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Review

The water cycle in closed ecological systems: Perspectives from the Biosphere 2 and Laboratory Biosphere systems

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Abstract

To achieve sustainable, healthy closed ecological systems requires solutions to challenges of closing the water cycle – recycling wastewater/irrigation water/soil medium leachate and evaporated water and supplying water of required quality as needed for different needs within the facility. Engineering Biosphere 2, the first multi-biome closed ecological system within a total airtight footprint of 12,700 m^2 with a combined volume of 200,000 m^3 with a total water capacity of some 6×10^6 L of water was especially challenging because it included human inhabitants, their agricultural and technical systems, as well as five analogue ecosystems ranging from rainforest to desert, freshwater ecologies to saltwater systems like mangrove and mini-ocean coral reef ecosystems. By contrast, the Laboratory Biosphere – a small (40 m^3 volume) soil-based plant growth facility with a footprint of 15 m^2 – is a very simplified system, but with similar challenges re salinity management and provision of water quality suitable for plant growth. In Biosphere 2, water needs included supplying potable water for people and domestic animals, irrigation water for a wide variety of food crops, and recycling and recovering soil nutrients from wastewater. In the wilderness biomes, providing adequately low salinity freshwater terrestrial ecosystems and maintaining appropriate salinity and pH in aquatic/marine ecosystems were challenges. The largest reservoirs in Biosphere 2 were the ocean/marsh with some 4×10^6 L, soil with 1 to 2×10^6 l, primary storage tank with 0 to 8×10^5 L and storage tanks for condensate and soil leachate collection and mixing tanks with a capacity of 1.6×10^5 L to supply irrigation for farm and wilderness ecosystems. Other reservoirs were far smaller – humidity in the atmosphere (2×10^3 L), streams in the rainforest and savannah, and seasonal pools in the desert were orders of magnitude smaller (8×10^4 L). Key technologies included condensation from humidity in the air handlers and from the glass space frame to produce high quality freshwater, wastewater treatment with constructed wetlands and desalination through reverse osmosis and flash evaporation were key to recycling water with appropriate quality throughout the Biosphere 2 facility. Wastewater from all human uses and the domestic animals in Biosphere 2 was treated and recycled through a series of constructed wetlands, which had hydraulic loading of 0.9–1.1 m^3 day^{-1} (240–290 gal d^{-1}). Plant production in the wetland treatment system produced 1210 kg dry weight of emergent and floating aquatic plant wetland which was used as fodder for the domestic animals while remaining nutrients/water was reused as part of the agricultural irrigation supply. There were pools of water with recycling times of days to weeks and others with far longer cycling times within Biosphere 2. By contrast, the Laboratory Biosphere with a total water reservoir of less than 500 L has far quicker cycling rapidity: for example, atmospheric residence time for water vapor was 5–20 min in the Laboratory Biosphere vs. 1–4 h in Biosphere 2, as compared with 9 days in the Earth's biosphere. Just as in Biosphere 2, humidity in the Laboratory Biosphere amounts to a very small reservoir of water. The amount of water passing through the air in the course of a 12-h operational day is two orders of magnitude greater than the amount stored in the air. Thus, evaporation and condensation collection are vital parts of the recycle system just as in Biosphere 2. The water cycle and sustainable water recycling in closed ecological systems presents problems requiring further research – such as how to control buildup of salinity in materially closed ecosystems and effective ways to retain nutrients in optimal quantity and useable form for plant growth. These issues are common to all closed ecological systems of whatever size, including planet Earth's biosphere and are relevant to a global environment facing increasing water shortages while maintaining water quality for human

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and ecosystem health. Modular biospheres offer a test bed where technical methods of resolving these problems can be tested for feasibility.

1. Introduction

A top challenge in creating bioregenerative life support and eliminating inputs to closed ecological systems is closing the water cycle. This requires methods of supplying water of sufficient quantity and quality to meet needs of life-forms inside the system. In very simple systems, this may only require return of irrigation water for food crop water demands. For systems with human inhabitants, supplying water of potable standard is required; as are methods of dealing with wastewater generated by human, technical or other subsystems inside the enclosure. In more complex enclosed ecosystems, such as the Biosphere 2 system which included marine and aquatic systems, pools, waterfalls, and streams in terrestrial ecosystems, in addition to food crops, domestic animals, and a crew, the diversity of water requirements and treatment/distribution/recycling subsystems are far greater.

The most advanced bioregenerative closed system including humans prior to Biosphere 2, was the Bios-3 facility in Krasnoyarsk, Russia. That 315 m^3 facility supported around a dozen food crops grown hydroponically, and crews of 2–3 people for closure experiments of up to 6 months. The water cycle was largely closed. Feces were dried and exported, the water recovered. During some of the later experiments conducted in Bios-3 urine was used as an additive to the hydroponic crop irrigation for wheat. This led to an increase in sodium in water and plant tissue, but not to unhealthy levels. The condensation of water evapotranspired by the plants in the three plant growth areas was an important part of the water collection and redistribution system. Most of this water was used in the hydroponic nutrient solution used to irrigate the plants. Water for human uses such as washing and cleaning was boiled, and potable water was further purified by ion-exchange filters. To improve health, potassium iodide and fluorides were added to the potable water; and salts added to improve its taste (Salisbury et al., 1997).

2. Biosphere 2 water system overview

Biosphere 2, a materially closed system of ecosystems with eight human inhabitants (Allen, 1991; Nelson et al., 1993; Dempster, 1989, 1990, 1993), includes a complete water recycling and purification system predominantly using the pathways of evapotranspiration, condensation, and constructed wetland wastewater treatment. Mechanical assistance to these processes is mainly fan driven air movement which brings humid air to cooling coils, and pumping to deliver water to usage points. Natural analogue fresh and marine water areas such as streams, pools, mangrove, and ocean support complex natural ecosystems. Algal turf scrubbers and protein skimmers helped remove nutrients from the marine ecosystems' waters (Biosphere 2's ocean and marsh biomes).

2.1. Water reservoirs and distribution within Biosphere 2

Table 1 shows the distribution of water reservoirs throughout Biosphere 2. Our review concerns the operation of Biosphere 2 during the period when it was operated as a closed ecological system (1991–1994), not when it was changed to a "flow-through" system which introduces external air and even water after 1995 (Odum and Marino, 1999). The ocean/marsh system contains the largest volume, with around 4×10^6 L or 63% of the total. Next in capacity are the soils (both of the farm and of the terrestrial biomes ranging from rainforest to desert) with 1 to 2×10^6 L or 21% of the total, depending on the state of hydration and seasonality of crops and biomes. The primary storage tank contains up to 8×10^5 L or ~12% of total water, condensate tanks can hold 1.6×10^5 L (~2%), streams and pools in the biomes contain 8×10^4 L (~1%) and the atmosphere contains around 2×10^3 L (~0.03%) of the total.

Table 1
Water reservoirs, fluxes, and residence times in Biosphere 2 (from Dempster, 1993, 1994; Tubiello et al., 1999).

Reservoir	Volume (L)	Percentage of Biosphere 2 water	Typical daily water flux (10^3 L)	Estimated residence time
Ocean/marsh	4×10^6	~61	3.4 ± 0.4	~1200 days
Soils	1 to 2×10^6	~23 (calculated on 1.5×10^6)	Irrigation: 18.3 ± 7.3 Soil drainage: 4.6 ± 10.6 Plant uptake and ET	~60 days
Primary storage tank	0 to 8×10^5	~12 (when full)	$+4.6$ to -4.8 ± 3.1	~80 days
Condensate and leachate tanks	1.6×10^5	~2 (when full)	$+2.8$ to -3.0 ± 9.7	~5 days
Streams and pools in biomes	8×10^4	~1		
Atmosphere	2×10^3	~0.03	12.4 ± 4.5 (evapotranspiration)	~4 h

In Biosphere 2, there were also systems that required saline water – the ocean and the marsh, with its gradient of salinity life-zones; as well as those that used freshwater, the agriculture and terrestrial biomes. We will discuss the principal technologies that were developed to supply water of the appropriate quality to each subsystem.

2.2. Condensate water collection and distribution

The overall water system is schematically diagrammed in Fig. 1. Condensation of water vapor from the atmosphere is one of the critical recycling steps. Evaporation and transpiration throughout all biomes, both from planted areas and from the exposed surface of water bodies, brings water vapor to the atmosphere. Relative humidity inside Biosphere 2 was generally high, typically in the 60–90% range. Condensation occurs within each biome at two different locations: (a) on the cooling coils of the air handlers, and (b) on the airtight glazing of Biosphere 2.

The air handlers recirculate air within each biome to control temperature and humidity. They do so utilizing both hot and cold water circulated inside closed-loop piping systems supplied by energy sources outside of the Biosphere 2 airtight enclosure. Condensate forms on the air handler cooling coils and is collected in trays from which it is pumped to collection tanks.

The glazing of Biosphere 2 is in direct contact with both inside and outside air. In cold weather, the latter imparts enough cooling to the glass to cause condensate to form on the inside surface. This condensate drains to the lower edge of the glass and is collected in a series of plastic extruded troughs. The network of troughs form a tributary system to the bottom edge of the glazing/space frame from where drain pipes subsequently deliver the water to the same condensate tanks.

Some areas of the glazing/space frame envelope are horizontal and condensed water does not run to one edge but collects and drips off. This condition is represented by the dashed lines descending from the "condensate" boxes to the individual biomes in the diagram. During cold weather, which at the Biosphere 2 site would typically include November through February, this pathway of condensate return can be a significant part of the "rainfall" delivered to the biomes.

Once collected, the condensate water is available for distribution. The dominant use by volume is for rainwater in the wilderness areas and irrigation of the agricultural systems. This is illustrated as delivery to the "Utility Water" and "Rainwater" tanks in the diagram from which further delivery is shown to each biome. Utility water in the agricultural area is a mixture of water draining through the farm's soils, condensate water and effluent from the constructed wetland sewage treatment systems (labeled as "Marsh treatment" in Fig. 1). The six toilets in Biosphere 2's human habitat are all served with water from the "Utility Water" supply. The domestic animal pens are also washed with utility water. Overflow from the condensate
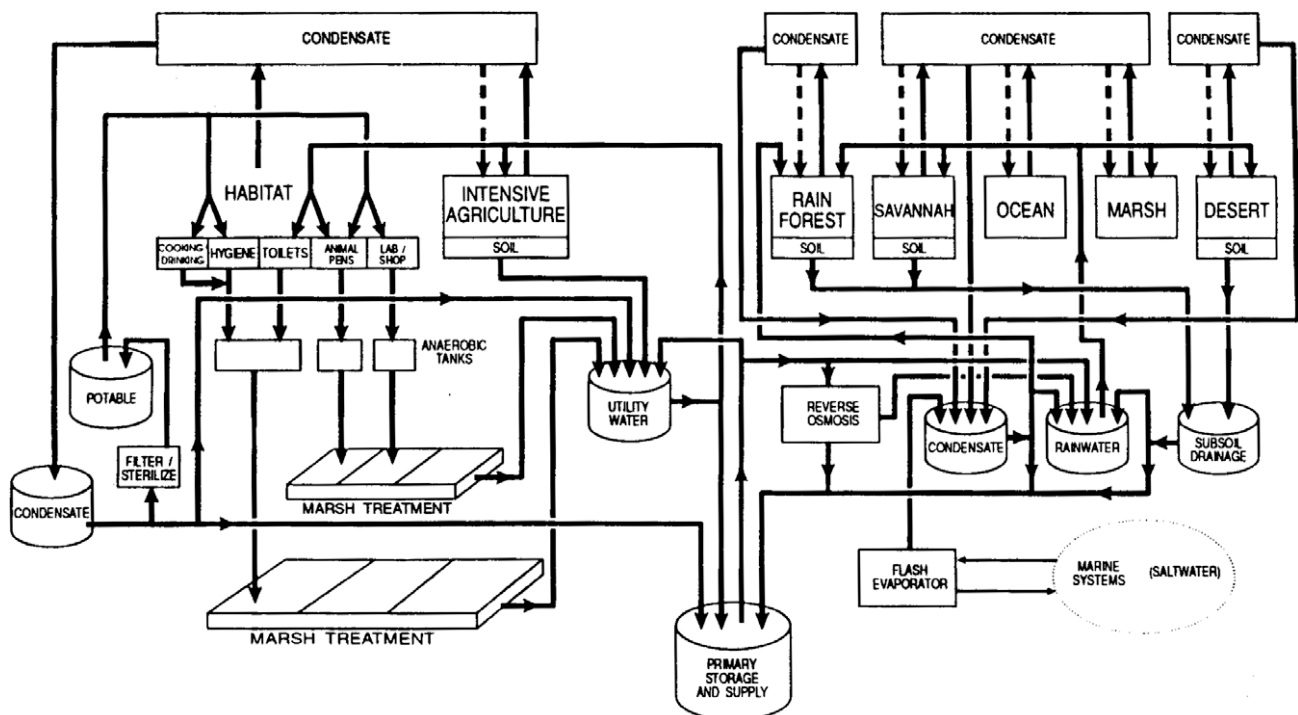
Fig. 1. Schematic of the water systems of Biosphere 2. "Marsh treatment" refers to the constructed wetlands which treated human residential wastewater, laboratory and workshop wastewater, and wastewater from the domestic animal pens.

storage goes to the very large (880,000 L capacity) "Primary Storage" tank.

The other condensate use of major importance is for potable water. Condensate is passed through two-stage filtration to 0.1 μm and ultraviolet sterilization to potable water holding tanks. Potable water is distributed to the human habitat for drinking, cooking, washing, and for use in the medical and analytic laboratories and the workshop as well as supplying drinking water for the domesticated animals. The analytical laboratory also has a reverse osmosis/deionization system which produces very pure (18 MΩ) water for washing glassware and other analytical purposes

In the wilderness, all of the biomes except the ocean receive direct rainfall from overhead sprinklers mounted in the space frame. In addition, there are drip irrigation networks to pockets that are not reached by the overhead sprinklers or need special watering schedules. Release of water through sprinklers or the drip network is controlled by programmable timers or by manual action. The schedule may have large variations due to planned events such as dormancy of an entire biome, for example – which typically was done for the desert in the winter months, and the savannah in the spring since this mimics conditions these systems normally encounter in nature.

In the intensive agriculture biome, crop irrigation is separately controlled according to the need of each of the 18 plots. Common faucets and garden hoses are also used for special areas and planter boxes requiring individual watering. The water level in rice paddies is constant at an overflow pipe that drains into a sump. A pump then maintains constant circulation from the sump to the paddy and back to the overflow. A float valve maintains the water level in the sump to make up for evapotranspiration losses from the rice paddy.

2.3. Marine systems water system

The marine biomes, saltwater marsh and ocean, together contain more than four million liters of saltwater. Volumetrically, they constitute the largest water system in Biosphere 2. The ocean holds some 2.65 million liters in a basin up to 7.6 m deep × 19 m wide × 45 m long. The saltwater marsh has five zones of vegetation progressing from the most saline-tolerant adjacent to the ocean to the least saline, a freshwater marsh, furthest from the ocean. A salinity gradient was designed to be achieved by intrusion of freshwater into the least saline zone counteracting a tidal influx entering the most saline zone. The "tide" was designed to be pumped from the ocean and propagates upward throughout the five zones similar to the propagation of natural ocean tide up a river delta, and then to partially drain from the marsh back into the Biosphere 2 ocean. This system was not implemented during the several years of closed system operation from 1991 to 1994.

Pumped recirculation is maintained in the ocean and all five marsh zones to assist continuous redistribution of nutrients and waterborne exchanges. There is also a vacuum operated system of wave generation. Seawater is alternately raised by vacuum and released in a chamber to create the movement to generate waves which are necessary for the health of marine ecosystems like coral reefs.

Excessive nutrient levels that would be created in the ocean were designed to be mitigated by a system of algae scrubbers. Algae scrubbers are shallow trays with growing algae, over which seawater is made to flow (Adey and Loveland, 1991). By growing, the algae extracts nutrients from the ocean water and so protects the delicate coral reef, which would be overgrown by marine algae if there were elevated levels of nutrients. Most of the algae is periodically scraped from the algae scrubbers, and dried, and allowed to regrow. During the first 2 year closure experiment, when it was found that the algae scrubbers were not adequately lowering nutrient levels, this system was supplemented by "protein skimmers" also known as foam fractionation or adsorptive foam separation (Aquarium design website). This is a process where air bubbles drive organic compounds out of a water solution. This organic material was skimmed off the ocean surface in the pipe collectors and was air-dried. The protein skimmer system helped the ocean maintain lower concentrations of nutrients.

The uppermost saltwater marsh zone is adjacent to a freshwater marsh which has a small overflow into the saltwater marsh. This, plus rainwater, combine to give a surplus of freshwater entering the saltwater marsh system over the amount removed by evapotranspiration. The excess is removed by a flash evaporative distiller. In this unit, fresh water is extracted from salt water by boiling in a vacuum at low temperature. The heat energy required is supplied by hot water circulated in closed-loop piping from energy sources outside of Biosphere 2.

2.4. Freshwater streams and pools

Natural analogue freshwater bodies existed in the rainforest, savannah, and desert of Biosphere 2. The rainforest mountain holds a pond that overflows in a waterfall down to a winding creek at ground level. Similarly, a stream of 43 m length × 1–2 m wide runs through the northern half of the savannah. A variety of aquatic organisms, including fish, inhabit these streams, which are continuously flowing due to recirculation pumps. In the desert, there is also a pond plus a seasonally wet and dry lakebed.

2.5. Human and domestic animal wastewater treatment and recycle

Constructed wetland sewage treatment systems have been developed by NASA scientists at Stennis Space Center and later applied in NASA test beds (Wolverton, 1989), and further developed by the creators of Biosphere

2 (Nelson et al., 1999; Nelson, 1998). Biosphere 2 was the first closed ecological system that was designed for recycling of all human waste products. In Biosphere 2, the wastewater system functioned as part of the sustainable food production system through the production of forage for domestic animals, and by the utilization of excess nutrients remaining in the wastewater effluent for crop irrigation (Nelson, 1997).

There are three separate sets of anaerobic holding tanks for receiving waste water from different sources. Each set has three individual tanks that are used in rotation in batch operation, which allows a few days of anaerobic digestion prior to release to marsh treatment. Toilet, hygiene, and kitchen wastewaters drain together to the human waste anaerobic holding tanks. Waste water from the animal pens drain to animal waste holding tanks, and waste from the analytical laboratory and machine shop drain to the lab/shop holding tanks.

The analytical laboratory uses very little wet reagent chemistry, and is not a source of pollutants into the water supply. Analytical procedures are almost entirely based on gas chromatography, mass spectroscopy, ion chromatography, and atomic absorption spectrophotometry which avoid the need for significant quantities of reagent wastes. Some small amounts of acids and bases are used but neutralize each other before release. Acids have a slight dominance and the imbalance is neutralized by NaOH. The amounts of salt created are negligibly small in the total water system.

Effluent from the anaerobic holding tanks, where anaerobic microbial digestion begins the treatment of organic waste, is then sent for further treatment in "marsh treatment beds", also known as constructed wetlands. There are two treatment beds, one devoted to wastewaters of human origin and one treating the combined effluents from the animal pens, laboratory, and machine shop. Water discharged from the marsh treatments returns to the utility water tanks and is again available for toilet water, animal pen washing or agriculture.

Daily wastewater input was around 1 m^3 (260 gallons) per day. Around 750 m^3 of wastewater were treated over the course of the 2 year closure experiment, 1991–1993. The created wetland totaled 41 m^2 of surface area with emergent and floating plants and produced a total of 720 kg, dry weight, of emergent vegetation and 493 kg, dry weight, of floating vegetation during the 2-year experiment. Plant productivity was limited by available sunlight as winter day length was shorter than summer day length and the glass and space frame shading reduced light levels by 50–60%. Analysis for Biochemical Oxygen Demand (BOD) indicated reduction was >75% with hydraulic retention times of around 4 days in the holding tanks and 3 days in the wetland treatment system (Nelson et al., 1999). UV lights were available as a method of final disinfection, but weren't used during the 2 year closure since the health status of the eight crew members was closely monitored, and they carried no infectious diseases prior to closure.

The constructed wetland system supported 14 species of floating (aquatic) and emergent (rooted) wetland species. The aquatic plants colonized open-water channels and the emergents utilized upland soil areas in the wetland. The wetland system was housed in several fiberglass tanks and submersible pumps maintained water recirculation between tanks. Loading to the system was on a batch basis after the primary settling tanks became full. The system served as habitat for insects (e.g., lady bugs) and animals (such as the Colorado cane toad) within the Biosphere 2 agricultural biome. Production of floating vegetation declined during the 2 year closure as shading from robust emergent vegetation increased. Occasional outbreaks of powdery mildew on *Canna* sp. were controlled by water spray and pruning of affected vegetation. The system operated with few problems, but technical changes after the 2-year experiment were instituted to make water sampling easier, to prevent overfilling of tanks and lower labor requirements. Little malodor was reported by the Biosphere 2 crew, and the constructed wetlands added to the diversity of attractive foliage within the facility (Nelson, 1998; Nelson et al., 1999).

2.6. Water storages and flux rates

It is characteristic of all cycles within closed ecological systems that because of far smaller reservoirs, and higher concentrations of biota, that biogeochemical cycles are greatly accelerated compared to the global biosphere or such cycles in natural ecosystems.

Table 1 presents flux rates and estimated residence times for water in Biosphere 2's major components. The atmospheric water vapor has the most rapid turnover time, with residence at 1–4 h. The condensate tanks have a residence time of ~5 days, the soils of about 60 days, primary storage tank of ~80 days, and the ocean/marsh has the longest residence time of around 1200 days.

In comparison, it is estimated that on planet Earth (Table 2), atmospheric residence time for water is around 9 days, soil moisture 30–60 days, shallow groundwater 100–200 years, and ocean water turnover is around 3000 years (UCAR, 2008). Table 3 presents the comparisons between rapidity of cycling in Biosphere 2 and the Laboratory Biosphere compared to those in the global bio-

Table 2
Residence time of water reservoirs in the Earth's environment (UCAR, 2008).

Reservoir	Residence time (average)
Oceans	3000–3230 years
Glaciers	20–100 years
Seasonal snow cover	2–6 months
Soil moisture	1–2 months
Groundwater: shallow	100–200 years
Groundwater: deep	10,000 years
Lakes	50–100 years
Atmosphere	9 days

Table 3
Water fluxes and residence times in Biosphere 2 and the Laboratory Biosphere compared to Earth's biosphere (from Dempster, 1993, 1994; Dempster et al., 2004; Tubiello et al., 1999).

Reservoir	Earth residence time	Biosphere 2 estimated residence time	Acceleration of cycle compared to Earth	Laboratory Biosphere est. residence time
Atmosphere	9 days	∼4 h	50–200 times	5–20 min (cycling time at least 12 times faster than Biosphere 2)
Ocean/marsh	3000–3200 years	∼1200 days (3.2 years)	1000 times	N/A
Soil water	30–60 days	∼60 days	Similar	∼10 days (six times faster than Biosphere 2)

sphere. In Biosphere 2, atmospheric water turnover is accelerated by a factor of ∼54, soil moisture is roughly comparable (although if you count drainage through the soils as comparable to the residence time for shallow groundwater, turnover is some 600 times faster), and ocean residence is 750 times faster.

2.7. Areas which require further research

2.7.1. Managing nutrient and salinity levels in agricultural irrigation waters and soils

Among the prime challenges of creating a long-term sustainable water cycle in food production for closed ecological systems is that of managing nutrient levels and salinity. As opposed to open systems, closed ecological systems have a finite and potentially recyclable amount of nutrients and salts upon closure. So unlike field agriculture which may be irrigating with water derived from elsewhere which is importing salts into the system which may build up over time, closed systems do not have an external source of such nutrients. The waste products of the inside crew contains nutrients and salts derived from their diet, which is largely supplied from food grown inside the system. During the first 2 years, some 83% of the human diet was supplied by crops grown inside Biosphere 2 during the 2 year closure (Silverstone and Nelson, 1996) and 100% was achieved during a 7 month second closure experiment in 1994 (Marino et al., 1999).

However, there may be problems that result from the mobility of salts leached from soil reservoirs into water systems and then being used as a source of irrigation water for the farm and terrestrial biomes.

There is some evidence for an increase of salinity in the agricultural soils of Biosphere 2 but reported data is far from consistent. Silverstone et al. (1999) report, from soil analyses conducted near the end of the 2 year closure experiment, 1991–1993, that only one (plot 7) of the eight plots tested had a salinity level, with an Electrical conductivity (EC) level at 5.9 dS/m, of clear concern for plant growth in the 0–30 cm depth critical to annual crops. The remainder varied from 1.9 to 2.7 dS/m with a variance of up to ±1.0. At greater than 90 cm (near the bottom of the soil profile) EC readings were sometimes higher, with three between 4.0 and 5.4 dS/m, one at 8.1 dS/m and the others similar to or lower than the top soil layer. Sodium Absorption Ratios were 7.1 in plot 7 and from 1.1 to 2.1

in the other seven plots in the 0–30 cm layer, and from 1.0 to 2.7 in the >90 cm depth. As a general rule, salt impacts on crops are negligible below an EC of 2.0, levels between 2.0 and 4.0 may start to impact the growth of sensitive plants, and are more generally adverse to growth at an EC of 4.0–8.0 (Kotuby-Amacher et al., University of Utah online pub.). Plot 7 contained *Leuceana leucocephela* fodder trees during the first part of the 2 year closure experiment, and received more frequent irrigation in an attempt to maximize growth. That plus the deeper roots of the trees may have led to that plot developing higher salinity than the others tested.

During the 2 year closure TDS was measured in the mixing tanks used to supply the agricultural irrigation supply, and purer condensate water was added as necessary to lower TDS to ≤500 ppm (equivalent to an EC of 1.0 dS/m). When tested by Michigan State University during the 2 year closure, Biosphere 2 agricultural irrigation water had an EC of 0.7 dS/m and a SAR of 1.0. Since soil leachate from the system had an EC of 1.8 and a SAR of 1.7; this indicates the soil leachate was generally diluted by an equal or greater amount of condensate water. Studies have shown that water is safe for supplemental irrigation if the EC is less than or equal to 1.0 dS/m and the SAR is less than or equal to 5 (Buckland, Alberta Irrigation). Thus, irrigation water used during the 2 year closure should not have resulted in significant salination of the agricultural soils. While Harwood et al. concluded that most soils were adequate for crop production, a few issues such as denitrification of rice paddy soils, a high C:N ratio (from 13:1 to 17:1) and high levels of inorganic nitrogen in irrigation and soil drainage (leachate) water. The high initial levels of soil organic matter (6–8%) which were declining at rates from 0.2% to 1.4% per year and were generally in the 4–6% level after over 3 years of cultivation (Silverstone et al., 1999).

Marino et al. (1999) report much higher EC levels in the IAB plots – ranging from four plots at around 2.0 dS/m, nine at 5.0–6.0, and four from 8.0–10.00 dS/m. These data are subsequent to 1995 and may reflect the consequences of a change in quality of irrigation water or the result of a continued increase in soil salinity. Marino et al. report after leaching with very-low salt water that was imported for the purpose, EC in the plots was lowered to 1.6–2.4 dS/m. They also report that by 1995 irrigation water contained up to 2000 ppm TDS (4.0 EC) and nitrate levels had increased to 100 ppm as contrasted with measurements of

20 ppm (February 1993 during the 2 year closure) and 40 ppm (March 1994) at the beginning of the second closure experiment. Despite the reported salinity and nutrient problems, Marino et al. report that crop production was significantly higher during the second closure experiment, including corn (maize) a low salt-tolerant crop, partly due to better crop management and crop selection based on experience from the first closure. This is a somewhat incongruous result if in fact the soils were becoming more inimical to plant growth through elevated salinity during this period.

These concerns indicate that further research is needed on methods of using recycled water in a closed-loop agricultural system using soils. Also of value would be employing improved methods of separating salts and removing nutrients if these measures are required. Since there are no imported nutrients or salts, it is still an open question whether a long-term equilibrium at levels compatible with good crop growth conditions will establish once short-term fluxes, such as reduction of organic matter from young soils, have stabilized.

2.7.2. Maintaining ocean water parameters for coral reef health

Coral, and many other ocean creatures, build their hard, protective shells from calcium and carbonate ions that they extract from the water around them. A reef results as millions of individual corals build their homes around and on top of each other over time, like the slow construction of an apartment building, one story after another. Coral reefs normally exist in natural ocean waters with a pH of 8.1–8.3. High CO_2 levels in the Biosphere 2 atmosphere were absorbed by its ocean waters and tended to make ocean pH more acid. In fact during the 2 year closure, Biosphere 2 ocean reached a pH of around 7.3 and ranged from that value to 8.1. A program of chemical additives of sodium bicarbonate, sodium carbonate, and calcium chloride was carried out during the 2 year closure experiment to maintain ocean pH closer to natural values, offsetting the impact of elevated CO_2. Studies done at the conclusion of the 2 year closure showed coral reef growth and reproduction had occurred (Dustan, personal communication).

Subsequent studies in the Biosphere 2 coral reef showed that elevated CO_2 could lead to reduction in carbonate saturation with the consequence of reducing growth, since corals depend on carbonate fixation for expanding their colonies. When excess atmospheric CO_2 dissolves into the shallow ocean, its natural chemical balance is disrupted and the water becomes more acidic. The ocean's natural buffering system responds by using carbonate ions to consume the acid. While this does keep the water from becoming too acidic, less carbonate is available for coral building and overall reef growth slows. The researchers concluded that in Biosphere 2, CO_2 levels must average below 1500 ppm to be compatible with coral growth, and that coral growth would be reduced by 10% with ambient CO_2 at twice current Earth atmospheric values ($\sim$760 ppm); and at 1000 ppm a 75% reduction in coral reef growth results (Langdon et al., 2000).

2.7.3. Increase of salinity in water reservoirs

As discussed above, salts leach out of Biosphere 2 soils as rainfall (irrigation) waters descend through soils which ranged from 1 m depth in the farm to up to 6 m in tropical rainforest soils. Agricultural leachate was collected in the utility tanks located below the farm in the technical basement of Biosphere and then mixed with condensate water and small quantities of effluent from the constructed wetland. The soil leachate from the terrestrial biomes (rainforest, savannah, thorn scrub, and desert) was routed to the primary storage tank. As needed for biome irrigation, some of this primary storage water was returned to the systems after desalination with a reverse osmosis system. RO water tended to be far lower in nutrients compared with wilderness condensate (WC). For example, RO nitrate and ammonium levels were 1.0 and 5.0 ppm while the WC has 211 and 54 ppm, respectively; RO has dissolved organic nitrogen levels of 4.2 ppm while WC has 52 ppm (Atkinson et al., 1999).

3. Laboratory Biosphere water cycle

The Laboratory Biosphere facility is a closed facility with a soil-based plant growth module and a variable volume chamber to allow for changes in air volume. Planting beds cover 5.5 m^2. With a volume of 33–40 m^3, total amount of water in the system is estimated at 0.3–0.5 m^3 with a mass of 300–500 kg (Table 4). Evapotranspiration from the planting bed provides a continuous supply of moisture into the air within the chamber. At a typical 20 °C and 40% relative humidity, the air only holds less than half liter of water as humidity. Even at 40 °C and 100% relative humidity, water in the air would be less than 2 L. The amount in the air is almost negligible by comparison to the amount in the remainder of the system. It was observed in the first operational run with a soybean crop that condensate collection rates are on the order of 2.5–3 L/h while the lights are on. This demonstrated that humidity is a very small reservoir of water – the amount of water passing through the air in the course of a 12-h operational day is two orders of magnitude greater than the amount stored in the air. Thus, if enough water is initially provided to wet the soil beds, it is evident that there

Table 4
Mass and volume of components in the Laboratory Biosphere facility (Dempster et al., 2004).

	Volume (m^3)	Mass (kg)
Fixed air	33.6	32
Water content (L)	$\sim$1.5–2	1.5–2
Variable air (lung)	0–9	0–8
Soil (dry)	1.46	1650
Soil moisture (L)	300–500	300–500
Total water	0.3–0.5	300–500
Plants (variable)	0–0.02	0–20 (estimate)

will be always be enough available to keep them wet – either in the soil beds themselves or combined among the three storages, condensate tank, sump, or mixing tank from which it can readily be provided to the soil bed again as needed. Residence time of soil water is around 10 days in the Laboratory Biosphere (Table 4). This is six times more rapid cycling than soil water in Biosphere 2, which may be attributed to the shallower depth (0.3 m in Laboratory Biosphere vs. 1 m in the agricultural area of Biosphere 2) and consequently larger impact of evapotranspiration.

Extraction of this moisture from the airstream passing through the air handlers is the means both to recapture the water for recycling and to control the humidity. As noted above, the air handlers cool the airstream to water vapor saturation at a selected temperature. The moisture condenses out of the airstream during this step and is collected in a tray in the bottom of each air handler. Drain tubes then take the condensed water through a tipping bucket rain gauge, which measures the amount collected, and then to a condensate collection tank which is equipped with a level sensor to report the quantity in this tank. The condensate water so collected is theoretically very pure which was also confirmed by measurement of total dissolved solids, giving a reading of 0 ppm on an instrument with minimum detection level of 1 ppm.

In general, there may also be water in the sump, either remaining from an original provision of water to the system or as may have drained down after irrigation of the soil beds, or both. This water is likely to have a substantial level of dissolved solids and also varying amounts of organic compounds such as from fallen leaves from planting beds above. The sump is also provided with a level sensor to report the amount of water plus a sump pump.

Another tank called the "mixing tank" stands at floor level below the condensate tank. By opening a drain valve, the condensate tank can be drained down by gravity into the mixing tank, and by operating the sump pump, the sump water can be delivered to the mixing tank, thereby creating a mixture in controllable proportions of water both from the condensate tank and from the sump. The mixing tank has a level sensor and a TDS sensor to report the water quantity and total dissolved solids, respectively.

A diaphragm pump draws water from the mixing tank to pressurize a bladder type pressure tank, which, in turn, is connected to the irrigation tubing for the planting beds. Each planting bed can be independently irrigated by opening a solenoid valve to its irrigation tubing.

Fundamental physical considerations define the way water recycling and distribution operates in this system. The soil moisture content may theoretically range from 0 to a maximum of about 45% by volume (at which point it would be draining rapidly to the sump). Given 1.46 m^3 of soil, this means a theoretical maximum of 650 L, but in practice we will initially provide only about 300–500 L to the whole system. The soil only receives water from the watering system, i.e., by controlled actions, and there are soil moisture sensors in each bed to report the moisture status.

4. Conclusions

Completing and managing the water cycle in closed ecological systems offer a wealth of useful experiments. Cycling times are vastly accelerated as compared to natural ecosystems or global systems such as the planetary biosphere.

Simple bioregenerative life support systems require recycling of irrigation water, collecting and mixing condensate and agricultural crop leachate to ensure adequate quantity and quality of irrigation water for continued crop growth. In addition, a human crew requires production and management of potable water and recycling methods for the wastewater and nutrients contained in human wastes.

Biosphere 2, the first "biospheric closed ecological system", required a far more complex set of requirements to accomplish water recycling. The inclusion of analogue natural ecosystems which required either freshwater or saline water made salt-management and removal critical. The human crew and inclusion of internal laboratories and workshops made minimizing water pollutants extremely important as well as developing methods, such as constructed wetlands to absorb and metabolize heavy metals and complex synthetic compounds, to handle and recycle chemical/industrial wastewater.

As the world's attention becomes focused on increasing demands for freshwater for human populations, agriculture and industry, technologies and experience with closed ecological systems in preventing unintentional water pollution and supplying requisite quality water becomes ever more necessary.

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