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Short communication

Bioregenerative recycling of wastewater in Biosphere 2 using a constructed wetland: 2-year results

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Abstract

During the 2-year closure experiment (1991–1993) inside Biosphere 2, a two-stage system comprising primary treatment in anaerobic holding tanks followed by circulation in constructed wetlands treated all human habitat and domestic animal barn wastewater, as well as effluent from workshops and medical/analytic laboratories. The system had an estimated hydraulic loading of 0.9–1.1 m^3 day^{-1} (240–290 gal d^{-1}). Plant production in the wetland treatment system was light-limited, but over the two years 720 kg dry weight of emergent wetland vegetation and 490 kg dry weight of floating aquatic plants were harvested from the 41 m^2 wetlands and used as fodder. The wastewater treatment system was part of overall strategy for nutrient recycling inside Biosphere 2 and effluent from the system was routed to the irrigation supply for the agricultural crops. The constructed wetlands enhanced habitat diversity, supported 14 species of vascular plants and provided aesthetic pleasure. Operation was batch loading, using both pumps and gravity feed. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Constructed wetlands; Wastewater treatment; Sewage; Nutrient reclamation; Closed system agriculture; Biosphere 2

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1. Introduction

This paper describes the bioregenerative wastewater recycling system of Biosphere 2 (Nelson et al., 1993a). In preparation for Biosphere 2, a smaller version of the wastewater recycling system was developed and operated in the Biosphere 2 Test Module, a 480 m^2 facility scaled to support one person. This wetland system was sized to handle human solid and liquid wastes plus kitchen wastewater (Nelson et al., 1991). Prior to this work, the most advanced bioregenerative closed ecological life support facility, Bios-3 in Krasnoyarsk, Siberia had only regenerated liquid wastes while fecal material was dried and exported (Terskov et al., 1979).

The wastewater treatment system in Biosphere 2 was a series of tanks containing wetlands arranged to recycle water back to the Intensive Agriculture Biome (IAB) (see Fig. 1). The wetland systems were developed from previous NASA work (Wolverton et al., 1975; Wolverton, 1987, 1990), but rather than using pure gravel substrate, soil planting areas supported the emergent (rooted) wetland vegetation, while open channels supported aquatic floating vegetation, and the system was modularized to fit into several fiberglass tanks connected by piping and recirculating pumps.

2. Methods

2.1. Analytic laboratory and measurement methods

Fodder measurements were made by weighing all cut material prior to feeding to animals. To determine wet weight:dry weight ratios, vegetation from the wetland treatment system was weighed then dried in ovens at 70°C. until weights became stabilized. In August 1993, BOD was determined using EPA method 405.1 (US EPA, 1983), a 5 day test with sample kept at 20°C. In November 1993, analysis for NH_4^{+1} (ammonium) and NO_3^{-1} (nitrate) was done by ion chromatography with chemical suppression of eluent conductivity, SM 4500 (APHA, 1992). Hydraulic loading of the system was extrapolated from a 3-month log (1992) of when holding tanks were opened and emptied. Dissolved oxygen in the wetland was measured with (Hach) portable meters, incident light with a portable light meter. Wastewater samples were exported monthly through the Biosphere 2 airlock from human and animal wastewater anaerobic tanks during the last year of closure, and from both sets of wetland tanks, and analyzed in the outside laboratories on site at Biosphere 2. These data were not made available for this paper but are in the Biosphere 2 data bank.

2.2. Wastewater treatment design

Nine anaerobic holding tanks receive three types of wastewater: 3×1.9 m^3 tanks receive human habitat wastewater, 3×0.95 m^3 tanks handle domestic animal wastewater and 3×0.95 m^3 tanks hold wastewater from the analytic and medical

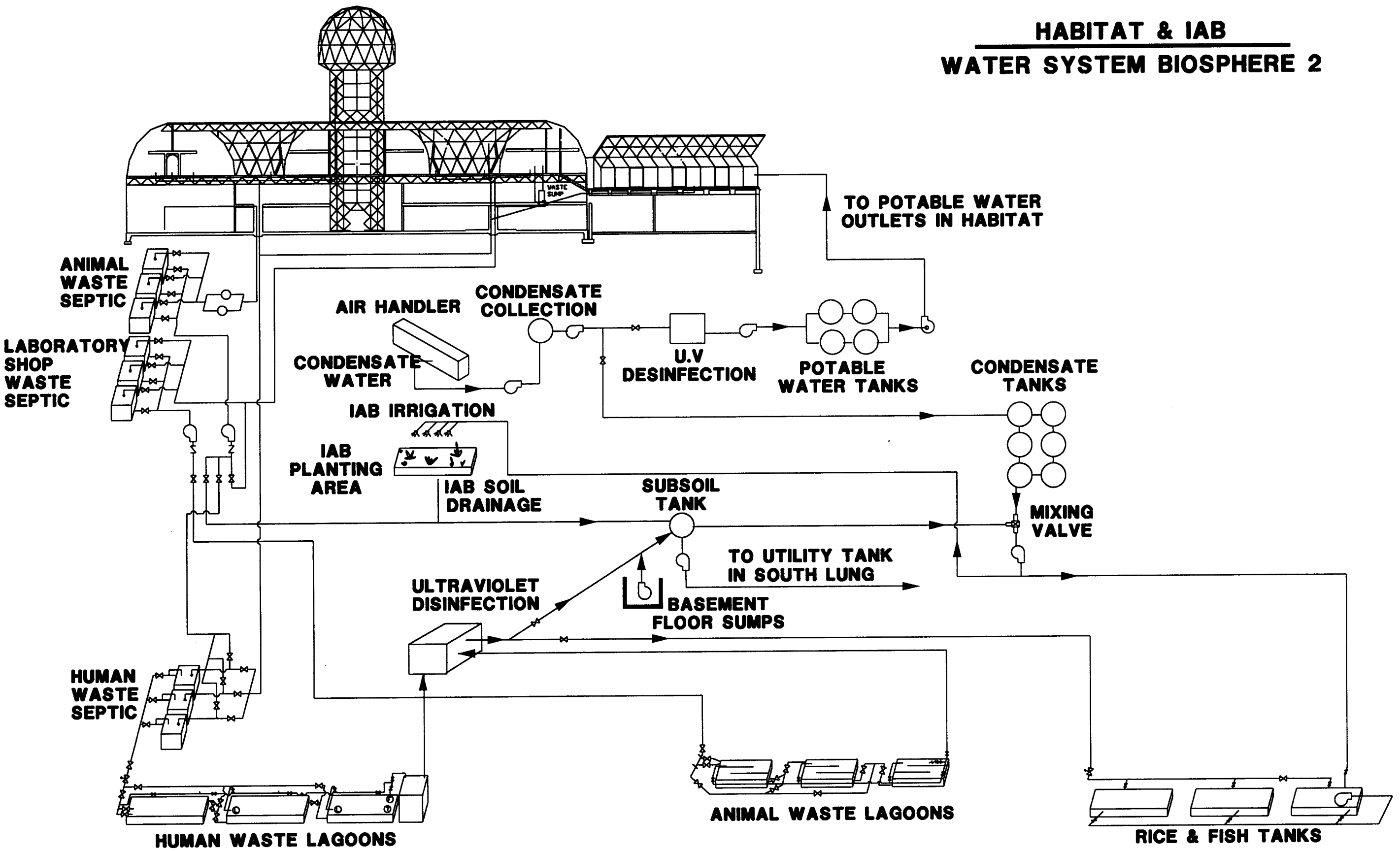

Fig. 1. Schematic of water systems in the Biosphere 2 Intensive Agriculture Biome (IAB) and Human Habitat, including the wastewater holding tanks and wetland lagoons.

laboratories. Hydraulic loading of the wetlands was done on a batch basis. Average residence time in the human habitat tanks was around 4 days, while residence times in the other systems were far longer (2–3 weeks).

The constructed wetlands consisted of two sets of fiberglass tanks. One system had two tanks 4.55×2.32 m and one is 2.15×2.32 m. The other system had three 2.15×2.32 m tanks. All tanks were 0.4 m deep. Total volume of gravel, soil and water was 16.4 m^3 and total area was 41.1 m^2. Effluent from the holding tanks enters the wetlands at the base of the primary lagoon through one of two perforated supply pipes and percolates up through the gravel, soil and plant root systems. The water is forced to follow a meandering path through the three marsh plant lagoons by a series of baffles. Sump pumps keep the wastewater recirculating between the three fiberglass tanks. A float switch activated submersible pump transfers water from the third wetland tank of each system past an ultraviolet disinfection unit, containing UV lamps with quartz sleeves. Since the Biosphere 2 crew during the two year closure were well-monitored medically, and entered free of infectious diseases, this disinfection unit was rarely used. Average residence time in the wetlands was about 4 days. Effluent from the wetland tanks was sent either to rice paddies or to the main agricultural irrigation mixing tanks.

3. Results

3.1. Development of the wetland ecosystem

The wetland vegetation of the systems developed rapidly under the stimulus of high nutrient-loading. Fig. 2a and b show the system when initially planted (with burlap bags holding the soil in place) and after closure in September 1991. The dominant rooted emergent plants include several varieties of canna lilly (*C. edulis*, *C. indica*, *C. flacida*) and reed (*Scirpus californicus*). Water hyacinth (*Eichhornia crassipes*) was the principal vegetation of the exposed water surfaces, along with some waterfern (*Azolla carolinea*), water meal (*Wolffia* spp.) and duckweed (*Lemna minor*) in areas near the glass spaceframe receiving better light. Table 1 lists the 14 vascular plant species of the wetlands.

3.2. Plant productivity and incident light

Plant biomass harvests during the two years yielded 723 kg dry wt. of emergent vegetation (mainly canna/bullrush) and 493 kg of aquatic plant material (water hyacinth) (Fig. 2). Light transmission through the glass spaceframes and structural shading lowered Biosphere 2 internal light to 40–50% of outside levels. Light was a limiting factor especially for the wetland system further away from the side windows. Six months into the two year closure, six 1000 watt high pressure sodium lamps were hung 1.5 m above water level, one above each tank of the two wetland systems to increase growth rates. The dense canopy of the wetlands proved very effective at light utilization. During the transition between first and second closure,

(a)

(b)

Fig. 2. The wetland plant lagoons (a) shortly after planting (spring 1991). Burlap was used to hold emergent plants and soil; (b) shortly after commencement of the closure experiment, September 1991; (c) Mark Nelson harvesting fodder from the human habitat wetland wastewater tanks. This fodder was fed to domestic animals and inedible plant material was composted.

on a clear sunny day (15 January 1994) outside solar insolation was measured with portable light meters as 1050 microEinsteins m^{-2} s^{-1} and above the plant canopy of a wetland near the glass it was 820 microEinsteins m^{-2} $s^{-1,}$ and above a wetland canopy with supplemental artificial lights light was 930 microEinsteins m^{-2} s^{-1}. For these systems, incident light at the water level below the plant canopy was 25 and 40 microEinsteins m^{-2} s^{-1}, respectively. Overall, plant productivity was much higher in seasons of greater insolation during the 2 year closure. For example, harvest records show that during 3 months of low light (November, 1992–January, 1993) fodder harvests from the wetland totaled 152 kg versus 242 kg harvested May–July 1993. During December 1991 and December 1992, light levels in the agricultural area measured by automatic electronic sensors averaged 9–10 Einsteins m^{-2} day^{-1} while in June 1992 and June 1993, incident light averaged 24–25 Einsteins m^{-2} day^{-1}.

(c)

Fig. 2. (*Continued*)

Table 1
Vascular plant species in the Biosphere 2 wetland wastewater treatment systems

Scientific name	Common name
Azolla caroliniana Willd.	Mosquito fern
Canna edulis Ker-Gawl.	Canna
Canna flacida Salisb.	Golden canna
Canna indica L.	Indian shot
Eichhornia crassipes (Mart.) Solms	Water hyacinth
Ipomea aquatica Forsk.	Water spinach
Lemna minor L.	Duckweed
Pistia stratoites L.	Water lettuce
Phragmites australis (Cav.) Steudel	Common reed
Sagittaria falcata Pursh	Wapato
Sagittaria montevidensis Cham. and Schlect.	Giant arrowhead
Scirpus californicus (C.Meyer)	Bullrush
Spirodela polyrhiza (L.) Schleid	Duckweed
Wolffia sp. (Horkel)	Water meal

3.3. Hydraulic loading and wastewater treatment

During the 2-year closure human habitat wastewater averaged 0.76–0.95 m^3 day^{-1}, domestic animal washdown averaged 0.66 m^3 $week^{-1}$ and lab water around 0.66 m^3 every 2 weeks. In practice, since the labs were designed to use no dangerous chemicals and no spills/accidents occurred, their effluent water was routed from the holding tanks directly to crop irrigation supply. An estimated total of 660–880 m^3 of wastewater was treated in the wetlands over the closure period.

Analytic data available to this paper were single analyses, so must be interpreted as only suggestive of system performance. BOD_5 was reduced from 123 mg/l in the holding tanks to 25 mg/l in effluent from the wetlands. Analysis for ammonium-Nitrogen and nitrate-Nitrogen showed that N was predominantly present as ammonium in the anaerobic holding tanks and wetlands, and was oxidized to nitrate in the crop irrigation tanks (Fig. 3). There was a predominantly reducing environment in the wetlands where dissolved oxygen levels in the wetland tanks were consistently low, typically measured around 1 mg/l.

3.4. Aesthetic and habitat creation benefits

The wetlands, which featured luxuriant vegetation including bright orange flowers on the canna lilies and purple water hyacinth flowers, had the appearance of a beautiful water garden rather than what is associated with a sewage treatment facility. The wetlands also provided habitat during the closure for many beneficial agricultural insects such as lady bugs, geckos, green anole lizards and even a Colorado River toad which ‘volunteered’ for the closure by stowing away in the wetlands.

4. Discussion

4.1. Problem areas and system modifications

Acceptability of the fodder by the domestic animals was a problem. While water hyacinth was accepted readily as a portion of their diet by the goats and chickens, during the last 6 months of closure, the goats only reluctantly and incompletely accepted canna/bullrush. To avoid overfilling of tanks and to save the labor involved in manual batch loading, hydraulic loading of the wetlands was converted to a flow-through design. Hardware was installed after the first closure experiment to permit easy sampling of both liquid and sediment portions of the holding tanks.

4.2. Role of wastewater regeneration in sustainable agricultural systems

The two-stage wastewater treatment systems accomplished their objective of providing a low-tech, low maintenance system for handling wastewater. In addition, fodder production from plant biomass was high, especially given the light limitations of the facility. The constructed wetlands were a source of aesthetic pleasure, as well as providing habitat for insects and other animals. For space life support

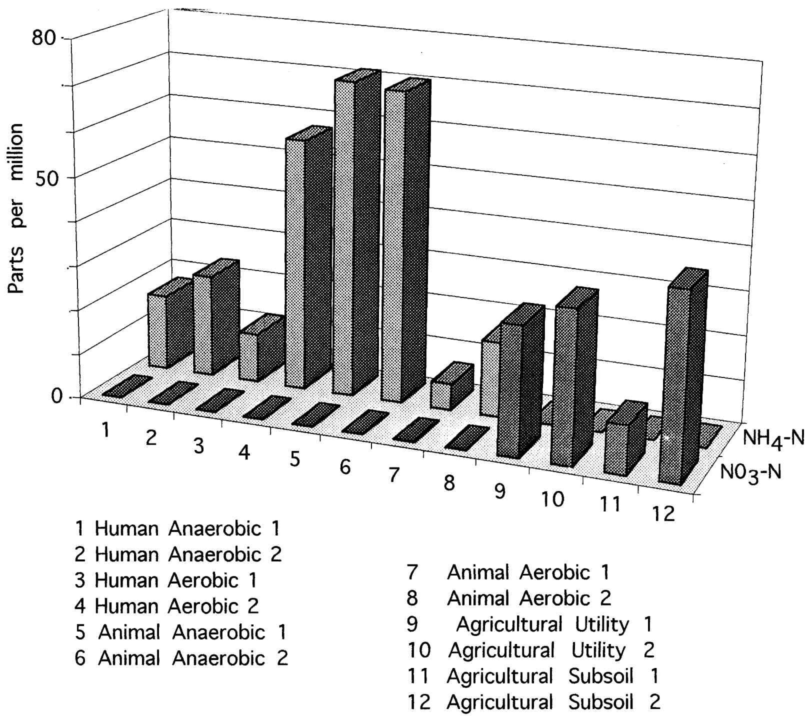

Fig. 3. Nitrogen in the form of nitrates and ammonium in the Biosphere 2 wastewater and agricultural irrigation systems.

systems, designers have increased interest in wetland approaches since they require less energy than high tech waste conversion approaches (such as wet oxidation or supercritical wet oxidation) and make available part of their original chemical bond energy (Swartzkopf and Cullingford, 1990).

Wetland sewage treatment has potential as a subsystem in sustainable agricultural systems. In closed ecological systems, and in the world's larger biospheric system, it is crucial to develop technologies that can utilize as resources what are now considered 'wastes'. The return of nutrients to food-producing soils is crucial to the maintenance of long-term fertility. This potential role of wetland sewage treatment systems goes beyond the mere 'containment' policy for minimizing loss of nutrients from soils and the contamination of groundwater (Nelson et al., 1993b).

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