-- $W_{o,g}$	285659	kg
$N_{t,c}$	16046	crop plants
N_t	17651	Mass-equivelent plants

Comparing oxygen and carbon dioxide so far, we get the following Table 12:

Table 12. Oxygen and Carbon Dioxide Balance for 3 Stages

	Oxygen		Carbon Dioxide	
Stage	**Min need (O_i)**	**provided (O_o)**	**Min need (C_i)**	**provided (C_o)**
People	30681.34			42198.1
Aquatic	67836.96			93293.49
Hydroponic		49068.03	68784.59	
TOTAL	98518.3	49068.03	68784.59	135491.59
Net (out – in)		*-49450.27*		*66707*

Looking at the 'Net' line we see that given the three stages examined, minimum populations of Aquatic and Hydroponic stages set by People Stage caloric needs, there is a need for oxygen and an excess of carbon dioxide. To meet the oxygen need, we size the Algae Reactor Stage, using its per capita value for o_o = 0.096944 kg/kg dry mass algae/day, and the delta of 49,450.27 kg/year: N_a = 49,450.27/(0.096944 * 365.25) = 1,396.54 kg dry mass algae. This population and the Table 12 values result in Table 13 stage level values for the Algae Reactor:

Table 13. First Attempt: Algae Reactor Stage Total Values per Year

	mass total stage	
N_a	**1396.54**	kg dry mass
B_i	3555	kg dry mass
W_i	59871	kg
-- $W_{i,g}$	27874	kg
-- $W_{i,m}$	31997	kg
C_i	68012	kg
B_o	49991	kg dry mass
--$B_{o,g}$	49991	kg dry mass
O_o	49450	kg
W_o	31997	kg
-- $W_{o,g}$	31997	kg

Given Table 13, however, biomass is not fully available to the Aquatic Stage, which is provided biomass by the Algae Reactor and Yeast-Bacteria Reactor. As a result, N_a needs to be increased to account for the biomass for the Aquatic stage. As a result the Algae Reactor Stage population needs to increase by a factor of $B_{i,f}/B_{o,a}$ as above. This multiplier is thus = 326,465 / 49,991 = 6.53 As a result, the new N_a = 6.53 * 1,396.54 = 9,120.07 kg dry mass. A second attempt for overall Algae Reactor stage values is in Table 14:

Table 14. Second Attempt: Algae Reactor Stage Totals Per Year (Minimum).

	mass total stage	
N_a	**9120.07**	kg dry mass
B_i	23217	kg dry mass
W_i	390983	kg
-- $W_{i,g}$	182030	kg
-- $W_{i,m}$	208953	kg
C_i	444152	kg
B_o	326465	kg dry mass
--$B_{o,g}$	326465	kg dry mass
O_o	322934	kg
W_o	208953	kg
-- $W_{o,g}$	208953	kg

This minimum size for the Algae Reactor, Aquatic, Hydroponic, and People stages results in the following balance for oxygen and carbon dioxide, in Table 15 below:

Table 15. Oxygen-Carbon Dioxide Balance for Four Stages

	Oxygen		Carbon Dioxide	
Stage	**Min need (O_i)**	**provided (O_o)**	**Min need (C_i)**	**provided (C_o)**
People	30681.34			42198.1
Aquatic	67836.96			93293.49
Hydroponic		49068.03	68784.59	
Algae Reactor		322934	444152	
TOTAL	98518.3	372001.64	512936.88	135491.59
Net (out – in)		*273483.34*		*-377445.3*

Given these minimum values, the Yeast-Bacteria Reactor must produce the missing carbon dioxide, but must also balance water and biomass, and consume oxygen. In other states of the farm, it may need to produce oxygen or other gasses. In considering what biomass is available to the Yeast-Bacteria Reactor, we need to add: People Stage biomass out, waste from food processing, biomass in vegetation growth from the Hydroponic Stage, and biomass excreted from the Aquatic Stage, then subtract the biomass needed for the Hydroponic Stage and needed for the Algae Reactor.

However, a simpler way to examine mass balance for the Yeast-Bacteria Reactor is by considering what ideally is not available to it. Assuming ideal transfers when needed, as needed, in this model, only the wet mass in growth locked into the Aquatic Stage juveniles and breeders is unavailable for now. This is a factor of $(R_f - 1)$ = 4%, or just $B_{o,g,j,f}$ = 526 kg dry mass. All other biomass grown or excreted each year is available. Similarly for water, $W_{o,g,j,f}$ = 1,740 kg. The total of these is 2,266 kg, which is less than 1% of the overall mass moving in the system, and will have to be initially supplied to the system (added in far below) and will move into the system as crops or mortality (since dead fish are recycled in the Yeast-Bacteria Reactor). As a result, we can examine the net balance for the entire system so far, ignoring the 2,266 kg:

Table 16. Mass Balance across Four Stages

Mass	People	Aquatic	Hydroponic	Algae Reactor	SUM
Oxygen (Oo-Oi)	-30681	-67837	49067	322934	**273482**
CO2 (Co-Ci)	42198	93293	-68783	-444152	**-377444**
Water (Wo-Wi)	17294	38194	-28190	-182030	**-154731**
Biomass (Bo-Bi)	-28811	-63597	47904	303248	**258744**
All masses in kilograms					

Note that the sum column essentially adds to near zero (due to rounding errors), pointing at the grand balance of the farm. The Yeast-Bacteria Reactor, due to excess oxygen and biomass, and a need for carbon dioxide and water, will perform aerobic reactions in this case. We assume a series of software and programming that uses the Reactor to optimally meet the balance, i.e. excesses are inputs, and needs are outputs.

Table 17. Minimal Yeast-Bacteria Stage Values for a Year

B_i	258744	kg dry
O_i	273482	kg
C_i	0	kg
W_i	0	kg
O_o	0	kg
B_o	0	kg dry
C_o	377444	kg
W_o	154731	kg

Given the productivity by dry kilogram of biomass of P_y = 289.88 kg/kg in per year, and summing the inputs (or outputs, as they balance), we can get the dry biomass size of the Yeast-Bacteria Reactor: $N_y = (B_i + O_i) / P_y$ = 1,836 kg dry biomass.

Table 18. Mass Balance for All Stages

Catagory	People	Aquatic	Hydroponic	Algae Reactor	Yeast Bacteria Reactor	SUM*
Oxygen (Oo-Oi)	-30681	-67837	49067	322934	-273482	**0**
CO2 (Co-Ci)	42198	93293	-68783	-444152	377444	**0**
Water (Wo-Wi)	17294	38194	-28190	-182030	154731	**0**
Biomass (Bo-Bi)	-28811	-63597	47904	303248	-258744	**0**
All masses in kilograms						
* = 2,260 kg mass is actually locked in juvenile and breeder fish						

DRAFT Aug 2015

Overall, the system mass balances, except for biomass and water absorbed in juvenile fish, breeder fish. In reality this would be balanced in initial inputs, and would cycle each year, requiring delicate work and controls to get close to a real balance.

To get the total population for Algae and Yeast-Bacteria reactors, we recapture the efficiency of 70% ideal (reflected in *N*) and as a result $T = N/Z = N/70\%$. For both, and assume throttling will be used to control both, resulting in the following table:

Table 19. Total and Mass-Equivalent Populations Minimum in the Space Farm

Stage	N	T	Notes
People	100	100	Habitat not sized
Aquatic	48366	207601	$U_f = 4.46$
Hydroponic	17651	17651	$U_t = 1$
Algae	9120.07	13028.67	Z=70%
Yeast-Bacteria	1836.0	2622.89	Z=70%

V. Sizes, Volumes, and Total Masses for the Farm

The goal of this paper is to size the farm itself, so it is assumed the People stage is not part of the farm itself. The rest of the stages are sized for volume and mass, diving mass among shipped from Earth, and in situ.

A. Sizing for the Aquatic Stage.

The Aquatic Stage is sized on volume in raceways, volume above raceways, and volume surrounding the raceways. Available data for volume per fish is mass based, V_f = 50 kg fish per cubic meter[13]. N_f is essentially in kilograms due to the size of the crop fish (i.e. each crop sized fish is 1.02 kg wet mass). As a result the water volume needed to fill the Aquatic Stage raceways is N_f / V_f = 48,366/ 50 = 967.32 m^3 = 967,320 kg. Assuming the raceways can be built using in situ materials adding 5% to the wet volume, each raceway uses $N_f / V_f * (1 + 5\%) = 1015.7$ m3 . Assuming the volume enclosing the raceways, including pipes, pumps, valves, and people access areas is 100% larger than the tank and walls, the resulting volume is $2 * N_f / V_f * (1 + 5\%) = 2031.4$ m^3. Mass is likewise estimated, using roughly 7% for the walls of the raceways, and an additional 5% for pipes, pumps, control systems, gas exchanges, and sterilizers, resulting in (967,320 * (1+7%))*(1+5%) = 1,086,784 kg total. Assuming a 3 m height, the Aquatic Stage covers nearly a tenth of a hectare (i.e. 677.12 m^2). This is roughly the same in gravity or no gravity, due to trades in equipment versus tank walls.

It can be assumed the water and structures of the stage (1,086,784 kg) are constructed using local materials. Given the complexity of pumps and control systems, these may have to be shipped from Earth, at a mass of 5%* 1,086,784 = 78,933 kg. Embryos (or gametes) of the initial crop and breeders would have to be shipped frozen, though this is a yet to be proven technology as noted in Ref. 14. Given the very small mass and volume of embryos (roughly 1 mm^3 each) it is more likely the cooling and defrosting machinery would be the largest mass cost for the organisms themselves. Assuming 50 embryos per cm^3 (50,000 per liter), and assuming 1.5 kg/liter, and assuming a 10 to 1 mortality, mass for the initial population is roughly 48,366 * 10 * 1.5/ 50,000 or around 15 kg. Even if doubled to 30 kg, this mass is trivial compared to the pump and pipe equipment for the stage. The shipped mass could be vastly reduced by using accumulative manufacturing and more in-situ resources, possibly by an order of magnitude.

B. Sizing for the Hydroponic Stage

The bulk of the volume for the Hydroponic Stage is in the enclosed gases and plants, mass is largely in pipes, media, water, and enclosures. It is already stated that each plant occupies 1.2 m^3 at a height of 2 m, dry mass of 1 kg. In addition, each plant will have a hydroponic bed of roughly 0.03 m^3 which is whetted, composed of roots, media, pipe, and water. Due to spacing and working area, each plant volume will need an additional 25% air volume. Given T_t of 17,651 plants, air volume is 1.2 * (1+25%) * T_t = 26,477 m^3. Whetted volume is similarly computed, assuming 0.03 m^3 for the roots and matrix: 0.03 * T_t = 529.5 m^3 . An additional 5% of total volume should be added for pumps, control equipment, and tanks, resulting in a grand total volume of (26,477 + 529.5)*(1 +5%) = 28,356 m^3. If the height of this stage is 3 m, the resulting area is almost a hectare (~9,452 m^2, ~2.34 acres). For comparison, on Earth, a typical tomato farm produces 80 US tons[15], or 73,000 kg wet mass per acre per year, versus the Hydroponic stage production of 86,879 kg per acre per year.

Mass for the Hydroponic stage can be computed as 1 kg dry mass per plant, as wet mass, or X_t * T_t = 123,557 kg, then adding whetted volume as mass: 123,557 + 529.5 * 1000 = 653,057 kg. It is assumed that the root media is hollow silica pebbles or fused regolith, of a similar mass to the water. Even so, scaffolds, lighting, pumps, controls, and separators should add 5%, or add 32,653 kg to get 685,710 kg total. We assume seeds will be shipped from Earth, with the 32,653 kg in equipment. Again, even 100,000 seeds are very small in mass (roughly a few kilograms total including packaging), adding an insignificant amount next to the mass of equipment to set up the Hydroponic stage.

C. Sizing for the Algae Reactor Stage

The Algae Reactor's mass composed of thin layers (tubes) of substrate, covered in algae bio-film (= wet biomass) , with light tubes inside each tube. See Fig. 7. Given these areas, in each unit there is 1.44 bio-film to other items (water, light tube, substrate) ratio. Given ideal placement, an extra 50% is required for spacing. Given wet biomass of algae (T_a * X_a = 130,287 kg) and assuming 1 liter per wet kilogram, total volume for the inside of the reactor is T_a * X_a * (1+50%) /1000 = 195.4 m^3 . Assume another 100% for structure, control systems, pumps and other machinery, to arrive at a volume of 390.8 m^3. Assuming a 3 m height, the footprint is 130.3 m^2 (or 0.13 hectares).

Mass for the stage is largely whetted volume, and assuming substrate and light tubes are double the mass density of water, and 25% of volume is substrate and light tubes and similar, mass is therefore 195.4 * 1000 * (1+25%) = 244,288 kg. Dry mass to seed the reactor may come from Earth, or be grown en-route using a small simple reactor. If the entire dry mass and substrate and lights is shipped (approximately T_a + 25% * 244,288 kg = 74,101 kg) , the construction time for the reactor is the only delay in operation. Given a small starter culture of 1 kg dry biomass, the entire dry mass can be grown in 82 days. Given an entire reactor minus dry mass and water, roughly 21,000 kg and 3 kg of culture, the reactor could be up in less than a month. People can be fed algae dry mass until other portions of the farm are up as well. As per Ref. 16 algae dry mass has roughly 3,000 kcal/kg, requiring 67 kg dry mass per day for the 100 colonists.

D. Sizing the Yeast-Bacteria Reactor Stage

The Yeast-Bacteria Reactor is a complex combination of layers and tanks. Assuming a mechanism to biomass volume ratio of 1:1, and T_y = 2,622.89 kg dry mass, and X_y = 10, volume is approximately T_y * X_y * 2 = 2622.89 * 10*2 = 52,458 liters = 52.5 m^3. Assuming another 50% due to more complex machinery, 78.7 m^3. Feeder and extractor tanks together should be sized for up to a month of effluent, assuming 10% for walls, i.e ($B_{o,p}$ + $W_{o,p}$ + $B_{o,w,f}$)*1.1/12 = 59,919 kg (or 59.9 m^3 volume). This makes a total volume of 78.7 + 59.9 = 138.61 m^3. Setting height at 3 m, floor area is 46.2 m^2, or 0.05 hectares.

Averaging for volume as water, then adding an extra 50% denser mass for the machinery, stage mass is roughly 207,910 kg. Of this mass, the complex equipment itself is likely to be shipped from Earth, or roughly 78,700 kg, and a small starter culture of a few kg. Like the algae, the dry mass of the reactor can likely be grown in a month from 3 kg of starter dry mass. As for algae, dry biomass from yeast and bacteria can be consumed by the human population, and tailored in chemical composition until other portions of the farm are up.

E. Total Footprint, Volume, Masses and Time to Operation

While the farm's overall size is within reason, it will take time to begin feeding the population. It will take a full Earth year to get all elements of the farm in operation, once on site, see Table 20 below. That said, in 35 days the Reactors can provide food of a type until the Hydroponic Stage comes up at 120 days, then Aquatic Stage at the year. The shipping weight of 264 metric tons is at least four loads on projected launch systems (i.e. NASA Space Launch

System) to low Earth orbit. There will be significant effort to assemble the farm, and significant use of in situ resources, and in the case of the reactors, significant improvements in technology. The farm will also require sophisticated control systems and engineers to write control code, similar to that for an oil refinery or biochemical factory on Earth.

Table 20. Size and Masses of the Space Farm Total, Including Shipping Minimums

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**	

F. The First Few Months

Until the Hydroponic Stage is complete, colonists will have to be fed using the Algae and Yeast-Bacteria reactors, which would require the Yeast-Bacteria Reactor to grow by over 5%. Time to full operation for all stages is shown in Fig. 12. As a mass balance, this scenario is shown in Table 21.

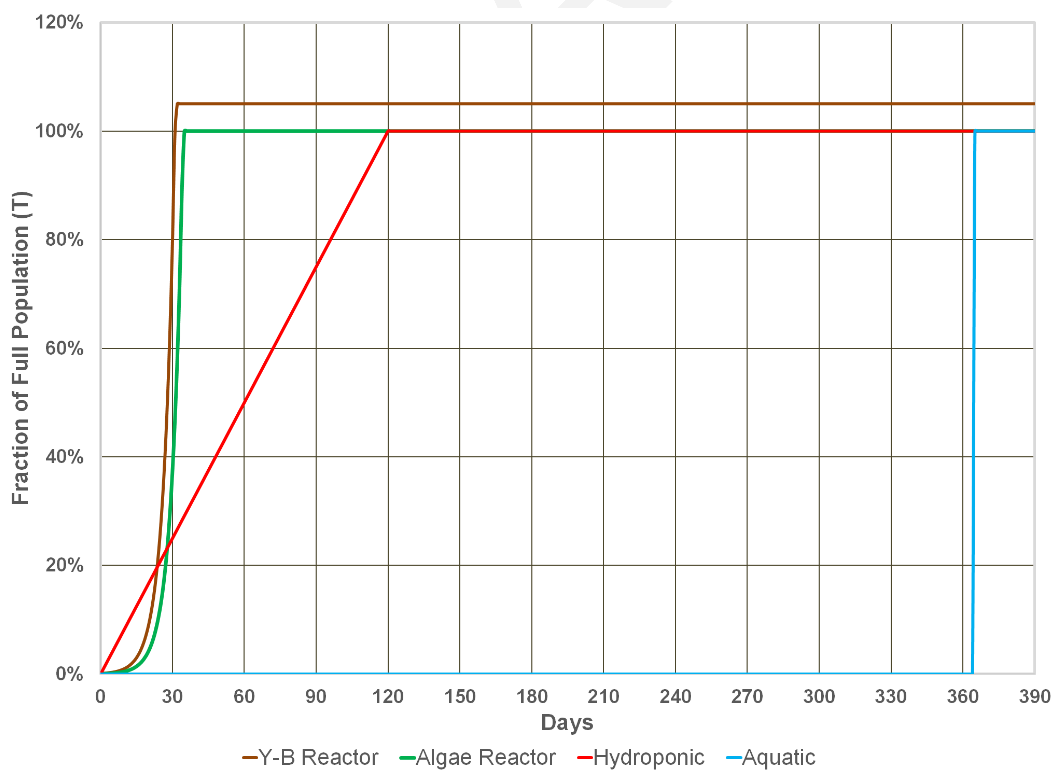


Figure 12. Time to Full Population Level

Table 21. First 40 Days, with Yeast-Bacteria Reactor upsized by ~5%.

	People	Algae Reactor	Yeast-Bacteria Reactor
B_i	39857	23217	274437.25
W_i	365254	390983	
O_i	30681	0	292252.27
C_i	0	444152	
IN SUM	435793	858352	**566689.52**
B_o	11046	326465	
O_o	0	322934	
C_o	42198	0	401954.19
W_o	382548	208953	164735.32
OUT SUM	435792.8	858352.44	**566689.52**
Mass Type			
Oxygen (Oo-Oi)	-30681.34	322933.61	-292252.27
CO2 (Co-Ci)	42198.1	-444152.3	401954.19
Water (Wo-Wi)	17294.3	-182029.63	164735.32
Biomass (Bo-Bi)	-28811.07	303248.32	-274437.25

G. Alternate Species

Many alternate species can be considered for both the Aquatic and Hydroponic stages.

For the Aquatic Stage, both fishes and crustaceans may be candidates. Tilapia are similar to silver carp in growth dynamics, including nearly identical per capita oxygen and other metabolic requirements as in Ref. 17. Tilapia are similar in food value (calculated from Ref. 18) to silver carp. Tilapia also have similar raceway volume requirements, though with twice as many fish per kilogram. Additionally, tilapia are less filter feeders, and require higher temperatures, and require sandy areas to nest.

Krill are another interesting candidate species, for the Aquatic Stage, as they can be considered by mass instead of individuals, readily filter algae, and are directly edible. For krill, however, the salt concentration of their environment would require additional osmosis or separation to pull out the salts. Krill would also require a very different tank design then larger fin fish.

For the Hydroponic Stage, many species have been raised in hydroponic environments on Earth. Soybeans are a high energy crop, though would require replacement every season, or genetic engineering. Many melons or beans might be candidates for in habitat growth, and to filter gray water. Vine plants could be in long rails and structures in walkways and along corners, using habitat space and providing greenery and oxygen. Greens, such as chards, could also be grown, though are lower in calories then tomatoes, and therefore not as an only crop.

VI. Conclusion

People cannot live on fish and tomatoes alone. Even the most gifted chefs would have difficulty making every meal palatable and balanced nutritionally. In reality, such a farm would likely employ many plant and animal species to improve dietary variety, and given lack of in situ resources, a higher percentage of total mass would have to be shipped into the colony. Given the ideal nature used to achieve balance, a more realistic model is desired and needed. It is further notable that mass will be lost due to leakages and inefficiencies, so that even in a few years, resupply or in-situ mining will be required to re-balance the system. All that said, this is an initial effort at a more complex farming construct. Additional work in realizing and sizing the farm, and possibly building scale elements, will be required to refine assumptions and guesses.

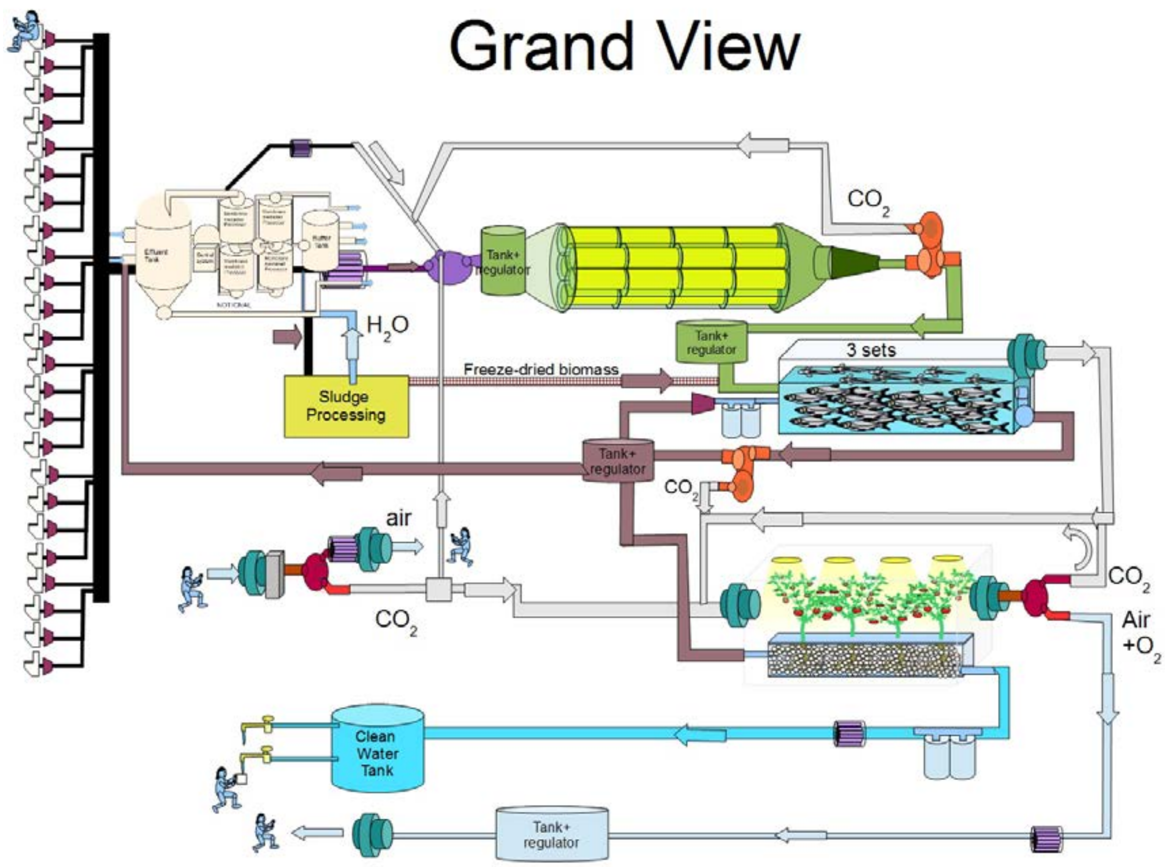


Figure 13. The Grand View of the Farm, Notional and Fanciful

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References

[1]Wieser, M., Holden, N., Coplen, T., Böhlke, J., Berglund, M.,Brand, W. et al. Atomic weights of the elements 2011 (IUPAC Technical Report), Pure Appl. Chem. Research Triangle Park, NC: International Union of Pure and Applied Chemistry, 2013.

[2]Jones, H. "Design Rules for Life Support Systems, 33rd International Conference on Environmental Systems (ICES) ." ICES40, 2003-01 -2356. Vancouver, BC: Society of Automotive Engineers, Inc, 2003. <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20040012725.pdf>.

[3]Garvey JE, Sass GG, Trushenski J, Glover D, Charlebois PM, Levengood J, Roth B, Whitledge G, Small BC, Tripp SJ, Secchi S. Fishing down the Bighead and Silver carps: reducing the risk of invasion to the Great Lakes. Carbondale, IL: U.S. Fish and Wildlife Service and Illinois Department of Natural Resources, 2012.

[4]United States Department of Agriculture, Agricultural Research Service, National Nutrient Database for Standard Reference Release 27, entry 15008. 31 7 2015. <http://ndb.nal.usda.gov/ndb/foods/show/4463?fgcd=&manu=&lfacet=&format=&count=&max=35&offset=&sort=&qlookup=15008>.

[5]United States Department of Agriculture National Nutrient Database for Standard Reference Release 27. 31 07 2015. <http://ndb.nal.usda.gov/ndb/foods/show/3258?fgcd=&manu=&lfacet=&format=&count=&max=35&offset=&sort=&qlookup=11529>.

[6]Hill, W., Pegg, M. Evaluating Asian Carp Colonization Potential and Impact in the Great Lakes Final Report to Illinois-Indiana Sea Grant. Champaign, IL: Sea Grant, 2008.

[7]Williamson, C. and Garvey, J. "Growth, Fecundity, and Diets of Newly Established Silver Carp in the Middle Mississippi River." Transactions of the American Fisheries Society, Vol. 134, Issue 6 (November 2005) (2005): 1423-1430.

[8]Schneider, James C., P. W. Laarman, and H. Gowing. "Length-weight relationships Chapter 17." Schneider, James C. Manual of fisheries survey methods II: with periodic updates. , Fisheries Special Report 25,. Ann Arbor, MI: Michigan Department of Natural Resources, 2000. Chapter 17.

[9]Pena, J. "Greenhouse Vegetable Production Economic Considerations, Marketing, and Financing." 30 05 2005. Texas A&M AgriLife Extension Service. 2015. <http://aggie-horticulture.tamu.edu/greenhouse/hydroponics/economics.html>.

[10]Graber, A. and Junge, R. "“Aquaponic Systems: Nutrient recycling from fish wastewater by vegetable production”." Desalination 246 (2009): 147–156.

[11]Kleinhenz, V., Katroschan, K., Schütt, F., Stützel, H. "Biomass accumulation and partitioning of tomato under protected cultivation in the humid tropics." European Journal of Horticultural Science (2006): 173-182.

[12]Doucha, J., Straka, F., Livansky, K. "Utilization of flue gas for cultivation of microalgae (Chlorella sp.) in an outdoor open thin-layer photobioreactor." Journal of Applied Phycology (2005): 403–412.

[13]Seltz, J. MEDITERRANEAN REGIONAL AQUACULTURE PROJECT, TECHNICS USED FOR INTENSIVE REARING AND ALIMENTATION OF FISH AND SHELLFISH, "Rearing Structures For Aquaculture" Ch. 10. Motta di Livenza, Itally: Food and Argicultural Organization of the United Nations, 1986.

[14]Streit Jr., D., Godoy,L.,Ribeiro, R.,Fornari, D.,Digmayer, M., Zhang, T. "Cryopreservation of Embryos and Oocytes of South American Fish Species." Yamashiro, Dr. Hideaki. Recent Advances in Cryopreservation, ISBN: 978-953-51-1644-8. Rijeka, Croatia: InTech, 2014. 130.

[15]Syngenta. Syngenta Kenya Tomatoes. 2011. 31 07 2015. <http://www3.syngenta.com/country/ke/en/products/Vegetable%20Seeds/Pages/Tomatoes.aspx>.

[16]Ghayal, M.S. and Pandya, M.T. "Microalgae Biomass: A Renewable Source of Energy." Energy Procedia Volume 32 International Conference on Sustainable Energy Engineering and Application (ICSEEA) 2012. Lisbon, Portugal: IARIA, 2013. 242–250.

[17]Rakocy, J. Tank Culture of Tilapia L-2409, SRAC Publication No. 282. Stoneville, MS: Southern Regional Aquaculture Center, 1989.

[18]United States Department of Agriculture, Basic Report: 15261, Fish, tilapia, raw . 31 07 2015. <http://ndb.nal.usda.gov/ndb/foods/show/4704?fgcd=&manu=&lfacet=&format=&count=&max=35&offset=&sort=&qlookup=15261>.

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