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Thinking big with whole-ecosystem studies and ecosystem restoration—a legacy of H.T. Odum

William J. Mitsch[a,*], John W. Day, Jr.[b]

[a] Olentangy River Wetland Research Park, The Ohio State University, 352 W. Dodridge Street, Columbus, OH 43202, USA
[b] Department of Oceanography, and Coastal Sciences and Coastal Ecology Institute,
School of the Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, USA

Abstract

Whole-ecosystem studies are in situ ecological studies and experiments of such a spatial and temporal scale as to include most if not all processes of the ecosystem. Principles of self-organization and self-design are key to whole-ecological function and often do not occur as vibrantly or conclusively at smaller scale experiments. Ecological feedback caused by organisms (e.g., beavers, plants that manage hydrology, ecosystem engineers, top-down control), pulses caused by events such as fire and floods, and emergent ecosystem properties caused by human wastes, recycling, and hydrologic modification are difficult if not impossible to be properly studied in small-scale experiments. Large-scale whole-ecosystem studies were pioneered in the 1960s and 1970s by H.T. Odum and colleagues with large drop nets in Texas coastal bays, rain forests enclosures in Puerto Rico, created coastal ponds in North Carolina, and sewage application to cypress swamps in Florida. The study in Florida investigated effects of wastewater additions to wetland function in cypress domes but unexpected fire in the experimental area led to adaptive research and the study of fire in field research and models. More recently we have been engaged in whole-ecosystem experiments, partially inspired by the work of Odum, at created wetlands in northeastern Illinois to investigate effects of water turnover on ecosystem function and in Ohio to provide insight on the long-range large-scale effects of hydrology and macrophyte planting on ecosystem function. We have also carried out major ecosystem-scale studies in coastal Louisiana, investigating the value of these ecological systems in treating wastewater and restoring lost landscape in coastal Louisiana. These studies in the Midwest and Mississippi delta form the basis of determining design standards on creating and restoring wetlands in the Mississippi River Basin to reduce the Gulf of Mexico hypoxia and regain many lost ecosystem functions over a large part of North America.

Keywords: Whole-ecosystem studies; Ecosystem restoration; Temporal scale; Mississippi river basin; Ecological engineering

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> *Obtaining data on biomass representative of the large systems of nature such as forests and seas is a very difficult task that has occupied ecological research for 50 years with thousands of methods and varying results. When small spots are studied or small samples taken, the data are not representative because of the large statistical variation that is characteristic of most ecosystems. Efforts to sample large sections of systems are laborious and expensive.*
>
> –H.T. Odum (1971, *Environment, Power, and Society*)

1. Introduction

Ecology is studied at many different scales—microcosms, mesocosms, whole ecosystems, and land-

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* Corresponding author. Tel.: +1-614-292-9774; fax: +1-614-292-9773.
E-mail addresses: mitsch.1@osu.edu (W.J. Mitsch), johnday@lsu.edu (J.W. Day Jr.).

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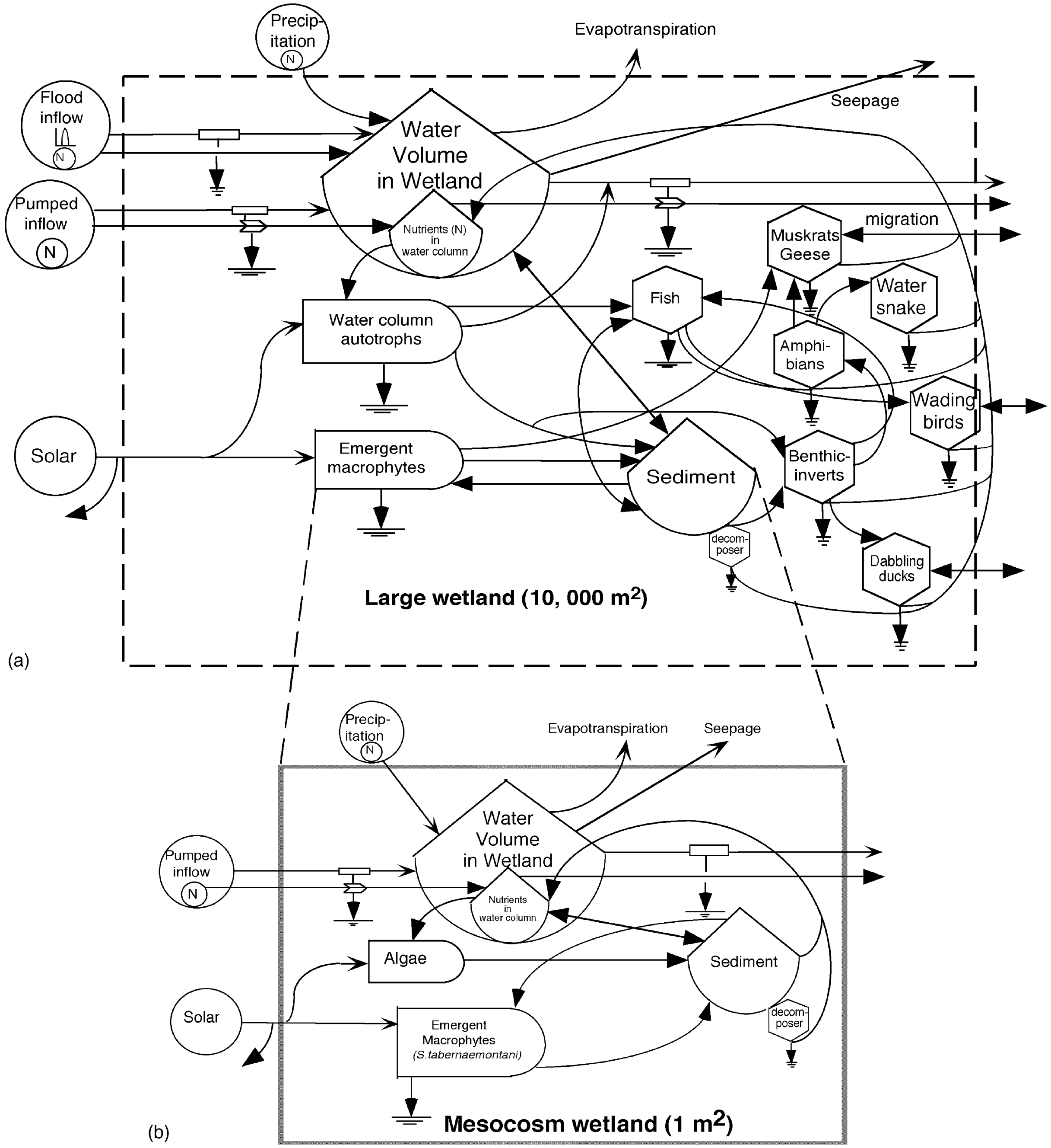


Fig. 1. Contrast in ecosystem complexity between (a) whole-ecosystem experiment wetland (1 ha) and (b) mesocosms wetland tub (1 m^2) at Olentangy River Wetland Research Park. From Ahn and Mitsch (2002).

scapes. This paper is about the development of whole-ecosystem studies in the USA from the early 1960s to the early 2000s and the contribution of H.T. Odum to that approach. *Whole-ecosystem studies* are defined here as in situ ecological studies of such a spatial and temporal scale as to include most if not all processes of the ecosystem. The importance of whole-ecosystem studies is more than just large size. For example, a mesocosm experiment may investigate the effects of nutrients on plants but a whole-ecosystem study is needed to investigate the role of nutrients on ecosystem functions, with plants being affected by the nutrients but also at the same time by herbivory, decomposition, sedimentation, and a host of other factors that are not independent of the nutrient inflow. A whole-ecosystem study purposefully does not simplify an ecosystem to derive cause and effect more easily; it attempts to include many more pathways and feedbacks in the system than do simpler systems (Fig. 1; Ahn and Mitsch, 2002). Theories now called self-organization, self-design, ecosystem engineering, and practices such as ecological engineering, adaptive research and ecosystem modeling emerged from whole-ecosystem studies; the impact of whole-ecosystem research on the teaching of ecology has been enormous.

The principles of self-organization and self-design are key to whole-ecosystem studies and often do not occur at smaller space and time scales (Mitsch and Jørgensen, 2004). Ecological feedback caused by organisms (concepts rediscovered as ecosystem engineers and top-down control), pulses caused by events such as fire and floods, and emergent ecosystem properties caused by human wastes, recycling, and hydrologic modification are key aspects of these studies.

Whole-ecosystem research has been carried out by many investigators on a wide array of ecosystems, e.g., forests (e.g., Likens et al., 1977; Sullivan, 1993; Beier and Rasmussen, 1994), lakes (e.g., Schindler, 1977; Schindler et al., 1997; Carpenter et al., 1996, 1998) and wetlands (e.g., Odum et al., 1977; Woodwell et al., 1979; Mitsch et al., 1995, 1998). Schindler (1998) reluctantly concluded that “whole-ecosystem experiments appear to be losing favor because they often cannot be exactly replicated and are expensive and difficult to execute, leading to many ecologists to favor small scales in order to obtain the satisfaction of statistical confidence.”

But there are powerful reasons for ecologists continuing whole-ecosystem studies and it is worthwhile to revisit the original ideas pioneered in the 1950s to the 1970s by H.T. Odum and colleagues on large-scale ecological studies and experiments. Odum was responsible for experimental enclosures in Texas coastal bays, rain forest enclosures in Puerto Rico, created coastal ponds in North Carolina, and applying sewage to cypress swamps in Florida. The study in Florida investigated effects of wastewater application to wetland function in cypress domes but unplanned fire in the experimental area led to adaptive research and study of fire in field research and models.

This paper will first present several whole-ecosystem studies developed by H.T. Odum and point out the important approaches and findings of these pioneer studies. Then the paper will explore more recent whole-ecosystem studies that were, at least in part, inspired by the earlier work by Odum. These later studies include whole-ecosystem experiments at created wetlands in northeastern Illinois to investigate effects of water turnover on ecosystem function and in Ohio to provide insight on the long-range large-scale effects of plant introduction on ecosystem self-design and a series of wetland studies in Louisiana on wastewater application to swamps and diversion of river waters to adjacent wetland areas to solve pollution and land-loss problems in that state. Disadvantages and advantages of whole-ecosystem research will be discussed along with a summary of major ecological restorations of the Mississippi Basin and Louisiana delta that are in early stages of development and that could be influenced in many ways by the pioneering work of H.T. Odum.

2. H.T. Odum and whole-ecosystem studies

Howard T. Odum (1924–2002) was one of the pioneers of ecosystem ecology. One of the notable features of the ecosystem research of H.T. Odum is that is was big: Big in thinking, big in scale, and big in impact. Students were attracted to his program because of the sheer boldness of attempts to study whole ecosystems at scales never before considered. In his book *Environment, Power, and Society*, Odum (1971) first tells his readers that one must look at ecosystem through a macroscope in addition to a microscope:

> *In the 1600s when Leeuwenhoek ushered in the centuries to be enlightened by the study of the invisible world with the microscope, and when some of the atomistic theories of the Greeks received step-by-step observable verification in chemical studies, concepts of the structure and function of the natural world emerged as parts within parts within parts .... Whereas two centuries of scientific progress were derived from the microscopic work, we find the contemporary world beginning to look through the macroscope.*

Scott Nixon (1995) states the appeal of studying under H.T.: “Almost all of us were drawn to study with H.T. because he was working at a large scale, on the ‘big picture.’ After years of specialized academic minutiae, it was exhilarating to deal with ecosystems, diurnal curves, network diagrams, and models.”

With the advent of analog and digital computers during and immediately after World War II, the ability to look at systems in science suddenly became possible. Following his classic studies of the energy flow in the flowing water ecosystem of Silver Springs, Florida (Odum, 1956, 1957), H.T. Odum developed a crude but innovative passive analog computer that appeared to be designed to simulate the energy flow in the Silver Springs system (Odum, 1960). Now complex systems could be investigated as whole systems, without the restraints of reductionistic approaches. Ecosystems could be now be evaluated as whole systems on the computer. Systems ecology had begun. Another part to this systems approach was to study the dynamics of systems as a whole in nature, often requiring unique research approaches. It is also clear that in order to have a budget sufficient to study whole ecosystems, the ecosystems had to be studied in the context of pollution affecting them or some other large-scale resource problem.

2.1. Texas shallow bay enclosure (1962–1963)

When Odum left University of Florida to become Director of University of Texas’ Port Aransas Marine Station on the Gulf of Mexico, one of the first attempts was made to investigate a whole coastal ecosystem, all at once. A helicopter-borne net, 16 m in diameter, was used to estimate fish biomass (Jones et al., 1963; Jones, 1965) of the shallow marine bays near the field station (Fig. 2). Odum (1971) described this enclosure appropriately: “Consistent with the ideal stated as a macroscopic view, sampling was done as though we were a giant far above the system oblivious of the fine scale variation. Unfortunately we had no giant.” Though drop nets had already been used routinely for shallow water, the idea was to attempt to sample aquatic communities in water deeper than 1 m. After overcoming a number of technical difficulties, the sampling with helicopter drop nets commenced in the late summer 1962. In the period September 1962 to August 1963, 17 out of 24 drops were successful (Jones, 1995). The drop net approach was discontinued when the contract expired, but the approach for quantifying fish biomass in a deep coastal system was an innovative attempt to try whole-ecosystem sampling where no one had attempted it previously.

2.2. Tropical rain forest enclosure (1964–1967)

One of the grandest attempts to capture a large segment of an ecosystem is the well-documented study led by Odum of a tropical rain forest in El Verde, Puerto Rico. The study is summarized in a 111-chapter tome titled simply “A Tropical Rain Forest” (Odum and Pigeon, 1970). The Atomic Energy Commission (AEC), a precursor agency to the current Nuclear Regulatory Commission (NRC), was interested in the effects of gamma irradiation caused by nuclear war or major reactor accidents on tropical rain forests. Odum was more interested in studying the tropical rain forest ecosystem and the implications of such studies on assisting human society. Odum (1970) asks: “The rain forest achieves complexity, high metabolism, and stability over geological time periods without surges and waste. Can we find in this example the clues for designing our own equally effective systems of man and nature?” Substantial AEC funding was provided for a multi-year research project in which one of the features was construction a giant cylinder 20 m wide and 22 m high to enclose a portion of tropical rain forest to estimate total carbon metabolism and evapotranspiration (Fig. 3). The tower, constructed in 1964, was used for 10 sets of metabolism measurements from June 1965 to January 1967. In one of the few attempts to measure the entire metabolism of a tropical rain forest, nighttime respiration averaged 0.47 g C per square meter per hectare and gross photosynthesis was esti-

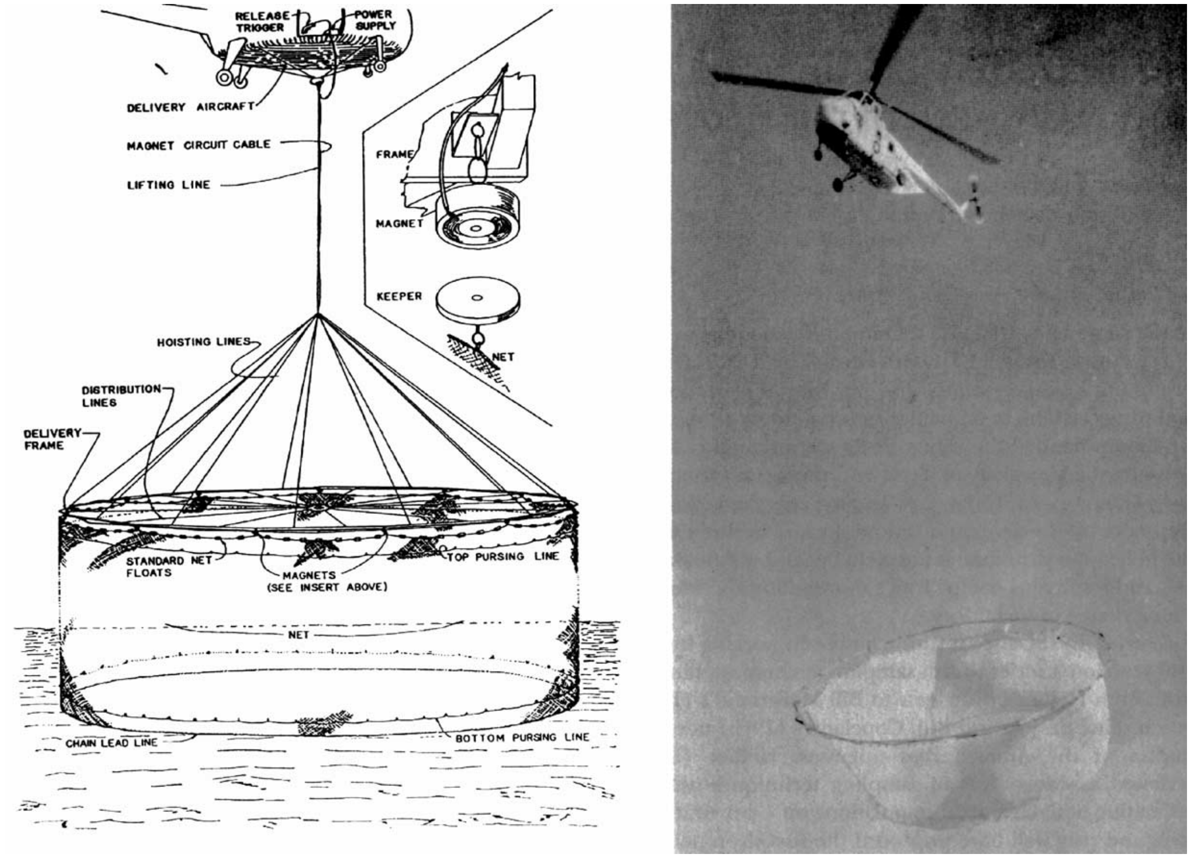


Fig. 2. Sixteen-meter diameter drop net used for coastal ecosystem studies in 1962–1963 by H.T. Odum-led Port Aransas Coastal Laboratory, University of Texas, in Gulf of Mexico marine bays. Illustration from Jones (1995).

mated to be 16.4 g C per square meter per day (Odum and Jordan, 1970). The air was discharged from the tower by a 2-m-diameter fan that turned the air over in the cylinder every 3–5 min as calibrated with CO_2 discharges from a fire extinguisher. The attempt to put a section of a tropical rain forest into a plastic cylinder to measure its overall metabolism was bold, innovative and clearly “whole-ecosystem.”

2.3. Multi-seeding experimental estuarine ponds (1968–1971)

Odum (1985, 1989) reported on one of the first studies described explicitly as an experiment in ecological engineering. Estuarine ponds were built in Morehead City, North Carolina to investigate ecological changes as the ponds received secondarily treated municipal wastewaters mixed with salt water. Three ponds received the sewage–salt water mixture and three ponds were controls, receiving only a tap water–salt water mixture (Fig. 4). All ponds were “seeded” with a high diversity of biotic communities from estuarine, freshwater, and sewage sources. Formally, the question being asked was “whether the self-organization process [of species arrangements] occurs readily there with new conditions from wastewater influence and how much time is required” (Odum, 1989).

The experiments demonstrated a rapid build-up of structure in the experimental ponds with heavy fringes of *Spartina* and blooms of the alga *Monodus* sp. in the fall and winter. Average annual net primary productivity was much higher in the wastewater ponds (2.6–3.6 g O_2 per square meter per day) than in the control ponds (1.1–1.3 g O_2 per square meter per day). Self-organization was relatively rapid and the study concluded that while the estuarine wastewater

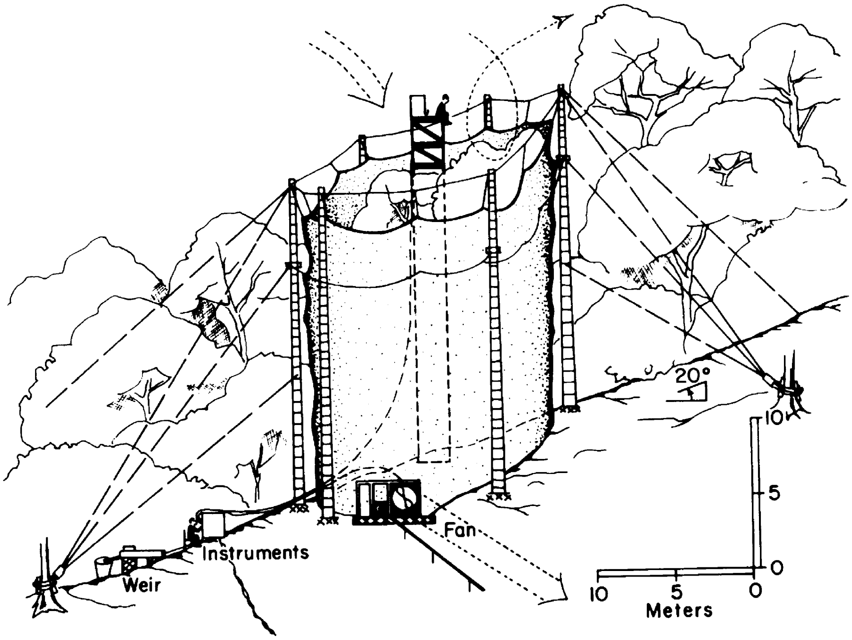


Fig. 3. Tropical rain forest enclosure used by H.T. Odum and colleagues to measure metabolism of tropical rain forest at the El Verde rain forest, Bio Piedras, Puerto Rico (Odum and Jordan, 1970).

ponds developed conditions that are often viewed as undesirable (e.g., algal blooms), they had organized ecological structure and could be valuable in an ecological engineering sense such as for the design of aquaculture systems or the use of ponds as natural tertiary treatment systems. Odum (1989) concludes that the design parameters such as inflows, loading rates, and other controls, along with the very important multi-seeding of as many species as possible, were important considerations in the ecological engineering of these estuarine ponds and that these parameters and seeding set the boundary conditions for a relatively rapid process of ecosystem development.

2.4. Wetlands for recycling domestic wastewater in Florida (1973–1978)

It is now common to see the application of ecological engineering concepts with the use of wetlands for treatment of domestic wastewater (Kadlec and Knight, 1996; Mitsch and Gosselink, 2000; Mitsch and Jørgensen, 2004). That was not the case in the 1970s; nor were wetlands even appreciated then. One of the first experiments to investigate the idea of recycling human wastes into wetlands was initiated in the early 1970s in Florida by H.T. Odum (see Odum et al., 1977 and Ewel and Odum, 1984). Whole-ecosystem experiments for the use of forested wetlands, particularly cypress domes dominated by *Taxodium ascendans* (a.k.a. *Taxodium distichum* var. *nutans*), for the treatment of high nutrient wastewater, were run for several years at the Whitney Trailer Park near Gainesville, Florida (Fig. 5a). Two cypress domes (0.5–1.0 ha in size) received treated wastewater from the trailer park at rates of about 2.5 cm per week (Fig. 5b). A third dome received an equivalent of low-nutrient groundwater inflow while a fourth served as a natural control (Fig. 5c). Measurements in shallow groundwater wells indicated that there was more than 90% removal of nutrients, organic matter, and minerals by the wetlands receiving wastewater (Dierberg and Brezonik, 1983, 1985). Furthermore, nitrogen and phosphorus concentrations in the foliage and branches of the trees increased as wastewater was added and decreased again after the treatment stopped. This study, which also involved studies of wetland hydrology, soils, modelling, and wildlife, demonstrated that forested wetlands could be used

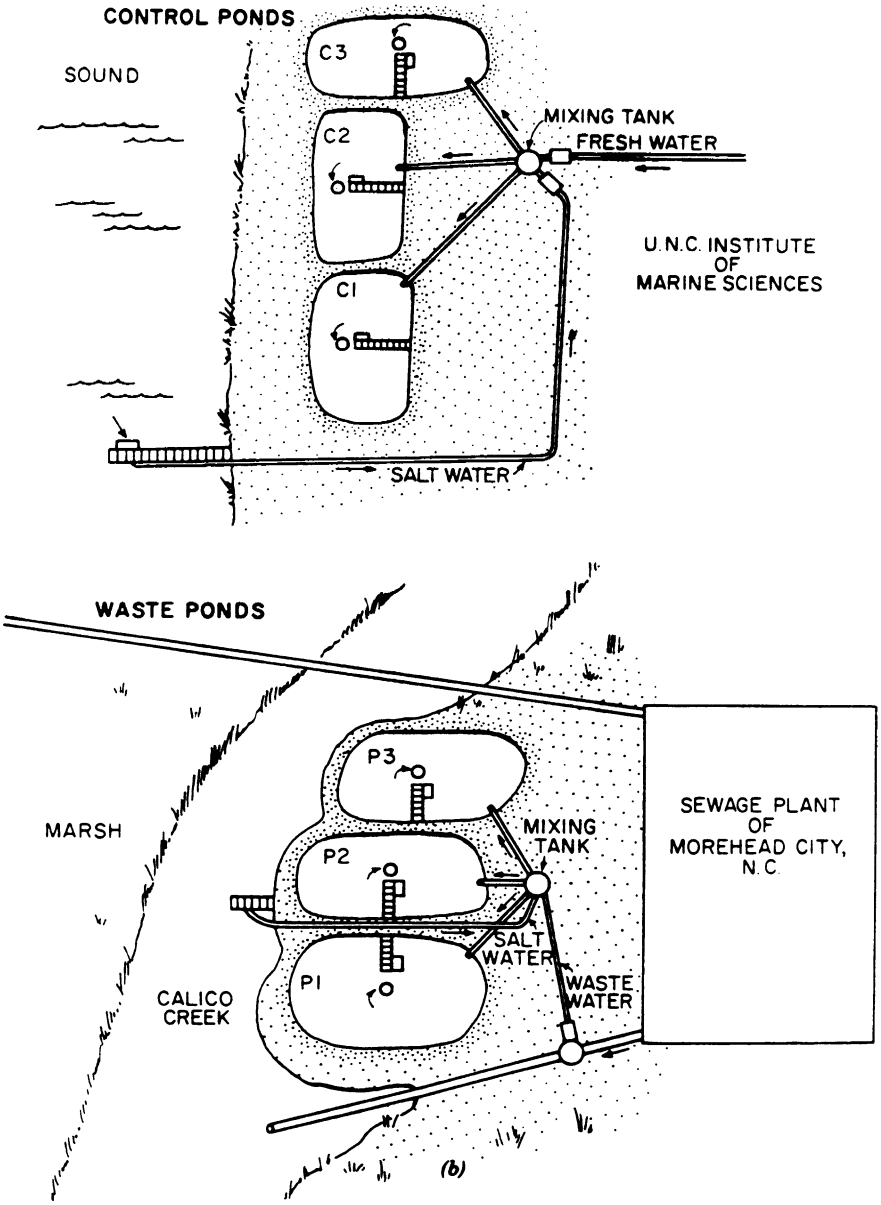


Fig. 4. Estuarine ponds constructed on marshes adjacent to Morehead City sewage plant, North Carolina by H.T. Odum. Pond were constructed to investigate self-organization in wastewater-influenced estuarine ponds (Odum, 1989), this material is used by permission of John Wiley & Sons, Inc.

in some cases to remove nutrients from wastewater with a minimum application of expensive and fossil energy-consuming technology (Table 1).

Another important lesson from this research was the application of "adaptive research" in large-scale research. Early in the study, a hot fire, set accidentally along a nearby railroad by welders, burned through the area and severely impacted the trees in the experimental domes. Odum, true to form, saw the dour look of the faces of all the graduate students and researchers at a special Saturday morning meeting in 1973 called to discuss what to do now that the fire had occurred. He cheerfully proclaimed: “Let’s study fire.” We did and the finding of our study (Table 2; Ewel and Mitsch, 1978) showed clearly that fire selectively removed both pines and hardwoods from the swamps and restored them to cypress monocultures that are typically found in healthy cypress domes. Fire cleanses swamps; H.T. Odum, a whole-ecosystem study, and a little spark taught us that.

Table 1
Energy costs of tertiary treatment in Florida cypress (*Taxodium*) swamps vs. conventional tertiary treatment (Mitsch, 1977)

	Cypress dome treatment	Tertiary treatment
Energy cost, kJ m^{-3}	3625	28000
Natural energy subsidy, kJ m^{-3}	3650	~0

Energy contribution from nature, in fossil fuel equivalents, is also indicated for the cypress dome treatment system.

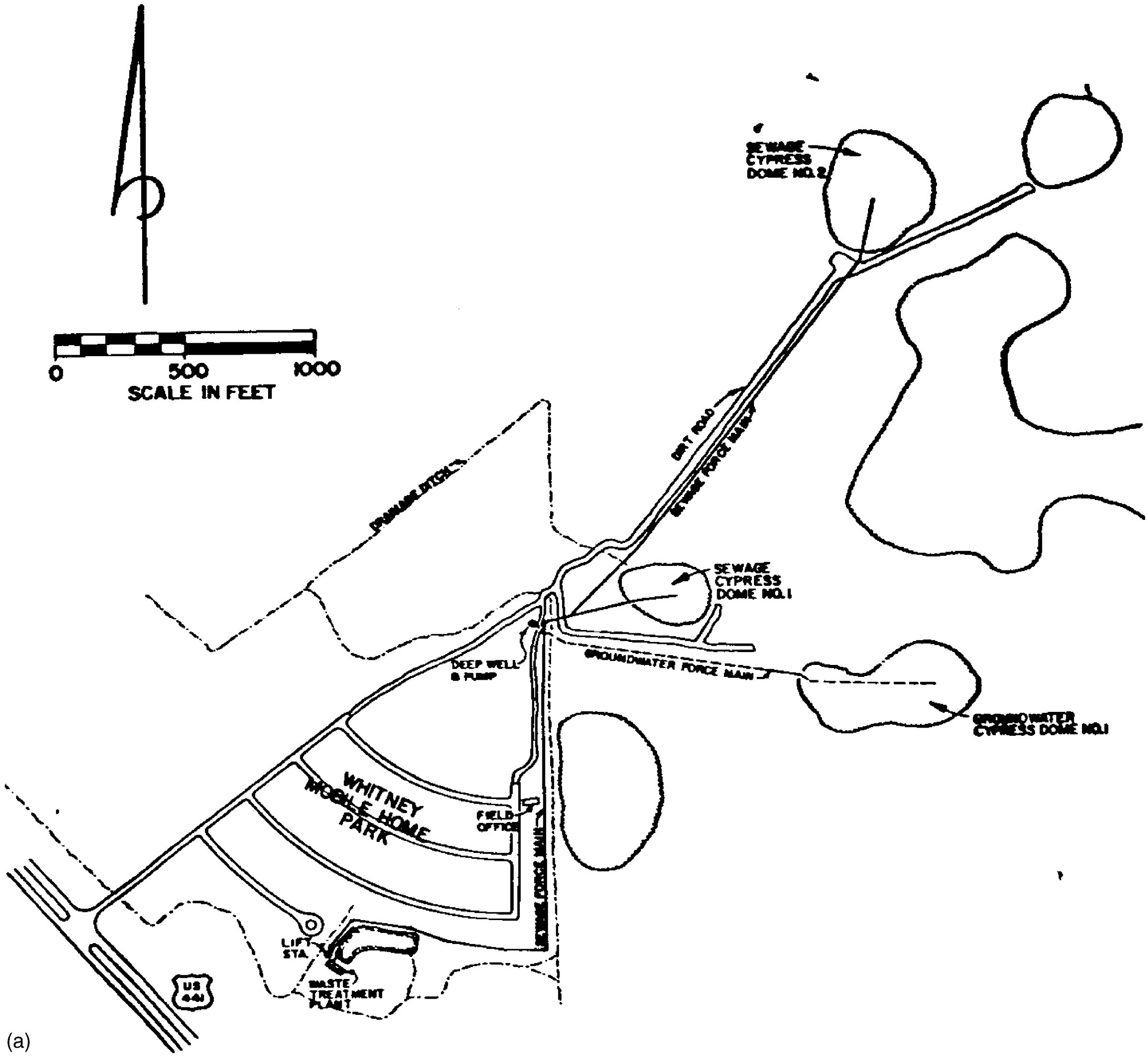


Fig. 5. (a) Two experimental cypress domes (numbers 1 and 2) that received treated sewage and one dome that received an equivalent amount of groundwater north of Gainesville, FL at Whitney Mobile Home Park, (b) aerial photo of experimental site showing extent of fire in surrounding pinelands, (c) aerial photo of natural control dome with surrounding pinelands in Austin Cary Forest (sketch from H.T. Odum Center for Wetlands, University of Florida; photos by W.J. Mitsch).

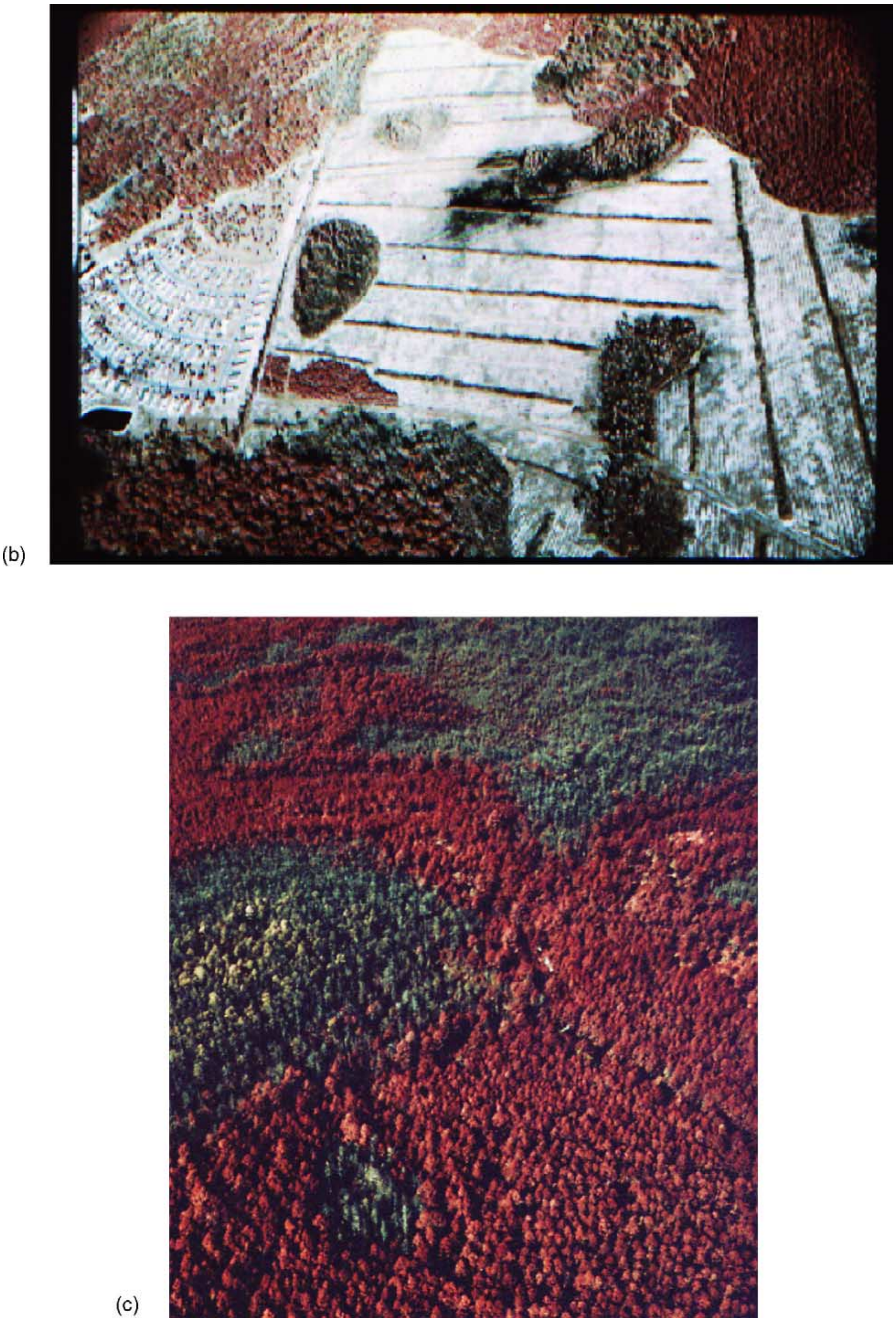


Fig. 5. (*Continued*).

Table 2
Effects of fire on two experimental cypress domes in H.T. Odum's whole-ecosystem experiment conducted in Gainesville, Florida (Ewel and Mitsch, 1978)

Dome	Tree	Percent of trees before fire	Percent of living trees after fire
1	Cypress (*Taxodium*)	51.9	96.2
	Pines (*Pinus*)	27.2	2.6
	Miscellaneous hardwoods	20.9	1.1
	Number of living trees	599	265
2	Cypress (*Taxodium*)	43.6	81.6
	Pines (*Pinus*)	14.2	1.4
	Miscellaneous hardwoods	42.2	17.0
	Number of living trees	1334	533

3. Studies with whole ecosystem continue

Many whole-ecosystem studies continued into the last two decades of the 20th century, stimulated at least in part by the experiments done earlier by Odum. Discussed here are several wetland studies that have taken place in the last two decades of the 20th century and into the start of the 21st by the authors of this paper. All studies had one thing in common—the functioning of whole ecosystems in large-scale studies was investigated to determine how that functioning could be focused on benefits for humans.

3.1. Created wetland hydrology experiment (1985–1994)

Restoration of entire rivers has been shown to be an elusive goal in many parts of the Midwestern United States because of significant loads of sediments and other non-point pollutants. In an ecological sense, we have paid too much attention to the stream itself and not enough to the interactions of the river with its floodplain. The Des Plaines River Wetland Demonstration Project north of Chicago in Lake County, Illinois, involved restoration of a length of a river floodplain and establishing experimental wetland basins on the floodplain where the dynamics of sediment and nutrient control can be determined in experimental fashion by using large pumps to introduce river water to the wetland basins. The project was the brainchild of Donald Hey and he was initially assisted by a committee of researchers led by Bob Kadlec, University of Michigan; Bill Mitsch, Ohio State University; and Arnold van der Valk, Iowa State University. The project had as its goals "to demonstrate how wetlands can benefit society both environmentally and economically, and to establish design procedures, construction techniques, and management programs for restored wetlands" (Hey et al., 1989) and was carried out at two scales. On the entire 182 ha site, woody and scrub vegetation has been replanted with native prairie species and oak savannas. Abandoned quarry lakes were connected to the river to give additional sediment trap efficiency and as backwater habitats for fish and shorebirds.

On the whole-ecosystem scale, four wetland basins (1.6–4.7 ha) were constructed and instrumented at the northern half of the site for precise hydrologic control to investigate the importance of hydrologic flow in otherwise similar wetlands (Fig. 6). Thus, different loading rates resulted in different overall residence time for the wetlands but the different flow rates were viewed as different hydrologic subsidies. Within this overall experimental design, there were several research questions that were asked. Will water quality improvement and sediment retention be lower in wetlands with high-flow rates? Will the differences in the major forcing function (hydrologic flow-through) lead to different ecosystem development? Will experimental wetlands with higher hydrologic flows be more productive? Will the increased flow-through bring substantially more sediments than can be assimilated, turning the subsidy to a stress?

Water was pumped through the wetlands at low (7–16 cm per week) and high (34–97 cm per week) rates of hydrologic subsidies while the basins were maintained at similar depths (approximately 0.7 m). Overall phosphorus retention was higher in high-flow wetlands (26–55 mg P per square meter per week) than in the low-flow wetlands (8–33 mg P per square meter per week) but percent retention of phosphorus was higher in low-flow wetlands (Mitsch et al., 1995). The higher river flow maximized phosphorus retention in terms of mass retention; the lower river flow optimized phosphorus retention in terms of removal efficiency. We believe that maximum power, i.e., maximum nutrient removal, a work process, as would have been predicted by Odum and Pinkerton (1955), rather than maximum efficiency (i.e., maximum nutrient percent efficiency), is the most important strategy for the ecosystem.

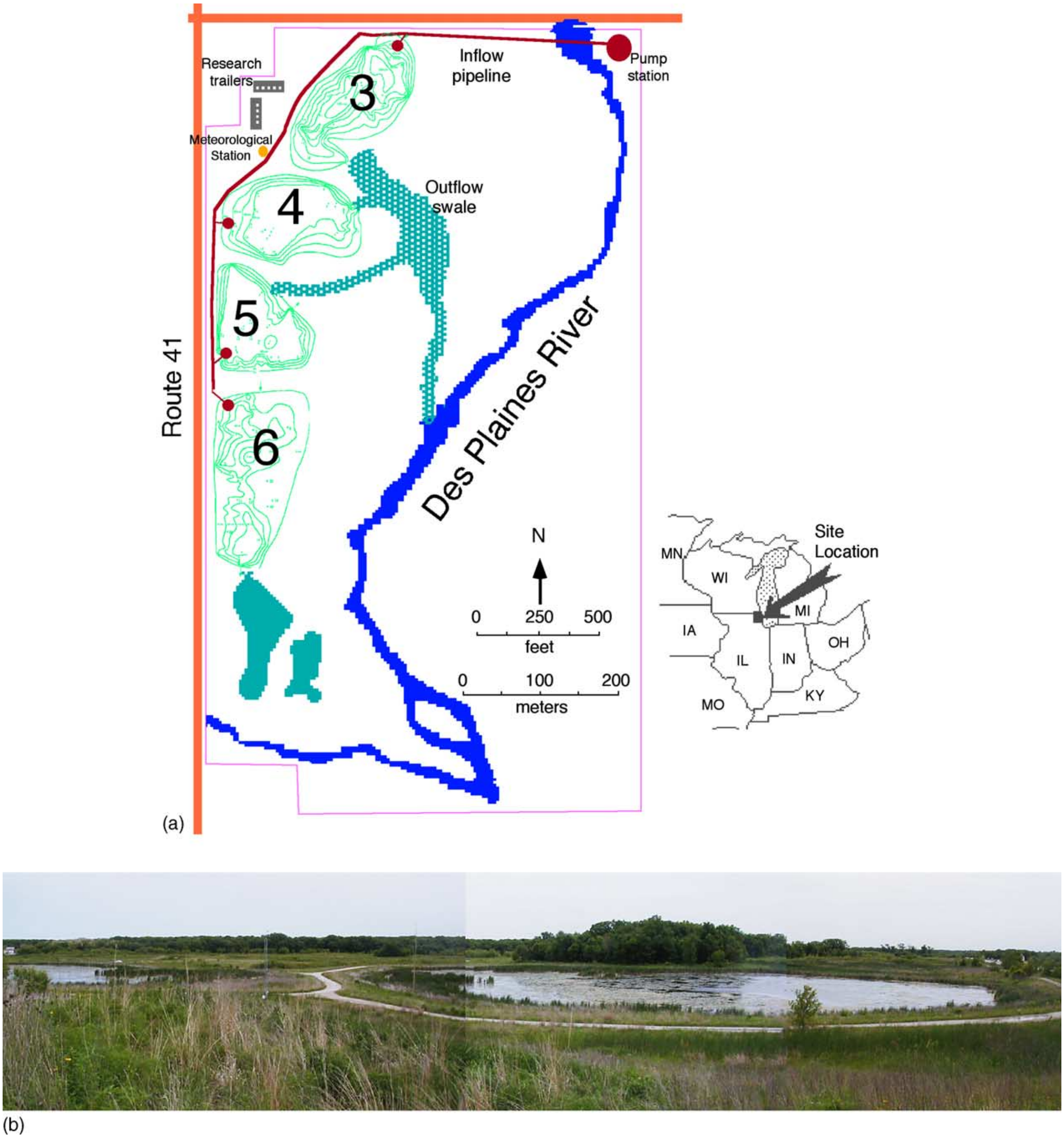


Fig. 6. Four experimental wetland basins at Des Plaines River Wetland Demonstration Project, Lake County, IL: (a) site map and (b) ground photograph.

The effects of flow conditions were also investigated for sedimentation (Brueske and Barrett, 1994; Fennessy et al., 1994a), aquatic metabolism (Cronk and Mitsch, 1994a), macrophyte productivity (Fennessy et al., 1994b), periphyton productivity (Cronk and Mitsch, 1994b), and nitrogen dynamics (Phipps and Crumpton, 1994). The study found, for example, that after 2 years of experimentation, wa-

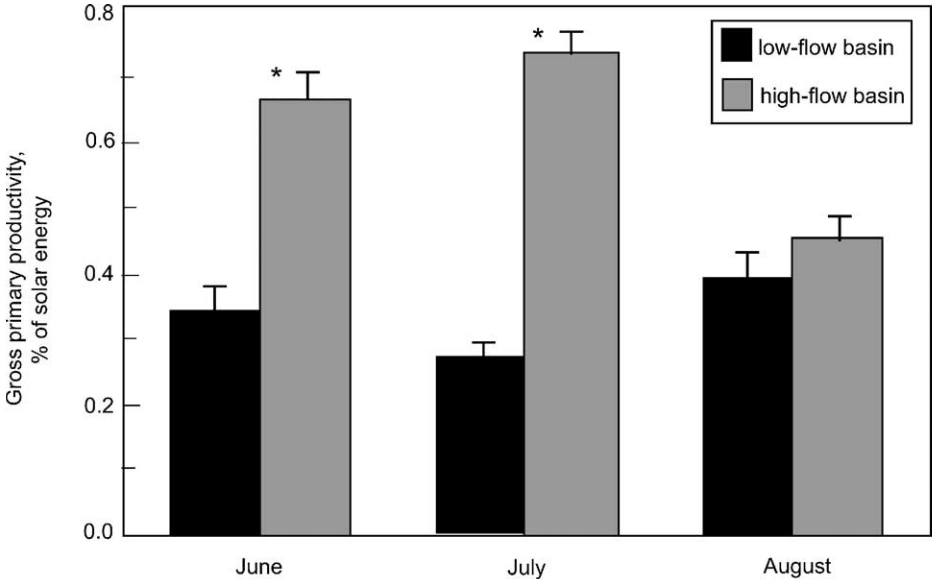


Fig. 7. Gross primary productivity in water column of low-flow and high-flow experimental wetland basins at Des Plaines River project, indicating the aquatic productivity was generally higher in wetlands receiving more hydrologic river inflow (from Cronk and Mitsch, 1994a).

ter column (phytoplankton and submerged aquatics) productivity was higher in high-flow wetlands than in low-flow wetlands (Fig. 7). A second energy subsidy enhanced ecosystem productivity. However, macrophyte productivity did not respond to the difference in hydrology over only 2 years of experimentation; that effect might take decades to manifest itself.

A detailed but generalized simulation model was developed first to describe the general nutrient dynamics (Christensen et al., 1994) and later to compare the distinction between low-flow and high-flow wetlands further (Wang and Mitsch, 2000). The latter model was robust as it was calibrated and validated with 3 years' data from four wetland basins with the different hydrologic conditions. The validated model was used to estimate many of the internal nutrient fluxes that otherwise could never be determined through field techniques (Fig. 8).

3.2. *Wetland assimilation of wastewater in coastal swamps (1988–2003)*

Over the past 15 years, coastal forested wetlands and marshes in the Mississippi delta have been used to assimilate secondarily treated municipal wastewater (see Breaux and Day, 1994; Day et al., 1999, in press). These are whole system experiments for two reasons. First, the sites generally are hundreds of hectares in size and contain whole ecosystems. Second, the sites are hydrologically isolated, often with low nutrient and productivity levels and potential or actual high rates

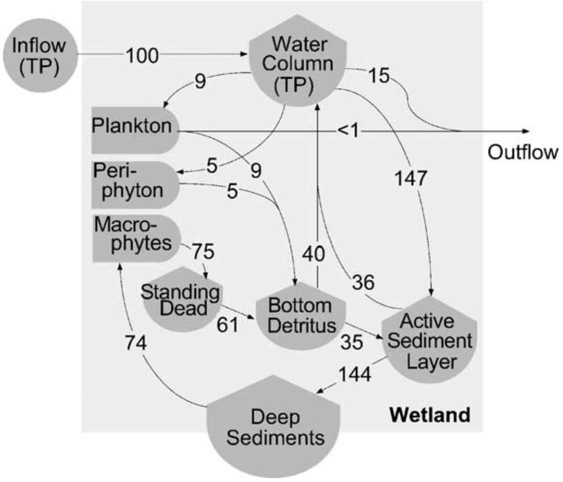


Fig. 8. Phosphorus budget estimated for Des Plaines wetlands from validated ecosystem models validated from four wetland basins over 2 years. Numbers are standardized for a phosphorus inflow of 100% (from Wang and Mitsch, 2000).

of wetlands loss. The use of wetlands for treatment of wastewaters has a number of important ecological and economic benefits. Adding nutrient-rich treated wastewater effluent to selected coastal wetlands has resulted in the following benefits: (1) improved effluent water quality; (2) increased accretion rates to help offset subsidence; (3) increased productivity of vegetation; and (4) financial and energy savings of capital not invested in conventional tertiary treatment systems.

Results from several wetlands that are receiving secondarily treated wastewater in coastal Louisiana demonstrate these findings (Table 3). At one site near Thibodaux, LA, where sedimentation accumulation was measured, rates of accretion increased significantly after wastewater application began in the treatment site (from 7.8 to 11.4 mm per year), and approached the estimated rate of regional relative sea level rise (RSLR) of 12.0 mm per year (Rybczyk et al., 2002). No corresponding increase was observed in an adjacent control site. This suggests that the application of nutrient-rich wastewater can help coastal wetlands survive sea level rise. In the same site, surface water nutrient reduction, from the effluent inflow to outflow (1.6 km), ranged from 100% for NO_3-N to 66% for total P (Zhang et al., 2000). Denitrification was a major pathway for nitrogen loss (Crozier et al., 1996; Boustany et al., 1997). At a second site at Breaux Bridge, LA, N and P were both reduced by more than 90% in a forested wetland that has been receiving wastewater effluent for 50 years (Blahnik and Day, 2000; Day et al., in press). Similar nutrient reductions occurred at other sites (Table 3).

Nutrient reduction at the treatment wetlands was due to three main pathways: burial, denitrification and plant uptake. Dendrochronological analysis at the Breaux Bridge site revealed that stem growth increased significantly in the treatment site after wastewater applications began, and was significantly greater than an adjacent control site (Hesse et al., 1997). Similar increases in productivity have been measured in a number of wetland treatment sites (Day et al., in press). Economic analyses comparing conventional and wetland systems indicate savings range from $500,000 to $2.6 million (Breaux et al., 1995; Cardoch et al., 2000; Ko et al., in press) and substantial energy savings (Ko et al., in press).

3.3. River diversions as a restoration tool (1991–2004)

Over the past century, there have been many changes in the Mississippi delta. These include massive loss of coastal wetlands, salt water intrusion, and deteriorating water quality (Turner and Rabalais, 1991; Day et al., 2000). An important factor contributing to land loss is the isolation of the Mississippi River from the delta by levees. In an effort to restore coastal wetlands, the State of Louisiana and the Federal government have constructed a number of structures to divert river water back into coastal wet-

Table 3
Loading rates and percent nutrient reductions in at wastewater treatment forested wetlands in coastal Louisiana (from Day et al., in press)

Site	Treatment basin (ha)	Nitrogen loading ($g\,m^{-2}$ per year)	Phosphorus loading ($g\,m^{-2}$ per year)	Nutrient	Concentration*		Percent reduction
					Effluent from treatment plant	Outflow from wetland	
Amelia	1012	1.96–3.92	0.22–0.42	TKN	2.98	1	66
				Total P	0.73	0.06	92
Breaux Bridge	1475	1.87	0.94	NO_3-N	0.8	<0.1	100
				PO_4-P	1	0.2	80
				Total P	2.9	0.3	87
St. Bernard	1536	2	0.42	TKN	13.6	1.4	89.7
				Total P	3.29	0.23	95
Thibodaux	231	3.1	0.6	NO_3-N	8.7	<0.1	100
				TKN	2.9	0.9	69
				PO_4-P	1.9	0.6	68
				Total P	2.46	0.85	66

* All concentrations are reported as milligram per liter.

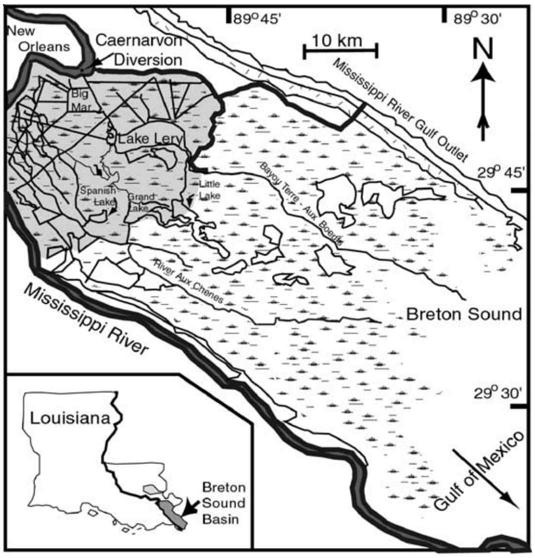


Fig. 9. Breton Sound Basin, Louisiana, with main region of estuary influenced by Caernarvon Diversion from Mississippi River highlighted in gray.

lands. We report here on an ecosystem level study of a diversion at Caernarvon, LA (Day et al., 2003). The Caernarvon freshwater diversion structure discharges Mississippi River water into the Breton Sound estuary located east of the river (Fig. 9). The estuary stretches for about 70–80 km from the diversion structure to the Gulf of Mexico. The upper 40 km of the estuary, encompassing an area of about 1100 km^2, is composed of extensive marshes, small to medium size water bodies, and channels, while the lower estuary is the open water Breton Sound. Thus, the upper estuary is weakly to moderately coupled to the lower estuary due to shallow, sinuous channels and extensive marshlands. The astronomical tide at the Gulf of Mexico end is about 35 cm but it is much less in the upper basin due to dampening effects of the marsh dominated area. Winds and diversions cause much higher water level variations than the lunar tide. Salinity is generally fresh in the upper basin except during prevailing south winds or very low diversion flow. The diversion has multiple objectives including maintaining a desirable salinity gradient, restoring deteriorating wetlands and enhancing fisheries.

River inputs have been ongoing since the 1991 opening of a gated river diversion structure. Discharge levels ranged from 185 m^3 per second for high flow, and 15 m^3 per second for low flow. The LSU research team measured the effect of river inputs on hydrology, marsh accretion, marsh productivity, water quality, biogeochemistry of wetland soils, benthic sediments, fish, shrimp and oysters using stable isotopes. They also measured phytoplankton production and the potential for eutrophication and developed spatial models to investigate interactions between freshwater discharge and nutrient interactions, and habitat changes. The high river pulse resulted in nearly 30% of the discharge flowing over the marsh, while most river water was transported in channels during the low pulse. Sedimentation on the marsh surface during the pulse was high. There were reductions in most nutrients as water flowed through the estuary. In the upper estuary, estimated removal rates of total nitrogen and nitrate during one 2-week pulse were 44 and 48%, respectively. Total phosphorus and phosphate were reduced by 48 and 15%, respectively. There was strong nitrate uptake by sediments and a major pathway of nitrogen loss is denitrification. Stable isotope analysis showed that nitrogen and carbon in river water were incorporated into estuarine organisms such as shrimps. Socio-economic analyses measured diverse opinions of stakeholders and proposed ideas to reduce conflicts and optimize the operation of the diversion facility. These results indicate that properly managed diversions of river water can contribute to sustainable management of the Mississippi delta.

3.4. Whole-ecosystem wetland experiment in self-design (1992–2004)

Wetland protection regulations in the United States and now elsewhere have led to the practice of requiring that wetlands be created, restored, or enhanced to replace wetlands lost in developments such as highway construction, coastal drainage and filling, or commercial development. It is clear from many studies of created and restored wetlands that some cases are successes, while there are still far too many examples that fail to meet expectations (NRC, 2001). In some cases expectations were unreasonable, as when endangered species habitat was expected in a heavily urbanized environment (Malakoff, 1998). But mostly, in our opinion, the failures are due to a lack of understanding of three factors: (1) wetland function; (2) the time required for wetlands to develop: and (3) the self-design capacity of nature (Mitsch and Wilson, 1996).

In a multi-year study at the Olentangy River Wetland Research Park (Fig. 10) in central Ohio, two 1-ha wetlands were created in river floodplain alluvium and river water has been continuously added to them with pumps since March 1994. In May 1994, just after the basins were created, one of the two wetlands was planted with 2400 rootstocks of 13 wetland species typical of Midwestern USA marshes. The second, hydrologically identical, wetland remained as a control. The hypothesis was that the wetlands would initially diverge in function but would eventually converge. The wetlands did diverge in function after 2 years but after 3 years, both wetlands were principally dominated by soft-stem bulrush *Schoenoplectus tabernaemontani* (a.k.a. *Scirpus validus*) communities and were thought to have converged (Mitsch et al., 1998). Researchers found that both planted and unplanted wetlands converged in most of the 16 ecological indicators (8 biological measures; 8 physiochemical measures) in those 3 years. But we had committed to a long-term study so the experiment continued. After 6 years, several communities of vegetation developed in the planted basin but a monoculture of *Typha* dominated the unplanted basin (Fig. 11). Residual effects of planting were thus evident 6 years after planting. The planted wetland had a more spatially diverse macrophyte community including communities dominated by *Sparganium eurycarpum, Scirpus fluviatilis, Typha* spp., and *Spartina pectinata*.

This study also supported a general principle that ecosystems with higher productivity are often less diverse than are low productivity systems. The planted wetland had a more diverse set of plant communities but was considerably lower in productivity. The *Typha* marsh that developed in the unplanted wetland had almost 50% higher productivity. Overall, there were dramatic functional differences between the two basins after 6 years that in all probability can be attributed to the initial planting (Fig. 12). The wetland planted by humans had 43% lower above-ground net primary productivity. Because there was less above-ground biomass, more sunlight could reach the water column, leading to higher gross primary productivity in the water column and hence higher dissolved oxygen in the planted wetland. This more oxygenated water column favored fish (mostly *Lepomis* sp.) over amphibians. The *Typha* wetland, with higher macrophyte biomass, had higher numbers of muskrats (*Ondatra zibithicus*), lower aquatic primary productivity and thus lower dissolved oxygen. That wetland had higher amphibian numbers and biomass (mostly bullfrog, *Rana catesbeiana*), higher snake (*Nerodia sipedon*) populations, but lower fish biomass. Interestingly, nutrient uptake by both wetland basins has been consistent, with nitrate-nitrogen reductions of 30–40% and soluble reactive phosphorus retention of 60–85% over 8 years, and there has been very little difference between the planted and unplanted wetlands over those years (Nairn and Mitsch, 2000; Spieles and Mitsch, 2000; Mitsch and Zhang, 2002). Clearly planting and human intervention does have an effect on self-design. If plant diversity, oxygenated waters, and fish are desired, then planting may make sense. If detrital productivity and amphibians are desired, it may be wrong to plant. Only a whole-ecosystem, long-term experiment could have suggested this.

Studies continue at the twin kidney basins at the Olentangy River wetlands of the effects of the planting as the basins go into their second decade; it appears that the differences after 10 growing seasons are diminishing and the ecosystems converging as hypothesized. Current studies, are now investigating the importance of hydrologic pulsing (Fig. 13) and results will be compared with the Louisiana diversion studies described above.

3.5. Restoring the Mississippi River Basin

It is our personal experience in the studies above described in Illinois, Ohio, and Louisiana, and before that as students of Odum at Florida (Mitsch in the cypess domes receiving treated sewage) and North Carolina (Day in the multi-seeded estuarine ponds) that has led us to a fortunate and timely collaboration as the 21st century started on what could be one of the biggest ecological restorations even seen—the restoration of the Mississippi River Basin. One of the most notable impacts of the water quality and hydrologic deterioration of the Mississippi River Basin has been the development of a hypoxic zone in the Gulf of Mexico that is 20,000 km^2, almost the size of the state of New Jersey (Turner and Rabalais, 1991; Rabalais et al., 1996, 1998). The basin delivers nitrates and other chemicals from the agricultural corn belt

Fig. 10. Olentangy River Wetland Research Park at Ohio State University (a) aerial photo showing two kidney-shaped experimental wetland basins discussed in this paper and (b) ground photo of experimental wetland 1 showing inflowing river water on right.

Fig. 10. (*Continued*).

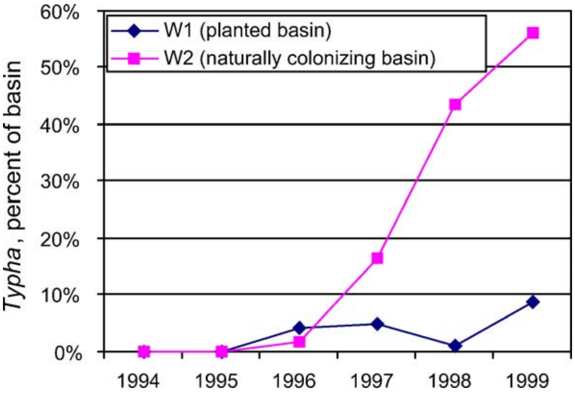


Fig. 11. Percent cover of cattail (*Typha* spp.) in planted and naturally colonizing wetland basins at Olentangy River Wetland Research Park, 1994–1999. Wetland 1 (W1) was planted with 2400 individual plants representing 13 species while Wetland 2 (W2) was not planted.

that are the chief cause of the Gulf hypoxia. The solution to this broad problem must include a basin-wide approach and that basin-wide approach needs to depend on research done at the ecosystem and landscape scales. A study done by us and others (Mitsch et al., 1999, 2001), at the request of a multi-agency Federal task force, led to the conclusion that an ecological problem on the scale of the hypoxia required ecological, not just technological, solutions, a concept second nature to us. A more recently convened National Technical Review Committee (NTRC), on which we both serve, is reviewing the Louisiana Coastal Area (LCA) $13 billion proposed coastal restoration for the U.S. Army Corps of Engineers. We determined that a watershed perspective is essential for that project's success. Recognition was made that the restoration of America's Mississippi–Ohio–Missouri (MOM) Basin is important for the ultimate success of the LCA.

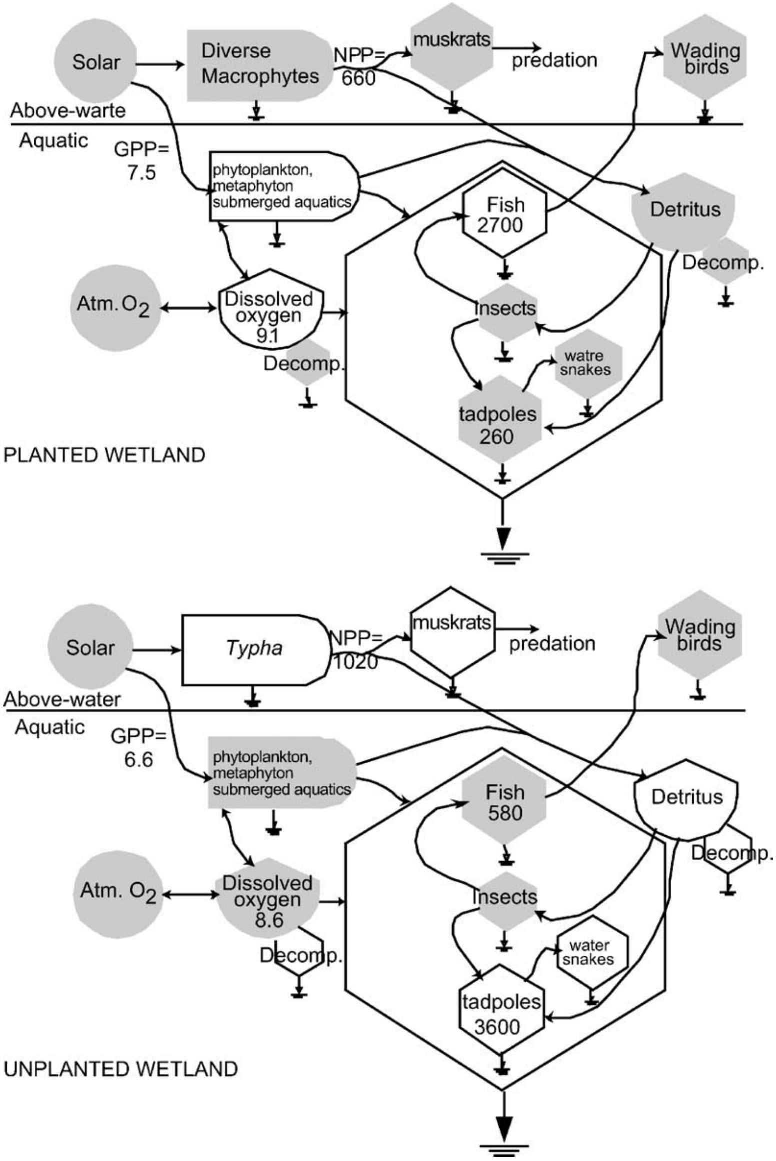


Fig. 12. Energy diagrams of planted and unplanted experimental wetland basins at Olentangy River Wetland Research Park after 6 years. Unshaded symbols illustrate components of each wetland ecosystem that were estimated to be higher as a result of planting (top) or natural colonization (bottom). Net primary productivity (NPP) is expressed as gram of dry weight per square meter per year. Gross primary productivity (GPP) of the water column is expressed as gram of oxygen per squaremeter per day. Dissolved oxygen is annual average for 1999 and 2000 in mg per liter. Fish and amphibian population estimates for 2000 and 2001 are given as number of individuals per hectare (from Mitsch and Jørgensen, 2004).

The connection between any Louisiana delta restoration and the 3 million square kilometer river basin is both obvious and essential. While the LCA involves “projects” that are physically located in the Louisiana delta and not in MOM, it is essential that the projects be in concert with efforts upstream.

Some plans are developing for removal of nitrates from the upper river basin but implementation has

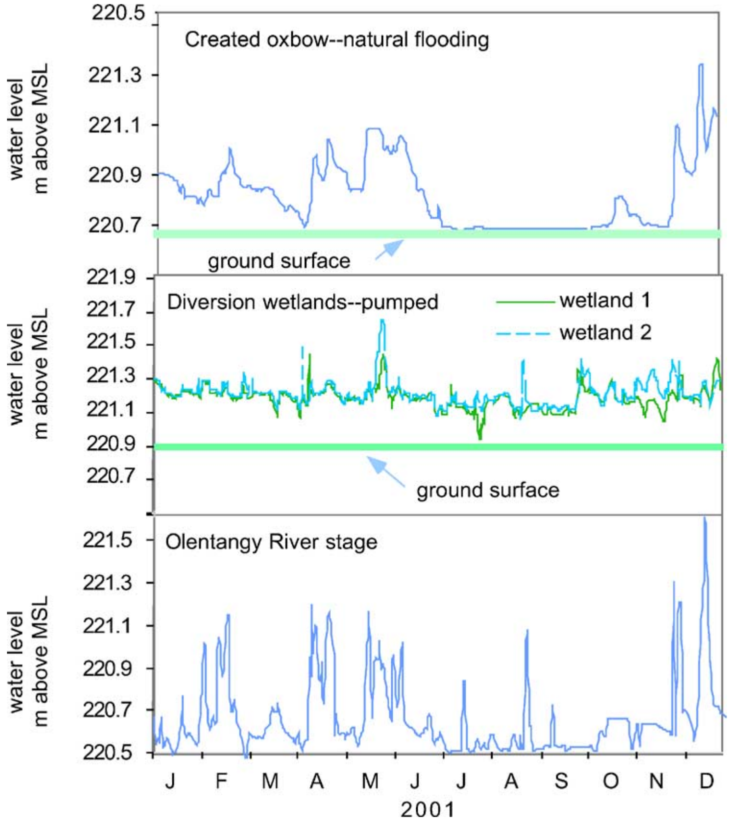


Fig. 13. Pulsing of oxbow wetland, pumped experimental wetlands and Olentangy River at Olentangy River Wetland Research Park, Ohio, 2001.

been slow. It is estimated that agronomic changes (use of less fertilizer, changing crops, N soil estimating techniques) could lead to a reduction of 20% of nitrate-nitrogen from reaching streams and rivers. These practices, by themselves, will not totally solve the hypoxia problem. If other solutions are not found, additional mandated reductions in fertilizer use may be the only option left to solve the problem, possibly resulting in reduced farm production and viability, an unwanted situation in our economy. Our study (Mitsch et al., 1999, 2001) recommended that in addition to these agronomic practices, there are two fundamental ecological approaches (Fig. 14) for reducing nitrogen and other nutrients from reaching the Gulf of Mexico:

1. Creation and restoration of ecosystems, principally wetlands and riparian forests, in excess of 10 million hectares, so that there is such a system between every farm and its downstream ditch, stream or river; and
2. Diversion of the Mississippi River into adjacent constructed and restored wetlands along its main stem and especially diversion of the Mississippi River in the Louisiana delta to distributaries during flood periods.

In other words, if we are to solve the large problems of the Mississippi River Basin, the Louisiana delta, and the Gulf of Mexico, we must reestablish huge areas of more or less natural ecosystems. The whole-ecosystem studies described above in Illinois, Ohio, and Louisiana that we were involved in provided invaluable data toward the planning of this strategy. These smaller scale whole-ecosystem studies that we participated in have given us confidence that ecological restoration on a large scale is both feasible and practical.

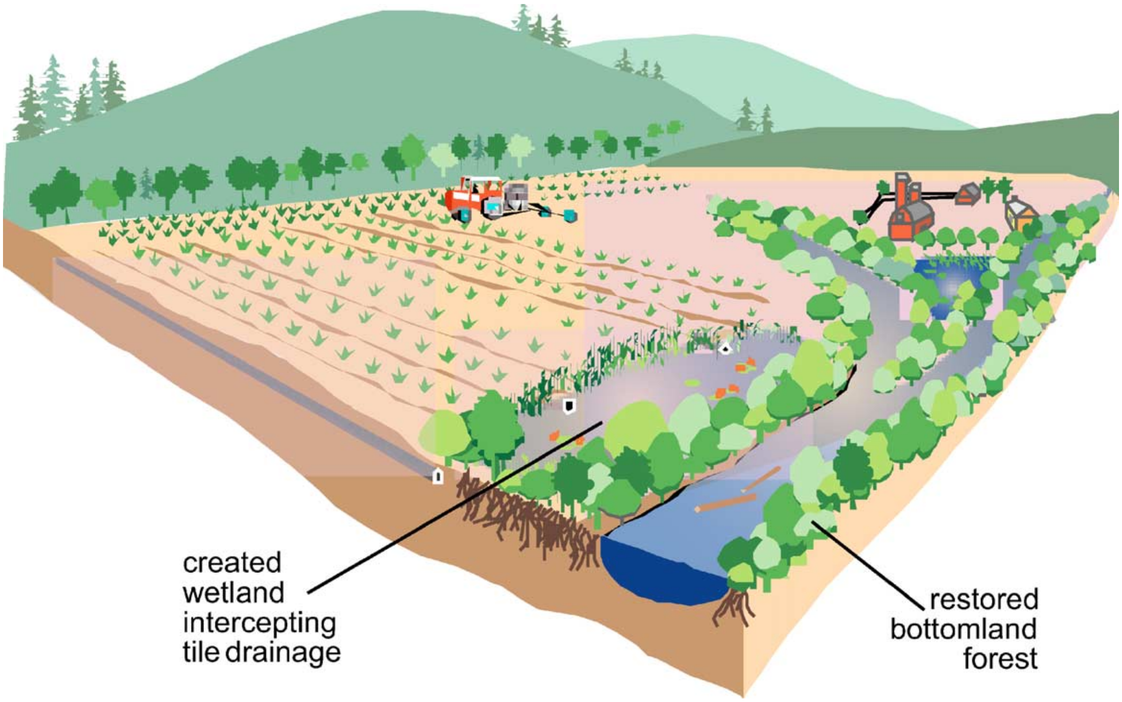


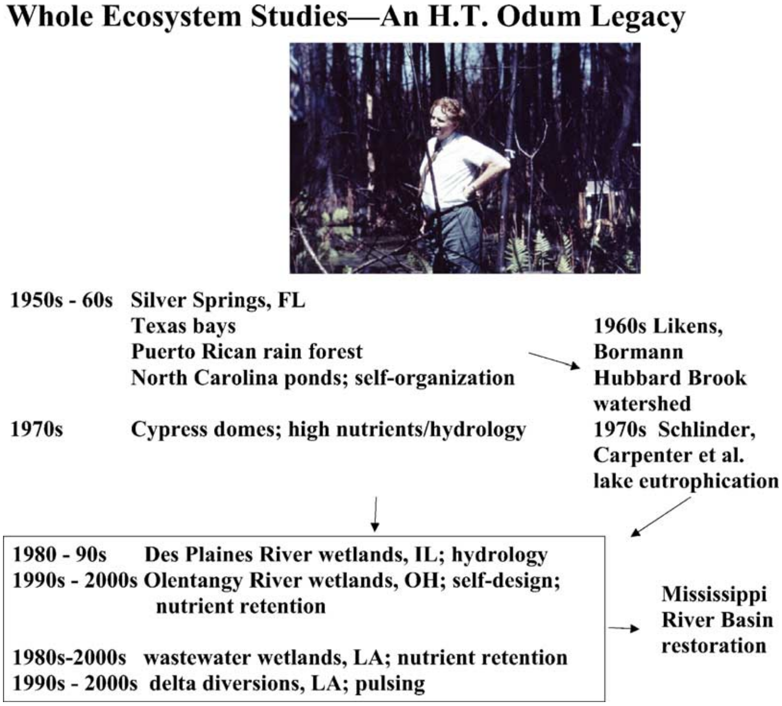
Fig. 14. Schematic of landscape in restored Mississippi River Basin where agricultural runoff is intercepted by wetlands (surface runoff) or riparian forest (subsurface drainage). Mitsch et al. (2001) estimated that 10 million hectares of such systems are needed to help control the Gulf of Mexico hypoxia (from Mitsch et al., 2001).

4. Whole-ecosystem studies—limitations and advantages

Whole-ecosystem studies and experiments have the disadvantage of the lack of replication and the cost of development and maintenance of the study or experiment. The time needed is usually beyond that provided by a research granting organization such as the National Science Foundation (exceptions are the Long-Term Ecosystem Research (LTER) projects) and often beyond a Ph.D. student's tenure at a university. The advantages are that the entire ecosystem is present in the study and that there are more opportunities for interact and adaptive research. Furthermore, in comparison with small-scale experiments that may isolate cause and effect one parameter at a time, the results achieved in a whole-ecosystem study could be closer to realism than those obtained from simplified small-scale systems (Ahn and Mitsch, 2002).

5. Odum's legacy

Howard T. Odum had a major effect on applying whole-ecosystem studies to human needs and indirectly in influencing others in similar studies (Fig. 15). His work in Florida springs, the Texas bays, the Puerto Rican rain forest, the North Carolina experimental ponds and the Florida cypress domes had an influence on us in the studies described above in Illinois, Louisiana, and Ohio. We also suspect that Odum had an influence on other early whole-ecosystem experiments such as those by Likens et al. (1977) on forest watershed experiments at Hubbard Brook in New Hampshire and Schlinder (1977) and Carpenter et al. (1996, 1998) on whole-lake studies in Wisconsin and elsewhere. We were influenced by those studies as well. If all of these whole-ecosystem studies and others such as current efforts for the restoration of the Florida Everglades eventually provide the science and engineering detail sufficient to restore the Louisiana



Whole Ecosystem Studies—An H.T. Odum Legacy

1950s - 60s Silver Springs, FL
Texas bays
Puerto Rican rain forest
North Carolina ponds; self-organization

1960s Likens, Bormann
Hubbard Brook watershed

1970s Cypress domes; high nutrients/hydrology

1970s Schlinder, Carpenter et al.
lake eutrophication

1980 - 90s Des Plaines River wetlands, IL; hydrology
1990s - 2000s Olentangy River wetlands, OH; self-design; nutrient retention

1980s-2000s wastewater wetlands, LA; nutrient retention
1990s - 2000s delta diversions, LA; pulsing

Mississippi River Basin restoration

Fig. 15. The legacy of H.T. Odum in whole-ecosystem studies, from stream, pond, bay, rain forest, and wetland studies to later studies by authors and proposed Mississippi River Basin restoration.

delta and the entire Mississippi River Basin, then it is appropriate that we give substantial credit to Howard T. Odum. This may be his most lasting legacy.

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