Towards Closed Environmental Control and Life Support for Space Habitats Part II: Reduced Risk and Increased Efficiency with Biological Systems

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Abstract.

The basic ECLSS modeled and described in Part I is extended using biological systems to reduce risk and increase efficiency. Value is extracted from waste biomass to provide ~50% of high quality human food while reducing the hydroponics growing area by 28%. Carbon recycling with biological systems is now 99% with reliance on SCWO limited to 1%. Haber/Bosch ammonia synthesis has been retained as the best method for replacing fixed nitrogen lost during recycling. Large amounts of water evaporated and recycled each day offer a convenient way to remove waste heat from growing areas, allowing high light levels in compact units. A difficult ethical question is whether human corpses should be recycled or buried elsewhere.

Key words. Environmental control, life support, food production, biological nutrient recycling, increased efficiency, risk reduction, super critical water oxidation, SCWO.

Acronym list. Environmental control life support system (ECLSS), super critical water oxidation (SCWO), feed conversion ratios (FCR), chemical oxygen demand (COD), biological oxygen demand (BOD), biological nitrogen fixing (BNF), air-conditioning (A/C), light emitting diode (LED) composting/vermiculture (C/V).

1. Introduction.

The ECLSS described in Part I [1], shows that crop plants are capable of providing the main requirements of clean air (principally by CO_2 removal and O_2 regeneration), clean water (recycled from wastewater) as well as nutritious food. It also demonstrates that food production must be an integral component of an efficient air, water and nutrient recycling, waste reprocessing and life support system. A simple spreadsheet model is used to show that mass balance can be achieved provided all waste biomass from food production is fully oxidized by SCWO to recycle nutrients, especially carbon and oxygen. Fixed nitrogen lost to the atmosphere as N_2 is replaced using Haber Bosch ammonia synthesis. These key items of equipment operate under conditions of high temperature and pressure, however, and are vulnerable to failure with severe consequences for the functioning of the ECLSS.

The basic system was inefficient with much edible biomass being recycled. Processes are now described for decreasing risk and increasing efficiency by using biological recycling systems to extract maximum value from crop biomass while increasing the range of foodstuffs. Discussion concentrates on food production and nutrient recycling and does not deal with ventilation, heat and humidity control or air and water quality management except where they impact directly on production and nutrient recycling.

2. Assumptions.

The assumptions in Part I are retained with the system operating at Earth gravity in air of standard composition at sea level pressure and illuminated by sunlight or artificial equivalent. Ionizing radiation is at Earth surface levels. All necessary resources are available. Current, and near term, technology is assumed.

3. Extracting additional value from solid crop and human waste and biological methods for recycling solid nutrients.

Crop waste is typically twice the mass of plant consumed [2] but has been expensively produced so value is extracted before recycling. A largely biological ECLSS has recently been described in some detail [2] and shows that these alternative recycling systems can also extract value from waste biomass and provide high quality protein and fats for human consumption. Kitchen waste and discarded human food is edible so becomes animal feed to produce meat, milk and eggs. In addition, animals grind and digest their food, ready for the next stage of processing, avoiding the necessity for mechanical shredding.

Food value could also be extracted from inedible crop waste and solid human and animal waste by microorganisms in fermenters to make proteins and fats before worms and edible fungi produce even more animal and human food [2].

Biological solid waste recycling systems reduce reliance on the vulnerable Haber Bosch and especially SCWO equipment. Animals eating the crop waste, together with fungal and microbial action during composting, recycle most carbon as CO_2 to the atmosphere. However, some carbon becomes locked up as refractory organic compounds (humus) [2] and no longer bioavailable. Humus is recycled by SCWO to return the carbon, and other nutrients including nitrogen, to the ecosystem. Although much of the nitrogen in biomass is in soluble form after composting, some remains locked up in humus and must be recycled using SCWO. During both composting and SCWO, some nitrogen is “lost” into the atmosphere as N_2. The nitrogen cycle is critical so the fixed nitrogen lost must be replaced.

These additional processes are included in the diagram of nutrient cycling in Figure 1. This is much more complex than the equivalent diagram in Part I which has just a hydroponics production unit. For clarity, the food producing units are coded green and the new sewage unit yellow. Processes are pale yellow while the primary consumer, man, is pink. The units are multiply connected so the proliferation of arrows necessary to illustrate this is unavoidable.

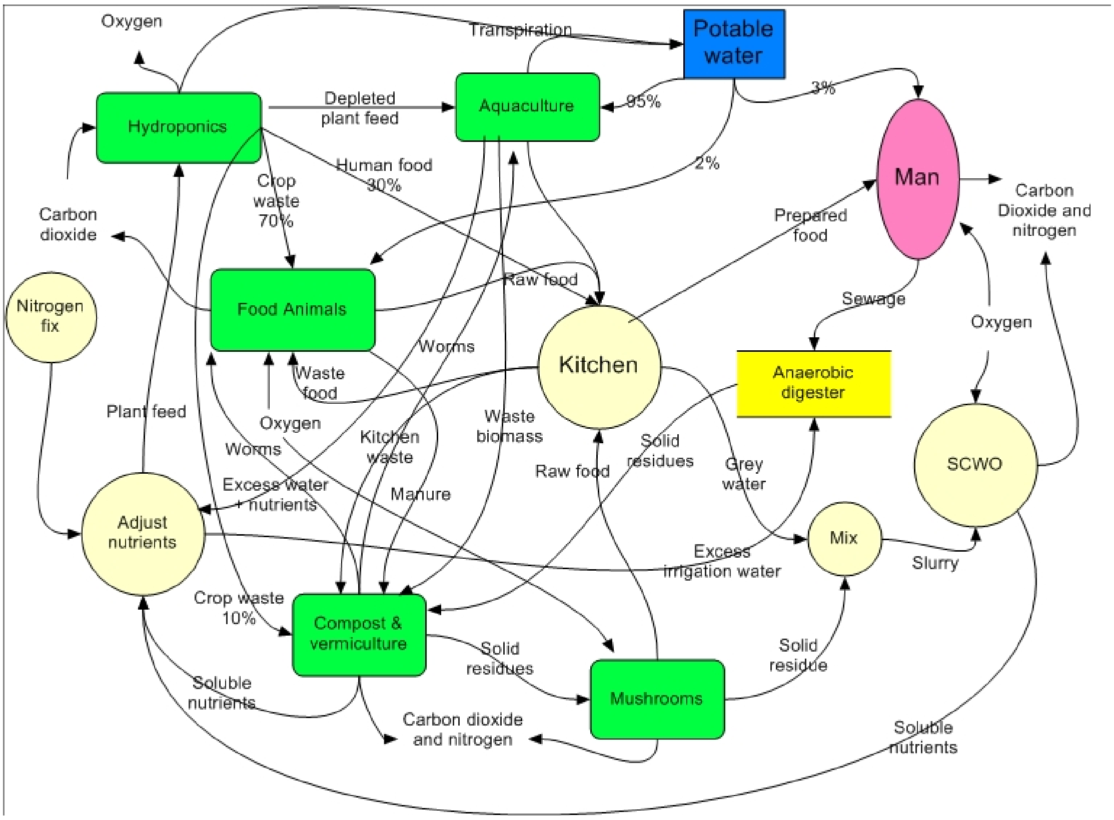

Figure 1. Nutrient flow diagram showing added value processes.

3.1 Food production methods.

Many plants can be grown in fresh water with added nutrients using hydroponic and aquaculture methods. Large quantities of fresh water will be required for many purposes and used water will need treatment to remove pollutants before recycling. Conveniently, water and nutrient recycling using plants is synergistic with food production since the same plants can fulfill both roles.

3.1.1 Hydroponics

Hydroponic methods for growing plants with their roots irrigated by aerated water containing an optimum mixture of nutrients described in Part I will not be repeated.

3.1.2 Aquaculture.

Aquaculture usually means the rearing of fish in ponds but could also describe the growing of water plants for food. A suitable range of water plants could give a balanced diet, lacking only protein, provided by fish.

There are a number of edible fresh water plants including watercress (leaves), taro and lotus (starchy roots) and water chestnuts (edible corms) as well as rice (grain). Most are anchored and grow in a layer of mud at the bottom of ponds, from which they extract minerals, but are supported by water and produce leaves, flowers and fruits above the surface. A significant difference from the annual crop plants grown hydroponically is that water plants are perennials and will grow continuously in the optimum conditions of the habitat. Water plants also grow vigorously and the large quantity of excess biomass produced is harvested regularly and recycled.

Plants of course include algae, which can be completely submerged. Edible varieties could be a source of animal food and have a secondary role in oxygenating and removing nutrients from water as part of the water treatment process [3]. Most freshwater algae are toxic so have not traditionally been eaten by humans. They could almost certainly be processed to remove toxins and make palatable food but this has not yet been achieved so algae are not included.

3.1.3 Animals fed on crop residues and food waste.

Insects are high in protein and rich in essential micronutrients, such as iron and zinc. They can be eaten directly or used as a processed food supplement for both humans and animals.

Insects don't need as much space as livestock and have high feed conversion rates, ~12 times better than for beef. They can be reared in relatively tiny areas on food scraps or animal manure under warm conditions.

There is arguably less of an ethical issue with raising and eating insects for food than there is with higher animals. They are not yet reared on a large scale, however, so have not been included.

Pollinating insects. Most crops are pollinated by bees, including honeybees. These are assumed to be present but are not discussed further.

Fish, crayfish and ducks.

The aquaculture unit supports fish that eat water plants supplemented with worms and waste food. Fresh water crayfish live on living and dead animal and plant material and could be introduced for debris removal and to provide additional protein. Large ponds also support ducks with some supplementary feed from worms and food scraps.

Goats, pigs and chickens.

Chickens and pigs are attractive for a space habitat because they can eat crop residues and waste human food to provide meat and eggs. Goats are particularly valuable because they eat rough vegetable waste and provide meat and milk.

Table 1 shows FCR (kg feed/kg product) for ten food animals [4]. Rearing costs, if included, would decrease these efficiencies somewhat but not affect the overall picture. Happily, the animals already identified for other reasons are also efficient at converting feed to human food. In order of decreasing efficiency, a suitable mix might be milking goats, broiler chickens, ducks, and pigs, followed by laying hens. Sheep and beef cattle are particularly inefficient and require grass pasture, limited in the habitat. Interestingly, milking cows are more efficient than goats, presumably because they have been highly bred for the purpose. They do, however, require special, high protein feed and are big animals so goats are more suitable.

Species	**Production**	**FCR**
Broiler	36 days to slaughter, no rearing costs	1.69
Turkey	126 days to slaughter, no rearing costs	2.46
Geese	98 days to slaughter, no rearing costs	3.26
Ducks	42 days to slaughter, no rearing costs	2.41
Pigs	22 weeks to slaughter, 4 litters of10 piglets	2.99
Sheep	1.72 lambs/litter, 4 litters	10.4
Beef	4 calves/cow	10.4
Layers	300 eggs/hen, including rearing costs	3.20
Goats	1200 kg milk/lactation, 4 lactations	1.03
Cows	8000 kg milk/lactation, 4 lactations	0.88
Carp	Fed soya supplement	1.5
Catfish	Fed on carp	4.5

Table 1. Summary of average FCR of ten production systems.

Table 1 also includes two freshwater fish species often reared in ponds for human consumption, carp [5] and the more flavorsome catfish [6]. The big difference in FCR between the largely vegetarian carp compared to the predatory catfish fed on carp is noteworthy. Carp are therefore used here.

The animal rearing unit has a mixture of milking goats, broilers and laying hens and a few pigs. Milking goats are culled at the end of their productive lives and replaced. Rearing replacement animals reduces the overall efficiency of milk production but is offset to some extent by eating culled animals and billy-goat kids after weaning. To allow for this, an FCR of 1.5 is used. New broiler stock comes from cockerels produced during hen replacement and eaten after 36 days together with culled old hens. Rearing costs are included in the FCR figure for hen replacement so an average value of 2.4 is used. The available food is divided equally between goats, chickens and pigs and an average FCR of 2.3 is used in the model.

Similarly, for the aquaculture unit an average FCR value of 1.9 is used for ducks and carp.

3.1.4 Mushrooms.

Fungi have no chlorophyll and, like animals, require a chemical source of energy and organic materials for growth and development. Many depend on dead plant material and manure and are invaluable in recycling.

Mushrooms are edible fungi that extract food value from woody plant material and animal manure while providing a further step to the composting process.

3.1.5 Fermentation.

Fermentation has a long history in food production especially in baking bread, brewing beer, and making cheese and yogurt. Processed foods such as marmite, and fermented products such as soy sauce and tofu, increase protein content and enhance flavor. These processes start with naturally occurring products and convert them into a more desirable form. For example, the marmite process uses yeast to convert sugars synthesized by plants into protein and dietary fiber.

In general, reprocessing complex compounds from plants and microorganisms using chemical and biological processes is well established and will almost certainly have a place in space habitats but is not included in the model.

3.2 Biological recycling of nutrients from solid and liquid waste.

Composting can be either aerobic or anaerobic. Microorganisms are essential to both processes but different types are required in each case. The two methods have advantages and disadvantages depending on the quantities and types of waste to be processed and the products desired. In either case, care will be needed to inoculate the waste with the appropriate soil biota without inadvertently introducing plant pathogens.

Waste water, such as grey-water from showers as well as sewage from which the solids have been screened, also needs to be treated. It is important that these processes be carried out either aerobically to avoid bad smells and the production of methane by methanogens, or in sealed units so these factors can be controlled. Wastewater in particular must be aerated to satisfy the chemical and biological oxygen demand (COD and BOD, respectively) of the treatment processes. Aerated waste water mixed with finely divided humus provides the dilute feed stream required by SCWO and avoids additional waste water treatment.

Water in storage ponds must be aerated, probably by submerged plants, to prevent stagnation and provide O_2 for fish.

3.2.1 Sewage treatment by anaerobic composting.

Material is shredded to increase the surface area available to microbes and increase the speed of digestion. Woody plant material breaks down much more slowly than softer materials and is processed mainly by fungi rather than bacteria. Small amounts can be shredded and composted in an airtight container, known as a digester. Biogas produced in anaerobic digesters consists of methane (50%–80%), carbon dioxide (20%–50%), and trace levels of other gases such as hydrogen, carbon monoxide, nitrogen, oxygen, and hydrogen sulfide. The relative percentage of these gases in biogas depends on the feed material and management of the process. For a closed ECLSS, these must be fully oxidized by SCWO before being released as CO_2 into the plant growing area.

Anaerobic digestion, used as a primary sewage treatment for human solid waste, enables the isolation of pathogens and control of intermittently introduced toxins such as antibiotics. The solid residue from the anaerobic digester is rich in nutrients such as ammonia, phosphorus, potassium, and more than a dozen trace elements. Some of these are soluble and, extracted with water, provide valuable fertilizer for the hydroponic growing system while nutrients in the remaining sludge are treated further by aerobic composting.

3.2.2 Aerobic composting and vermiculture.

Composting carried out aerobically minimizes the production of methane and hydrogen sulphide. To achieve this, the compost is mixed periodically to ensure good aeration. Woody plant stems and inedible animal waste such as skin, hair, feathers and bones are broken down only slowly and it is likely that biological systems may need to be supported by some mechanical grinding processes. It is important to maintain a good carbon/nitrogen balance for efficient composting.

Worms with their associated gut flora have an important part to play because they are especially efficient at mixing and breaking down plant material. Excess worms can be used as high protein supplement for human food or animal feed.

Large scale composting can be completed in two or three weeks. Volumes are reduced by ~60 - 80% and similar proportions of carbon are released into the atmosphere as CO_2 [7]. Even though the production of CH_4, H_2S and NH_3 is minimized by aeration, some of these gasses will be evolved and may need to be treated by oxidation and scrubbing. The black, crumbly, odorless material that results from composting contains many plant nutrients and is passed to the mushroom unit.

3.3 Nitrogen fixing.

During both composting and SCWO, some nitrogen is “lost” into the atmosphere as N_2. A total denitrification loss of 4.3 grams of nitrogen per day has been estimated [2] which equates to 43 kg for a 10,000 person habitat, a significant amount. Most of the fixed nitrogen that is lost comes from the hydroponic (25%) and aquaculture (25%) units as nitrogen gas, because of uncontrollable denitrification in microscopic anoxic environments. Relatively small nitrogen gas losses occur from the vermiculture unit and from the sewage treatment system and the remaining 50% arises from SCWO. The nitrogen cycle is therefore a critical part of ECLSS recycling and the lost fixed nitrogen must be replaced. In Part I, Haber Bosch synthesis of ammonia was used but some plants [8] use symbiotic bacteria in root nodules for biological nitrogen fixing (BNF) of water-soluble compounds for their own use. These nodule bacteria are ubiquitous in soil but not necessarily in the hydroponic media which will need to be inoculated. Once established, the bacteria will reduce the need for nitrogen by the plant which must have low nitrogen, high potash feed to ensure flowering. High protein peas, beans and other pulses (legumes) use BNF which is consequently already included in the primary food production unit.

If leguminous plants were grown especially for BNF it would greatly increase productivity, including O_2 production, but would double the growing area required and need more CO_2 and other nutrients. To make this fixed nitrogen available to other plants the excess high-quality biomass needs recycling, partly as animal feed. This in turn means increasing recycling capacity. It is not clear at this stage whether these complications make BNF using additional plants cost effective.

The creation of artificial symbioses between nitrogen-fixing microorganisms and plants of agricultural importance is a primary research goal to reduce the demand for chemical nitrogen fertilizers. If these attempts are successful then an additional nitrification unit may become unnecessary [8].

Since nitrogen fixing in plants is actually performed by associated bacteria, it should be possible to use similar microorganisms directly. One possibility is single cell algae in fermenters [3] but they have low food value and it is difficult to recycle algal biomass [2].

To avoid such complications, fixed nitrogen loss continues to be replaced from Haber Bosch synthesis.

4. Extending the one-man model of human metabolic requirements and mass balance of macronutrients [1] to include animals, fungi and micro-organisms.

In addition to the hydroponic primary production unit are now aquaculture, food animals, aerobic composting/vermiculture and a mushroom unit. Sewage is treated by anaerobic fermentation and the solid residue passed to the C/V unit as shown, together with all other major nutrient flows, in Figure 1. The residual refractory organic residues are fully oxidized and recycled using SCWO.

4.1 Growing areas required.

The plant biomass production system described in Part I required a total plant growing area of between 180 and 200 m^2. Additional space is required to raise animals and house fermenters and composters but these will be modest in comparison to the area needed for plants. On balance, the recapture of protein and calories contained in the remaining 70% crop waste by the added subsystems should result in a significant reduction of total area required [2].

4.2 The value-added model.

The simple model previously described [1] is extended to include the additional processes outlined in Section 3 and illustrated in Figure 1.

The model is for a "steady state" man neither gaining nor losing weight. Occupants who increase weight, such as growing children, would affect the balance and lock-up carbon and other key nutrients making them unavailable for recycling. A major challenge is to schedule the growing phase of crops, when more O_2 is produced than CO_2 absorbed, with the harvesting and recycling phase, when the reverse is true. Excess oxygen produced by growing plants without recycling accumulates and needs to be removed. In practice, crops must be grown in succession so that some plants are always at every stage of the cycle and to ensure a regular food supply.

Air liquefaction, and the temporary storage and release as necessary of liquid oxygen, enables management of fluctuations in production.

As before, the system is greatly dependent on the number of consumers, with small habitats that have low occupancy rates being the most difficult to manage.

4.2.1 Simplifying assumptions.

The model described in Part I assumes that plants fix 5g.m^{-2} of carbon, the growing area is 180m^2 and there is 5 g of carbon in 12.5 g of food (dry matter) [2]. Food is 1/3 of this biomass and the carbon content of faecal and urine dry matter is 14% and 50%, respectively. Goat's milk contains 13% solids, eggs 24% and meat 30%, of which 50% is carbon. Assuming equal amounts of each are produced gives an average value of 22% solids. The 2/3 waste biomass is of both high and low quality, defined [2] as having nitrogen contents of >2% and 0.5 - 2.0% of the dry mass, respectively.

4.2.2 Description of the extended model.

The main biomass production unit is the previously described [1] hydroponic system. The next largest unit is aquaculture followed by the animal production, composting/ vermiculture and mushroom units. Of the total biomass produced, approximately 20% (on a nitrogen basis) becomes human food. About 70% is estimated to be higher quality biomass fed to the animal production and aquaculture units, and the remaining 10% goes to the C/V unit. This last provides about 4% high quality protein feed (worms), 2/3 to the animal and 1/3 to the aquaculture units, respectively. Transfer between units depends on biomass suitability for human or animal food or for regenerating nutrients into plant available forms.

The large aquaculture unit provides water storage as well as being a food production system. About 95% of the condensate from both growing units goes through the aquaculture unit to harvest soluble nutrients for the main food production hydroponic unit.

It is assumed that biogas from the anaerobic digester consists of CO_2 and CH_4 (trace gases are ignored) but the SCWO unit converts it all to CO_2. All particulate human waste from the digester is mixed with low quality biomass, including aquaculture waste and animal manure and added to the vermiculture unit with worms as the output. It is assumed that 20% of the waste biomass is recycled by the digester and 50% of the remainder by aerobic composting/vermiculture before passing the remaining 40% to the mushroom unit. The mushroom unit converts ~25% of this to edible biomass, releasing ~50% as CO_2 and leaving a refractory organic residue of ~25% to be periodically harvested and recycled using SCWO.

The optimum mix of animals and fungi is not known, requiring additional simplifications. Animal metabolisms are deemed to be equivalent to humans with similar food, water and oxygen requirements and outputs of carbon dioxide and liquid and solid wastes. The human data for each of these are therefore multiplied by an appropriate factor depending on the amount of high quality waste biomass produced without specifying the numbers and mix of animals. Eggs, milk and meat as human food are included on a dry matter basis without attempting to differentiate.

4.2.3 Results and Discussion.

Unit	**Water in**	**Water out**
	(kg)	(kg)
Human	30.95	30.95
Hydroponics	292.40	292.40
Aquaculture	893.22	893.22
Food animals	22.11	22.11
Sewage	1.7	1.7
Composting	2.15	2.15
Mushrooms	2.15	2.15
SCWO	33.85	33.85

Table 2. Water balance across the production and recycling units.

Evapotranspiration has been measured at ~200 to 700 g of water per day per g of biomass produced by photosynthesis [2]. The hydroponics unit described in Part I was in a controlled environment with high humidity and CO_2 levels to limit evapotranspiration to 180 g per g of dry biomass. This value is again used for the hydroponics unit but 700 g for the aquaculture unit. This is because aquaculture is assumed to be carried out mainly in "open air" ponds, largely for amenity purposes, with uncontrolled evaporation from the surface as well as from evapotranspiration from marginal and emergent (not completely submerged) plants. Using these figures, clean water from evapotranspiration is 292.4 kg and 634.4 kg from the hydroponic and aquaculture units, respectively. The values for humans include 2 kg evaporated as sweat and during breathing for which figures are available. These values are conservative since water vapor from animals and evaporation during washing and other activities has not been estimated. However, this would be condensed in the air-conditioning (A/C) units and returned with that from plant transpiration to the aquaculture unit.

Most (875.84 kg) of the total 928.9 kg of condensed water (which includes the 2 kg from human breathing), plus an additional 17.38 kg from toilets, animal wash-down and urine goes to the aquaculture unit. One man (the model uses data for a man—women and children need less of course) requires 30.95 kg, while 22.11 kg goes for animal drinking and cleaning purposes. Some 258.55 kg water, plus 33.85 from SCWO, passes through the aquaculture unit to pick up nutrients before entering the hydroponics unit. Water is assumed to pass through the sewage, composting and mushroom units without loss until it is sterilized and recycled via SCWO.

While it is beyond the scope of this paper to examine heat management and transfer, it is worth noting that almost a tonne of water evaporating and condensing per person per day requires attention. The latent heat of vaporization of water is 2,257 $kJ.kg^{-1}$ (0.63 kWh) so 184 kWh and 400 kWh is required each day to evaporate water in the hydroponics and aquaculture units, respectively. Equivalent amounts of heat are released when water vapor condenses in the A/C units. A habitat with 10,000 occupants would therefore evaporate and condense ~9,300 t of water per day, transferring ~5.8 GWh of heat energy in the process.

It would seem appropriate to co-locate the A/C units with growing areas and recycle heat directly to maintain a steady temperature. However, because plants use light of wavelengths between 400 and 700 nm, only 45 % of solar (white light) energy is used for photosynthesis. (LEDs producing light of optimum frequencies could improve efficiency but look strange to humans and be inappropriate for occupied areas.) Furthermore, fixation of one CO_2 molecule during photosynthesis, with a quantum requirement of ten (or more), gives a theoretical maximum efficiency of ~13% [10] although thermodynamic arguments indicate it is 8-9% [10]. Further reductions in efficiency due to reflection, respiration requirements of photosynthesis, and the need for optimal solar radiation levels give a final value of 4-6%. Assuming 5% efficiency, 95% of light energy becomes waste heat which must be removed. Evapotranspiration offers a convenient transport mechanism with waste heat from the A/C units pumped to heat exchangers connected to radiators outside the habitat. This self-cooling mechanism should enable high light levels in compact multilayer growing units that would otherwise overheat.

This may work for compact growing units illuminated by LEDs but not for “open air” ponds and growing areas. Indeed, heat energy transfer in such systems may produce “weather” with warm moist air rising and drawing dry cool air in at “ground” level as winds. The winds would be deflected by Coriolis forces to give the spiral patterns familiar on Earth. Cumulus clouds form between ~360 and 2,000 m so something similar may occur in large habitats. If this happens, water vapor in convection cells will condense when reaching cooler air to form “cumulus” clouds and, if conditions are right, rain. Exact effects will be highly dependent on habitat architecture and difficult to predict. For example, clouds could shade a light source mounted axially in a cylindrical habitat but trapped heat would then raise the local temperature and evaporate the clouds. Weather management may therefore become necessary with large scale heat and ventilation equipment used to avoid cloud formation by managing humidity and heat flow, dumping waste heat, and recycling condensed water.

Unit	Carbon in	kg	Carbon out	kg
Human	Food from Hydro	0.20	CO_2 breath	0.28
	Food from Aqua	0.01	Faeces to sewage	0.03
	Food from Animal	0.09	Urine to sewage	0.01
	Food from Mush	0.02		
	Sub-total	**0.31**	**Sub-total**	**0.32**
Hydro	CO2	0.65	To Human Food	0.20
			To Hi Qual Bio	0.39
			To Lo Qual Bio	0.07
	Sub-total	**0.65**	**Sub-total**	**0.65**
Animal	Food Hi Qual Bio	0.29	CO_2 Breath	0.29
	Food Worms	0.03	Manure to C/V	0.01
			Urine to C/V	0.00
			To Human food	0.02
	Sub-total	**0.32**	**Sub-total**	**0.32**
Aqua	Aqua CO_2	0.19	Water plants to F&D	0.07
	Aqua Hi Qual Bio	0.10	To human Food (F&D)	0.09
	Aqua Worms	0.01	Excess bio to C/V	0.12
	Aqua Food (F&D)	0.07	F&D Manure ox	0.01
			CO_2 F&D breath	0.07
			F&D Urine to ox	0.01
	Sub-total	**0.37**	**Sub-total**	**0.37**
Sewage	Sewage Faeces	0.03	Solids to C/V	0.02
	Sewage Urine	0.01	Sewage CO_2	0.01
	Sub-total	**0.04**	**Sub-total**	**0.04**
C/V	C/V Lo Qual bio	0.07	Solids to mush	0.08
	C/V Sewage solids in	0.02	Off-gas CO_2	0.11
	C/V Excess bio	0.12	Worms to animals	0.04
	C/V Manure	0.01		
	C/V Urine	0.00		
	Sub-total	**0.22**	**Sub-total**	**0.23**
Mush	Solids from C/V	0.10	To human food	0.02
			Solids to SCWO	0.02
			Off gas CO_2	0.05
	Sub-total	**0.10**	**Sub-total**	**0.09**
SCWO	Solids from Mush	**0.02**	CO_2	**0.03**
	Total carbon	**2.03**		**2.05**

Table 3. Carbon balance between the units for the one-man model.

Table 3 shows the carbon balance between the various units. Calculations with the one-man model show that the CO_2 required by the hydroponic and aquaculture growing units is 3.07 kg, in fair agreement (~3% difference) with the 3.16 kg produced by humans and animals breathing and by the oxidation of carbon in the various units. Similarly, the amount (2.30 kg) of O_2 produced by plants agrees well (~3% difference) with the 2.23 kg required by humans and animals and to oxidize and recycle carbon. When the 2.3 kg of O_2 produced by the model is compared with the 2.84 kg calculated independently (using the CO_2/O_2 molar ratio of 0.95:1) agreement is less good at ~9% difference. This is probably because of inconsistent or inaccurate input data or is a consequence of oversimplifying a very complex system. Nevertheless, despite this limitation, the model is self-consistent and reasonably accurate at calculating the various nutrient flows between units.

Bearing this in mind, it is clear that the principal objective of extracting added value from the biomass produced by the hydroponics unit has been achieved. On a carbon only basis, and for the same total daily intake, ~50% of human food now comes from the aquaculture, animal production and mushroom units with the remaining 50% as vegetables from the hydroponic unit. Most (75%) of this extra food is of high quality from milk (25%), eggs (25%) and meat (25%) from goats and chickens in the animal unit with a further 8% meat and fish from aquaculture and 16% of mushrooms.

The extra food production has been achieved with a smaller hydroponics section (130 m^2 reduced from 180 m^2) although this is off-set to some extent by space for animal pens and composting modules. The area required for the aquaculture unit depends on the depth of water in the ponds used for cleaning water, providing nutrients to the hydroponics unit and growing edible water plants for ducks and fish. Large amounts of water are required in any case so no additional storage volume is to be expected, although more space is needed for open ponds. The relatively small amounts of food (1/3 the meat from the animal unit) produced by aquaculture could be increased significantly with larger pond areas, or fish rearing tanks. In addition, edible water plants suitable for humans could be grown.

The second important objective of adding biological systems to the simple model in Part I was to reduce reliance on SCWO to recycle the entire daily carbon budget of 2.04 kg. Table 3 shows clearly that the biological systems recycle 99% of this, leaving just 1% to be dealt with by SCWO—a clear justification of the approach.

5. Ethical issues.

Amenity planting within the living areas would provide an important psychological boost to the occupants. There is no reason why many of these plants should not also be productive, and perhaps small fruit trees would be valued. Similarly, it is to be expected that people living in a comfortable habitat will want pets ranging from goldfish through songbirds, cats and dogs to, in very large habitats, horses. Pets are of course luxury items and a drain on resources but some will almost certainly be present in most habitats.

Finally, there is the question of how human corpses are to be disposed of. Options include cremation and recycling of ashes, repatriation to Earth for burial or burial in space or on the surface of some other planet or moon. It could be argued that options that remove nutrients and water from the habitat would be detrimental to the other inhabitants and therefore unethical. This might lead to a requirement to replace the water, carbon and other important compounds contained in a corpse removed for burial outside the habitat.

6. Conclusions.

The basic closed ECLSS described in Part I has been extended using biological systems. Despite limitations in the model, the principal objective of extracting added value from waste biomass has been achieved. On a carbon only basis, and for the same total daily intake, ~50% of human food of higher quality now comes from the added value units while reducing the hydroponics area by 28%. The optimum mix of suitable animal and plant species is not known but some possibilities are proposed.

Reliance on SCWO to recycle nutrients has been minimized with biological systems recycling 99% of carbon with 1% treated by SCWO. Biological methods of fixing nitrogen are problematic so the Haber/Bosch equipment is retained. If nitrogen fixing genes can be added to all crop plants future systems may not require it.

Large amounts (930 kg) of water are evaporated per day per inhabitant and recycled by A/C systems, conveniently removing waste heat from inefficient (5%) photosynthesis, enabling higher light levels in compact growing units. Weather management may be necessary in large habitats to avoid cloud formation, dump waste heat, and recycle condensed water.

A difficult ethical question is whether human corpses should be recycled or removed for burial elsewhere.

7. References.

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