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Ecological design applied

John Todd[a,b,*], Erica J.G. Brown[a,b], Erik Wells[b]

[a] *Ecological Design Program, School of Natural Resources, George D. Aiken Center,*
The University of Vermont, Burlington, VT 05405-0088, USA
[b] *Ocean Arks International, 176 Battery Street, Burlington, VT 05401, USA*

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Abstract

Over the past three decades ecological design has been applied to an increasingly diverse range of technologies and innovative solutions for the management of resources. Ecological technologies have been created for the food sector, waste conversion industries, architecture and landscape design, and to the field of environmental protection and restoration. The five case studies presented here represent applications of ecological design in five areas: sewage treatment, the restoration of a polluted body of water, the treatment of high strength industrial waste in lagoons, the integration of ecological systems with architecture, and an agriculturally based Eco-Park. Case #1 is an Advanced Ecologically Engineered System (AEES) for the treatment of sewage in Vermont, a cold climate. The facility treated 300 m^3 per day (79,250 gallons per day) of sewage to advanced or tertiary wastewater standards, including during the winter months. A number of commercial byproducts were developed as part of the treatment process. Case #2 involved the treatment of a pond contaminated with 295 m^3 per day (77,930 gallons per day) of toxic leachate from an adjacent landfill. A floating Restorer was built to treat the polluted pond. The Restorer was powered by wind and solar based energy sources. Over the past decade the pond has improved. There has been a positive oxygen regime throughout the water column, bottom sediments have been digested and the quality of the sediment chemistry has improved.

The biodiversity of the macrobenthos of the pond has increased as a result of the improved conditions. Case #3 involved the treatment of 37,850 m^3 per day (1 million gallons per day) of high strength waste from a poultry processing plant utilizing a dozen AEES Restorers. The technology has resulted in a 74% drop in energy requirements for treatment and has dramatically reduced the need for sludge removal. Currently, sludge degradation is proceeding faster than sludge accumulation. Case #4 includes several examples of buildings that utilize ecologically engineered systems to treat, recycle and permit the reuse of wastewater. The new Lewis Center for Environmental Studies at Oberlin College is a recent example of this trend. Case #5 describes the work that is leading to the creation of an urban, agriculturally based, Eco-Park in Burlington, Vermont. Waste heat from a nearby power station will provide year round climate control in a structure developed for food processing businesses, including a brewery, and for the onsite growth of diverse foods in integrated systems. We also describe a project to amplify the value of waste organic materials through biological conversion to high value products such as fish, flowers, mushrooms, soils amendments, and livestock and fish feeds. An ecologically designed fish culture facility will be an integral part of the Eco-Park complex. The project is intended to demonstrate the economic viability of integrative design in an urban setting and to address the important issue of locally based food production.

Keywords: Ecological design; Advanced Ecologically Engineered System (AEES); Waste conversion; Restorers; Applied ecology; Wastewater treatment; Integrated food production; Eco-Park

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[*] Corresponding author.
E-mail address: jtodd@cape.com (J. Todd).

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1. Introduction

For the past 30 years, the Todds and their associates have been applying the teachings of ecology to resource management and infrastructure support in both industrial and agrarian societies (Todd, 1977; Todd and Todd, 1980, 1984, 1994). This work has included the development of ecological technologies for food production, fuel generation, waste conversion, water purification, chemical detoxification, environmental restoration, and ecological innovation in architecture that created bioshelters. In 2002, the Lemelson-MIT program in innovation and invention recognized this effort as a significant new direction in the evolution of technology (Brown, 2002). Ecological design, engineering and economics are beginning to play a significant part in mainstream society.

We owe a great debt to the ecologists who saw their science as having a role to play in the design of future societies. In North America, the brothers Eugene Odum and Howard T. Odum laid out the conceptual framework for the practice of ecological design (Odum, 1959, 1971). By applying ecological theory, their students and colleagues have made significant contributions to technological problem solving (Mitsch and Jorgenson, 1989; Etnier and Guterstam, 1997). As we enter a new century it is important to reflect that the industrial era of the 19th and 20th centuries brought wealth and power to a number of cultures, but did so at the expense of the environment, biodiversity, and the stability of Earth’s self-regulating systems. The task of righting the balance between society and nature is essentially ecological. It requires that the wisdom of ecosystems be applied to a fundamental redesign of human support technologies. It has been cogently argued that such a redesign could reduce the negative human footprint on the Earth by up to 90% (Hawken et al., 1999). Such is the promise of applied ecology.

2. Putting theory into practice: five case studies in North America

Todd and Josephson (1996) described the precepts and theoretical foundations that provide the framework for the design of living technologies. From this theory has grown a technology referred to as Advanced Ecologically Engineered System (AEES). AEESs use the natural abilities of living organisms to break down macromolecules and metabolize organic nutrients typically found in wastewater and polluted water bodies. To date, they have primarily been designed either as tank-based systems for the treatment of point-source waste or floating systems placed on existing bodies of water that receive non-point-source pollution. Over the last decade, the implementation of AEES and other ecological technologies into sectors of mainstream society has progressed significantly through the work of Ocean Arks International (OAI).[1] This article provides an overview of the evolution of ecological technologies in the past decade and their relevance to our work in waste and wastewater treatment, environmental repair, architectural integration, food production, and the development of an agriculturally based Eco-Park. The application of these technologies are presented in a series of case studies that are recent or ongoing. Projects were selected based in part upon their availability to visitors. It is our desire to maintain working examples of ecological design for others to study and improve upon. To fully appreciate these ecological “engines”, with their biological complexity and diversity, direct contact with the systems themselves is often important.

2.1. *Sewage treatment in cold climates: south Burlington, VT AEES*

A tank-based AEES was constructed in south Burlington, Vermont in 1995 to determine if the technology is capable of treating sewage to high standards in a northern New England climate, particularly during the cold and short day-length seasons. The AEES facility was housed within a 725 m^2 (7800 ft^2) greenhouse (Fig. 1).[2] It contained two parallel treatment systems designed to treat 300 m^3 per

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[1] Ocean Arks International is a not-for-profit organization dedicated to the development of ecological design and its implementation into society.

[2] This facility was one of a series of AEES demonstration projects in four states sponsored by the US EPA through a grant to the Massachusetts Foundation for excellence in Marine and Polymer Sciences. Ocean Arks International was a subcontractor to the Massachusetts Foundation on all of these projects. Dr. Todd was the principal investigator. Living Technologies Inc. provided engineering, construction and operations on the Vermont AEES.

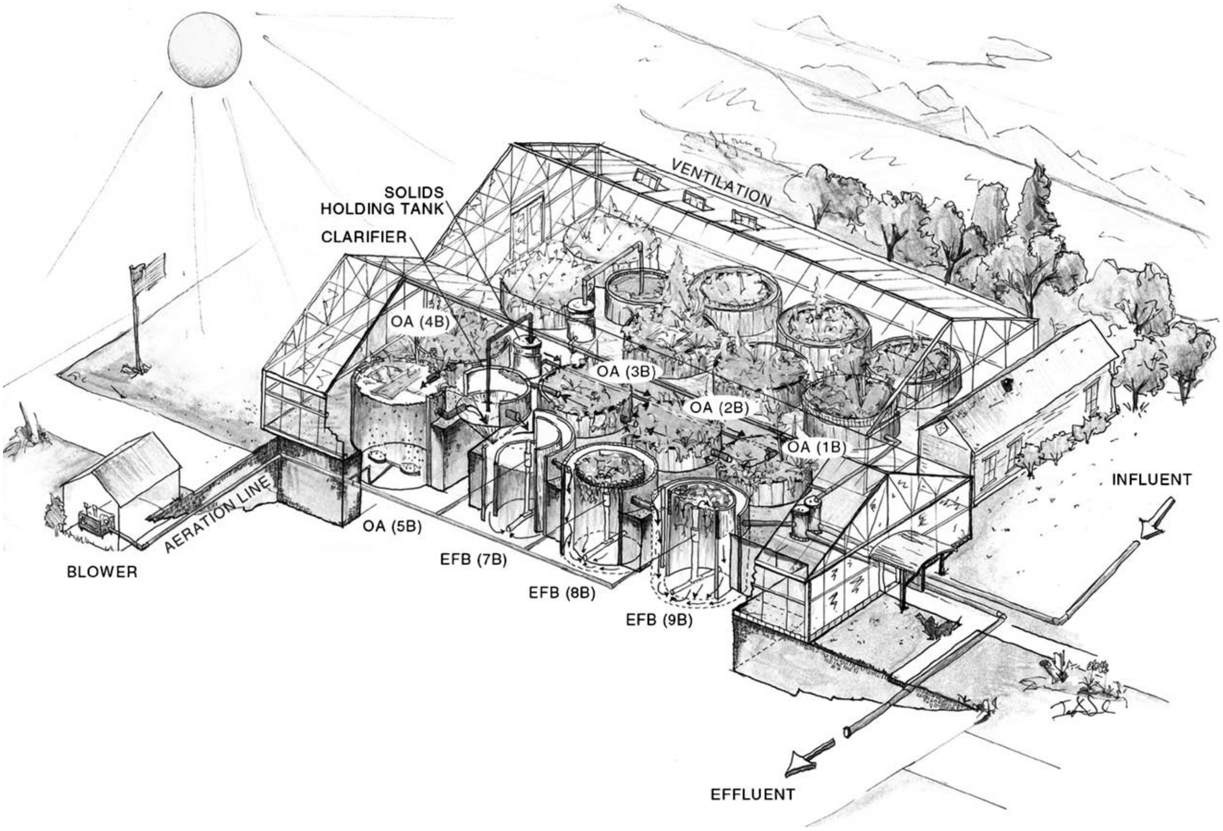

Fig. 1. Process diagram of the south Burlington, VT AEES. This facility is located adjacent to the city of south Burlington municipal wastewater treatment system. It treated 300 m^3 per day (80,000 gallons per day) of municipal wastewater to tertiary standards from 1995 through 1999. It is located next to a local brewery and is currently being converted into a waste conversion and food production facility. Illustration by Ian Ambler.

day (80,000 gallons per day) of sewage from the city of south Burlington to advanced tertiary wastewater standards for carbonaceous biochemical oxygen demand ($CBOD_5$), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), ammonia (NH_3), nitrate (NO_3) and total nitrogen (TN). The performance target for removal of fecal coliforms in the system was 2000 cfu/100 ml without disinfection (Fig. 3).

The Vermont AEES was biologically diverse. Over 200 species of vascular and woody plants were evaluated for their effectiveness and suitability for waste treatment between 1995 and 2000. Plants were evaluated for: (1) their ability to tolerate sewage, (2) the extent of the root zones, (3) disease and pest resistance, (4) ease of management, and (5) secondary economic value. The plants were physically supported on the surface of the water by rigid plant racks designed to provide gentle flow over the roots in a highly aerated and turbulent surrounding environment (Fig. 2). The system was designed to utilize microbial communities attached to plant roots, as well as flocculating bacteria in the open water, to affect treatment. Invertebrates, including micro-crustacea, and freshwater clams provided biological filtration, while snails and fish were incorporated into the design to digest residual biosolids.

The flow was split between two 150 m^3 per day (40,000 gallons per day) treatment trains with a hydraulic retention time (HRT) of 2.9 days. The facility was started in December 1995, operated at its design flow capacity by May 1996 and was maintained at this steady state until the end of 1999.

Fig. 2. Photograph of tank at the south Burlington, VT AEES. This planted aerobic tank is one of the first in a series of similar tanks used for treatment of municipal waste in Vermont. The roots of plants installed in racks on the top of the tank provide the necessary diverse microhabitats for effective and efficient treatment.

Each treatment train was comprised of nine tanks connected in series. Each tank was 4.6 m wide × 4.6 m deep (15 ft × 15 ft). Raw effluent entered and was mixed in an anoxic reactor. An ecological gas scrubber, employing higher plants and a soil/bark/compost media, was mounted over the anoxic reactor tank to control odors normally associated with raw sewage.

The wastewater flowed from the anoxic reactor into four aerobic reactors. Dense plantings were maintained on surface racks (Fig. 2). The waste then flowed to a clarifier covered with floating aquatic plants. Biosolids from the clarifier were recycled to the anoxic reactor or wasted. Downstream of the clarifier were three tanks containing ecological fluidized beds (EFBs) in series.[3] The EFB is in essence a submerged trickling filter capable of supporting higher plants mounted over an outer ring of open water. Benthic organisms, including mollusks, are physically supported by the media that comprises the inner part of the EFB. Depending upon water quality and their position in the series, the EFB's could be operated anoxically to aid denitrification, or aerobically for polishing and final filtration.

The Vermont AEES facility's performance has been described in detail by Austin (2000). The facility met and exceeded its design parameters, for $CBOD_5$, TSS, TKN, NH_3, NO_3^- and TN as well as fecal coliform bacteria (Fig. 3). A high level of performance was maintained even during the coldest months (Fig. 4). Phosphorus design standards were also met, but the AEES technology has yet to demonstrate phosphorus removal beyond what would be expected in a nitrifying activated sludge process.

One of the goals of the project was to grow organisms that not only provided treatment but also

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[3] United States Patent #5,486,291 23 January 1996 and United States Patent #5,618,413 8 April 1997.

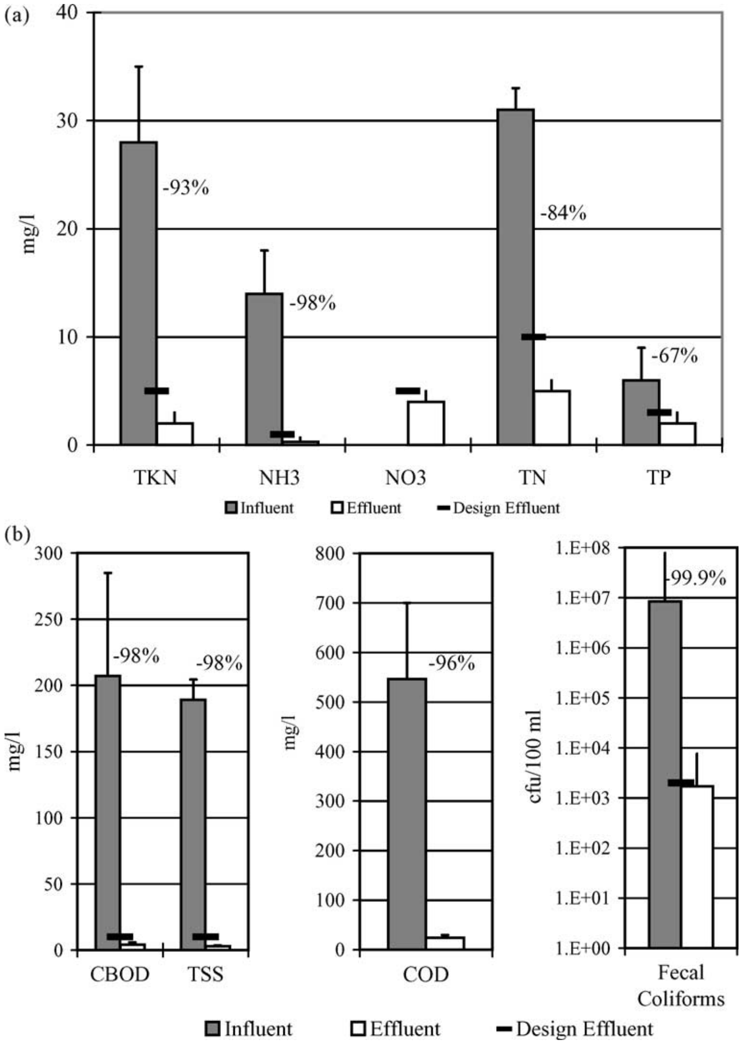


Fig. 3. Summary of influent and effluent data for the south Burlington, VT AEES. Influent and effluent water chemistry data presented below represent averages and standard deviations of weekly samples taken between May 1996 and December 1999. Black horizontal lines represent the design effluent for the system. Data source: Austin, 2000.

had potential economic benefits. Botanicals with economic value included young trees such as *Taxodium distichum* L. (bald cypress), *Zantadeschia aethiopica* L. (Calla Lily), and plants used for environmental remediation or wetland mitigation. Fish grown and harvested from the system included *Notemigonus crysoleucas* M. (golden shiners) and other bait fish, *Pimephales promelas* R. (fathead minnows), and ornamental fish including *Carassius auratus* L. (goldfish) and Japanese koi. All of the fish species fed upon organic material and plankton produced internally within the facility.

One of the most striking aspects of the Vermont facility was its beauty. It remains a frequently visited educational facility and is currently operated as a test facility for the treatment of different types of high strength organic wastes including brewery wastes. It is also a site where new economic byproducts from both liquid and solid waste conversion processes are being developed.

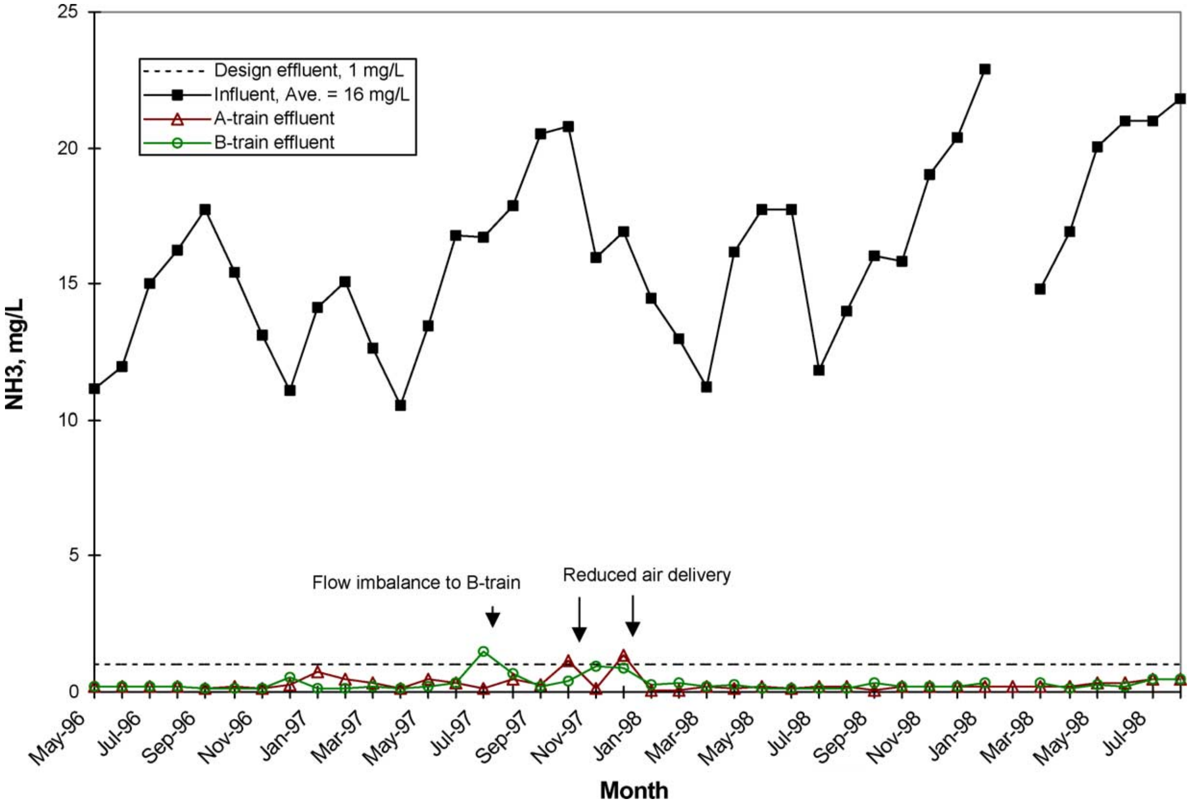


Fig. 4. Mean monthly ammonia influent and effluent concentrations. Ammonia effluent concentrations were consistently below design standards despite seasonal differences and varying influent loads. Units are mg/l. Graphic and data source: Austin, 2000.

2.2. Environmental restoration: Flax Pond, MA

Flax Pond is a 15 acre (6 ha) pond in Harwich, Massachusetts that has been heavily impacted for decades by leachates from an adjacent landfill and unlined septage holding lagoons. By 1989, the pond was closed to recreation and fishing because of contamination caused by the daily intrusion of 295 m^3 (78,000 gallons) of leachate from the landfill (Horsley et al., 1991). The pond had low oxygen levels, high coliform counts, excessive sediment build up, and organic pollutants in the water column including volatile organic compounds (VOCs). Macro-benthic organisms were absent from many of the bottom sampling stations. Flax Pond had unusually high sediment concentrations of total phosphorus (300 times greater) and iron (80 times greater) compared with other Cape Cod ponds (K.V. Associates, 1991). Ammonia levels in the sediments were found to be as high as 8000 mg/kg. The pond is delineated into an eastern zone and a western zone; the cloudier eastern zone is the predominant zone of impact from the landfill (Fig. 5). The pond had a maximum depth of 6 m and stratifies in its western end.

In the autumn of 1992 construction of the first floating Pond Restorer was completed and anchored in the eastern end (Fig. 6). It employed a windmill and solar panels for electrical generation and was capable of circulating through its nine cells up to 380 m^3 per day (100,000 gallons per day) of water drawn from the bottom of the pond. The first three cells were filled with semi-buoyant pumice rock that supported diverse benthic life including freshwater clams of the genera *Unio* and *Onodonta*. Since phosphorus was limiting in the pond's water column, we added a slow release form of a clay-based soft phosphate to the EFB cells in the Restorer. We routinely undertook bacterial augmentation and mineral enrichment in the first three cells.

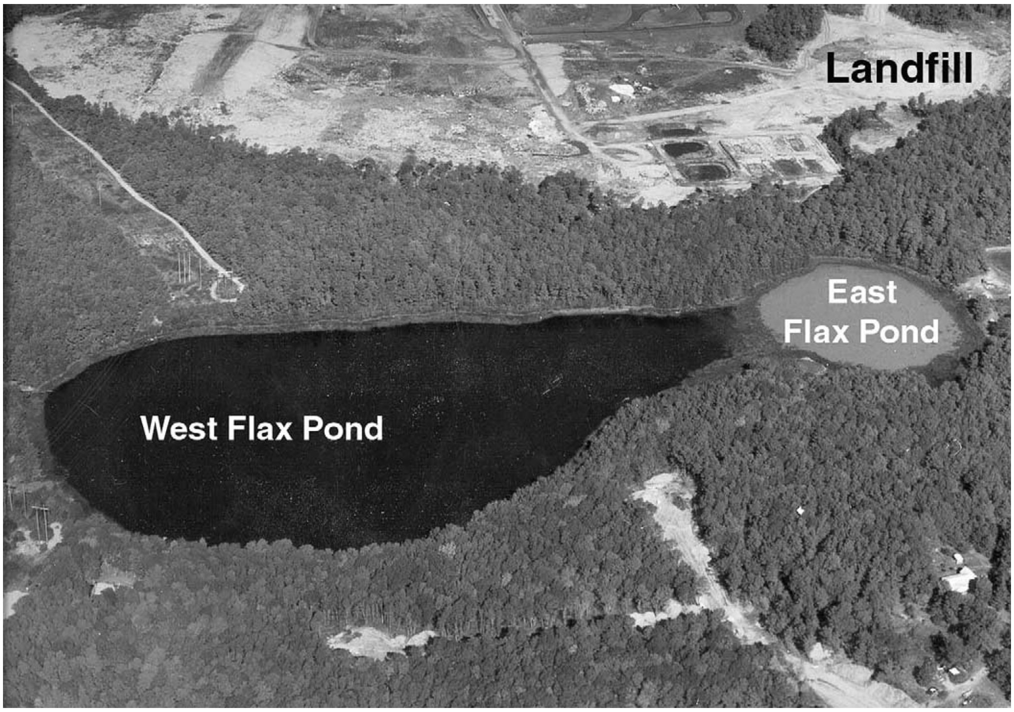


Fig. 5. Aerial photograph of Flax Pond and surrounding landscape, MA. The eastern end of Flax Pond receives the majority of the incoming groundwater leachate from the nearby landfill. There is little mixing between the eastern and western ends of the pond. The Pond Restorer is located in the eastern end.

The final six cells supported over two dozen species of terrestrial plants on racks. The Restorer was not operated during the winter months to allow the pond to freeze completely.

The first noticeable effect of the Restorer on the pond was the return of a positive oxygen regime to the bottom. By 1995, the sediment depth throughout the pond had been reduced by an average of 64 cm representing a total of 38,000 m^3 of digested sediments.

Between the years 1999 and 2001, dramatic changes in the sediments took place, including large reductions (exceeding 50%) in total phosphorus, ammonia and TKN (Figs. 7 and 8). Total iron increased in the western end and decreased slightly in the eastern end of the pond. Alkalinity followed a similar pattern. We do not know which internal mechanisms were involved in the changes in sediment phosphorus, however TKN reduction must be associated with nitrification and denitrification in the sediments (nitrates were below detectable limits in all sediment samples in both 1999 and 2001).

Water clarity and the overall health of the pond has improved over the past decade, and biodiversity has increased. The physical part of the original Restorer system is beginning to age after a decade of operations, and in 2002 it will be shut down and replaced with three floating upwelling windmills. We do not know if Flax Pond will be able to maintain itself, including its current positive oxygen regime, with the minimal management and low budget approach planned for the future. Large volumes of polluted leachate from the adjacent landfill are projected to continue impacting Flax Pond for at least next 20 years.

2.3. Organic industrial wastewater treatment: floating AEES Restorer, MD

In the late 1990s, the design of the Pond Restorer used in Flax Pond evolved into a linear AEES Restorer design for use on new and existing wastewater treatment lagoons (Fig. 9). This technology combines the benefits of the small footprint AEES tank-based

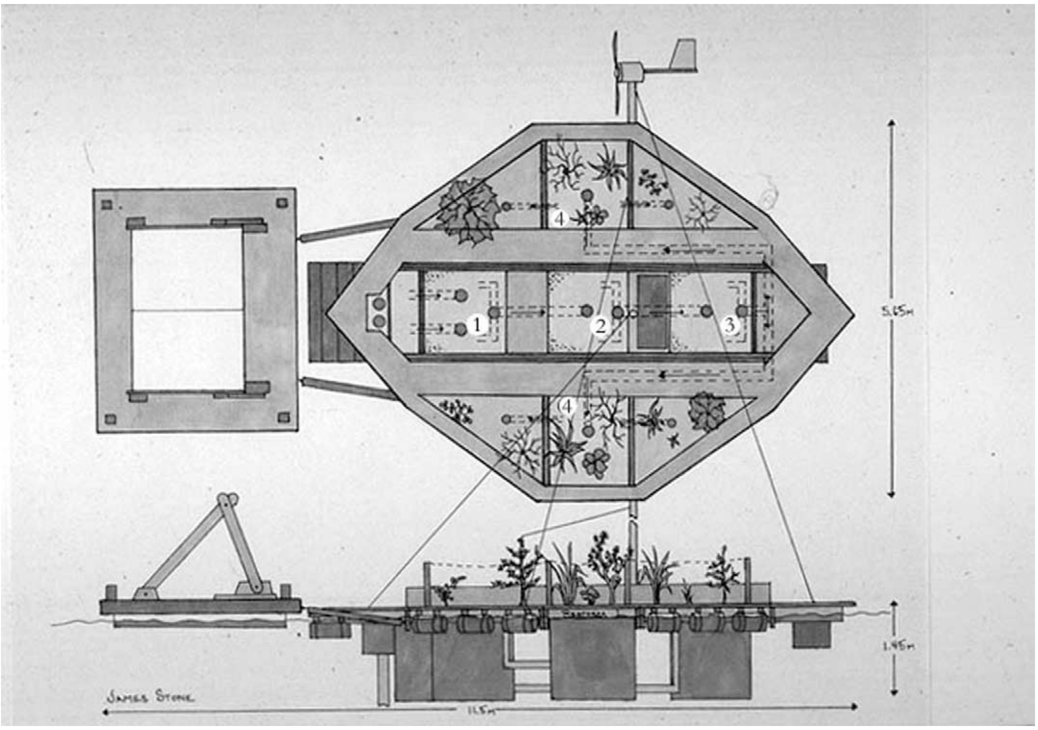


Fig. 6. Diagram of Restorer installed in Flax Pond, MA. This Restorer houses three ecologically fluidized beds (EFBs) and six cells containing wetland plant communities. Water is drawn from the bottom of the pond and circulated through the EFBs in the center of the Restorer and then out through the wetland cells. Circulation rate is 378 m^3 per day (100,000 gallons per day). Illustration by James Stone.

technology (Section 2.1) with the simplicity and efficiency of constructed wetlands. The first large-scale wastewater application of the floating AEES Restorer technology was installed in June 2001 on a wastewater treatment lagoon that treats 3785 m^3 (1 million gallons per day) of high strength poultry processing waste in coastal Maryland. The installation was a retrofit design to upgrade the efficiency and treatment of an existing lagoon treatment system. The Restorers were installed in a 34,100 m^3 (9 million gallon) storage lagoon downstream of a lagoon that had been run as a Sequencing Batch Reactor (SBR) for over 15 years. Twelve Restorers run 43 m (140 ft) each across the lagoon and are secured from the banks in multiple cells, creating a serpentine flow pattern with floating baffles. Twenty-five species of native plants (25,000 individuals) were installed in plant racks on the outside edges of the Restorers (Fig. 10). The plants are a critical element in the technology. Their roots provide surface areas and nutrient support for microbial communities, some nutrient uptake and they shade/inhibit suspended algae in the lagoons. Water is treated in the open areas on each side of the Restorers with fine bubble linear aerators installed at the bottom of the lagoon. The center zones of the Restorers, with suspended fabric media provide surface area for attached growth microbial communities and as such are submerged, aerobic, fixed film reactors.

The transition between the old SBR system and the new Restorer lagoon took place in October 2001. Although it is too early to present definitive quantitative data, qualitative successes of the project in these early stages are worth noting. Since start-up of the Restorer system, effluent standards have not exceeded state permit levels. The electrical energy use in the lagoons has been reduced by approximately 74% compared to the former SBR system. Energy reduction is the result of higher biological reaction rates in the Restorer lagoon and the efficiency of the new aeration design. Sludge has been trucked for 20 years from the

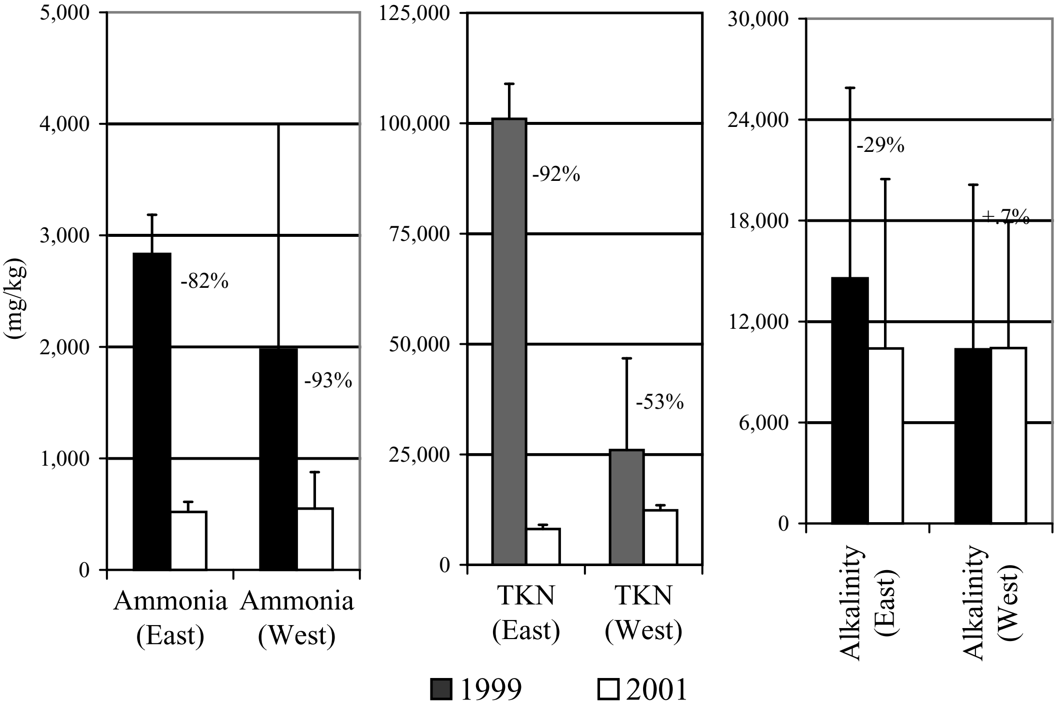


Fig. 7. Sediment nitrogen data summary for Flax Pond, MA (1999 and 2001). The graphs show means of three samples in the eastern end of the pond and four samples in the western end. Sample sites were identical between the 2 years. A certified laboratory in Massachusetts analyzed the samples. Bars show standard deviations. Changes in sediment chemistry are noted as percents for each parameter.

poultry processing plant for land application at nearby farms. The sludge comes from a variety of locations within the wastewater system, including the lagoons. Since installation of the Restorers the average truckloads of sludge leaving the processing facility have decreased significantly. This overall sludge reduction is the direct result of reduced sludge coming from the Restorer lagoon. Operation of the former SBR system required wasting of sludge for 8 h every day from the lagoons. Following installation of the new Restorer system, sludge is wasted for approximately 1 h every few weeks. In addition, 45 sludge judge samples have been taken monthly within the Restorer lagoon. Since August 2001 total sludge levels have decreased by approximately 10 cm (4 in.). This decrease indicates that sludge degradation is faster than sludge accumulation, even as the lagoon treats waste. When the project completes its first full year of operation, quantitative data will be available to accompany these early qualitative notes.

We have recently completed an AEES Restorer for the treatment of canals into which raw sewage is discharged in the city of Fuzhou in southern China. The first phase of the project involves cleaning up a 600 m stretch of the Baima canal. If successful, the project will be expanded to include up to 80 km of polluted canals in the city.

2.4. Architectural integration: Oberlin College, OH

In recent decades architecture has begun to include ecologically designed systems within structures for air purification, humidity control, water re-use, waste treatment and food production. The bioshelters developed by the Todds were highly integrated ecologically designed systems for living and life support (Todd and Todd, 1994).

A number of new buildings have employed ecologically engineered technologies for waste treatment, water reuse and education including the Ontario,

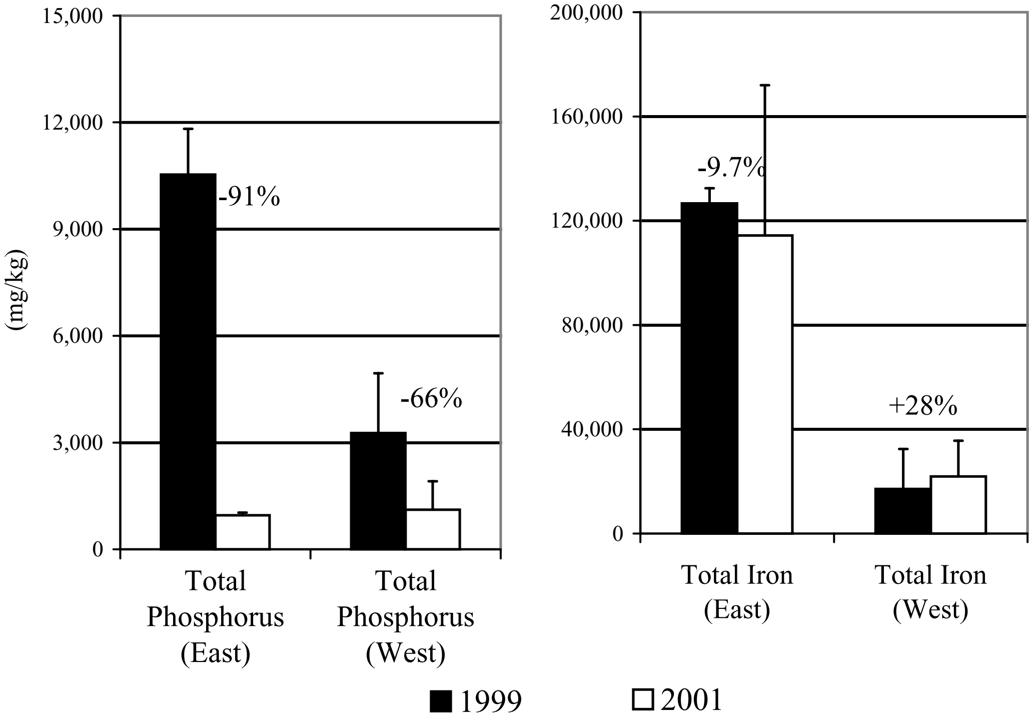


Fig. 8. Sediment phosphorus and iron data summary for Flax Pond, MA (1999–2001). The graphs show means of three samples in the eastern end of the pond and four samples in the western end. Sample sites were identical between the 2 years. A certified laboratory in Massachusetts analyzed samples. Bars show standard deviations. Changes in sediment chemistry are noted as percents for each parameter.

Canada, Boyne River School and the Kitchener/ Waterloo YMCA rural campus. The most recent of these is the Lewis Environmental Studies Center at Oberlin College in Ohio. The building itself is an outstanding example of high performance and sustainable design and integration with an ecologically integrated landscape. The building includes renewable energy, natural day-lighting and non-toxic and recyclable materials (Fig. 11). Within the structure is an AEES system for sewage treatment and biological research. This system, similar to the Vermont AEES, includes tanks connected in series and a constructed wetland within the building (Fig. 12). The tanks support a diverse community of tropical and temperate plants. The purified wastewater is sterilized with UV before reuse in the toilets in the building.

There is a growing interest in redefining the functioning of buildings in ecological terms. This is driving some architects towards conceptualizing buildings as "organisms". New light transmitting designs and self-regulating technologies optimize internal climates and support a diversity of ecological elements within the buildings. Nature is increasingly being brought indoors for practical and aesthetic reasons. No where is this better expressed than in the Alterra Institute building in Wageningen, Holland (Steiner, 2000). The Ecological Design Studio at the University of Vermont is applying these concepts to the retrofit of aging campus buildings.

2.5. Integration of industrial and agricultural sectors: proposed Eco-Park in Burlington, VT

Ecological design concepts are starting to be applied to the development of integrated economic systems in an industrial context. One challenge of applied ecology is the creation of new living technologies capable of supporting the infrastructures of human societies. An Eco-Industrial Park has been defined as, "a community of businesses that cooperate

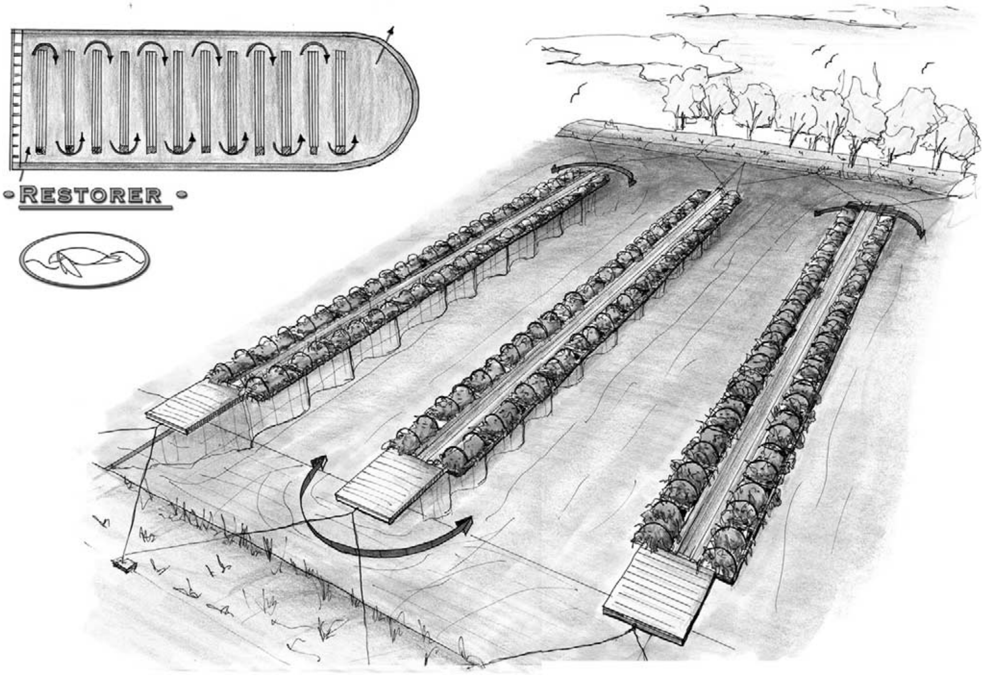


Fig. 9. Drawing of lagoon with floating AEES Restorers. This drawing shows the serpentine flow pattern through the AEES Restorer system installed on a wastewater treatment lagoon. Also shown are the fixed-film reactors installed beneath the planted Restorers. Illustration by Ian Ambler.

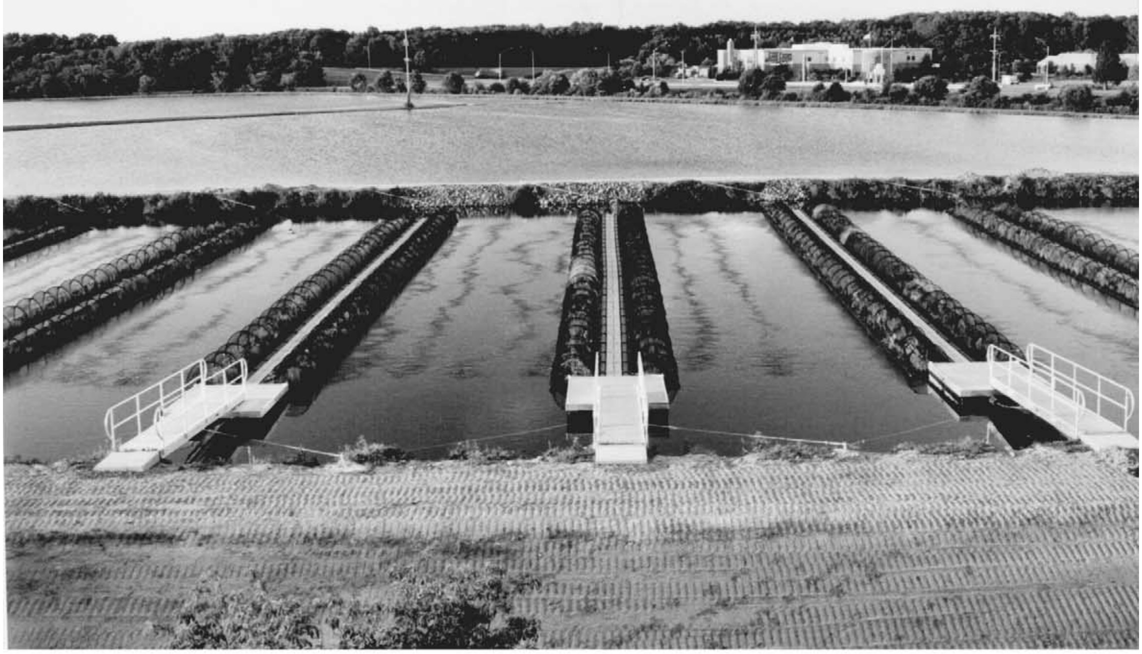
with each other, and with the local community, to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat) leading to economic gains, improved environmental quality, and equitable enhancement of human resources for business and local community" (President's Council on Sustainable Development, 1996).

The city of Burlington and the Intervale Foundation established the Intervale Community Enterprise Center (ICEC) to develop a year round, agriculturally based Eco-Park in a 280 ha flood plain within Burlington's city limits. The Eco-Park will derive most of its energy from the utilization of waste heat from the 53 MW McNeil power station. The McNeil power station, one of the nation's largest wood chip fired electrical generating facilities, is situated in the Intervale.

The project has brought together a number of allied businesses including a brewery, several food processors, a restaurant, and a host of Intervale growers and suppliers to the Eco-Park. The University of Vermont's ecological design studio will also be housed in the complex. The structure that will support the project combines greenhouses with a conventional light manufacturing facility in a 3800 m^2 (40,900 ft^2) structure. The complex, to be completed in 2003, will be heated with hot water from the power station, thereby utilizing energy that is now wasted.

The food culture team at OAI has been developing some of the agricultural components for the Eco-Park. Our approach has been to start with readily available organic wastes and through ecological processes convert the wastes to high value products. Our goal is ecological and economic amplification of organic materials in an integrated manner similar to that developed by Yan and Ma (1991). On a pilot scale the materials we are using include spent grain from a local brewery, straw, and bedding from an organic poultry operation. There are several stages in the conversion of materials.

Stage 1: The organic materials are blended, pasteurized and inoculated with oyster mushroom spawn (*Pleurotus ostreatus* (Jacq: Fr.)). The substrate is placed in plastic bags punched with holes and placed



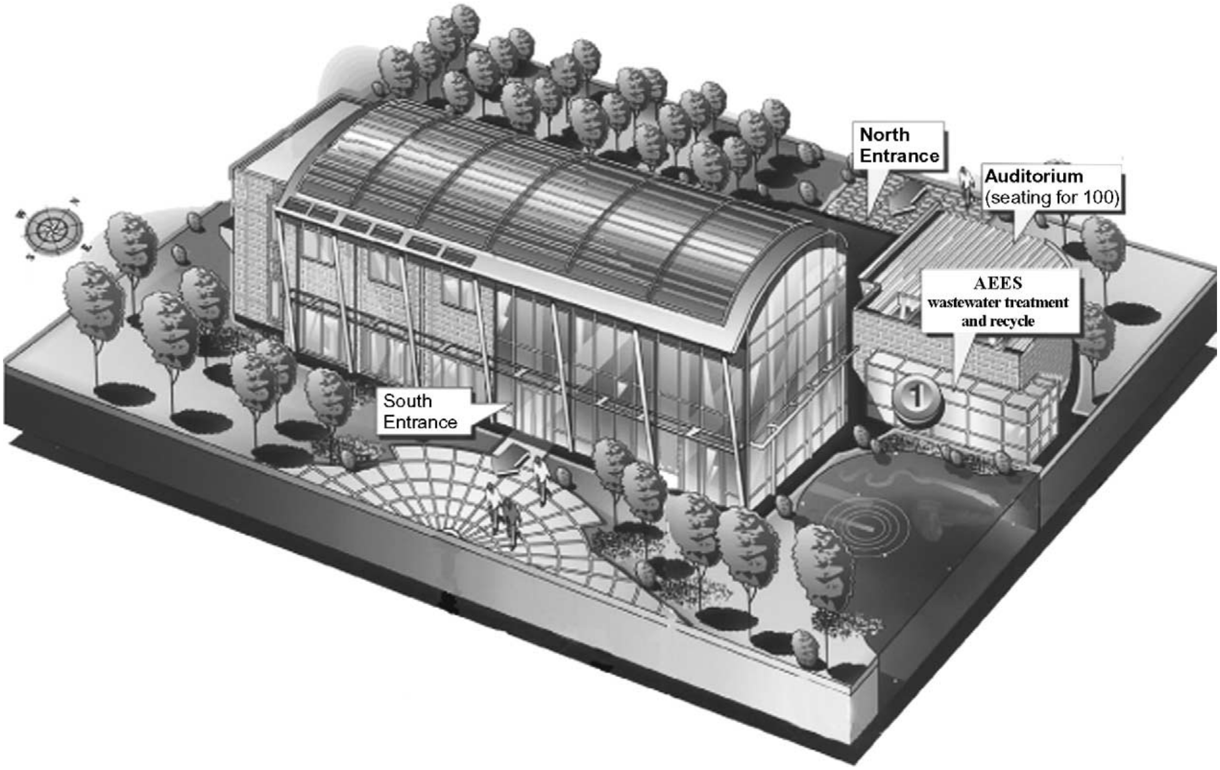


Fig. 11. Diagram of Oberlin College, OH sustainable building project.

in a mushroom incubator room. When the bags are fully colonized by the mushroom mycelium they are transferred to a grow room for fruiting and harvest. Biological efficiency of conversion, the ratio of wet weight of harvested mushrooms to the dry weight of the substrate, has exceeded 60%. After harvest the remaining substrate has the potential to be used as a high quality animal feed for livestock. In the process of mushroom production the vegetative forms of fungi colonize the straw and spent grains and produce essential amino acids such as lysine. Tests with cattle and the fish tilapia have demonstrated a ready acceptance of the material.

Stage 2: The spent mushroom substrate is placed in earthworm or vermiculture chambers. The earthworms rapidly converted the materials to enriched compost. The earthworms, a product of the process, were then blended with aquatic plants, *Azolla* sp. (water fern) and *Lemna* spp. (duckweeds), to produce protein-rich fish feeds.

Stage 3: The mushroom/earthworm based compost is then utilized in the growing of tropical plants in pots and the culture of salad greens. No additional fertilization to the compost is required for the production of greens. After several harvests of salad greens the medium is then utilized as a soil amendment or

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Fig. 10. Photographs of AEES Restorers in a poultry processing wastewater lagoon, MD. The top photograph shows five of the 12 Restorers installed in sequence on a wastewater treatment lagoon for poultry processing waste in Maryland. Each Restorer is 5 m wide and 44 m long. Gentle linear aeration in the open water channels provides efficient mixing and aeration. The diverse plant communities are shown close-up in the bottom photograph. Plant roots grow directly into the water column and provide the necessary surface area for efficient attached growth treatment.

Fig. 12. Photograph of AEES at Oberlin College, OH.

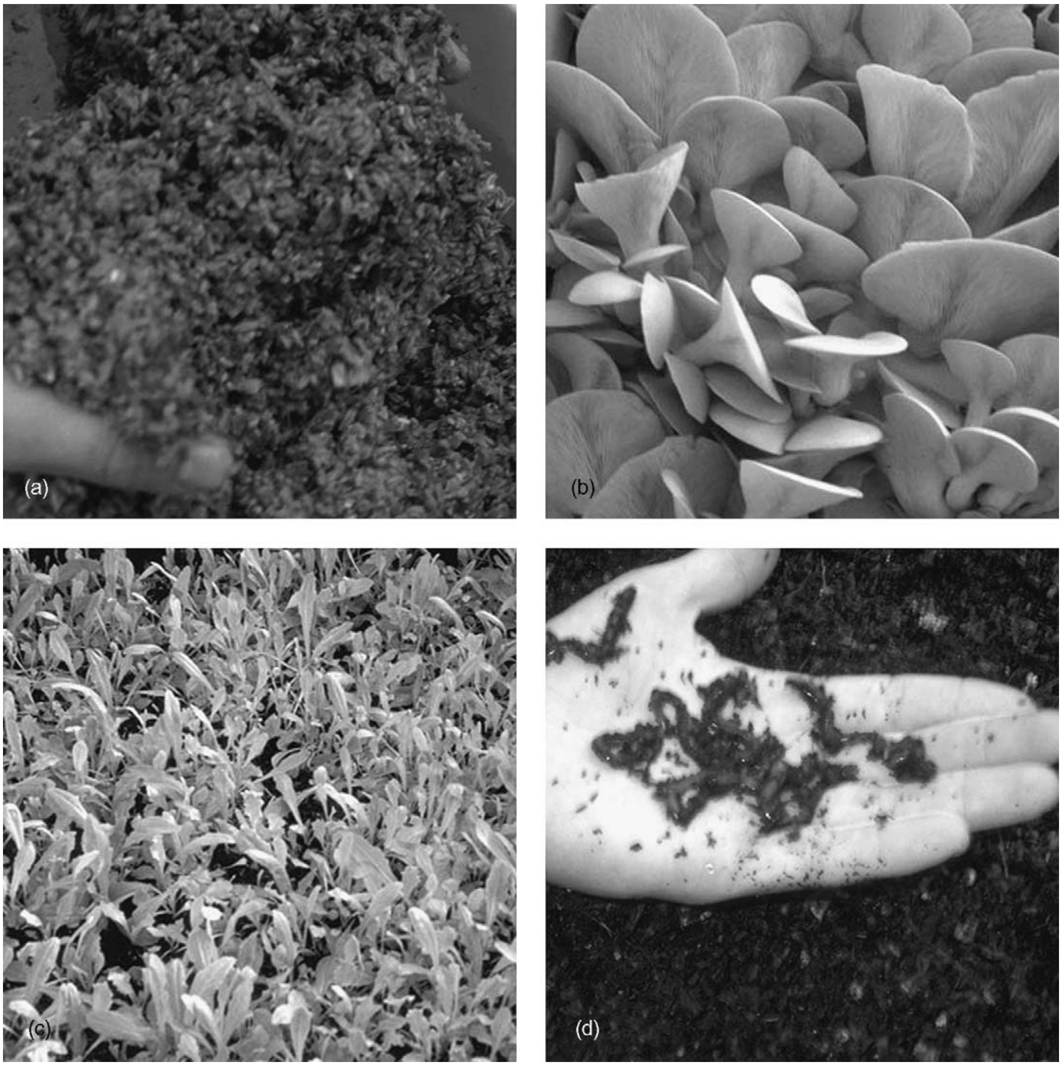

Fig. 13. Photographs of integrated waste conversion and food production, VT. (a) Spent grain from a local brewery provides the substrate for red-worm, (b) oyster mushroom, (c) salad greens production, (d) mushrooms and greens are sold to a local restaurant and food cooperative and worm castings can be harvested and sold to local gardeners.

as a potting soil. The composite photograph (Fig. 13) shows the brewery waste substrate, the mushroom culture, the earthworms, and salad greens under cultivation. At the new Eco-Park, we will increase the conversion of waste materials from the current pilot scale, to a system capable of handling up to 15 t of organic material on a daily basis.

Another key component in the design of integrated food systems for urban settings is aquaculture. The food team at OAI has designed recirculating systems based upon four tank modules for the culture of aquatic animals. To date, we have successfully cultured *Oreochromis* sp. (tilapia) and *Perca flavescens* M. (yellow perch) in these systems. The illustration (Fig. 14) shows the relationship between four ecological cells to support fish during their culture. The illustrations depict how the aquaculture systems work. The fish are isolated in Cell #1. They are fed algae turf screens from the cells downstream and zooplankton that flow into the tank in the recirculating water. Cell #2 converts fish wastes to stable sediments that support rooted aquatic plants and filtering organisms. Subsequent cells continue to improve water quality and convert the nutrients into internal food webs. Horticultural crops (Fig. 15) are also incorporated into the design to provide water quality improvement and additional products.

Stocking rates for yellow perch were one fish per 9 l and for the tilapia up to one fish per 7.5 l. The system is designed to produce feeds for the fish

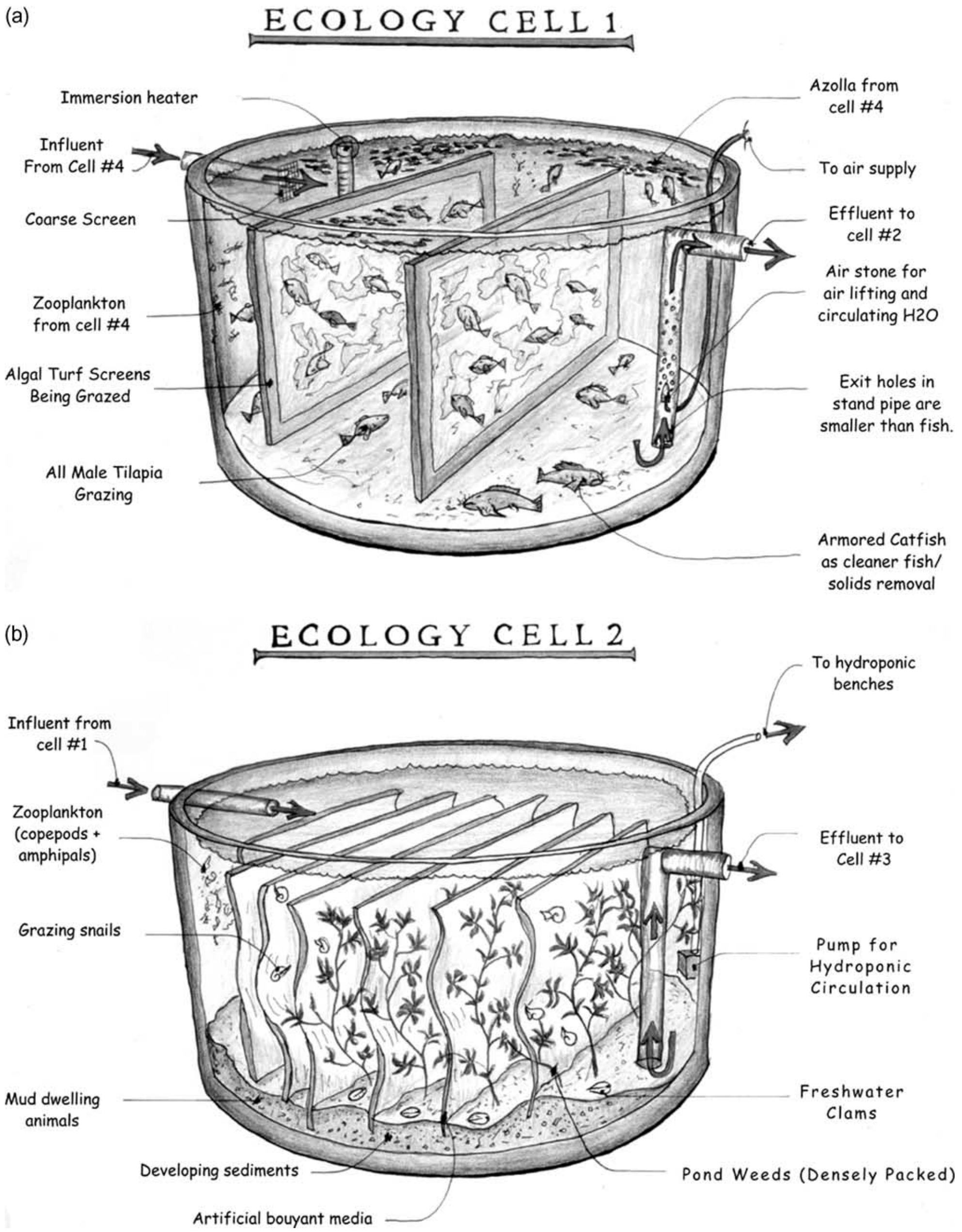

Fig. 14. Drawing of ecological aquaculture tanks used in research train, VT. Illustrations by Ian Ambler.

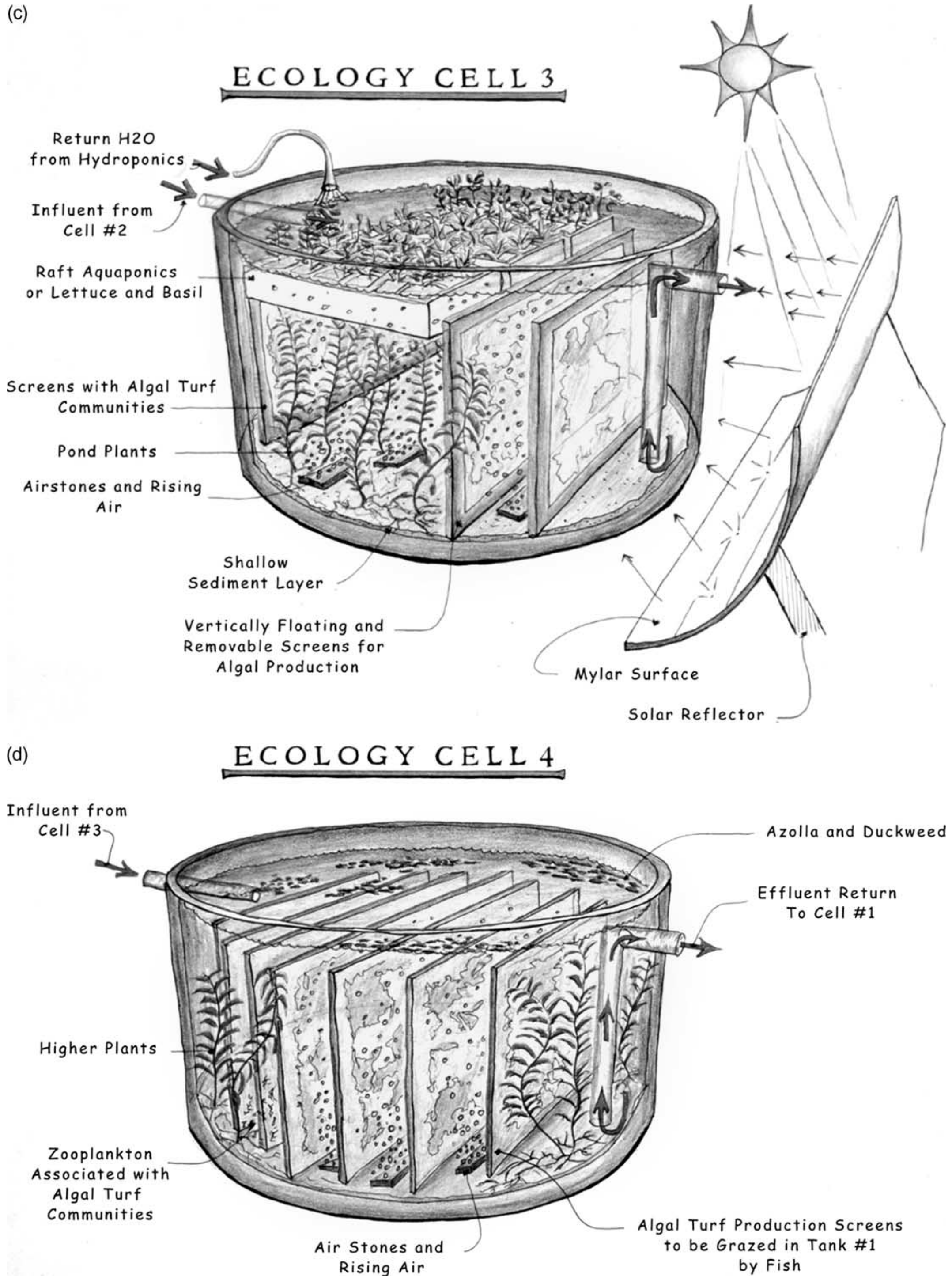

Fig. 14. (*Continued*).

Fig. 15. Photograph of tomato plants grown hydroponically in an ecological aquaculture research train, VT.

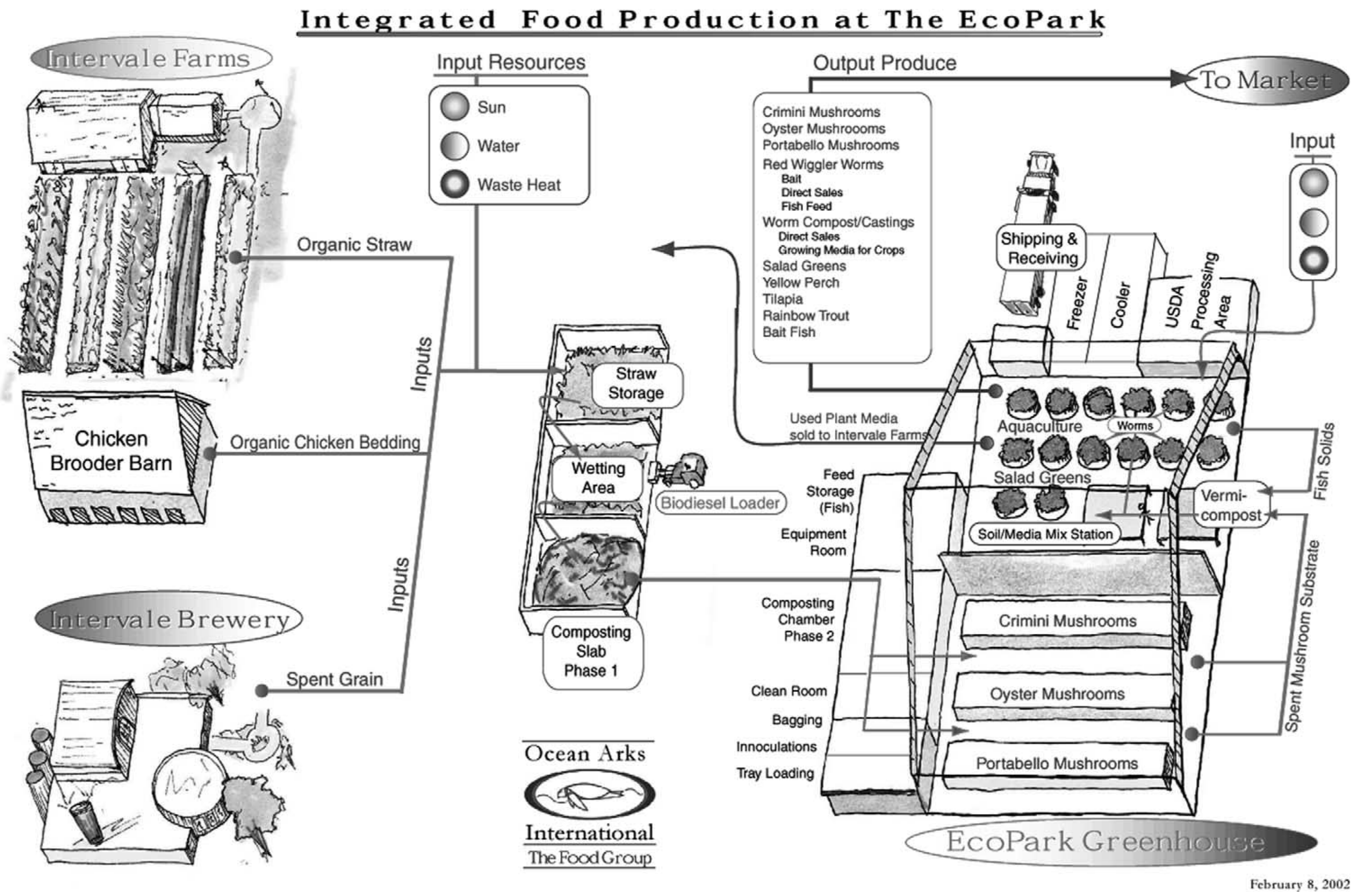

Fig. 16. Flow scheme of Eco-Park proposed for the Intervale Burlington, VT. Illustration by Ian Ambler.

internally, including attached algae turfs and their associated communities, floating aquatic plants including *Lemna* and *Azolla*, zooplankton, and snails. External feeds to the system include earthworms and commercial feeds. These ecosystem based fish culture systems have proven to be efficient. The feed conversion ratios (FCR)[4] calculated on the basis of external feeds added to the system have been less than 1. Since feed conversion ratios of 1.5–2.5 are the norm for conventional aquaculture (McLarney, 1987), we expect that the difference is due to the ability of the system to produce its own fish feeds internally.

Fig. 16 depicts the layout of the food system currently being developed at the Eco-Park. The multiplicity of pathways for nutrients and materials to flow in the production of a diversity of crops is an integral part of ecological design. If such an approach proves to be economically viable in an urban setting, as we predict it will be, the larger issue of food security can be addressed through the application of applied ecological concepts.

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[4] The FCR is the ratio of the dry weight of external feeds to the total weight gain of the fish.