Closed Ecological Life Support Systems

– Cycling of carbon, nitrogen and water

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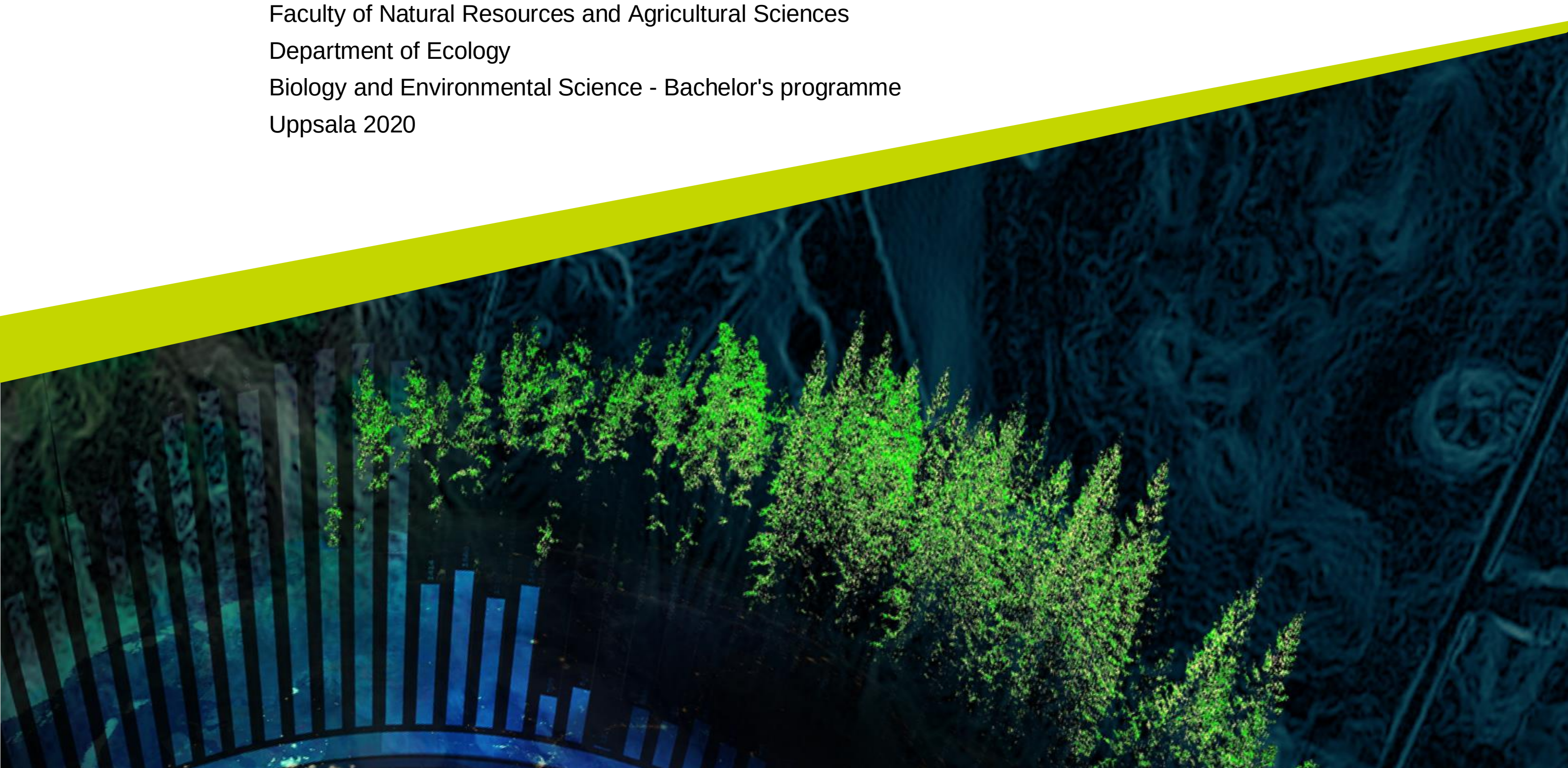

Closed Ecological Life Support Systems – cycling of carbon, nitrogen and water

Slutna ekologiska livsuppehållande system – kretslopp av kol, kväve och vatten

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Abstract

Materially closed life support systems containing biological components that provide atmosphere, food and water for a human crew has been investigated for use in space travel since the 1960s. The internal cycling of organic material is the essence of these systems and their design and function is the question at issue for this thesis, which has been conducted as a literature study.

Different approaches for closed life support systems, almost purely biological as well as involving physicochemical control and buffer systems are presented. The experiments include Bios-3, Biosphere 2, CEEF and MELiSSA. These systems have different approaches with advantages and disadvantages and encounter different problems. They are built around the production of organic matter by photosynthetic organisms, mainly higher plants, which produce food and drive the water cycle through their transpiration and respiration. Energy in the form of light is assumed to be available. To close the carbon cycle, organic waste must be oxidised to carbon dioxide, making carbon available for re-fixation by the plants. Nutrients must also be recovered in a form available for plant uptake, nitrogen in particular has been considered.

Complete closure has not been achieved. Leakage of atmosphere from the systems prove to constitute a significant problem, removing substantial amount of nitrogen and oxygen from the system. In addition to facilitating future long-range space missions these concepts and techniques might also prove particularly useful in establishing a more sustainable society.

Keywords: closed ecological system, cycling, closure, life support, biosphere, CEEF, MELiSSA, Biosphere 2, bioregenerative, CELSS, environmental

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1. Introduction

Our lives on this Earth is utterly dependent on a vast and complex ecological life support system - a system we are part of and interact with whatever we do. It provides us with oxygen to breathe, fresh water to drink and food to eat. Humanity's influence on the balance of this system has increased dramatically over the course of our history and the full effects of our activities on it has yet to be seen.

From the experiments of Joseph Priestley in the 1770's, where he realised that plants "refresh" the air allowing animals to breathe (*Joseph Priestley, Discoverer of Oxygen National Historic Chemical Landmark*), the idea to recreate the functionality of Earths life support system is not new. The dream of building a new home on another planet by bringing earth with us is not an uncommon theme in works of fiction or science. Enclosed bottle gardens where plants thrive for decades without watering or added nutrients, with sunlight for energy, are simple such systems (Wilkes 2013). From that the leap is not so great to the idea of building a garden large enough to allow animal or even human life to thrive inside the bottle. Putting it simply, this is the idea behind a closed ecological life support system. Creating new bottles for us to live in. Doing so might also give us larger insight into the balance and function of our own original bottle, planet Earth.

Research on this topic was of great interest during the space race between the USA and the Soviet Union but interest seem to have lessened since then, although some projects are still ongoing. At present Japan and China seem to be the most active in the field (own observation). The work in many other fields hold relevance however, from urban gardening projects to cultivation of insects for consumption, biological water purification, carbon sequestration and waste recycling. Establishing a small closed ecosystem requires a continuous cycling of nutrients on a much shorter timescale than we normally see on earth, simply because of the difference in mass of all the nutrient pools. Fluctuations in the pools are for the same reason also greater.

The aim of this essay was to describe the design and major experiences of some of the major closed life support system experiments made in USA, the Soviet Union, Europe and Japan. Focus is on the cycling of carbon, nitrogen and water as the largest building blocks of organic matter. The approaches of these systems differ in the number and type of species they try to include, their methods of nutrients cycling – be it biological or psychochemical - as well as the portion of their crew's food they expect to produce in system.

1.1. Concept

Closed ecological systems are defined as biological systems with full material internal recycling, open to exchange of energy with the surrounding (Figure 1) (Cooke 1971; Taub 1974; Odum 1994; Gitelson & Lisovsky 2008). Such systems have been tested to work as life support for space exploration since the 1960s (Gitelson et al. 2003). Life support in this context means that the ecological system serve to maintain atmospheric composition, recycle water and produce food for the benefit of the crew (Taub 1974; Tamponnet & Savage 1994; Hanford 2006; Nelson et al. 2010).

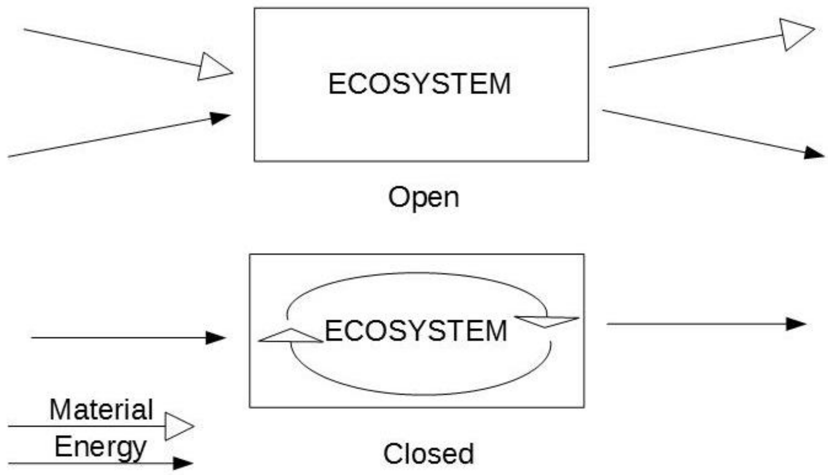

Figure 1. Visualisation of difference between an open and closed system. After Tamponnet & Savage (1994).

This could potentially also be done using chemical or mechanical systems, rather than ecological ones with living organisms, and could include mechanical devices such as filters or shredders as well as incinerators or the use of chemicals for oxidation of organic waste. The main benefit of using a biological system, instead of the physicochemical ones that are primarily used in today's space stations, is that biological organisms are needed to produce food. This is something that cannot currently be done by purely non-organic means (Tamponnet & Savage 1994; Lasseur *et al.* 1996; Hanford 2006). As such, space-faring missions up until today has relied on bringing stored goods with them and for longer missions, such as the international space station (ISS), required continuous resupply of food (Wieland

1998). While a system with complete internal cycling might be more cumbersome for a short duration operation, the mass needed to sustain it does not increase for longer missions in the way a non-recycled system depending on stored goods would (Figure 2.) (Cooke 1971; Taub 1974; Nelson *et al.* 2010).

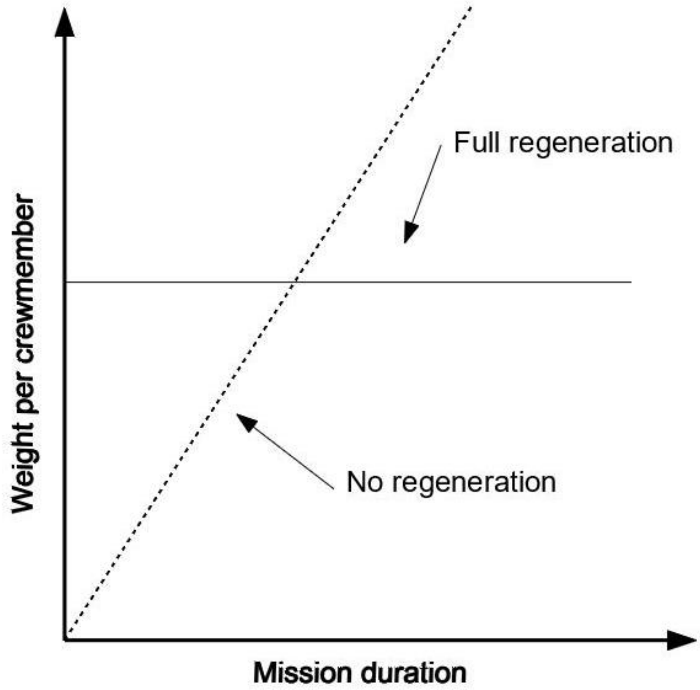

Figure 2. Stored goods needed in a system with full internal recycling, a regenerating system, and a system depending on stores, i.e. non-regenerating. After Cooke (1971).

This has obvious benefits as the supplies needed to supply a crew over longer periods of time soon reach cumbersome proportions. Sustaining a single person for one year requires over eight tonnes of supplies (Calloway, 1975 see (Schwartzkopf 1992)).

If perhaps the least of the problems, sending objects into space are expensive. USA: s national aeronautics and space administration (NASA) estimate a cost of 10 000 dollar per pound (22 046 dollar per kilogram) just to bring objects into orbit (Dunbar 2008).

Furthermore, the study of closed ecological systems might increase our knowledge and understanding of the function of our own biosphere (Cooke 1971; Nelson *et al.* 2003; Milcu *et al.* 2012) and illuminates the need and the possibility for recycling rather than spending as if we had access to infinite resources as a way to manage our environment (Nelson *et al.* 2003).

1.2. Cycles

1.2.1. Carbon

The primary systems driving the carbon cycle is the opposed reactions of carbon fixation by photosynthetic organisms and the release of carbon dioxide by respiration from producers, consumers and decomposers (Townsend 2008; Campbell 2015).

For a closed system the rate of carbon fixation needs to be balanced with the rate of respiration from the crew and the release of carbon dioxide from decomposition of waste (Figure 3). Making this balance precarious is the presence of little or no buffering storages, compared to natural ecosystems, because of the need to minimise the weight of the system.

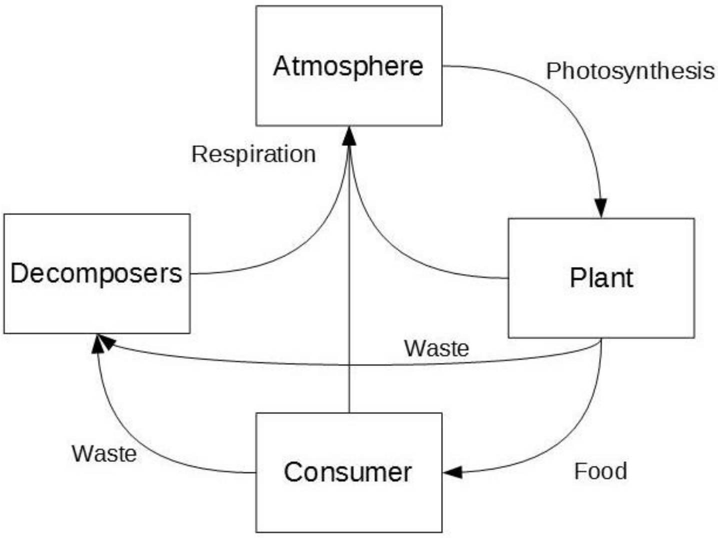

Figure 3. Carbon cycle in a system without buffering storages. After Townsend (2008).

1.2.2. Water

Water is essential to life and makes up a major part of all organic life, over 80 to 90 percent of plant mass (Epstein 1994; Raven 2005). In the global water cycle the largest part of evaporation occurs from oceans with a relatively small portion coming from plant transpiration (Townsend 2008). However, the largest part of the water cycle in a closed system will be from transpiration from plants without the buffering effect of large water bodies, as most of the system's water are likely to be in constant circulation.

During photosynthesis water is split into oxygen and hydrogen with oxygen being emitted in gaseous form and hydrogen being incorporated into biomass. Water is also a product of respiration, alongside carbon dioxide and energy, with organic matter and oxygen powering the reaction (Campbell 2015). The water cycle can therefore be said to include oxygen. The carbon cycle include fixation from carbon dioxide, incorporation into organic matter and the subsequent oxidation of organic matter that recombines it with oxygen to again form carbon dioxide (Campbell 2015). The cycling of water and carbon is thus tightly tied together.

1.2.3. Nitrogen

The largest storage of nitrogen in our biosphere is in the form of nitrogen gas (Townsend 2008) making up some 78 percent of our atmosphere by volume (Williams 2016). Major fluxes in the nitrogen cycle include shifts to and from gaseous forms, its incorporation in organic material and subsequent change to mineral forms during decomposition (Townsend 2008). Nitrogen is one of the major nutrients required by plants, taken up preferably in the form of ammonium or nitrate. Some microorganisms can fix nitrogen gas into a useable form and plants in symbiosis with such microbes can thus gain access to this store of nitrogen (Epstein 1994). In our natural biosphere the cycles of carbon and nitrogen are intimately tied (Gruber & Galloway 2008) due to the need of organic life to incorporate these elements in their biomass (Epstein 1994; Raven 2005).

To completely close these cycles and ensure the lasting functionality of the system a complete transformation of organic waste matter to carbon dioxide, water and nitrogen in a form that is useable to plants is required. This must also be done at a rate that matches that of plant uptake and production to maintain equilibrium and avoid accumulation or depletion of elements in different parts of the cycle.

1.3. Terms and definitions

Complete closure, a complete recycling of all parts of an ecological life support system seems currently unobtainable, if nothing else through leakage of atmosphere. For reference, the international space station (ISS) leaks 0.227 kg of its atmosphere per day (Schaezler *et al.* 2011) which is approximately 0.02 percent of its atmosphere.

While there are complex ways of calculating the closure of natural systems with respects to the local cycling of nutrients (Allesina & Ulanowicz 2004), these do not typically include water, oxygen or carbon dioxide and so are of limited use to us in this case (Nelson *et al.* 2013). A common way to express the degree of closure of a closed system is to measure the amount of the crew's diet that is produced by the system or simply the amount of material that needs to be added per unit of time to keep it running (Salisbury *et al.* 1997; Gitelson *et al.* 2003).

Gitelson *et al.* (2003) describes the closure of the BIOS-3 experiments using a calculation of how much that needs to be added to the system to keep it running compared to what the crew would otherwise need. If the system would require 1 kg to be added and the crew's needs was 20 kg, the system requires five percent input of total crew needs, thus being 95 percent closed. Nelson *et al.* (2013) defines closure as how large a portion of the system that is being exchanged with its surroundings.

The following definitions were decided by leading researchers at a workshop in Siberia in 1989 (Nelson *et al.* 2010).

Bioregenerative technology uses biological systems in concert with other technology or by itself to provide life support resources such as air, food or water. These are a vital part in so called *controlled environmental life support systems* (CELSS) and *closed ecological life support systems*. The difference between these being that the CELSS has a lower degree of closure and rely on brought stores of resources for its continual function while the closed ecological life support systems approaches material closure and so require little or no such stores. Both systems can include purely technical or chemical systems alongside biological ones (Nelson *et al.* 2010). Both these systems are focused solely on providing food for their human inhabitants and so contain mainly one food producing ecosystem which separates them from the so called *biospheric systems* who have increased complexity, being comprised of more than one coexisting ecosystem. These systems may be used for more direct comparisons to the global system as a whole or be aimed at more long-time life support systems where the increased complexity might produce additional stability over longer periods of time (Nelson *et al.* 2010). *Biospheric systems* are like the closed ecological life support systems aimed to be materially closed but open to exchange of energy as well as information.

While this terminology will be used in this paper, it should be noted that it is not universally adopted, and a variety of other abbreviations and terms are used.

1.4. Other problems not discussed here.

Construction of closed ecological systems in such a foreign environment as the vastness of space or on the surface of other planets face a multitude of problems besides those immediately related to the closure of the system, which are the ones in focus for this thesis. These include but are not limited to:

- Microgravity and other environmental factors (e.g. ethylene and carbon dioxide concentration, humidity and ventilation), have been shown to hinder some species, including *Arabidopsis* and wheat, from completing their life-cycle, seed to seed, as well as lower their overall growth rate (De Micco *et al.* 2014).
- Food and dietary requirements of the crew (Gitelson & Lisovsky, 2008; Nelson et al., 2013).
- Selection of plants, self-pollinating, adaptable to growing solution etc. (Mitchell, 1994).
- Supplying plant roots with water, nutrients and air in micro- or zero gravity conditions (Wright et al., 1988).
- Genetic stability of the populations in the system (Ashida, 2003)

2. Material and method

A thorough literature review was undertaken, identifying key research within the area and tracing the most relevant scientific debates. The reliance on publicly available research is a limitation of the study, as ongoing, classified or for other reasons not published research will not be included. However, it is judged that this is a minor concern for the limited, in terms of time and available resources, scope of this study. Because of this, focus was also set on the most prominent completed experiments. The need to restrict the search to sources available in English further limits the study, especially in the CEEF and Bios-3 case.

Searches were done on Web of Science for “closed ecological life support systems” and other relevant phrases, in a later stage also for the names and abbreviations of the different projects. In turn, additional literature referenced by relevant articles was also located. Some selection was done for articles which had been frequently referenced in the field. From the journals used *“Advances in Space Research”, “Acta Astronautica”* and *“Ecological Engineering”* is among the most referenced.

3. Results

3.1. BIOS-1/2/3

The Bios series of experiments, located in Krasnoyarsk in Siberia, started in 1964 with Bios-1. This system used *Chlorella* algae to absorb carbon dioxide from and provide oxygen to one person in a closed cycle. 17 litres of algae culture produced sufficient oxygen to support a 70 kilogram human (Gitelson *et al.* 2003; Gitelson & Lisovsky 2008).

The Bios-2 experiment was started in 1969, introducing higher plants into the cycle for food production, establishing a closed water cycle and adding recovery of nutrients from human solid waste. Closure of the gas and water cycle were successful, but treatment of solid waste did not turn out to be cost effective given that food, mostly in the form of meat products, were still being introduced into the system. As such organic waste would also have to be removed from the system to achieve balance of carbon and other nutrients (Gitelson *et al.* 2003). Gitelson *et al.* (2003) also concluded that the recovery of elements from inedible plant biomass was of greater importance than that from human solid waste, as that would constitute a larger mass. Large parts of plant biomass are generally inedible, and vegetables make up most of a human diet.

Problems with unwanted growth of algae and microflora in the hydroponic systems were also noted which decreased production of higher plants, primarily wheat, significantly (Gitelson *et al.* 2003).

Testing of Bios-3 including human crews began in December 1972. Bios-3 was made up of four compartments, of equal size and hermetically sealed from each other, with a total volume of 315 cubic metres. The entire complex was encased in a rectangular box of stainless steel. A series of tests were done over different timespans, the longest manned being six months, and with different configurations of the system. Bios-3 differed from its predecessors by housing a larger crew, 2-3 persons, having a much higher degree of closure regarding food and by being entirely controlled and maintained by its crewmembers. Plant production used a conveyor system, growing plants in different age groups simultaneously, to achieve a continuous and even food production and carbon dioxide fixation rate. The crops were grown in hydroponic solution on an area of 63 square metres, with light provided by xenon lamps (Salisbury *et al.* 1997).

Over time a catalytic furnace designed to destroy airborne volatile compounds was included due to the suspicion that this would eliminate a toxic build-up observed in the earliest experiments (Salisbury *et al.* 1997; Gitelson & Lisovsky 2008). After this addition, atmospheric concentrations of ammonia, acetic acid, acrolein and hydrogen sulphide, as well as general levels of aldehydes, alcohols, thiols, organic substances and carbon monoxide still fluctuated somewhat over the course of the experiments, but stayed within acceptable parameters (Gitelson & Lisovsky 2008). To further close the system with regards to oxygen, carbon and hydrogen, a furnace for combustion of inedible biomass was also added. The nutrients in the ash were not recovered (Salisbury *et al.* 1997).

In one of the culminating experiments, a dryer for solid human waste was incorporated and urine was used in the nutrient solution for growing of wheat. Because of the latter however an accumulation of sodium chloride was observed in the nutrient media and later in wheat roots and stalks but seemed to have little effect on productivity for the timespan of the experiment (Salisbury *et al.* 1997).

Using this setup, the Bios-3 system reached a closure of 95 percent. Just under six hundred grams were needed to be added daily compared to the 13 kilograms of materials needed daily by the two crewmembers. The main difference was water, making up 10.8 of those 13 kilos. The construction also leaked atmosphere with an average rate of 0.020-0.026 percent by volume per day (Salisbury *et al.* 1997).

Of the material that still needed to be added, the largest portion were nutrients for plants and additional food in the form of freeze dried meat, making up 350 and 208 grams per day respectively (Gitelson *et al.* 2003). A purely vegetarian diet was not seriously considered because: ”Siberians must have their meat!” (Salisbury *et al.* 1997).

3.2. Biosphere 2

The largest closed ecosystem constructed so far, covering an area of 1.2 hectares with a volume of 180 000 cubic metres, was built in southern Arizona in the USA with construction starting 1987 (Nelson & Dempster 1996). The goal was to approach the complexity and variation of Biosphere 1 (Earth) and it was set up to include a range of different ecosystems including rainforest, savannah, ocean and desert each containing multiple microhabitats. Approximately 3000 different species were introduced or inoculated into the system from corresponding natural habitats (Nelson *et al.* 1993). This includes over 86 different plant species used for food production and goats, pigs, chickens and fish (Nelson & Dempster 1996).

Starting in September 1991 an experiment with eight crewmembers began that would last two years (Nelson & Dempster 1996). Their stay did involve some unexpected problems, including a drop in oxygen on account of uptake by carbon in internal concrete walls (Allen *et al.* 2003), which made it necessary to introduce pure oxygen into the complex for the crews' safety (Nelson & Dempster 1996). Roughly 80 percent of the crews' nutritional needs was filled by food produced within the complex, which was lower than expected. This was partly because sunlight was dampened by the constructions canopy which in turn limited plant production (Allen & Nelson 1999). The internal water cycle was successfully closed (Nelson & Dempster 1996) and had a cycling time of a few weeks (Nelson *et al.* 1993).

The atmospheric concentration of carbon dioxide averaged 1500 ppm but varied between daily averages of 1060 ppm during June of 1992 and 2466 ppm during December of 1991. Daily fluctuations occurred with a magnitude of 500-800 ppm (Nelson *et al.* 1993). This was because of the daily and seasonal cycles of photosynthetic activity based on available sunlight. This is also the case for the natural biosphere but in Biosphere 2 fluctuations were more pronounced, 500-800 ppm daily compared to 10 ppm yearly in the natural biosphere (US Department of Commerce 2019), because of the difference in relative amounts of carbon in the atmosphere and biomass for the systems. While in the natural biosphere the relation between carbon in living biomass and in the atmosphere is roughly 1:1, this relation for Biosphere 2 was 100:1. A large amount of carbon was also stored in organic material in the soil, a relation of 5000:1 to atmospheric carbon in Biosphere 2 compared to 2:1 for the natural biosphere (Nelson *et al.* 1993). The crew regulated the carbon balance by influencing the growth of biomass within the system, but they also used a system for sequestering carbon dioxide into calcium carbonate. Carbon could then be released back into the atmosphere by heating the calcium carbonate to 950 degrees Celsius, however the equipment for this step malfunctioned during the first half of the two year experiment (Nelson *et al.* 1993). The following reactions describe the transformations of CO_2 to calcium carbonate:

$$\mathrm{CO_2 + 2NaOH \rightarrow Na_2CO_3 + H_2O}$$
$$\mathrm{Na_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2NaOH}$$

With heating to 950 °C

$$CaCO_3 \rightarrow CaO + CO_2$$

Atmospheric leakage stayed under 10 percent of the total volume per year, or less than 0.03 percent a day (Allen *et al.* 2003).

A wetland system was used for biological recycling of liquid waste while dry waste and inedible plant parts were decomposed (Nelson & Dempster 1996). Water from the wetland system was then used for irrigation, bringing nutrients back to the producers (Nelson *et al.* 1993).

3.3. Micro Ecological Life Support System Alternative (MELiSSA)

The MELiSSA system was constructed by the European Space Agency (ESA) alongside multiple partners. The system consisted of a series of bioreactors facilitating the fixing of carbon dioxide, the production of oxygen, the decomposition of waste material as well as production of food by higher plants and the cyanobacteria *Arthrospira platensis* (Godia *et al.* 2002; Albrecht *et al.* 2005). Lighting of the *Arthrospira* culture was done by halogen lamps (Gòdia *et al.* 2004). Primarily designed for use on planet surfaces, i.e. with gravity, at least parts of the cycle are expected to be functional in microgravity (Poughon *et al.* 2009).

MELiSSA contained five separate compartments, including a production compartment where food was grown, a consumer compartment made up of the crew and three compartments for degradation of waste matter (Figure 4) (Godia *et al.* 2002).

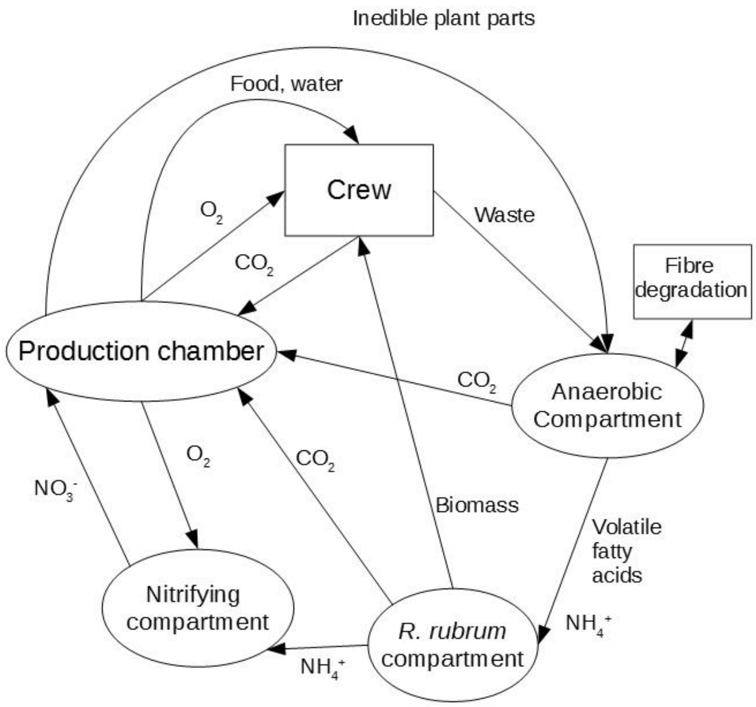

Figure 4. Schematic of the MELiSSA system. After Godia et al. *(2002).*

The waste cycle of MELiSSA started with degradation of organic matter by anaerobic thermophilic bacteria under lowered pH to inhibit the production of methane (Albrecht *et al.* 2005; Hendrickx *et al.* 2006). However, this alone did not achieve a degradation high enough to be satisfactory. A degradation efficiency of at least 55 percent was required. Additional systems tied to the first compartment was designed, mostly aimed for the degradation of fibres. Experiments with *Fibrobacter succinogenes*, from the bovine rumen, as well as supercritical water (water under high temperature and pressure) oxidation using hydrogen peroxide was performed and gave satisfactory results. The main products of this first step, volatile fatty acids and ammonium, were then led to the second compartment while any produced carbon dioxide was fed to the production step. (Albrecht *et al.* 2005).

The second compartment consisted of a culture of the photoheterotrophic purple bacteria *Rhodospirillum rubrum* which turned the input from the previous step into biomass that could potentially be harvested as a food source, additional ammonium as well as carbon dioxide and water. Waste degradation then ended with a culture of *Nitrosomonas* and *Nitrobacter,* facilitating conversion of ammonium to nitrate for use in the production chamber (Hendrickx *et al.* 2006). Lasseur *et al.* (1996) theorized a 99.5 percent closure of the MELiSSA system with respect to nitrogen.

3.4. Closed Ecology Experiment Facilities (CEEF)

Construction of CEEF started 1994 in Rokkasho, northern Japan (Nitta *et al.* 2000), and learning from the experience of Biosphere 2 steps were taken to eliminate all building materials that could possibly absorb oxygen (Nitta 1999). The facility consisted of separate modules for habitation, animal raising, waste treatment and cultivation of plants to better enable study of flows between the different modules and experiments on them in isolation. Waste treatment was based on wet oxidation which made it necessary to include a nitrogen fixation device since the primary nitrogen output from this system was nitrogen gas (Nitta 1999). The nitrogen gas is processed, with the addition of hydrogen and oxygen gas from electrolysis of water, to form ammonia and ammonium nitrate for use as fertiliser (Sakamoto *et al.* 1997).

The fast turnover of organic material made rapid adjustments necessary and therefore physicochemical rather than biological controls were used (Nitta 1999). Buffers of carbon dioxide and oxygen were used to make up for fluctuations in respiration and assimilation rates. Carbon dioxide was continually removed from the atmosphere using solid amine to be later added as needed (Tako *et al.* 2008). As in Bios-3, staggered growing cycles was used to decrease oxygen and carbon dioxide fluctuations as well as even out production of food (Nitta 2003).

Physicochemical degradation of waste was chosen because of the long time required to achieve a high degree of degradation by biological methods. In addition, a large storage of degrading organic matter would be required in a biological system to match the rapid uptake of nutrients by growing crops (Nitta 2003). When waste was not processed, during a manned week-long experiment, the result was an abundance of oxygen and a shortage of carbon dioxide in the system during this time (Tako *et al.* 2008).

NO_x gases (NO and NO_2) from pyrolysis of human faeces, were handled by three subsystems including potassium permanganate for oxidation of NO and activated carbon for adsorption of NO_2 (Tako *et al.* 2008).

Transpired water was collected through condensation and used to both replenish the plant nutrient solution and as drinking water for the crew and animals in later experiments. 818–938 litres were collected per day from the 150 m^2 cultivation areas. 82 percent of the crews’ food, in fresh weight, was grown inside the complex as well as all of the feed for the goats (Tako *et al.* 2008). The majority, 90 m^2, of the cultivation area had lighting by high pressure sodium lamps while 60 m^2 had solar lighting (Nitta *et al.* 2000). Waste hydroponic solution was reused after filtration, concentration and replenishment of spent nutrients (Tako *et al.* 2008).

4. Cycling of matter in the experiments

In this section I will briefly summarise the cycling of three nutrients examined by this paper, as attempted in the presented experiments. Table 1 provides an initial overview, also including the percentage of the crew's food produced within the systems.

Table 1. By what method the carbon, nitrogen and water cycle was maintained in the different experiments and how much of the crew's food, by weight, that was produced in system (Allen & Nelson 1999). Bio and PC being biological and physicochemical methods of regulation, respectively.

	Carbon	**Nitrogen**	**Water**	**Food (%)**
Bios-3	Bio & PC	Bio (limited)	Transpiration	95
Biosphere 2	Bio & PC	Bio	Transpiration	81
CEEF	Bio & PC	PC	Transpiration	82
MELiSSA	Bio & PC	Bio	Transpiration	-

4.1. Carbon

Recovery and cycling of carbon in closed life support systems are facilitated through degradation of organic matter to carbon dioxide either through biological or physicochemical systems, or a combination of the two. If this is not done the result will be an excess of oxygen and a lack of carbon dioxide. Staggered plant cultivation, controlled decomposition and buffers are used to minimize and balance the fluctuations between respiration and carbon fixation. For Biosphere 2 a buffer system of calcium carbonate was utilised (Nelson *et al.* 1993) while CEEF used solid amine to capture and store carbon dioxide (Tako *et al.* 2008).

Complete cycling, full conversion to carbon dioxide of food waste and faecal matter will or will not be wanted depending on the closure of the system regarding food, as decomposition does consume oxygen. Import of food to the system introduce carbon which upon decomposition to carbon dioxide might be more than the system is able to capture again in its photosynthetic components, leading to a shortage of breathable oxygen. Complete decomposition might therefore not always be desired (Wheeler 2003).

It has been calculated that a food production of 40 percent of the crews needs will be sufficient to supply it with oxygen and handle carbon fixation (Poughon *et al.* 2009), though differences between systems is to be expected. The question of carbon storage would then be of interest to account for the overflow and to remove the need for transport of materials from the systems. Carbon storage could be achieved by the creation of a carbon based soil, or perhaps by the production of woody biomass if woody plants are part of the system (Wheeler 2003).

4.2. Nitrogen

Methods for recovery of nitrogen in plant available forms vary from complex biological steps in MELiSSA to purely physicochemical in CEEF or largely non-existent as in Bios-3. Bios-3 used urine from the crew in the hydroponic solution, but otherwise imported all plant nutrients from outside the system (Salisbury *et al.* 1997). MELiSSA utilised bacteria to oxidise nitrogen in organic material to nitrate (Godia *et al.* 2002) while CEEF used wet oxidation followed by physicochemical processes to produce ammonia and ammonium nitrate (Sakamoto *et al.* 1997). Capability for nitrogen cycling approaches 100 percent in the MELiSSA system (Lasseur *et al.* 1996).

Leakage of atmosphere from the systems proves to be a large source of nitrogen loss. Bios-3 leaked 0.02 percent of its atmosphere per day (Salisbury *et al.* 1997), constituting some 20.9 kg of nitrogen over a year. The same rate of leakage from a system the size of Biosphere 2 would come to 11.9 metric tonnes of nitrogen lost per year. That is assuming an atmosphere with the composition of Earth's, with 78 percent nitrogen and a pressure of one atmosphere. This becomes a problem if the atmosphere outside the system is of a different composition than the one within, such as on another planet or in space.

4.3. Water

The cycling of water in these systems depend on the uptake and transpiration of water by plants, collection by condensation and additional chemical and or physical systems for purification. For drinking water some salts need also be added to water recovered this way (Salisbury *et al.* 1997).

5. Discussion

I have looked at a few different systems attempting to recreate parts of the terrestrial life support system. They have approached the problem in somewhat different ways, with Biosphere 2 going for a more complex ecosystem and the others a smaller number of specifically chosen species. These systems have accounted a few problems along the way that we can learn from, but largely functioned as intended. Additional problems would likely crop up over longer time periods, but I would consider them proof that the concept is valid, if not without difficulties.

In the presented experiments, closure of the water cycle seemed to be the least problematic to achieve. Some problems occurred with the oxygen levels, maintaining the equilibrium with carbon, loss through leakage and absorption into structural elements of the construction. Large efforts have been made to attain a closed nitrogen cycling, notably in MELiSSA by biological and in CEEF by physicochemical means. For nitrogen, leakage of atmosphere from the systems constitute a significant loss due to atmospheric composition. This might be minimised through improvements in the construction but is unlikely to ever be eliminated. Changing the atmospheric composition to contain less nitrogen could reduce this loss, at the cost of the elements used to replace it. The effects of such a change on plants or other organisms, including humans, is an area where further study is required.

Degradation of waste is shown, unsurprisingly, to be a vital part of establishing a closed system. The need to keep the system size down does lead to the need for fast cycling of materials which currently seem to exclude the use of purely biological methods. Use of physicochemical systems does have their own disadvantages though, primarily increasing energy requirements and their relative vulnerability. If some part malfunctions in a faster cycling system, the problem becomes that much more critical. A mechanical or chemical system can also not regrow if damaged the way a biological may. In a more biological system, the waste itself can also be used as substrate for beneficial degraders, for use as food or otherwise. Physicochemical systems for smaller adjustments in a biological system, combining the two like seen in MELiSSA, might be a reasonable compromise.

The carbon cycle of these systems has been reasonably managed. However, it cannot be said to have been closed as none of them have managed to produce all its food in system, making it necessary to import food and thus carbon into the system. As there is a problem with leakage of atmosphere, we also have carbon in the form of carbon dioxide escaping the system, alongside nitrogen and oxygen. Stabilizing the carbon content proved problematic in Biosphere 2 who in contrast to the other experiments relied on only natural sunlight, rather than using lamps, resulting in daily and seasonal fluctuations following light availability. This can likely not be eliminated as plants do require these cycles for maximum growth and reproduction. In a system with artificial lighting the cycles could be staggered between different growing rooms however, minimising total fluctuations.

While getting carbon back into circulation is a priority in these systems this is likely not the case for our terrestrial system, because of no need to keep it isolated from the atmosphere. Of greater importance would possible be to extract as much of the nutrients from organic material as possible while leaving large parts of the carbon itself deadlocked to remove it from the cycle and reduce its effect as a greenhouse gas. While a closed system will likely want to stay as close to natural atmospheric composition as possible, it could also be prudent to investigate the reactions of crops and ultimately crew to deviations in this composition. Such knowledge could also be useful to prepare for the changes we bring to our own biosphere.

Nitrogen has been one of the most researched elements for cycling especially in the MELiSSA system and CEEF. It is also, in my opinion one of the most likely to be problematic as loss of atmosphere over times removes large quantities of it from the systems, if the atmosphere is of a terrestrial composition. Large efforts have been devoted to recover nitrogen from waste products and to make them available in a form usable to the primary producers of the systems. MELiSSA uses biological processes with different strains of bacteria converting nitrogen whereas CEEF uses a more purely chemical approach. The short- or long-term problems with the cycling of other nutrients than nitrogen seem left less explored and might thus benefit from further research and testing. I have found little mention even of the remaining macronutrients; potassium, calcium, magnesium, phosphorus and sulphur. Trace elements were being monitored during the Bios -3 experiments but were found to be difficult to control (Gitelson & Lisovsky 2008). Granted most of them are required in significantly lower amounts and can therefore more easily be supplemented but achieving a closed cycling would still be preferable.

Trying to sustainably support human life in a limited space is a problem which application for future society could possibly be monumental. Maximising the

production of food and recycling of nutrients will likely become a question of outmost importance as greater demands will be place on our ability to produce food and supply clean water to an increasing human population.
While recycling of water would, arguably, be the most useful part of this for utilisation on earth today the way that it is being done, i.e. mainly via transpiration of plants, makes it hard to use in isolation. Methods for growing food on small areas in an energy efficient way will also likely be of great importance in the future. The applicability of the methods discussed above may be limited by their current heavy reliance on technological systems. The focus on enduring systems inherent in closed systems life support can, I believe, be of great benefit, especially if focus turns more towards low-tech constructions. This would be reasonably given the experience gathered from multiple experiments (Blüm *et al.* 1999; Gitelson *et al.* 2003), stating that the technological components are the weakest link in these systems. On that note I am of the opinion that the trend to more and more rely on technological controls and buffers is unfortunate. While these do have their place in closed ecological system design, I would rather see them as back-up systems to a more robust biological equilibrium. Doing so would probably require more complex systems including an increased number of species however, likely needing more volume and mass, approaching a biospheric complex. It would be interesting to investigate the ability to transform one into the other, starting with a simpler system for short duration missions and gradually turning it into a biospheric system for the establishment of long duration planetary bases for example. Manukovsky *et al.* (1997) describes the creation of a soil based growing system developed from a hydroponic one, perhaps a first step towards doing so.

While this has not been the focus of this work, developing the most efficient way to produce a dietary sufficient crop is of clear significance, for example to establish food production supplying starving or malnourished populations. As noted, a drawback is that the systems do tend to be technology heavy. Much of this however is to stabilise the variations in carbon fixation and respiration, which is of less importance as the global system does have the large buffer systems the isolated systems lack. Furthermore, as the Earth at present suffer from an accelerated introduction of carbon dioxide to the atmosphere from fossil fuels, a system working as a carbon sink might not be disagreeable.

As a water treatment system CEEF produced around 5 litres of water per square metre of growing area. With a water consumption of 180 litres per person and day, which was the amount measured in Swedish households in 2007-2008 (Energimyndigheten 2016), 36 square metres would be required per person. While this is perhaps not unfeasibly much, a decrease in water usage would be preferred.

This growing area would also, if compared to Bios-3 crop area of 63 metres square for two to three crew members, be enough to supply said person with at least the vegetable part of their diet. Using the above numbers for Uppsala municipality in Sweden, recycling all the water and growing the vegetable part of the food for all 225164 inhabitants would require 8.1 square kilometres or 0.4 percent of its land area (Statistiska Centralbyrån 2019a; b).

We are currently driving the biochemical cycles on our planet away from previous equilibria by utilising long time buffer storages over short periods of time. This is not a viable option for the long turn. Not only will the deposits we are using ultimately run out, but perhaps more importantly, we are driving the system away from the conditions we evolved for and have lived under as humanity thus far. The effects on the largely closed system of Earth will take a long time to fully manifest. It might therefore be of interest to look at smaller systems to both gain some understanding for what effects our actions might have and what we might potentially do to mitigate some of them and to be able to present it in a way that will be easily recognisable. Or simply to help us prepare to survive in this new world we are creating.

Due to the limited size of these systems, changes happen fast. You can see a response to a change in your behaviour almost immediately, making it necessary to act fast to correct it. If looking at it from this perspective, perhaps a sense of urgency could be transferred to our own. This I believe is the main reason why we see so little action today, to try to mitigate the changes we have brought to our own life support system. The changes simply take a longer time to become obvious because of the large buffers and vast scale. While life on Earth will most certainly survive and adapt, many species, including our own, might not.

Thus, I do unfortunately believe that the late Professor Stephen Hawking was correct when he said that we need to spread to survive. All our eggs are in one basket and we are very vulnerable here to our own folly. Perhaps we, as many will say, do deserve to go extinct but a species will fight for its survival and it is my belief that ours lie in constructing new homes for ourselves beyond the boundaries of Earth.

To quote Professor Stephen Hawking: “We know there is at least one advanced civilization with the propensity for destroying species, ecosystems, atmospheres and weather patterns, perhaps entire planets and it happens to live on earth. Spreading out may be the only thing that saves us from ourselves” (Breakthrough 2016, 00:04:05)

6. Conclusions

- An almost complete recovery of carbon, nitrogen and water in CELSS is currently possible from organic material.
- Gas leakage from CELSS constitutes a significant loss of nitrogen and oxygen.
- Too strong focus on technological solutions instead of biological processes to regulate biogeochemical cycles in CELSS might decrease the life span of the systems.
- Methods and technology researched might be of great benefit to society.

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