Biological Processes in Closed Ecosystems

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ABSTRACT

Understanding of sustainable closed ecosystems will be necessary before we can appreciate Earth's capacity for life as well as for space settlement. This overview estimates the biological processes necessary to support one person on a sustainable basis.

We estimate flows of nitrogen, carbon, water and dry matter. The total surface area of the system is approximately 300 square meters, with the main food production hydroponic system equal to about half the surface area. The hypothesized system is composed of seven main areas: a food biomass production hydroponic unit [130 m^2], nitrogen fixing legume system [125 m^2], a combined potable water security storage system and aquaculture production unit [5 m^2] which is also key to nutrient regeneration, Regeneration Unit 1; two additional nutrient regeneration units: a vermiculture unit [9 m^2], Regeneration Unit 2, and a fungi unit [9 m^2], Regeneration unit 3; a waste management/biomass processing area [10 m^2], and a soil synthesis module [9 m^2] where all refractory material is accumulated.

Because of the critical role of nitrogen, the starting point for this analysis was to determine nitrogen flows. Human diets require about 15 g nitrogen per person per day. Since less than a third of plant biomass is edible, one would think that total food production containing 45 g of nitrogen per day would be sufficient. This simplistic approach ignores losses of nitrogen in living systems, from microbial denitrification and from nitrogen deadlocked in refractory organic waste material. By following the fate of nitrogen and making estimates of its fate in the subsystems, we estimate total nitrogen losses to be at least 25 grams per person per day, or 170% more than that contained in the food. The total nitrogen flow in a closed biosystem will be approximately 59 grams of nitrogen per person per day. Human food mass required is about 800 g dry food per person per day. This closed biosystem will generate about 4,100 g dry biomass per person per day. Of this total, about 25% will remain as refractory organic matter. Projected nitrogen content of this refractory matter is 2.5% of the organic mass, and the ash content is 22%.

Replacement of nitrogen lost to the living system is one of the primary requirements of a closed system. Biological nitrogen fixation is the system of choice here, but it is a relatively slow process and requires a large plant surface area for legume production. Assuming a high fixation rate of 0.2 g nitrogen per meter squared per day by a legume capable also of producing a fraction of the biomass suitable for human food, the

surface area of this section is about the same as the food production hydroponic system.

The primary engineering trades between biological and physicochemical processes are in nitrogen fixation, and in oxidation of refractory organic material or "deadlocked" material. Approximately 80% of the lost nitrogen is in the refractory material. Treating less than two liters per day of humus could release nutrients and substantially reduce the need for biological nitrogen fixation. Conversely, generation of refractory organics would allow soil synthesis, a potentially positive result. Total dry matter soil synthesis rates are about 1.1 kg per day containing 78% organic matter, with the organic matter containing 2.5% nitrogen. If this refractory biomass were mixed with regolith to produce a rich top-soil-like material at 3% organic matter content, the system could generate 10 metric tons of dry topsoil per year. At a soil depth of fifteen cm, the rate of soil synthesis would be 45 square meters per year. In three years the synthesized soil production area would yield a soil area sufficient for a large fraction of food production. Alternatively, deadlocked material could be used to produce fuel, biochemicals, structural and aesthetic materials

INTRODUCTION

The requirements for a closed environment life support system are clean air, clean water, nutritious food, at minimum complete nutritional requirements, at best, optimal nutritional requirements, and complete waste recycling. A fully closed system requires plants for primary production, and must have efficient waste reprocessing. Those are big steps. Biology is helpful since organisms are self-regulating within wide parameters. A fully closed system is economically desirable for any inhabited off Earth structure with a design life more than five years.

A completely closed life-support system is a system of subsystems. The subsystems must be optimized to maximize overall system performance, not to optimize subsystem performance. For example, it is possible to grow sufficient wheat for one person in 25 m^2, but that requires an unrealistic degree of control over the nutrient solution. Furthermore, wheat is not an optimal human nutrient.

Like any mature engineered system, a closed system will require iterative development. Time will be required for design, test; redesign and retest. The ability to evaluate many design options quickly will allow earliest success.

A closed system must be robust. Redundant systems of different design for functions are desirable. The system requires adequate margin, that implies a larger atmosphere mass, larger water cache, and a food cache.

The system should be designed for minimum cost. Commercial off-the-shelf equipment should be used where possible to minimize cost and maximize reliability. Ideally, most of the manufactured mass could come from Home Depot.

Gravity, either natural or artificial, is highly desirable. Gravity allows the use of off-the-shelf pumps to circulate water, enables air circulation by convection, and allows easy separation of liquid and gas phases. Gravity obviates the need to filter air for particulates.

Full-time solar illumination is highly desirable. It minimizes the electrical power requirement for plant growth. Therefore, settlement location should be chosen carefully. By this criterion, free space settlements would be preferred to settlements on planetary surfaces.

Inefficient closed systems are easy, an example is the whole Earth biosphere, or an Ecosphere, available by mail order. Both are energetically and materially inefficient. Both have very high light flux per unit biomass, and both have an enormous ratio of air, water and soil to biomass.

A satisfactory closed environment life support system for space settlement should require less than 5 tons of air, 5 tons of water, 5 tons of biomass and 20 kW of energy, in the form of solar illumination plus electricity, per person. This paper summarizes a first order approach to estimate requirements to support a single person in a closed system controlled by biological processes. The results emphasize the magnitude of the challenges in developing compact, sustainable closed systems.

Long term space flight forces us to consider human requirements in nearly completely closed systems, that is, truly sustainable cycles minus in situ resources such as water, carbon, nitrogen, trace elements and energy. Superimposed on this problem is the need to make the systems as small and as efficient as possible using minimum energy to drive the system. For those of us trained in biological processes and Earth systems, we assume that this means understanding and optimizing biological processes with minor inputs from chemical and physical operations.

It should be obvious that the closer one gets to defining and developing a feasible closed system for human settlement of space, the closer we will be to understanding how to make the Earth a sustainable system as well.

APPROACH

In order to estimate closed biosystem sizes and productivity, human caloric and nitrogen requirements were estimated, then nitrogen and water flows to support these requirements were quantified. We assumed that solar energy would not be limiting and that gravity would be necessary. We projected the fate of these materials over a long period, and the implications of these results. We discuss the possible need for physicochemical processes. All estimates are for one adult male with dietary energy requirements of 3,500 kcal per day, an energy to mass ratio in food of 4.5 cal/g dry matter, and the majority of the biomass containing an average nitrogen content of 2.2% of the dry matter and carbon content equal to 40% of the dry mass. The closed sustainable system is composed of four main sub-systems and twenty separate processes.

BACKGROUND

The most ambitious attempt to define a sustainable closed systems to date was Biosphere 2, a 16,000 m^2, seven biome system with 20 tons of living material meant to support eight adults – sustainably for 100 years [Eckart 1995]. The Biosphere 2 area provision of 2,000 square meters per person contrasts to 2 to 10 square meters suggested as the minimum in the simpler Bios-2 system developed by Russian scientists, and the 10+ square meters suggested in Eckart's excellent 1995 summary "Spaceflight Life Support and Biospherics." All those systems had significant undefined components and they are far removed from being completely sustainable closed systems for long-term human habitation.

These two Earth-based approaches to define what ecosystems humans are using on Earth can be contrasted to the above minimum closed system estimates. We note that much recent work on the carrying capacity of Earth calculates a cropland area requirement of around 2,000 meters squared per person to support a vegan diet and ten times this for meat eaters. The Ecological Footprint is an effort to calculate the surface area of Earth that is required by various lifestyles. The energy intensive U.S. society requires 100,000

m^2 of ecologically active land area to live sustainably, whereas more limited lifestyles have requirements ten times less. These provide an interesting contrast to the minimal closed system requirements for human habitation stated above which are nearly equal in the case of Biosphere 2, but over 100 times greater than those for minimal closed system needs.

HYPOTHESIZED SYSTEM

The flow of materials in the proposed closed ecosystem emphasizes a number of important concepts – many that differ from all other closed ecosystems work. First, emphasis on waste treatment should not focus on traditional pollution control that attempts to convert all materials to the most oxidized forms, such as with aerobic composting, without regard to energy consumption and adverse residue generation. Instead, the main focus of waste treatment in a closed system should be on recycling nutrients to higher value products. This should be done in a minimum energy-consuming manner, and energy production should be emphasized as long as nutrients are not destroyed nor toxins generated.

Second, human water needs are very much secondary to plant requirements, so the emphasis in the water cycle must be on food production requirements, not potable water for drinking.

Third, the main sink of nutrients and carbon into non-biologically recyclable materials is the overriding challenge in defining the requirements of a closed system. This loss of materials in continuing cycles is sometimes referred to as "deadlocked" material. Emphasis on these closed systems needs to consider a quantitative definition of the fraction of material tied up in this fashion – including rate of formation, characteristics, and quantities. After a quantitative definition of refractory formation is obtained, efforts need to be made to convert this negative characteristic into a positive. For example, allowing this sink to accumulate organic carbon and nutrients is the Earth's soil manufacturing process. Mixing this accumulated material with regolith may be the soil generation step required to establish the wide range of food production systems for long term success of closed systems in space settlements.

Fourth, the material balances for water, carbon and nutrients in a closed biological system suggest that the most important design limiting factor may be the conversion of plant available forms of nitrogen into nitrogen gas. Because of the importance of protein in all living systems, this nitrogen loss should be considered unacceptable and provision must be made to replace it with physicochemical or biological processes. Biological fixation is considered to be the preferred sustainable process to replace organic nitrogen lost to denitrification.

The hypothesized processes are intended to address these four concerns of closed systems and to provide alternatives that enhance the possibilities of developing self-designing, and self-correcting biological systems to support a sustainable closed system.

NITROGEN CYCLE IMPLICATIONS

Food Nitrogen Requirements and "Lost" Material.

Human food requirements must include nitrogen components, mainly protein, that contain 15 to 18 grams per person per day. Only a portion of the photosynthesized biomass is available as human food. Assuming that a third of the harvested biomass could be human food, total biomass nitrogen production requirement would be 45 grams per person per day.

At first, correction of biomass production for the fraction that becomes human food would be thought to result in required total biomass fixed nitrogen. However, because a certain fraction of nitrogen will be converted to inert forms in various processes, this total must be corrected for these losses and this results in requirement for a larger biomass production. Total nitrogen required is equal to nitrogen in human food and non food biomass, plus that lost in processes such as microbiological denitrification of oxidized forms of nitrogen, volatile forms like ammonia, and organic nitrogen stored in refractory humus material.

The challenge with non human food biomass becomes two-fold – mobilization of nutrients from this biomass to support further plant biomass production, but with efficient conversion of the energy to food, fuel or other useful by-products during the regeneration process. Wasting this biomass by combustion is one alternative, but it results in additional problems, such as recovery of nitrogen in plant available forms. It should be obvious that since this crop waste is more than twice human food biomass, that its conversion to a form suitable for human consumption would be highly desirable. Aquaculture production is assumed to play an important role for its capability to use this low quality biomass to efficiently produce high quality protein.

Losses of Nitrogen via Volatile Conversions, Denitrification, and Refractory Mass Synthesis.

Estimates for losses of nitrogen are based on denitrification losses in various subsystems, and conversion of biomass to refractory organic matter. Denitrification is particularly problematic because of the wide range of microorganisms that can accomplish this anoxic conversion. Even in aerobic systems, micro-anoxic areas will support the loss of nitrogen at very high rates. Purposeful loss of nitrogen in hydroponic waste water treatment systems can remove ten grams of nitrogen per meter squared per day, although most values are much lower. We assume here that careful management of oxidized forms of nitrogen, and fully aerobic environments will limit denitrification. A total denitrification loss of 4.3 grams of nitrogen per day is assumed.

All non-food biomass is to be consumed by fish, worms, or processed by fungi and microorganisms. Non-food biomass is assumed to have an available energy fraction equal to 70% of the total. That is 70% of the organic matter measured as ignitable solids at 550C can be converted to carbon dioxide and water. Estimation of the fraction of remaining material and its composition is based on simple nutrient mobilization/immobilization models described briefly in the following.

The remaining particulate refractory material is assumed to contain all of the initial ash and an equal proportion of nutrients. Note that if the biomass contains 5 percent ash, the remaining organic matter will be 30% of the initial plus the initial ash. Thus, for 100 units of dry matter, 66.5 units will be converted to new cell mass in other living organisms, bioenergy, carbon dioxide and water, and 33.5 units will remain. The remaining material will have 33.5% of the initial mass of nutrients and an ash content of 15%, or an increase of 300% over the initial ash fraction in the plant mass.

In addition to the refractory plant mass, some fraction of decomposer biomass will also remain. Two alternative pathways are considered – aerobic or anaerobic. Decomposers are assumed to be represented by the microbial mass as: $C_5H_7O_2N$. Note the high nitrogen fraction of decomposer organics, about 12%. The protein content of microbes is around 78%, thus the term "single-cell protein." Initial yield of aerobic decomposers is assumed to be 0.5 g organic matter per gram of organic matter oxidized to carbon dioxide and water, and the corresponding yield for anaerobes is 0.15g, or less than one third aerobic yields. After all readily available organic matter is processed to inorganic end-products, it is assumed that 20% of the microbial biomass remains or is refractory. Thus in an experiment where 70% of the initial organic matter is removed such as in the above example, the remaining 28.5 units of organic matter will represent 25.9 units of refractory plant mass and 2.5 units of refractory microbial mass.

Note that the high nitrogen requirements of aerobic decomposers results in enriched refractory or humus material. Insufficient nutrients would inhibit the decomposition rate. In the above example where a total of 33.5 units of refractory material remain, if the initial plant nitrogen is 1.5% of the dry matter, this model suggests that remaining refractory matter will have an organic nitrogen content of 2.1% of the total dry mass including the ash, and 2.5% of the refractory organic matter. The refractory dry mass has an enriched nitrogen content 40% higher than the original plant mass. If the decay takes place under anaerobic methanogenic conditions, the nitrogen content would be lower – 1.7% of the organic matter and 1.4% of the total dry matter. The refractory fraction of nitrogen in the dry matter is lower than the initial fraction because of the increased ash content.

Wherever significant quantities of ammonia exist, some will vaporize, given appropriate pH and temperature. In a closed system, where large quantities of water vapor is condensed, most of volatilized ammonia would be trapped in this water and returned to biomass production. For simplicity, we assume that this loss is zero.

LIVING SYSTEM REQUIREMENTS

Water Requirements and Waste Water Treatment

Minimum human water requirements vary from 2.3 to 4.0 liters per person per day for drinking and another nine liters for hygiene uses [Eckart 1996]. This compares to the 380 liters per person per day average value used to design sewage treatment facilities. A total human consumption of 30 liters per day has been recommended for long-term closed systems, and this value is assumed here. Note that conventional water requirements for food and biomass production is several hundred times this minimum human requirement. For this reason, we focus on water requirements of crop plants rather than human water requirements.

Initial approaches have focused on developing a complete water recycling system that converts sewage directly to drinking water. Such emphasis is misplaced in closed systems because of the high plant water requirements. If food production via photosynthetic processes is included in the closed system, extensive treatment of human wastes is eliminated as a condition of operation of the system. Instead, recycling carbon and mobilizing nutrients contained in the wastes becomes the focus of waste water treatments. Sustainable water in closed biosystems is provided by management of the quantity and quality of the condensed transpired water. It is likely that volatiles absorbed into the condensed water will be a larger long-term problem than ultra-efficient sewage purification.

As each component of this closed system is considered it is interesting to ask “How would the focus on nutrient recycling change municipal water treatment practices?” Our analysis indicates that preliminary sewage treatment could be accomplished to provide a safe medium that would support a plant system such as a sewage farm, a constructed wetland, or a more sophisticated hydroponic treatment system. Such an approach would de-emphasize production of extremely high quality water and shift the focus to energy generation via wasted organics and utilization of nutrients for plant production purposes. Instead of waste treatment and discharge facilities we would have waste water treatment parks with various useful by-products generated along with recharge of potable water into groundwater or surface waters.

A two-stage waste water treatment system is recommended for rapid conversion of biodegradable carbon and mobilization of nutrients in human wastes. The first stage is anaerobic followed by aerobic polishing. Anaerobic preliminary treatment is useful because the minimum microbial yield assists in nutrient regeneration and energy generation. Aerobic polishing provides additional nutrient conditioning. Although contaminated solids from other sources could be added to this anaerobic stage, it is likely that nearly all organic matter would be better used as feedstock for one of the biological regeneration units rather than to convert them to methane gas.

It is likely that the waste water treatment system could be totally eliminated since it would be possible to use one of the subsequent regeneration units to condition the waste water. For example, the waste water could be pasteurized and directly diverted to the vermiculture or soil synthesis units. Biodegradable carbon would be converted into worm biomass, carbon dioxide and water. The main reasons for a human sewage treatment system are isolation of pathogens, control of intermittently introduced toxins, and positive control over the nutrients in the waste stream.

To provide extensive treatment capacity in as small a volume as possible, the empty tank reactors are supplemented with small biofilm reactors. These biological treatment units provide a reservoir of organisms, and a greatly enhanced treatment capacity. Anaerobic biofilms have exceptional resiliency. They can be stored without nutrients for years, and return to initial processing potential in a matter of days.

After the waste water is treated, it is transferred to a reservoir that serves as one of the sources of mobilized nutrients to feed the hydroponic plant systems. Flow of materials in the human waste management module is summarized in Table 1.

Table 1: Summary of flow of nitrogen in human waste through biological treatment.

INFLUENT N		EFFLUENT N	
SOURCE MATERIAL	AMOUNT, grams N/Person-d	MATERIAL	AMOUNT, grams N/Person-d
Influent Wastewater	15	Treated Effluent Wastewater	11.6
--	--	N Volatile Losses	1.0
--	--	N in refractory Particulate Mass	2.4
Summary of Flows	15	Refractory Biomass [as dry]	0.28

Estimated nitrogen concentrations in the treated waste water are 420 mg/l as either ammonia-nitrogen or nitrate-nitrogen.

SYSTEMS SIZE AND MANAGEMENT ASSUMPTIONS

An iterative process is necessary to estimate total nitrogen flows including potential losses and nitrogen quantities stored in a refractory form. After these total nitrogen losses are estimated, it is possible to identify the total biomass that must be generated above human food needs to continuously support plant nutrient requirements. Three types of biomass are generated: consumable human food, high quality biomass not acceptable for human food, and low quality biomass. The nitrogen content of biomass differentiates high and low quality non-human food. High quality biomass is food waste, and plant leaves, with a nitrogen content greater than 2% of the dry mass. Low quality biomass has a nitrogen content between 0.5 and 2.0% of the dry mass.

Biomass production occurs in six different areas – each with a different portion and type of human food production potential. The main production unit is a hydroponic system, probably using the nutrient film technique to minimize size and mass. The next largest unit is the legume nitrogen fixing unit, followed by the aquaculture system, Regeneration Unit 1; a vermiculture unit, Regeneration Unit 2; and a mushroom/fungi system, Regeneration Unit 3. A final subsystem is the soil synthesis unit that receives all humus and refractory matter from the three regeneration units.

Of the total biomass, approximately 20% is human food, on a nitrogen basis. About 70% is estimated to be higher quality biomass that is fed directly to an animal protein production unit, and the remaining 10% is fed directly to the vermiculture unit which in turn provides about 4% as direct high quality protein feed to the aquaculture unit.

Transfer of materials between units depends on biomass quality and the potential to be human food while regenerating nutrients into plant available forms. Condensate recovery is divided between a potable water storage unit and the aquaculture system. The large aquaculture unit acts as a water storage system, as well as a food production unit. Over 95% of the condensate flow goes through the aquaculture unit to harvest soluble nutrients in a form that could be fed directly to the main food production hydroponic units. All particulate human and aquaculture waste is added directly to the vermiculture system. Also, all low quality biomass is added to the vermiculture unit. Note that the red worms from the vermiculture unit could be used as a backup human food protein and supply as much as 20% of the diet.

Organic matter is intermittently transferred from the vermiculture unit to the mushroom/fungi unit where much of the remaining biodegradable mass is converted to edible mushrooms or final inorganic end-products. Finally, refractory organic matter is intermittently harvested from the fungi/mushroom unit and stored in the soil synthesis unit.

Food Production and Water Requirements

The size of the plant biomass production system is based on average protein and calorie requirements. We made two simplifying assumptions to estimate total surface area of plant production systems: first, that total human food requirements are less than 800 g per person per day (approximately 320 g of fixed carbon per person per day), and second, that the average photosynthetic process fixes carbon at a rate of 5 g of carbon per meter squared per day. Following these two assumptions, the total plant production area would be 180 square meters if one third of this biomass became human food. The recapture of protein and calories contained in the remaining 70% crop waste by the aquaculture subsystem reduces this area to 130 square meters.

Evapotranspiration of water is closely linked to photosynthesis in Earth crops. Measured evaporation of water varies from 200 to over

700 grams of water per gram of dry plant biomass fixed by photosynthesis. For many years, water circulation and evapotranspiration were thought to be fixed components of plant growth. Today we know that evapotranspiration can be uncoupled from photosynthesis, and that evaporation can be limited by controlling humidity, and by increasing carbon dioxide concentration. Trade-offs to limit evapotranspiration relate to nutrient concentrations and pathogen growth on plants.

Evapotranspiration will be assumed to be controlled at less than 200 grams water per gram of dry plant mass produced. Minimum flow rates to the hydroponic system will be 325 liters per day. Remaining flow of water to all other units will be about 400 liters per day making condensate recovery requirements of 730 liters per day. Support for this rate of water recovery requires an average evapotranspiration of 180 grams of water per gram of plant produced.

The choice of food and plants that would be included in primary food production remains a major challenge and unknown. Self-reproducing, hardy plants that can grow for many generations are obviously necessary. Micro algae have been identified as having the capability to produce the desired oxygen, manage CO2, and generate sufficient protein to support higher life. Microalgae, however, have many drawbacks. They are unpalatable and difficult for humans to digest. They also have an extremely high refractory fraction.

A candidate plant studied in the Russian biosphere research shows significant promise to be hardy, self-reproducing, self-regulating, and a producer of human food. This plant is Chufa , *Cyperus esculentus* L. var. *sativus*. Common names are tiger nut, zulu nut and ground almond. It is a perennial sedge that produces small edible tubers underground.. The top of the plant is grass-like from 6-36 inches tall. Chufa grows well on all types of soil from muck to rock land. Chufa has been cultivated as livestock forage as well as human food. Close relatives are hardy weeds. These characteristics show promise for its cultivation in hydroponic systems requiring minimal control.

While seldom grown as a food item in home gardens, chufas were grown on about 2,000 farms mostly in Florida in the United States in 1944. In 1941, 7,000 acres were planted for hog pasture in Florida and over 3,000 bushels were dug from 170 additional acres. The nuts weigh about 44 pounds per bushel. In the 1980s, chufas were still grown for livestock feed on a few farms in the Florida Panhandle [Stephens 1994].

Regeneration Units.

Regeneration Unit 1: Aquaculture.

The flow of nitrogen in and out of the aquaculture unit, referred to as Regeneration Unit 1 is shown in Table 2.

Table 2. Summary of N flows in Regeneration Unit 1 aquaculture production. Values are in grams of nitrogen per person per day.

INFLUENT N		**EFFLUENT N**	
SOURCE MATERIAL	AMOUNT, g N/Person-d	MATERIAL	AMOUNT, g N/Person-d
Plant Biomass	36	Human Food [Fish]	10
Plant Biomass from N2 Fixation	18	Particulate Waste to Vermiculture	23

Biomass from fungi	3	N Losses to N2	1+
--	--	Soluble Nutrients to Hydroponic Unit	23
Summary of Flows	5		57

Of the total nitrogen flow in the system, Regeneration Unit 1, the aquaculture unit, is responsible for 84% of the total, emphasizing the importance of this nutrient-mobilizing and food producing component.

Besides the flow of food from this unit, there are two other effluents – particulate wastes containing about half of the input nitrogen and soluble flow-through condensate that leaches out the other half of nutrients which exist in a solid state. The particulate wastes are generated at around 5% dry matter resulting in a flow of around 38.6 liters per day containing 193 grams per day of dry matter. The other half of input nitrogen is in the form of ammonia at a quantity of 23 grams per day. Flow to the hydroponic system is 704 liters per day with an ammonia-nitrogen concentration of about 32 mg/liter. Combining human waste water flow increases the average ammonia input concentration to 47 mg/liter. That concentration is well within the optimal concentration range of nutrient solutions for hydroponic systems.

Regeneration Unit 2: Vermiculture.

Regeneration Unit 2 is a vermiculture production system. Table 3 summarizes the flow of nitrogen in this unit.

Table 3. Summary of nitrogen flows in Regeneration Unit 2 , Vermiculture. Values are in grams of nitrogen per person per day.

INFLUENT N		**EFFLUENT N**	
SOURCE MATERIAL	AMOUNT, g N/Person-d	MATERIAL	AMOUNT, g N/Person-d
Low Quality Biomass	7.3	Losses to N2	0
Particulate waste from Aquaculture	23	Food to Aquaculture Unit	3
--i	3	Filtrate and particulate wastes to Regen.#3.	27.3
Summary of Flows	30.3		30.3

Inadvertent conversion of reduced forms of nitrogen to nitrogen gas is one of the most important and limiting aspects of closed systems. We assume that the biomass production system is water-based, in other words, a hydroponic system. Most of the fixed nitrogen that is lost, 22% of the total, about 13 g of nitrogen per person per day, comes from this unit as nitrogen gas, because of uncontrollable denitrification in microscopic anoxic environments. Relatively small nitrogen gas losses occur in Regeneration Units 1 and 2, and from the waste treatment system. The combined potential losses, however, are equal to more than the fixed nitrogen contained in human edible food. The nitrogen fixation unit must be capable of replacing these losses. Unless nitrogen fixation can simultaneously produce human food, it will become a major activity and concern for all material flows. Although nitrogen fixation with plants is a slow process, we assumed for purposes of this design study that it would be the primary process for nitrogen replacement. Alternative sources of biologic nitrogen fixation to be considered include micro-algae and anaerobic fermentation. Nitrogen fixation is an area where the physicochemical Haber Bosch process should be considered.

Regeneration units are intended to minimize deadlocked material, that is inorganic minerals and refractory organics not readily liberated to plant usable form by biologic processes. Once most of the mobilization of nutrients has occurred, the remaining material has the appearance and characteristics of organic soils. Thus, these processes reflect the natural processes that generate soil. This step may be useful in two ways. Eventually, plant production on soil systems may be desirable and a soil creation step may be viewed as positive instead of being a negative, deadlocked nutrient problem. Some desirable plants may be particularly difficult to grow in hydroponic systems and this unit would allow them to be cultivated. This could be particularly important for the legumes to be used for nitrogen fixation. The vermiculture unit receives all of the particulate waste from the aquaculture unit and all of the low quality biomass, a total of about 40% of the biomass. Because of the preprocessing of this organic matter by the cultured fish, we assumed that the fraction converted to high quality worm mass is relatively small. All of the net production of worm mass is fed to the aquaculture unit. The quality of protein from the vermiculture unit is sufficient for human consumption, so it could be a backup human food supply. Its primary mission, however, is to aid the microbial systems in oxidizing organic matter and regenerating nutrients.

Regeneration Unit 3: Fungi System.

All of the remaining processed organic matter is intermittently harvested and added to the fungi unit, Regeneration Unit 3. The flow of nitrogen in this unit is summarized in Table 4.

Around 50% of the remaining organic is biodegradable. Certain fungi have the capability to use refractory compounds including lignin. Since lignin is a primary refractory component, it is possible that this unit may be capable of converting a much higher fraction of the refractory organic matter than is assumed here.

Table 4. Summary of nitrogen flows in Regeneration Unit 3 , Fungi. Values are in grams of nitrogen per person per day.

INFLUENT N		**EFFLUENT N**	
SOURCE MATERIAL	AMOUNT, g N/Person-d	MATERIAL	AMOUNT, g N/Person-d
Particulate and filtrate waste from Regen #2 [vermiculture unit]	27.3	Losses to N2	0
--		Food	2
--		**Transfer to Soil Synthesis Unit**	25.3
Summary of Flows	27.3		27.3

Soil Synthesis Unit.

The final stage in biomass processing is the accumulation of refractory organic matter. The flow of nitrogen in this unit is summarized in Table 5. This material represents the ultimate deadlocked organic matter, or the total refractory mass. It is also Nature's soil synthesis system. Less than 3% of the dry mass is derived from human solid waste with the remainder from plant and decomposer mass. Most of the biomass is assumed to be produced with a nitrogen content of around 2 percent of the dry weight and a low ash content, around 5% of the dry weight. Products range in nitrogen content from 1% to over 10% of the dry mass. The final refractory organic matter has an estimated nitrogen content of around 2.5% and an ash content of 21.6%.

Table 5. Summary of N flows in Soil Synthesis Unit. Values in grams of nitrogen per person per day.

INFLUENT N		**EFFLUENT N**	
SOURCE MATERIAL	AMOUNT, g N/Person-d	MATERIAL	AMOUNT, g N/Person-d
Particulate and filtrate waste from Regen 3 [vermiculture unit]	25.3	Losses to N2	0
Refractory Solids From Waste Tmt.	2.4	Food & Biomass	7
--	--	**Storage in refractory organic matter.**	20.7
Summary of Flows	27.7		27.7

The total amount of refractory nitrogen is estimated to be 20.7 grams per person per day. Inclusion of nitrogen losses from denitrification (4.3 g of nitrogen per person per day) results in a total loss of nitrogen to plant production of 25 grams per person per day. This loss is equal to 170 percent of human food nitrogen needs.

One obvious approach to simplify this system is to use a physicochemical approach to destroy the organic matter and mobilize the plant nutrients. A candidate process is super critical water oxidation. It is likely that such an oxidation process would be useful as a backup to the biological processes. Total processing requirements are approximately 2.1 kg per day of wet mass at 50% dry matter.

A more valuable role of this final stage material may be to provide a soil-based system for future food production. Rich top soils contain three to five percent organic matter. If this material were mixed with regolith to obtain this concentration of organic matter, it would generate 10,000 kg of topsoil per year. If this quantity were distributed to a depth of 15 cm, the topsoil production rate would be 40 to 50 meters squared of crop production area per person per year. Thus, in two to four years, sufficient soil-based plant production surface area would accumulate to support significant food production.

It is interesting to compare the composition of organic matter in soils undisturbed by modern agriculture practices and the industrial revolution. Organic matter content was estimated to be 3 to 5%, and the nitrogen content was about 3% of the organic matter. Therefore, we estimate the organic nitrogen in this hypothesized soil generating step to approximate that resulting from natural cycles.

Nitrogen Management.

The preceding estimates of food and water flows emphasize the importance of nitrogen management in closed systems. Our assumptions regarding losses of nitrogen are probably low, especially in relation to the hydroponic system. We know relatively little about conserving nitrogen to obtain close to 100 percent in many living systems.

A sustainable system must replace nitrogen losses. Two options exist for replacement of nitrogen. One is a version of the Haber Bosch process equipment to convert nitrogen gas into ammonia – the source of about half of the fixed nitrogen on Earth today. The second option is to use biological nitrogen fixation. Unfortunately, nitrogen fixation is a highly energy intensive process, and biological fixation rates are relatively slow. Depending on the length of the growing season, measured fixation rates for legumes vary from 0.008 to 0.18 g nitrogen per meter squared per day. Application of algal processes might be a viable source, however, the low food value of algae, and difficulty of mobilization of fixed nutrients in algal biomass represent significant challenges. We assume that legumes can be identified that will achieve near maximum fixation rates of 0.2 g nitrogen per meter squared per day, and that this rate can be maintained for 365 days per year. Under this assumption, we estimate the nitrogen fixing module to be about as large in surface area as the hydroponic biomass production unit.

The preceding calculations show that physicochemical oxidation processes, and Haber Bosch nitrogen fixation could decrease the size of the system. This assumes, of course, that nitrogen gas is efficiently conserved. We believe, however, a great benefit of biological processes is the potential to generate soil for a soil-based agriculture.

Estimated Total System Requirements for Sustainable Water, Food, and Oxygen.

A summary of the system requirements is given in Table 6. These preliminary area requirements show that a total of 130 square meters per person is needed for food production, water recycling, and carbon and nutrient recycling. The required area is nearly doubled when fixed nitrogen regeneration is included. Therefore, the total area requirements for a completely sustainable closed ecosystem is estimated to be approximately 300 square meters per adult human.

CHALLENGE AND IMPACT OF INCREASED UNDERSTANDING OF CLOSED ECOSYSTEMS.

The challenge to understand and develop minimum sized, sustainable closed systems is huge. It is understood by most in the field to be a distant goal that may never be reached. Just understanding the simplest closed system has taken decades. As emphasized by Gitelson et al [2003], the education that will result from R&D focus on closed systems and potential solutions to some of Earth's problems may be the greatest near term benefit of such efforts.

Table 6. Summary of unit processes, their functions, and limitations in a closed biosystem for sustainable food and water management for a single adult male [72 kg].

UNIT	DESIGN BASIS & FUNCTION	COMMENT
I. POTABLE WATER SYSTEM A. Temporary Drinking Water	Provides seven days of treated drinking water storage @ rate of 30 liters per person per day.	Buffer tank between condensate storage/aquaculture unit and potable water storage
B. Condensate Storage Provides 100+ days of potable water.	Dual purpose as Regeneration Unit #1 Aquaculture Production and potable water storage. Volume ~ 5,000 liters	Combined storage and Aquaculture production requires additional treatment. Separated particulate waste transferred to Regeneration #2, Vermiculture Unit. Condensate recovery flows through this unit washing dissolved nutrients into the hydroponic plant production system,
II. HUMAN WASTE MANAGEMENT SYSTEM A. Temporary Storage	Provides 2 to 7 days storage. Volume ~ 210 liters.	Buffer unit
B. Anaerobic Treatment 1. First Stage.	Preliminary anaerobic treatment and biosolids separation. Empty tank volume of 150 to 300 liters.	First of two stages.
2. Second stage	Second stage biofilm reactor. High rate, highly efficient Wastewater treatment. Off-line recycle.	Provides nearly complete degradation.

UNIT	DESIGN BASIS & FUNCTION	COMMENT
3. Third stage	Anaerobic Buffer with biosolids. Excess biosolids transferred to Regen Unit #2 - Vermiculture.	Completes bio treatment and converts some nutrients to oxidized forms (i.e. nitrates, sulfates, phospates, etc).
4. Aerobic biofilm -	Supplement to aerobic suspended solids treatment in stage 3. This unit supports process stability and high efficiency. Volume ~30 liters.	As above.
5. Treated and separated Biosolids holding tank	Temporary and short term storage.	Option provided for Pasteurization and/or oxidation of refractory material.
6. Biogas holding/use.	Methane storage. Volume of 200 liters.	
7. Mobilized nutrient storage.		
8. Hydroponic System for wastewater microbial control prior to biomass production units.	Suspended solids & microbe reduction from combined wastewater from waste and Regeneration Units. Hydraulic area. loading rate is <5 cmperday, surface area of ~ 15 m2.	This unit could be part of an aesthetic design in the living area.

UNIT	DESIGN BASIS & FUNCTION	COMMENT
III. NUTRIENT REGENERATION UNITS A. Unit #1 Aquaculture Production and Condensate Storage	Combined potable water Storage and low quality biomass conversion to food, and nutrient regeneration. Approximately 7 days of Condensate volume storage.	Combined water and biomass conversion requires careful management. Biomass could be structural or Aesthetic.
B. Unit #2. Vermiculture	Conversion of low quality biomass and other waste products to high quality protein for aquaculture food and backup human food supply. Area of 5 m2, depth depends on available humus, approximately 30 cm.	Receives raw, low quality biomass and stabilized biosolids from wastewater treatment.
C. Unit #3. Mushroom/ Fungi System.	Receives effluent from Regen. Unit #2. Surface area of 4 m2, Depth of 30 cm.	Receives raw, low quality biomass.
• BIOMASS PRODUCTION A. Hydroponic plant Production	Nutrient film technique hydroponic plant production of a variety of food plants for food and other purposes. Based on assumed productivity, area required is 160 m2 /person	Produces a variety of plants in soil-less culture.

UNIT	DESIGN BASIS & FUNCTION	COMMENT
B. Nitrogen-fixing plant production.	Application of hydroponic/soil-based system. Alternatives include algal film and /or microbial system. Area required at maximum N2 fixation rate reported for crops at 0.2 g N/m2-d, 365 days per year is 100 m2/person.	A nitrogen fixing with significant food production potential is specified.
C. Soil Synthesis	Refractory or "deadlocked" material accumulates in this unit process. An area of 4 m2 is set aside for this purpose.	Some natural processes such as seed propagation may require soil-based plant production
V. BACKUP PLANT PRODUCTION UNITS	A small area would provide extreme secure area for plant protection in case of plant destruction emergencies. This would be less than 10 m^2.	

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