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Ecological engineering: A field whose time has come

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Abstract

Ecological engineering is defined as "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both." It involves the restoration of ecosystems that have been substantially disturbed by human activities such as environmental pollution or land disturbance; and the development of new sustainable ecosystems that have both human and ecological value. While there was some early discussion of ecological engineering in the 1960s, its development was spawned later by several factors, including loss of confidence in the view that all pollution problems can be solved through technological means and the realization that with technological means, pollutants are just being moved from one form to another. Conventional approaches require massive amounts of resources to solve these problems, and that in turn perpetuates carbon and nitrogen cycle problems, for example. The development of ecological engineering was given strong impetus in the last decade with a textbook, the journal *Ecological Engineering* and two professional ecological engineering societies. Five principles about ecological engineering are: (1) It is based on the self-designing capacity of ecosystems; (2) It can be the acid test of ecological theories; (3) It relies on system approaches; (4) It conserves non-renewable energy sources; and (5) It supports biological conservation. Ecology as a science is not routinely integrated into engineering curricula, even in environmental engineering programs, while shortcoming, ecologists, environmental scientists, and managers miss important training in their profession—problem solving. These two problems could be solved in the integrated field of ecological engineering.

Keywords: Ecotechnology; Self-design; Self-organization; Ecological conservation

1. Introduction

We are now in a position to make a substantial contribution to the "greening" of the planet through ecological engineering. The present era's approach to human history is retrospective, both politically and ecologically. While not necessarily questioning all we have built and engineered to date, we should be determining (1) whether to continue practices as usual (and whether we can afford to do so), and (2) what new approaches are available to engineers for restoring the "bodily functions" of nature on which we depend. Signs all around us indicate that a paradigm shift is taking place both within and outside the engineering profession to accommodate ecological approaches to what was formerly done through rigid engineering and a general avoidance of any reliance on natural systems. For example, engineers, ecologists, resource

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managers, and even politicians are now redesigning the plumbing in the southern Florida Everglades to a plan that is friendlier to the natural environment. As part of that effort, the Kissimmee River in Florida is being "restored"—at an enormous cost—to something resembling its former self before it was straightened 20 years ago (Fig. 1). Discussions are now in progress as to how and where to restore the Mississippi River Basin to a more natural state by removing dikes, restoring wetlands and riparian forests, and even letting the Louisiana Delta flood once again to save the enormous cost of floods and to save the Gulf of Mexico from its terrible hypoxia that now spreads over an area the size of New Jersey (Mitsch et al., 2001). A restoration of 4000 ha of coastal salt marshes is currently occurring in the Delaware Estuary in eastern USA (Fig. 2). Agricultural engineers, known for the efficiency with which they drained the landscape, are retooling in many locations to rebuild wetlands and reverse the drainage. Civil engineers, long the nation's river straighteners, are now involved in removing dams and restoring meanders. In Jutland, Denmark, engineers and scientists are presently bringing the Skern River, Denmark's largest river, back to its old meandering course (Fig. 3). This is now the century of ecological engineering and ecosystem restoration in many parts of the world.

Fig. 1. Part of the Everglades area restoration includes restoration of the Kissimmee River from central Florida to Lake Okeechobee. At left is a restored meander and at right is the channelized river. Illustration courtesy of Lou Toth, photo by Paul Whalen, South Florida Water Management District, West Palm Beach, FL, reprinted with permission.

Fig. 2. Maurice River Township salt marsh restoration site, one of several locations of coastal marsh restoration along Delaware Bay in eastern United States (photo by W.J. Mitsch).

2. Definition of ecological engineering

We now define *ecological engineering as the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both* (see Mitsch, 1996, 1998). This definition varies slightly from the definition we gave (Mitsch, 1993; Mitsch and Jørgensen, 1989), where ecological engineering was defined as "the design of human society with its natural environment for the benefit of both." We now believe, with hindsight, that "the design of human society" was perhaps too ambitious a goal for a fledgling field and would be much more than engineers and scientists can or should do. In fact, it would be social engineering. But "the design of sustainable ecosystems" is clearly a sustainable goal that can be achieved for individual projects, watersheds, and even landscape scales.

In a word, ecological engineering involves creating and restoring sustainable ecosystems that have value to both humans and nature. Ecological engineering combines basic and applied science for the restoration, design, and construction of aquatic and terrestrial ecosystems. The goals of ecological engineering and ecotechnology are:

1. the restoration of ecosystems that have been substantially disturbed by human activities such as environmental pollution or land disturbance; and
2. the development of new sustainable ecosystems that have both human and ecological value.

(a) (b)

Fig. 3. Restoration of the Skern River in western Denmark back to its old meandering course: (a) straight stream prior to restoration; (b) meandering stream after channel restoration (photos by W.J. Mitsch; from Mitsch and Jørgensen, 2004, reprinted with permission, Wiley).

It is engineering in the sense that it involves the design of the natural environment through quantitative approaches and that our approaches rely on basic science. It is a technology whose primary tool is the self-designing ecosystem. It is biology and ecology in the sense that the components are all of the biological species of the world.

3. History of ecological engineering

The term ecological engineering was coined by Howard T. Odum in the 1960s and has since been used extensively in the North America, Europe, and China. Odum defined ecological engineering as “those cases in which the energy supplied by man is small relative to the natural sources, but sufficient to produce large effects in the resulting patterns and processes” (Odum, 1962) and “environmental manipulation by man using small amounts of supplementary energy to control systems in which the main energy drives are still coming from natural sources” (Odum et al., 1963). Odum (1971) elaborated on the breadth of ecological engineering in his book *Environment, Power and Society* by stating that “the management of nature is ecological engineering, an endeavor with singular aspects supplementary to those of traditional engineering. A partnership with nature is a better term.” He later stated in *Systems Ecology* (Odum, 1983) that “the engineering of new ecosystem designs is a field that uses systems that are mainly self-organizing.”

Concurrent but separate from the development of ecological engineering concepts in the West was a similar development of the term “ecological engineering” in China. Under the leadership of Ma Shijun, known as “the father of ecological engineering in China,” ecologists in China began using the term “ecological engineering” in the 1960s, with much of that work written in Chinese language publications. In one of the first publications in western literature, Ma (1985) described the application of ecological principles in the concept of ecological engineering in China. Much of the approach to environmental management in China began as an art, but in the past two decades there has been explicit use of the term “ecological engineering” in China. It was first used to describe a formal “design with nature” philosophy for wastewater. Ma (1988) later defined ecological engineering as: “... a specially designed system of production process in which the principles of the species symbiosis and the cycling and regeneration of substances in an ecological system are applied with adopting the system engineering technology and introducing new technologies and excellent traditional production measures to make a multi-step use of substance.” He suggested that ecological engineering was first proposed in China in 1978 and is now used throughout the whole country, with about 500 sites in 1988 that were practicing agro-ecological engineering, defined as an “application of ecological engineering in agriculture” (Ma, 1988). That number was updated to about 2000 applications of ecological engineering in China by the early 1990s (Yan and Zhang, 1992; Yan et al., 1993). Qi and Tian (1988) suggested that “the objective of ecological research [in China] is being transformed from systems analysis to system design and construction,” stating that ecology now has a great knowledge base from observational and experimental ecology and is in the position to meet global environmental problems through ecosystem design, the main task of ecological engineering. Yan and Yao (1989) describe integrated fish culture management as it is practiced in China as ecological engineering because of its attention to waste utilization and recycling. Part of the Chinese special approach to ecological engineering is based on China’s historical background (Yan et al., 1993), some facets of which are compatible with modern ecological theory. The most influential theory in Chinese philosophy is the yin-yang. The symbol for yin-yang resembles two fish, one eating the tail of the other. The dots, while resembling an eye, suggest that to prevent any force from reaching an extreme, the system contains a seed of its opposite to maintain a balance. A related philosophy is that of five elements in which there is mutual restraint of five elements—fire, water, wood, metal, and soil. This outlook suggests, as does the yin and yang, the balance of promotion and restraint (Yan et al., 1993).

With these philosophies, a concept close to ecological engineering developed in China and the East probably centuries ago. The emphasis of our recent definitions of ecological engineering in the West has been a partnership with nature and research has been carried out primarily in experimental ecosystems with some full-scale applications in aquatic systems, particularly shallow ponds and wetlands. Ecological engineering, as pioneered by Ma and others in China, however, has been applied to a wide variety of natural resource and environmental problems, ranging from fisheries and agriculture, to wastewater control and coastline protection. A more detailed comparison of western and Chinese approaches to ecological engineering are discussed in Mitsch (1991, 1995) and Mitsch et al. (1993).

Meanwhile, there was a similar development of the field of ecotechnology in central Europe in the mid-1980s. Uhlmann (1983), Straskraba and Gnauck (1985) and Straskraba (1993) defined ecotechnology as the "use of technological means for ecosystem management, based on deep ecological understanding, to minimize the costs of measures and their harm to the environment." Straskraba (1993) further elaborated on this point and called ecotechnology "the transfer or ecological principles into ecological management." In this paper, we consider ecological engineering and ecotechnology as similiar but agree that the former term involves mostly creation and restoration of ecosystems while the latter term involves managing ecosystems. Which is the more encompassing term is difficult to say but it could be, as Straskraba (1993) suggested that "Ecotechnology is in a sense broader [than ecological engineering,] being that environmental management [ecotechnology] is considered not only the creation and restoration of ecosystems."

The marine scientist John Todd in New England USA was also a leader in applying both the term and the concepts of ecological engineering to wastewater treatment, first at his New Alchemy Institute and later at his Ocean Ark Center. The term "ecological engineering" was applied to the treatment of wastewater and septage in ecologically based "green machines," with indoor greenhouse applications built both in Sweden and the United States in the late 1980s (Guterstam, 1996; Guterstam and Todd, 1990; Peterson and Teal, 1996; Teal and Peterson, 1991, 1993). Here the applications are described as "environmentally responsible technology [that] would provide little or no sludge, generate useful byproducts, use no hazardous chemicals in the process chain and remove synthetic chemicals from the wastewater" (Guterstam and Todd, 1990). All applications within this subset of ecological engineering have the commonality of using ecosystems for treatment of human wastes with an emphasis on truly solving problems with an ecological system rather than simply shifting the problem to another medium.

The field of biospherics, which was interested in the eventual habitation of humans in space, became another field with connections to ecological engineering, particularly when Biosphere 2, a glass-enclosed set of ecosystems, was built in the Arizona desert. This project, described in detail in a special issue of *Ecological Engineering* (Marino and Odum, 1999) may have been on the outer fringe of ecological engineering, as it needed a 10 MW power plant for its fans to move air, its HVAC systems to keep temperatures reasonable, and its pumps to create a hydrologic cycle. The important value of Biosphere 2 is clear: ". . . we should appreciate and try to understand the workings of the ecosystems in the biosphere that we have" (Mitsch, 1999).

Our 1989 book entitled "*Ecological Engineering: An Introduction to Ecotechnology*" (Mitsch and Jørgensen, 1989) and the subsequent initiation of the scientific journal *Ecological Engineering: The Journal of Ecotechnology* in 1992 brought ecological engineering principles and practice to a much wider audience. A 1993 workshop in Washington, DC, sponsored by the US Scientific Committee on Problems in the Environment (SCOPE), led to the establishment of an international project on "Ecological Engineering and Ecosystem Restoration" in Paris in 1995 as part of the SCOPE project. That committee, developed several special issues based on workshops held around the world that have been subsequently published in *Ecological Engineering* (Table 1). These volumes give a good glimpse of the array of international approaches to ecological engineering, in developed economies (Hüttl and Bradshaw, 2001; Lefeuvre et al., 2002), in developing economies (Wang et al., 1998), and in economies in transition (Mitsch and Mander, 1997). In the meantime, the International Ecological Engineering Society (IEES) was established in Utrecht, The Netherlands, in 1993 and the American Ecological Engineering Society (AEES) in Athens, Georgia in 2001. Our book *Ecological Engineering and Ecosystem Restoration* (Mitsch and Jørgensen, 2004), illustrates how far the field has developed since the 1989 book.

Table 1
Workshops and subsequent special issue publications of Scientific Committee on Problems in the Environment (SCOPE) project "Ecological Engineering and Ecosystem Restoration" (from Mitsch and Jørgensen, 2004)

Workshop title	Workshop location and date	Special issue publication
Ecological engineering in central and eastern Europe: remediation of ecosystems damaged by environmental contamination	Tallin, Estonia 6–8 November 1995	Mitsch and Mander (1997)
Ecological engineering in developing countries	Beijing, China 7–11 October 1996	Wang et al. (1998)
Ecological engineering applied to river and wetland restoration	Paris, France 29–31 July 1998	Lefeuvre et al. (2002)
Ecology of post-mining landscapes	Cottbus, Germany 15–19 March 1999	Hüttl and Bradshaw (2001)

4. Basic concepts in ecological engineering

There are some basic concepts that collectively distinguish ecological engineering from more conventional approaches to solving environmental problems with engineering approaches. These include the following concepts about ecological engineering:

(1) It is the based on the self-designing capacity of ecosystems;
(2) It can be the acid test of ecological theories;
(3) It relies on system approaches;
(4) It conserves non-renewable energy sources; and
(5) It supports biological conservation.

These concepts are discussed in more detail below. Much of this text is from Mitsch and Jørgensen (2004).

4.1. Self-design

Self-design and the related concept of self-organization are important properties of ecosystems to understand in the context of creation and restoration of ecosystems. In fact, their application may be the most fundamental concept of ecological engineering. Self-organization is *the property of systems in general to reorganize themselves given an environment that is inherently unstable and non-homogeneous*. Self-organization is a systems property that applies very well to ecosystems in which species are continually introduced and deleted, species interactions, e.g., predation, mutualism, etc., change in dominance, and the environment itself changes. Since ecological engineering often involves the development of new ecosystems as well as the use of pilot-scale models such as mesocosms to test ecosystem behavior, the self-organizing capacity of ecosystems remains an enigma to ecologists yet an important concept for ecological engineering.

There are two ways that systems can be organized—by rigid top-down control or external influence (imposed organization) or by self-organization (Table 2). Imposed organization, such as done in many conventional engineering approaches, results in rigid structures and little potential for adapting to change. This of course is desirable for engineering design where predictability of safe and reliable structures are necessary such as for bridges, furnaces, and sulfur scrubbers. Self-organization, on the other hand, develops

Table 2
Systems categorized by types of organization (from Pahl-Wostl, 1995)

Characteristic	Imposed organization	Self-organization
Control	Externally imposed; centralized control	Endogenously imposed; distributed control
Rigidity	Rigid networks	Flexible networks
Potential for adaptation	Little potential	High potential
Application	Conventional engineering	Ecological engineering
Examples	Machine	Organism
	Fascist or socialist society	Democratic society
	Agriculture	Natural ecosystem

flexible networks with a much higher potential for adaptation to new situations. It is thus the latter property that is desirable for solving many of our ecological problems. Here, when biological systems are involved, the ability for the ecosystems to change, adapt, and grow according to forcing functions and internal feedbacks is most important.

We define *self-design* as the *application of self-organization in the design of ecosystems*. The presence and survival of species in ecosystems after their introduction by nature or humans is more up to nature than to humans. Self-design is an ecosystem function in which the chance introduction of species is analogous to the chance development of mutations necessary for evolution to proceed (Mitsch, 1998). Multiple seeding of species into ecologically engineered systems is one way to speed the selection process in this self-organization (Odum, 1989). In the context of ecosystem development, self-design means that if an ecosystem is open to allow "seeding" of enough species and their propagules through human or natural means, the system itself will optimize its design by selecting for the assemblage of plants, microbes, and animals that is best adapted for existing conditions. The ecosystem then "designs a mix of man-made and ecological components [in a] pattern that maximizes performance, because it reinforces the strongest of alternative pathways that are provided by the variety of species and human initiatives" (Odum, 1989).

Fig. 4. Olentangy River Wetland Research Park at Ohio State University, Columbus, OH, USA, showing two kidney-shaped experimental wetlands. Basin on right was planted with 12 species of wetland plants; basin on left was not planted. Photo is after six growing seasons in 1999. This represents a long-term experiment in self-design. Photo courtesy of Olentangy River Wetland Research Park.

A whole-system ecosystem experiment that has developed for almost a decade involves wetlands at the Olentangy River Wetland Research Park in Ohio, USA, where continual introduction of river water over a decade has accelerated the natural process of self-design. Mitsch et al. (1998) describe how 2500 individuals of 12 plant species were introduced to one wetland basin while the other remained an unplanted control, essentially testing the self-design capabilities of nature with and without human help. Both basins (Fig. 4) had identical inflows of river water and hydroperiods. After only 3 years, there was convergence of wetland function of the planted and unplanted basins with 71% of functional indicators essentially the same in the two basins. This convergence in year 3 followed the second year where only 12% of the indicators were similar. Most importantly, hundreds of taxa, both aquatic and terrestrial, were continually introduced to these wetland basins, primarily because the wetland basins were hydrologically open systems, and many taxa survived. In 3 years, over 50 species of macrophytes, 130 genera of algae, over 30 taxa of aquatic invertebrates, and dozens of bird species found their way naturally to the wetlands. After 6 years, there were over 100 species of macrophytes but a continued effect of the initial planting was still observed in ecosystem function. The continual introduction of species, whether introduced through flooding and other abiotic and biotic pathways, appeared have a much more long-lasting effect in development of these ecosystems than did the introduction of a few species of plants. But both are important in self-design.

By contrast to the self-design approach, the approach that is more commonly used today by many biologists for much of what we call ecological restoration may be even closer to conventional engineering than is ecological engineering. There has sometimes been reference to this idea of a forceful "design" of ecosystems as the designer approach and the produced ecosystems as *designer ecosystems* (van der Valk, 1998). There is more honesty in this term than many are willing to acknowledge. This designer approach, while understandable because of the natural human (not only engineer's) tendency to control events, is less sustainable than an approach that relies more on nature's capacity to self-design. In these cases, the introduction of specific organisms is the goal and the survival of these organisms becomes the measure of success of the project. Systems are being designed in both cases, perhaps without the precision of systems that engineers design with physics and chemistry as their main sciences. Biology adds to the variability of the systems but otherwise design and predictable structures are carried out and desired.

As we described in our early book (Mitsch and Jørgensen (1989): "Ecological engineering is engineering in the sense that it involves the design of this natural environment using quantitative approaches and basing our approaches on basic science. It is technology with the primary tool being self-designing ecosystems. The components are all of the biological species of the world."

4.2. The acid test

Restoration ecologists have long suggested the tie between basic research and ecosystem restoration, stating that the best way to understand a system, whether a car, a watch, or an ecosystem, is to "attempt to reassemble it, to repair it, and to adjust it so that it works properly" (Jordan et al., 1987). Ecological engineering will be the ultimate test of many of our ecological theories. Bradshaw (1987) has described the restoration of a disturbed ecosystem as the "acid test of our understanding of that system." Cairns (1988) was more direct: "One of the most compelling reasons for the failure of theoretical ecologists to spend more time on restoration ecology is the exposure of serious weaknesses in many of the widely accepted theories and concepts of ecology." Bradshaw (1997) calls ecosystem restoration, when done properly, "ecological engineering of the best kind." Ecological theories that have been put forward in the scholarly publications over the past 100 years must serve as the basis of the language and the practice of ecological engineering. But just as there is the possibility of these theories providing the basis for engineering design of ecosystems, there is also a possibility of finding that some of these ecological theories are wrong. Thus ecological engineering is really a technique for doing fundamental ecological research and advancing the field of ecology.

4.3. A systems approach

Pahl-Wostl (1995) argues that just as self-organization is a property of a system as a whole, it is meaningless at the level of the parts. Ecological engineering requires a more holistic viewpoint than we are used to doing in many ecosystem management strategies. Ecological engineering emphasizes, as does ecological modeling for systems ecologists, the need to consider the entire ecosystem, not just species by species. Restoration ecology, a sub-field of ecological engineering, has been described as a field in which "the investigator is forced to study the entire system rather than components of the system in isolation from each other" (Cairns, 1988).

Conversely, the practice of ecological engineering cannot be supported completely by reductive, analytic experimental testing and relating. Approaches such as modeling and whole-ecosystem experimentation are more important, as ecosystem design and prognosis cannot be predicted by summing parts to make a whole. One must also be able to synthesize a great number of disciplines to understand and deal with the design of ecosystems.

All applications of technologies, whether of biotechnology, chemical technology, or ecotechnology, require quantification. Because ecosystems are complex systems, the quantification of their reactions becomes complex. Systems tools, such as ecological modeling, represent well-developed approaches to survey ecosystems, their reactions, and the linkage of their components. Ecological modeling is able to synthesize the pieces of ecological knowledge, which must be put together to solve a certain environmental problem. Ecological modeling takes a holistic view of environmental systems. Optimization of subsystems does not necessarily lead to an optimal solution of the entire system. There are many examples in environmental management where optimal management of one or two aspects of a resource separately does not optimize management of the resource as a whole. Ecological engineering projects, while they usually have one or more specific goals, will try to balance between the good of humans and the good of nature.

4.4. Non-renewable resource conservation

Because most ecosystems are primarily solar-based systems, they are self-sustaining. Once an ecosystem is constructed, it should be able to sustain itself indefinitely through self-design with only a modest amount of intervention. This means that the ecosystem, running on solar energy or the products of solar energy, should not need to depend on technological fossil energies as much as it would if a traditional technological solution to the same problem were implemented. The system's failure to sustain itself does not mean that the ecosystem has failed us (its behavior is ultimately predictable). It means that the ecological engineering has not facilitated the proper interface between nature and the environment. Modern technology and environmental technology, for the most part, are based on an economy supported by non-renewable (fossil fuel) energy; ecotechnology is based on the use of some non-renewable energy expenditure at the start (the design and construction work by the ecological engineer) but subsequently dependence on solar energy.

A corollary to the fact that ecological engineers' systems use less non-renewable energy is that they generally cost less than conventional means of solving pollution and resource problems, particularly in systems maintenance and sustainability. Because of the reliance on solar-driven ecosystems, a larger part of land or water is needed than would be technological solutions. Therefore, if property purchase (which is, in a way, the purchase of solar energy) is involved in regions where land prices are high, then ecological engineering approaches may not be feasible. It is in the daily and annual operating expenses in which the work of nature provides subsidies and thus lower costs for ecological engineering alternatives.

4.5. Ecosystem conservation

We solve human problems and create ones for nature. That has been the history of mankind, at least in the western world. We need to adopt approaches to solving (at least) environmental problems not only to protect streams, river, lakes, wetlands, forests, and savannahs. We need to work symbiotically with nature where we use her public service functions but recognize the need to conserve nature as well. The idea of nature conservation is so important that it needs to become a goal of engineering, not just one of its possible outcomes. We must seek additional approaches to reduce the adverse effects of pollution, while at the same time preserving our natural ecosystems and conserving our non-renewable energy resources. Ecotechnology and ecological engineering offer such additional means for coping with some pollution problems, by recognizing the self-designing properties of natural ecosystems. The prototype machines for ecological engineers are the ecosystems of the world.

Ecological engineering involves identifying those biological systems that are most adaptable to the human needs and those human needs that are most adaptable to existing ecosystems. Ecological engineers have in their toolboxes all of the ecosystems, communities, populations, and organisms that the world has to offer. Therefore, a direct consequence of ecological engineering is that it would be counterproductive to eliminate or even disturb natural ecosystems unless absolutely necessary. This is analogous to the conservation ethic that is shared by many farmers even though they may till the landscape and suggests that ecological engineering will lead to a greater environmental conservation ethic than has been realized up to now. For example, when wetlands were recognized for their ecosystem values of flood control and water quality enhancement, wetland protection efforts gained a much wider degree of acceptance and even enthusiasm than they had before, despite their long understood values as habitat for fish and wildlife (Mitsch and Gosselink, 2000). In short, recognition of ecosystem values provides greater justification for the conservation of ecosystems and their species. A corollary of this is the point made by Aldo Leopold that the tinker's first rule is to not throw away any of the parts. The ecological engineer is nature's tinker.

5. What we do now

We are approaching an age of diminishing resources, the growth of the human population is continuing, and we have not yet found means to solve local, regional, and global pollution and renewable resource shortage problems properly. When the first green wave appeared in the mid and late sixties, it was considered a feasible task to solve the pollution problems. The visible problems were mostly limited to point sources and a comprehensive "end of the pipe technology" (=environmental technology) was available. It was even seriously discussed in the US that what was called "zero discharge" to the nation's waterways could be attained by 1985. In fact, the US Congress decreed in the 1970s that the streams and rivers of the country needed to be fishable and swimmable by 1983. When that date came, a significant percentage of those streams and rivers was hardly ready for swimming or fishing.

It became clear in the early 1970s that zero discharge would be too expensive, and that we should also rely on the self-purification ability of ecosystems. That called for the development of environmental and ecological models to assess the self-purification capacity of ecosystems and to set up emission standards considering the relationship between impacts and effects in the ecosystems. Meanwhile, we found that the environmental crisis was much more complex than we initially thought. We could for instance remove heavy metals from wastewater but where should we dispose the sludge containing the heavy metals? Resource management pointed towards recycling to replace removal. Non-point sources of toxic substances and nutrients, chiefly originating from agriculture, emerged as new, threatening environmental problems in the late seventies. It was revealed that we use as much as about 100,000 chemicals that may threaten the environment due to their more or less toxic effects on plants, animals, humans and entire ecosystems. In most industrialized countries comprehensive environmental legislation was introduced to regulate the wide spectrum of different pollution sources. The focus on global environmental problems such as the greenhouse effect and the decomposition of the ozone layer added to the complexity. Trillions of dollars have been invested in pollution abatement on a global scale, but it seems that two or more new problems emerge for each problem that we solve. Our society does not seem geared to environmental problems—or is there perhaps another explanation?

Environmental technology offers a wide spectrum of methods that are able to remove pollutants from water, air and soil. These methods are particularly applicable to cope with point sources. We have, for instance, many environmental technological methods for coping with different wastewater problems. To select the right method (or most often the right combination of methods), a profound knowledge of the applicability of the methods and of the processes and characteristics of the ecosystem receiving the emission is necessary.

Clean technology, while not in our definition of ecological engineering explicitly, explores the possibilities of recycling byproducts or the final waste products or attempting to change the entire production technology to obtain a reduced emission. It attempts to answer the pertinent question: couldn't we produce our product by a more environmentally friendly method. It will to a great extent be based on environmental risk assessment, LCA and environmental auditing. Sometimes it is referred to as *industrial ecology*.

Sustainability has become another of the buzz words of our time. It is used again and again in the environmental debate—sometimes in a wrong context. It is therefore important to give a clear definition to avoid misunderstandings later. The Brundtland report (World Commission on Environment and Development, 1987) produced the following definition: *sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*. Note, however, that this definition includes no reference to environmental quality, biological integrity, ecosystem health, or biodiversity. Conservation philosophy, which portends to seek a sustainable society, has been divided into two schools: resourcism and preservationism. They are understood respectively as seeking maximum sustained yield of renewable resources and excluding human inhabitation and economic exploitation from remaining areas of undeveloped nature. These two philosophies of conservation are mutually incompatible. They are both reductive and ignore non-resources, and seem not to give an answer to the core issue—how to achieve sustainable development—although preservationism has been retooled and adapted to conservation biology. Taken as a whole, conservation ecology cannot provide all the answers to a sustainable society either.

6. The new approach—ecological engineering

The state of our environment, combined with a dwindling of non-renewable natural resources available to solve environmental problems, suggests that the time has come for yet a new paradigm in engineering that involves ecosystem and landscape scale questions and solutions. There are a great number of environmental and resource problems that need an ecosystem approach, not just a standard technological solution or even clean technology development. We have finally recognized that we cannot achieve the complete elimination of pollutants owing to a number of factors and that we need new approaches better in tune with our natural ecosystems. In our attempts to control our own environment, we have also seen that we have tried to control nature too much at times, with disastrous consequences, such as enormous floods, invasive species, and air and water pollution being transported hundreds and thousands of kilometers instead of tens of kilometers. But why now and why do we offer this new field to engineers, whom many blame for the difficult situation in which we find ourselves?

Ecological engineering is needed because we only have limited nonrenewable resources too solve all of our environmental problems, because we now just move pollutants around in a kind-of shell game, and because secondary effect of technological fixes are other pollution problems at a larger scale.

6.1. Limited resources

We have a finite quantity of resources to address to the problems of pollution control and natural resource disappearance. This is particularly true for developing countries that wish to have the standard of living and technologies of developed countries but currently must deal with pollution problems often more serious that those in the developed world.

The limited resources and the high and increasing human population force us to find a trade-off between the two extremes of pollution and totally unaffected ecosystems. We cannot and we must not accept a situation of no environmental control, but we cannot afford zero-discharge policies either, knowing that we do not provide one-third of the world's population with sufficient food and housing.

6.2. The shell game

When we control pollution through technological means, we are often playing a shell game with the pollution. Toxic substances present in municipal wastewater cannot be biodegraded in a mechanical-biological wastewater treatment plant but will, depending on the water solubility, be found either in the treated water or in the sludge. If the sludge is used as soil conditioner in agriculture the toxic substance will contaminated the soil—or if the sludge is incinerated it may cause air pollution or be found in the ash. We may use scrubbers to prevent sulfur emissions from power plants and then be faced with enormous solid waste storage problems from the sludge left behind. We build solid waste facilities and water pollution control systems and atmospheric emissions of the greenhouse gas methane result. We use industrial wastewater treatment methods to remove heavy metals from a factory and then must dispose of metal-rich sludge. We burn sludge and solid wastes and we create air pollution problems. We are moving materials around in a shell game—if it is not under one shell, it is under another.

6.3. Climate change, bigeochemical pollution, and the secondary pollution effect

We are now faced with the fact that even seemingly inert CO_2 is considered a pollutant. It is the chief atmospheric gas thought to be causing changes in our climate and international efforts through treaties such as the Kyoto Treaty are attempting to limit the burning of fossil fuels to minimize future climate changes. If expensive environmental technology is being used to solve a pollution problem, we are solving a problem of one type and may probably be causing global emissions of CO_2 to increase at the same time.

Problems of excessive buildup of chemicals in the biosphere are not limited to CO_2. It has been estimated that we match the amount of nitrogen that nature fixes throughout the biosphere, (Fig. 5). We are fixing nitrogen to produce fertilizer, we are fixing nitrogen from N_2 and O_2 in the atmosphere and N stored in fossil fuels through high-temperature combustion of fossil fuels, particularly by the automobile, and we are planting crops that fix additional nitrogen from the atmosphere. We have doubled the inflow of nitrogen to

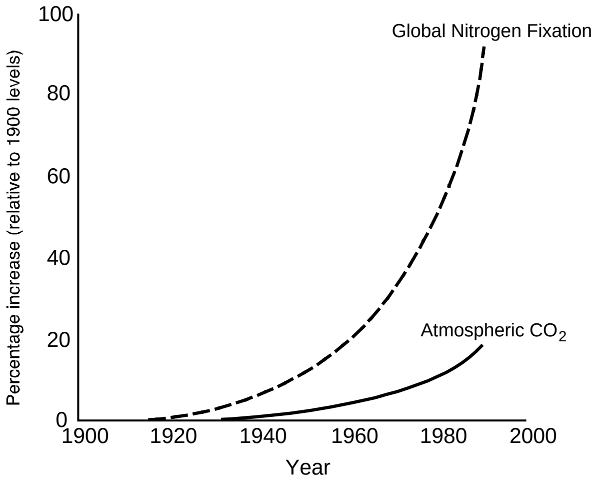

Fig. 5. Pattern of increase in atmospheric carbon and increase in bioavailable nitrogen in the 20th century (modified from Vitousek et al., 1997; from Mitsch and Jørgensen, 2004, reprinted with permission, Wiley).

the biosphere, in contrast to the net increase of 20% of carbon in the atmosphere since 1900 (Fig. 5).

We have undoubtedly used a great amount of fossil fuel in the economy to develop the technology that is solving some of our pollution problems. The amount of energy used is generally proportional to the cost of the technology, and the carbon dioxide emission is proportional to the amount of fossil fuel used. The use of soft technologies, low-cost technologies wherever possible, such as those afforded in ecologically engineered systems, are therefore more important than ever in pollution abatement that does not, in an indirect way, cause more increases of CO_2 and nitrogen.

7. Ecological engineering—an overdue alliance

Engineering and ecology are ripe for integration into one field, not separate approaches that are often adversarial. Ecology as a science is not routinely integrated in engineering curricula, even in environmental engineering programs. Engineers are missing the one science that could help them the most in environmental matters. Likewise, environmental scientists and managers are missing a crucial need in their profession—problem solving. While tremendously competent at describing problems and maybe even managing ecosystems one species at a time, ecologists are not well versed in prescribing solutions to problems. The basic science of ecological engineering is ecology, a field that has now matured to the point where it needs to have a prescriptive—rather than just a descriptive—aspect. Matlock et al. (2001) describe an interesting course curriculum for US universities for ecological engineering that would have courses in quantitative ecology (population, community, ecosystems), restoration ecology, as well as modeling, economics, and engineering.

Ecological engineering is now, in effect, being practiced by many professions under a great variety of names, including ecotechnology, ecosystem restoration, artificial ecology, biomanipulation, ecosystem rehabilitation, nature engineering (in Holland), hydroecology (in eastern Europe) and bioengineering (originated in Germany) but with very little theory to back the practices. Engineers are building wetlands, lakes, and rivers with little understanding of the biological integrity of these systems. Ecologists and landscape architects who now design ecosystems with home-spun methodologies that must be relearned each time. Engineers who design ecosystems relearn the approaches each time and do not generally publish their successes in the open literature. The theory has not yet connected with the practice.

Some of the ecotechnological methods are not new and, in fact, some have been practiced for centuries, particularly in China. In earlier times, these methods were considered as good, empirical approaches. Today, ecology has developed sufficiently to understand the scientific background of ecological engineering, to formalize usage of these approaches, and to develop new ones. We must understand not only how we can influence the processes in the ecosystem and how the ecosystem components are linked together, but also how changes in one ecosystem can produce changes in neighboring ecosystems.

We must acknowledge that there are two billion more people on earth and that the non-renewable resources are more limited today than 20 years ago (Fig. 6). We therefore need to find new ways. We have attempted to solve the problem by use of available technology. It has partially failed. Therefore we must think more ecologically and consider additional means. Ecological engineering, if properly applied, is based on ecological considerations and attempts to

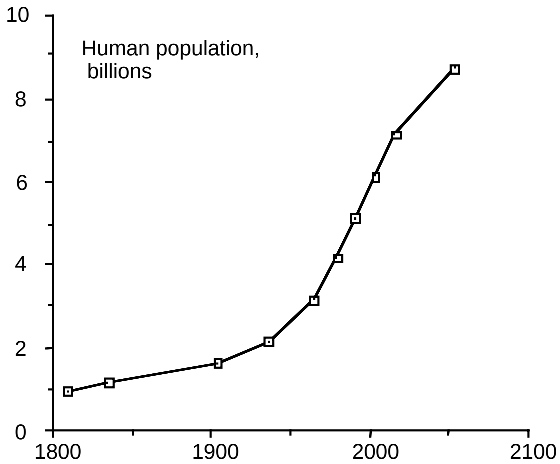

Fig. 6. Change in population, 1805–1999. For the period 1999–2050, an optimistic prognosis predicts that the population growth will level off after the year 2015. In the period 1805–1975, the growth was been more than exponential (from Mitsch and Jørgensen, 2004, reprinted with permission, Wiley).

optimize ecosystems (including limited resources) and man-made systems for the benefit of both. It should therefore afford additional opportunities to solve the crisis. We have had several energy crises during the past 30 years and we know that new crises will appear in the future. Therefore we have to rely more on solar-based ecosystems, which are the bases for ecological engineering.

In the short term, ecological engineering could bring immediate attention to the importance of "designing, building and restoring ecosystems" as a logical extension of the field of ecology. In the long term, it will provide the basic and applied scientific results needed by environmental regulators and managers to control some types of pollution while reconstructing the landscape in an ecologically sound way. The formalization of the idea that natural ecosystems have values for humans, other than directly commercial ones, is also a benefit of ecotechnology and will go a long way toward enhancing even further a global ecological conservation ethic.

Our experience with the formal field of ecological engineering and its possibilities is limited today. We have had one decade of formal peer-reviewed experience in the journal *Ecological Engineering* and a few academic settings in the world where the field is only beginning to be taught. Although the results we do have look very promising, we need to integrate the application of ecological engineering much more in our educational systems in the future. This will require a much deeper understanding of the reactions of nature to our activities. This will therefore require a continuous development of ecology, systems ecology, applied ecology, ecological modeling, and ecological engineering. Ecological engineering offers us a very useful tool for better planning in the future. It will be a real challenge to humankind to use this tool properly.

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