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What is ecological engineering?

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ABSTRACT

Ecological engineering, defined as the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both, has developed over the last 30 years, and rapidly over the last 10 years. Its goals include the restoration of ecosystems that have been substantially disturbed by human activities and the development of new sustainable ecosystems that have both human and ecological values. It is especially needed as conventional energy sources diminish and amplification of nature's ecosystem services is needed even more. There are now several universities developing academic programs or departments called ecological engineering, ecological restoration, or similar terms, the number of manuscripts submitted to the journal *Ecological Engineering* continue to increase at an rapid rate, and the U.S. National Science Foundation now has a specific research focus area called ecological engineering. There are many private firms now developing and even prospering that are now specializing in the restoration of streams, rivers, lakes, forests, grasslands, and wetlands, the rehabilitation of minelands and urban brownfields, and the creation of treatment wetlands and phytoremediation sites. It appears that the perfect synchronization of academy, publishing, research resources, and practice is beginning to develop. Yet the field still does not have a formal accreditation in engineering and receives guarded acceptance in the university system and workplace alike.

1. Introduction

In 1996, I presented a paper at the first *EcoSummit* in Copenhagen, Denmark, that provided several recommendations for the then newly forming field of ecological engineering (Mitsch, 1998). The paper was titled the "Ecological engineering—the 7-year itch" (Mitsch, 1998) because it was presented seven years after our definition and principles were published in the first textbook on ecological engineering entitled "Ecological Engineering: An Introduction to Ecotechnology" (Mitsch and Jørgensen, 1989). I was starting to get nervous that the field was straying from principles and to a hodge-podge of case studies and pollution control projects, many of which were not even ecological engineering. I was also concerned that ecological engineering was not being embraced by either the engineering or ecology communities and that the convergence of these two fields into a third transdisciplinary field was simply not happening. In that paper (Mitsch, 1998), I presented six recommendations:

1. Ecologists need to recognize the applied nature of their field to offer prescriptions, not just descriptions, for environmental problems.
2. Engineers need to understand that biological and ecological sciences are fundamental to their tasks.
3. A formal accreditation of ecological engineering should be developed in concert with existing engineering accreditations.
4. Universities need to integrate ecology and engineering into rational and rigorous programs of ecological engineering.
5. Ecologists and engineers need to work together and understand each other's language.
6. An international dialog needs to continue to establish the scientific basis, limitations and opportunities for ecological engineering.

This paper will review the history of ecological engineering and its progress in light of these 16-year-old recommendations. In that period, the world has changed and ecological engineering may be more relevant than ever in times of diminishing resources and calls for sustainability. In an academic and social analog of natural selection, this field and profession based on sustainability and maintained as small seeds in a few universities in the 1970s through 2000s may now be "selected for" in the 2010s and 2020s. Ecological engineering is essential for a sustainable world.

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1.1. Ecosystems and complexity

The fundamental unit of ecological engineering must remain the ecosystem—ecological engineering must involve the creation and restoration of an ecosystem. An ecosystem's presence or absence is the fundamental test of whether someone is talking about ecological engineering, or perhaps only environmental engineering (the application of technology to solve environmental problems; principle examples include design of wastewater treatment, water treatment, and air pollution control systems) or simply "green engineering" (sometimes referred to as ecotechniques, or even green architecture). Natural ecosystems are complex entropy-fighting systems, and in that complexity comes an infinite amount of feedbacks and adaptations that contribute to resiliency. Human society, as a "part of" nature and not "apart from" nature would do well to recognize and use the important functions of nature (rather than destroy them) to provide a resilient and sustainable society.

2. Goals and definitions of ecological engineering

The goals of ecological engineering, as described by Mitsch and Jørgensen (1989, 2003, 2004) and Mitsch (1993, 1996), 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 values.

The definition of ecological engineering evolved over that period to "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both" (Mitsch, 1993, 1996, 1998; Mitsch and Jørgensen, 2003, 2004). Ecological engineering has been further described (Mitsch and Jørgensen, 2004) as being classified into 5 different categories:

1. Ecosystems are used to reduce or solve a pollution problem.
2. Ecosystems are imitated or copied to reduce a resource problem.
3. The recover of ecosystems is supported after significant disturbance.
4. Existing ecosystems are modified in an ecologically sound way.
5. Ecosystems are used for the benefit of humankind without destroying the ecological balance.

2.1. Ecosystem restoration

The sister field of *ecosystem restoration* was described by Bradshaw (1997) as "ecological engineering of the best kind." Restoring the landscape has a rich history going back to Aldo Leopold in Wisconsin (Leopold, Sand County Almanac) and Tony Bradshaw in the minefield restorations of England (Bradshaw, 1987, 1997). Ecological restoration was defined 20 years ago in an U.S. National Academy of Sciences (NAS) publication as "the return of an ecosystem to a close approximation of its condition prior to disturbance" (NRC, 1992). The field developed rapidly since then and has been re-defined as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER, 2004). There are many other terms that have been used to describe parts of ecological engineering including *ecosystem rehabilitation* (actions that repair indigenous ecosystem function and structure), *nature engineering*, *habitat reconstruction* and *reclamation* (stabilization, amelioration, increase in utilitarian or economic value; rarely uses indigenous ecosystems as a model) (Aronson et al., 1993; Mitsch and Jørgensen, 2004). All define parts of ecological engineering. Earlier terms such as *synthetic ecology* are less frequently used now.

There is little debate anymore as to whether ecosystem restoration should be considered a part of ecological engineering. It should be the heart and soul of the field. In wetland management in the USA, for example, it is frequently suggested that restoring a wetland is greatly preferred over creating a new wetland. Yet both approaches need the "science" of wetland ecology (knowledge of soils, hydrology, vegetation, biogeochemistry, etc.) and the "engineering" of landscape and hydrologic design.

3. Early history of ecological engineering

H.T. Odum is often described as the father of ecological engineering. Ecological engineering is mentioned in a few of his publications in the 1960s (Odum, 1962; Odum et al., 1963). In Odum's enduring classic *Environment, Power and Society* (Odum, 1971; republished after his death as Odum, 2005) he described ecological engineering as "the management of nature . . . an endeavor with singular aspects supplementary to those of traditional engineering." In his systems tome *Systems Ecology* (Odum, 1983) ecological engineering was described as "the engineering of new ecosystem designs . . . that uses systems that are mainly self-organizing." That theme of self-organization was emphasized in Odum (1989) but more strongly in his most comprehensive description of ecological engineering (Odum and Odum, 2003), which was published a year after his death.

At the same time, Ma Shijun was developing a concept referred to as ecological engineering in China, with the idea first published in Western literature in the 1980s (Ma, 1985; Ma and Yan, 1989). He has been referred to as the "father of ecological engineering in China."

Occasional university courses were taught in ecological engineering in the mid-1970s—"Ecological Engineering and Systems Ecology" that I taught at Illinois Institute of Technology in Chicago being one example in 1975–1978. But the first substantive publication to describe ecological engineering definitions and principles was not published until a decade later by Mitsch and Jørgensen (1989), partially as a result of a 1986 Fulbright Fellowship to Copenhagen, Denmark. Visits to China by Mitsch and Jørgensen in 1987–1989 led to significant Chinese contributions to the Mitsch and Jørgensen (1989) book and solidified the comparison of Chinese and Western versions of ecological engineering (see Mitsch, 1991; Mitsch et al., 1993). That enthusiasm for ecological engineering in China continues to this day (Barot et al., 2012).

The first international ecological engineering meeting was held in Trosa Sweden in 1991 and the scholarly journal *Ecological Engineering* that this paper is published in was started in 1992. An ecological engineering workshop—under the purview of the National Research Council (NRC) of the U.S. National Academy of Science (NAS)—was held at in Washington, DC, USA, in 1993. There was a brief mention of that meeting in *Environmental Science & Technology* (*ES&T*) and a summary paper on ecological engineering appeared in a cover story journal article in *ES&T* that year (Mitsch, 1993). That Washington, DC, workshop served as the springboard for the approval of a SCOPE (Scientific Committee on Problems of the Environment) project in Paris in 1994 entitled "Ecological Engineering and Ecosystem Restoration," that ultimately led to the publication of four journal special issues emanating from international meetings on ecological engineering held in Estonia, China, France, and Germany (Table 1).

Both an international and an American organization dedicated to ecological engineering were founded at the end of the 20th century and continue to this day. The International Ecological

Table 1
Series of 4 workshops and subsequent special issue publications of international SCOPE (Scientific Committee on Problems of the Environment) international project on "Ecological Engineering and Ecosystem Restoration.".

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

Engineering Society (IEES) was founded in 1993 at a small meeting hosted by Jos Verhoeven at the University of Utrecht in Utrecht, The Netherlands. The American Ecological Engineering Society (AEES) had its beginnings with a meeting held in Columbus, OH, USA, in 1999 and was formally launched with its first meeting in 2001 at the University of Georgia in Athens, GA. Soon afterwards, two ecological engineering textbooks were published in one year (Mitsch and Jørgensen, 2004; Kangas, 2004) and ecological engineering programs have begun to slowly develop in several university settings in the USA.

4. Concepts and principles of ecological engineering

Principles of ecological engineering and related fields have been published by Mitsch and Jørgensen (1989, 2003, 2004), Mitsch (1998), Straskraba (1993), Zalewski (2000), Bergen et al. (2001) and Odum and Odum (2003). In fact, more principles have been developed for this field than many others. Yet there seems to be a continual hue and cry for yet more principles (Jones, 2012). Some of the more basic concepts, some of which could be principles as well, are self-design, acid-test, systems thinking, natural energy use, and ecosystem conservation.

4.1. Self-design

Self design is one of the basic cornerstones of ecological engineering. It is the application of self-organization in the design of ecosystems. Nature contributes to the final design of ecosystems as much or more than does the human designer. This has been one of the most consistently used ecological engineering principles as "design" is one of the most important words in engineering.

4.2. Acid test of ecological theories

Creating or restoring an ecosystem is not usually experimental science. So few if any general scientific principles can be developed from ecological engineering. But when an ecosystem is created or restored, general principles already in existence in the field of ecology can be disproved. Bradshaw (1987), who has described the restoration of a disturbed ecosystem as the "acid test of our understanding of that system" has stated that because we cannot prove that a restored ecosystem proves an ecological theory, we will "learn more from our failures than from our successes since a failure clearly reveals the inadequacies in an idea, while a success can only corroborate and support, and can never absolutely confirm, an assertion." Cairns (1988) was more direct in this point: "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."

4.3. System thinking

As described by Mitsch and Jørgensen (2004), system thinking is required when ecosystems are created or restored. It is not the time to think about linear cause and effects but rather the ecosystem as a whole.

4.4. Natural energy use

Traditional engineering, by its very nature, depends on the energy in society. It has its successes partially due to the fact that seemingly any problem can be solved if enough energy is focused on solving that problem. "Engineering" and "energy" even have the same etymological roots. Ecological engineering uses self-designing ecosystems at its core so it is, by definition, a field that focuses on natural energies, often solar, wind, and hydrologic energies that have already been manifest in ecosystems. We now have a formal term—ecosystem services (Costanza et al., 1997; Costanza, 2012)—for the human values that nature provides.

A fundamental concern in society is that we are now running out of energy to fuel our future. While there are of course claims to the contrary, it is now considered conceivable that we simply will not have as much energy resources in the future as we have had in the past. In a graphic similar to the all-too-accurate projections by Hubbert (1962) on the production and consumption of specific energy resources such as oil (the graphics became known as "peak oil" curves), Clugston (2007), as one example, projected that it may be that we are going to go through a "peak energy" of human society of 570–710 Quads (quadrillion British Thermal Units (BTU)/year) by 2025–2030 (Fig. 1). The approaches and principles of ecological engineering need to be established now so that we can call on the ecosystem services of nature even more when we need them on the other side of the energy peak.

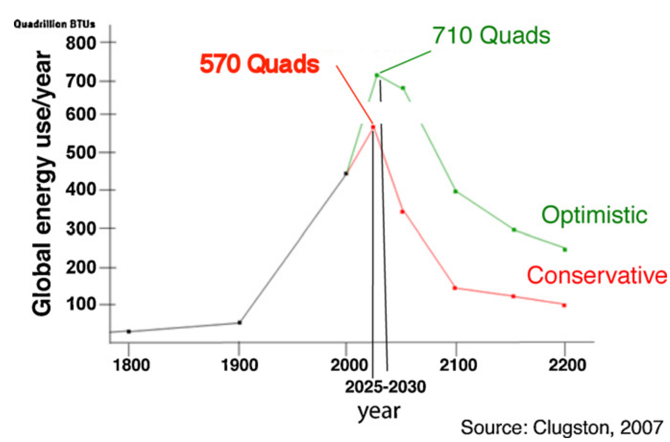

Fig. 1. Energy use and projected use in the world, 1800–2200 (Clugston, 2007). Units on graph are quadtrillion (10^{15}) British Thermal Units (BTU). A BTU is equal to 252 calories or 1.055 kJ.

Table 2
Special issues published in the international journal *Ecological Engineering*, 1992–2011.

Year	Title of special issue	Volume and issue number	Special issue editor; origin of special issue including meeting location and date
2011	Biogeochemical aspects of ecosystem restoration and rehabilitation	Vol. 37, issue 7	Ulo Mander; 6th International Symposium on Ecosystem Behaviour, BIOGEOMON, Helsinki, Finland, June 29–July 3, 2009
	Advances in pollutant removal processes and fate in natural and constructed wetlands	Vol. 37, issue 5	Joan Garcia; 3rd International Symposium on Dynamics and Control of Pollutants in Wetlands (WETPOL 2009), Barcelona, Spain, September 20–24, 2009
	Enhancing ecosystem services on the landscape with created, constructed and restored wetlands	Vol. 37, issue 1	Jan Vymazal; 8th INTECOL International Wetlands Conference, Cuiabá, Brazil, July 20–25, 2008
2010	Managing denitrification in human dominated landscapes	Vol. 36, issue 11	L.A. Schipper, A.J. Gold, and E.A. Davidson; Workshop on Denitrification in Managed Ecosystems, Narragansett, RI, USA, May 12–14, 2009
	Interaction among groundwater, surface water and ecosystems: a key issue for integrated water management	Vol. 36, issue 9	D.-I. Mueller-Wohlfeil, H.P. Nachtnebel, and M. Zalewski; 2nd International Multidisciplinary Conference on Hydrology and Ecology (HydroEco09), Vienna, Austria, April 20–25, 2009
	Carbon, nutrient and metal retention in wetlands in a restoration context	Vol. 36, issue 5	Jos Verhoeven; WETPOL Meeting, Tartu, Estonia, September 16–21, 2007
	Vegetation and slope stability	Vol. 36, issue 3	Alexia Stokes; 2nd International Conference 'Ground Bio- and Eco-engineering: The Use of Vegetation to Improve Slope Stability – ICGBE2', Beijing, China, July 14–18, 2008
	BioGeoCivil Engineering	Vol. 36, issue 2	H.M. Jonkers and M.C.M. van Loosdrecht; 1st International Conference on BioGeoCivil Engineering, Delft, The Netherlands, June 23–25, 2008
2009	Lake Taihu eutrophication: control countermeasures and recycling exploitation	Vol. 35, issue 11	B. Qin; Nanjing, China
	The Houghton Lake wetland treatment project	Vol. 35, issue 9	R. Kadlec; Michigan, USA
	Molecular and microbial advances in wetland science	Vol. 35, issue 6	K. Tonderski; WETPOL Meeting, Tartu, Estonia, September 16–21, 2007
	Pollution control by wetlands	Vol. 35, issue 2	U. Mander and W.J. Mitsch; WETPOL Meeting, Tartu, Estonia, September 16–21, 2007
2008	Ecological management and sustainable development in the humid tropics of Costa Rica	Volume 34, issue 4	B. Kohlmann, W.J. Mitsch, and D.O. Hansen; EARTH University, Costa Rica, and The Ohio State University, USA collaboration
2007	Forest rehabilitation after disturbance	Vol. 31, issue 3	R.F. Hüttl and W. Gerwin: The World Congress of the International Union of Forest Research Organisations (IUFRO), Brisbane, Australia, 2005
	Wetland restoration	Vol. 30, issue 2	Michael Trepel; Society for Ecological Restoration International Conference, Zaragoza, Spain, September 12–18, 2005
	Carbon sequestration and landscape ecology in Western Europe	Vol. 29, issue 4	R.F. Hüttl and T. Fischer; 1st World Congress of Agroforestry, Orlando, FL, USA, June 27–July 2, 2005
2006	The growth of ecological engineering	Vol. 28, issue 3	J.F. Martin and W.J. Mitsch; 5th Annual AEES Conference, Columbus, OH, USA, May 18–20, 2005
	The Everglades nutrient removal project	Vol. 27, issue 4	K.R. Reddy, R.H. Kadlec, and M.J. Chimney; Florida, USA
	Advances in coastal habitat restoration in the northern Gulf of Mexico	Vol. 26, issue 1	P. Chapman and D. Reed; CREST Symposium "Advances in Coastal Habitat Restoration in the Northern Gulf States" Thibodaux, LA, USA, July 2003
2005	Constructed wetlands for wastewater treatment	Vol. 25, issue 5	J. Vymazal; Seventh INTECOL Wetland Conference, Utrecht, The Netherlands, July 25–30, 2004
	Delaware Bay salt marsh restoration	Vol. 25, issue 3	J. Teal and S.B. Peterson; Massachusetts, USA
	Riparian buffer zones in agricultural watersheds	Vol. 24, issue 5	Ü Mander, V. Kuusemets, and Y. Hayakawa; International Workshop on Efficiency of Purification Processes in Riparian Buffer Zones, Kushiro City, Japan, November 5–9, 2001 and International Conference on Ecological Engineering (IEES), Christchurch, New Zealand, November 25–29, 2001
	Wetland creation, restoration, and conservation	Vol. 24, issue 4	W.J. Mitsch; Wetland Invitational, Olentangy River Wetland Research Park, Columbus, USA, May 15–16, 2003
	Landscape and ecosystem development after disturbance by mining	Vol. 24, issues 1–2	R.F. Hüttl and W. Gerwin; International Conference "Disturbed Landscapes. Analysis, Modeling and Valuation," Cottbus, Germany, September 24–27, 2002
2003	The philosophy and emergence of ecological engineering	Vol. 20, issue 5	D. Gattie and W.J. Mitsch; 1st Annual AEES Conference, Athens, GA, USA, April 39–May 2, 2001
2002	Ecological engineering applied to river and wetland restoration	Vol. 18, issue 5	W.J. Mitsch, J.-C. Lefeuvre, and V. Bouchard; SCOPE Workshop, Paris France, July 29–31, 1998
2001	Ecology of post-mining landscapes	Vol. 17, issues 2–3	A.D. Bradshaw and R.F. Hüttl; Symposium "Ecology of Post-Mining Landscapes" Cottbus, Germany, March 1999
	Ecosystem restoration for plant diversity conservation	Vol. 17, issue 1	Symposium on Nature Restoration, University of Groningen, The Netherlands, August 1998
	Integration of ecology and engineering in the aquatic environment	Vol. 16, issue 3	D.P. Hamilton and C.E. Oldham; Nedlands, WA, Australia
	Ecohydrology	Vol. 16, issue1	M. Zalewski; International Hydrological Programme Symposium on Ecohydrology, Lodz, Poland, May 1998

Table 2 (*Continued*)

Year	Title of special issue	Volume and issue number	Special issue editor; origin of special issue including meeting location and date
2000	Forests and Energy	Vol. 16, issue S-1	R.F. Hüttl, O. Bens, and B.U. Schneider; 1st Hannover EXPO2000 World Forest Forum, Hannover, Germany, 2000
	Restoration of a severely impacted riparian wetland system—the Pen Branch Project	Vol. 15, issue S-1	C. Barton, et al.; USDA Forest Service, Aiken, SC, USA
1999	Nitrogen and phosphorus retention in wetlands	Vol. 14, issue 1-2	W.J. Mitsch and A.J. Horne, Columbus, OH and Berkeley, CA, USA
	Biosphere II	Vol. 13, issues 1-4	B. Marino, H.T. Odum, and W.J. Mitsch; Cambridge, MA; Gainesville, FL, and Columbus, OH, USA
	Constructed and natural wetlands for pollution control	Vol. 12, issue 1-2	C. Tanner, G. Rasin, and G.E. Ho; V International INTECOL Wetlands Conference, Perth, WA, Australia, September 22–28, 1996
1998	Ecological engineering in developing countries	Vol. 11, issue 1-4	R. Wang, J. Yan, and W.J. Mitsch; SCOPE workshop. Beijing, China, October 7-11,1996
	Ecological engineering at EcoSummit 96 in Copenhagen	Vol. 10, issue 2	W.J. Mitsch and M. Brown; EcoSummit 1996, Copenhagen, Denmark, August 19–23, 1996
	Degradation and restoration of forests	Vol. 10, issue 1	W. Kilian and J. Fanta; Workshop on "Degradation of Forests Sites and Possibilities for their Recovery", XXII IUFRO World Congress, Tampere, Finland, 1995
1997	Ecological engineering in Central and Eastern Europe: remediation of ecosystems damaged by environmental contamination	Vol. 8, issue 4	Mitsch and Ü Mander; SCOPE Workshop, Tallinn, Estonia, November 6–8, 1995
1996	Ecological engineering for nature development: examples from Western Europe	Vol. 7, issue 4	J.T. Verhoeven; Ecological Engineering for Ecosystem Restoration Conference, Zeist, The Netherlands, November 1994
	Mesocosms and ecological engineering	Vol. 6, issue. 1/3	P. Kangas and W. Adey; College Park, MD and Washington, DC, USA
1995	Phosphorus dynamics in the Lake Okeechobee watershed, FL, USA	Vol. 5, issue 2/3	K.R. Reddy and E.G. Flaig; Gainesville, FL, USA
	The role of vegetation in created and restored wetlands	Vol. 5, issue 1	B. Gopal and W.J. Mitsch; IV International INTECOL Wetlands Conference, Columbus, OH, USA, September 1992
	Ecological engineering applied to agricultural and land use planning	Vol. 4, issue 3	S.E. Jorgensen: ISEM 8th International Conference on the State of the Art of Ecological Modelling, Perth, Australia, December 6–10, 1993
	Restoration and creation of wetlands—scientific basis and measuring success	Vol. 4, issue 2	W.J. Mitsch; Columbus, OH, USA
1994	Creating freshwater marshes in a riparian landscape: research at the Des Plaines River Wetlands Demonstration Project	Vol. 3, issue 4	W. Sanville and W.J. Mitsch; Duluth, MN and Columbus, OH, USA
	Environmental degradation due to heavy metals and acidifying deposition	Vol. 3, issue 3	H.M. Seip, L. Pawłowski and T.J. Sullivan; Polish-Scandinavian Workshop, Oslo, Norway, May 1992
	Forest ecosystem development on degraded and reclaimed sites	Vol. 3, issue 1	J. Fanta; Workshop "Forest Ecosystems Development on Degraded and Reclaimed Sites", Centennial IUFRO Congress, Berlin, Germany, September 2–4, 1992
1993	Ecological engineering in China	Vol. 2, issue 3	W.J. Mitsch, J. Yan, and J. Cronk; Columbus, OH, USA and Nanjing, China
1992	The role of created and natural wetlands in controlling nonpoint source pollution	Vol. 1, issue 1/2	R.K. Olson; US EPA Workshop on the Role of Created and Natural Wetlands in the Control of Rural NPS Pollution, Arlington, VA, USA, June 10–11, 1991

As described by Day et al. (2009):

> We believe that in coming decades the restoration and sustainable management of rich natural ecosystems will be equally as important as the protection of existing wild areas. It will be a different kind of conservation because restored ecosystems will exist in a mosaic of intensively used areas, such as agroecosystems . . .
>
> In a time of resource scarcity, especially energy, we suggest that ecological engineering (sometimes referred to as ecotechnology), including agroecology, is an appropriate basis for sustainable ecosystem management. Probably one of the most important shifts is for ecology to become more prescriptive and less descriptive, mostly through the growth of the ecological fields of ecological engineering and ecosystem restoration. Ecologists have a rich history of describing ecosystems and their functions but are less well trained in solving ecological problems. These new fields relate to solving ecological problems, borrowing approaches from engineering and landscape architecture. There are many active efforts in ecological engineering around the world . . .

4.5. *Ecosystem conservation*

Nature provides many valuable ecosystem services for humans. Of course, many of these values come from the harvest of plants and animals for food and fiber. The identification of these as well as many non-market values of nature, as for example illustrated by Costanza et al. (1997), has led to an increased emphasis on conservation by illustrating that nature has value. The development of new sustainable ecosystems and their values by ecological engineering will have the same effect.

Ecological engineers, then, 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

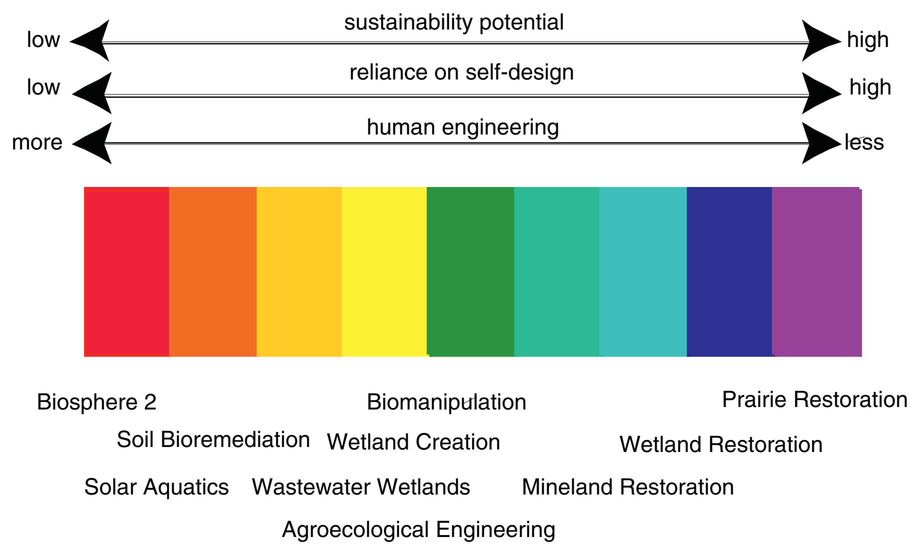

Fig. 2. A spectrum of ecological engineering practices based on high or low sustainability potential, high or low reliance on self-design, and high or low conventional engineering investment.
From Mitsch (1998).

necessary. This is analogous to the conservation ethic that is shared by many farmers even though they may till the landscape. In short, recognition of ecosystem values provides greater justification for the conservation of ecosystems and their species.

Aldo Leopold, the great Midwestern USA conservationist, stated this concept much more eloquently. As compiled by Aldo's son Luna Leopold after his father's death (Leopold, 1972):

> The last word in ignorance is the man who says of an animal or plant: "What good is it?" If the land mechanism as a whole is good, then every part is good, whether we understand it or not. If the biota, in the course of eons, has built something we like but do not understand, then who but a fool would discard seemingly useless parts? *To keep every cog and wheel is the first precaution of intelligent tinkering.*

5. Practice of ecological engineering

Ecological engineering is being practiced over a wide spectrum of approaches and ecosystems all over the world, sometimes with a great reliance on self design and sustainability, sometimes with less (Fig. 2). Among some large projects, salt marsh restoration on Delaware Bay in eastern USA was based on a concept of self-design of tidal creeks and plant introduction for several of its site restorations (Teal and Weinstein, 2002; Peterson et al., 2005). The Skjern River restoration in Jutland, Denmark, was developed with necessary compromises from full stream restoration, as for example dikes were removed from their position adjacent to the river but were re-established several hundred meters away from the river to protect households and farm buildings (Pedersen et al., 2007). Principles of ecological engineering have also been used to propose ecological solutions to the Gulf of Mexico hypoxia (Mitsch et al., 2001) and the restoration of the Mississippi River delta (Costanza et al., 2006; Day et al., 2009) among other projects. Even the 2010 Gulf of Mexico oil spill needed ecological engineering rather than the ridiculous wastes of money for traditional engineering that, in the end, did little good and probably a great deal of harm (Mitsch, 2010).

5.1. *Ecological engineering in the academy*

A number of academic programs in ecological engineering have begun to develop in North American universities. Oregon State University renamed its agricultural engineering department as Biological and Ecological Engineering and a Division of Environmental and Ecological Engineering has been developed at Purdue University. The University of Florida offers a graduate-level certificate in ecological engineering. Student groups and programs in ecological engineering are at University of Florida, Ohio State University, Virginia Tech, University of California Davis, McGill University among others.

There is still not a formal degree program in the USA or elsewhere specifically called ecological engineering. This is despite surveys that have suggested, at least from the student's perspective, there is overwhelming favor for ecological engineering curricula with more social, biological, chemical, and earth sciences than is currently taught in environmental engineering (Diemont et al., 2010). And few if any ecological engineering programs have ever been discussed in ecology programs or departments; participation in ecological engineering by ecologists is rare. One contraction to this is in France, where Gosselin (2008) argues that ecological engineering has become popular, partially because applied ecology development there has been weak compared to other countries.

5.2. *Journal as an indicator*

Our international journal *Ecological Engineering* has been, in many ways, the bellwether of the field of ecological engineering (Fig. 3). Since 2005 there has been a 2.5-fold increase in the number of manuscripts submitted to the journal (from 173 to 606). Between 2006 and 2010 the citation index increased from 1.33 to 2.20. While many of the papers in the journal continue to focus on the design of treatment wetlands for improving water quality, there are now papers on restoration of almost all types of ecosystems (forests, river, coral reefs, salt marshes, mangroves) and on such fields as phytoremediation, agroecology, and green roofs. There have been 50 special issues in the journal from 1992 through 2011 covering a wide range of topics related to ecological engineering (Table 2) including 25 issues in the last 9 years. Not surprisingly, 15 of the

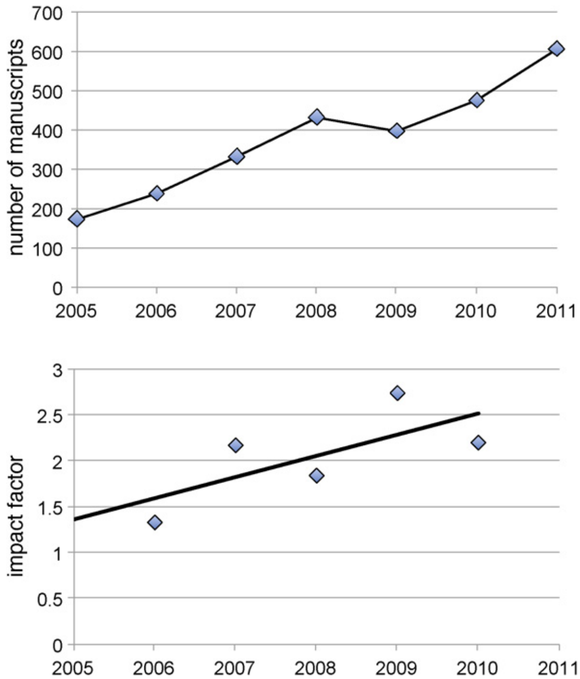

Fig. 3. (a) Pattern of number of manuscripts received, and (b) trend of citation impact factor for the international journal *Ecological Engineering*, 2005–2011.

50 special issues deal with wetlands—either treatment wetlands or natural wetland restoration. But there are also several special issues on restoring terrestrial (forest) and agricultural landscapes. Several special issues have focused on specific aquatic and terrestrial sites such as the Florida Everglades and Delaware Bay in the USA, Lake Taihu in China, and the "Black Triangle" forests of Central Europe. There are only a few coastal (salt marsh) restoration special issues and none on mangrove, sea grass or coral reef restoration to date.

5.3. Research programs

Formal research programs called ecological engineering are rare. A significant development in ecological engineering research began about the 2007 in the USA when National Science Foundation (NSF) established a research program in Environmental Sustainability. The program "supports engineering research with the goal of promoting sustainable engineered systems that support human well-being and that are also compatible with sustaining natural (environmental) systems" (http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=501027). There are four principal general research areas which are identified for support in this program:

- industrial ecology,
- green engineering,
- ecological engineering,
- earth systems engineering.

This inclusion of ecological engineering into a grouping of sustainable engineering approaches that also includes industrial ecology and green engineering as separate fields has given credence to the idea that they are indeed separate and ecological engineering alone is based on the ecosystem paradigm.

6. Conclusions

There are several conclusions I am left with as I review the progress over the last 35 years of ecological engineering development in the world and especially since I wondered out loud in my EcoSummit presentation in Copenhagen in 1996 if ecological engineering would survive.

- There has been remarkable progress in the development of ecological engineering principles and practices. Limitations now appear to be related to social and disciplinary regulations and lack of acceptance by tradition-bound disciplines.
- Ecological engineering needs non-linear engineering thinking. There is still little application of self-design and problem solving on mega-scale ecological problems is needed more than ever. It is still not clear if self-design will ever be accepted in the current engineering paradigm.
- Ecological engineering programs controlled by engineers alone will ultimately fail because rigid accreditation requirements will convert the field to traditional engineering practices and because of the lack of ecological training in engineering. Ecologists, who have not been particularly active in the development of the field or establishment of its academic programs, need to get involved. I agree with Gosselin (2008) who suggests that ecological engineering and sustainable development will "breathe new life" into the old fields of engineering and ecology if we allow it.
- Engineers and scientist both need to recognize Mother Nature (self-design) and Father Time (it takes time) are in charge in designing functional ecosystems.
- With energy and other limitations clearly in our future, if ever there was a transdiscipline whose time has come, it is ecological engineering.

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References

Aronson, J., Floret, C., Le Floch, E., Ovalle, C., Pontanier, R., 1993. Restoration and rehabilitation of degraded ecosystems in arid and semiarid regions. I. A view from the south. Restor. Ecol. 1, 8–17.
Barot, S., Lata, J.-C., Lacroix, G., 2012. Meeting the relational challenge of ecological engineering within ecological sciences. Ecol. Eng. 45, 13–23.
Bergen, S.D., Bolton, S.M., Fridley, J.L., 2001. Design principles for ecological engineering. Ecol. Eng. 18, 201–210.
Bradshaw, A.D., 1987. Restoration: the acid test for ecology. In: Jordan III, W.R., Gilpin, M.E., Aber, J.D. (Eds.), Restoration Ecology: A Synthetic Approach to Ecological Research. Cambridge Univ. Press, Cambridge, pp. 23–29.
Bradshaw, A., 1997. Restoration of mined lands using natural processes. Ecol. Eng. 8, 255–269.
Cairns Jr., J., 1988. Restoration ecology: the new frontier. In: Cairns Jr., J. (Ed.), Rehabilitating Damaged Ecosystems, vol. I. CRC Press, Boca Raton, FL, pp. 1–11.
Clugston, C., 2007. Global peak energy: implications for future human populations. Energy Bull., http://energybulletin.net/node/34120.
Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.
Costanza, R., Mitsch, W.J., Day, J.W., 2006. A new vision for New Orleans and the Mississippi delta: applying ecological economics and ecological engineering. Front. Ecol. Environ. 4, 465–472.

Costanza, R., 2012. Ecosystem health and ecological engineering. Ecol. Eng. 45, 24–29.

Day Jr., J.W., Hall, C.A.S., Yáñez-Arancibia, A., Pimentel, D., Ibañez Marti, C., Mitsch, W.J., 2009. Ecology in times of scarcity. BioScience 59, 321–331.

Diemont, S.A.W., Lawrence, T.J., Endreny, T.A., 2010. Envisioning ecological engineering education: an international survey of the educational and professional community. Ecol. Eng. 36, 570–578.

Gosselin, F., 2008. Redefining ecological engineering to promote its integration with sustainable development and tighten its links with the whole of ecology. Ecol. Eng. 32, 199–205.

Hubbert, M.K., 1962. Energy Resources. National Academy of Sciences, National Research Council, Washington, DC, publication no. 1000-D.

Hüttl, R.F., Bradshaw, A.B. (Eds.), 2001. Ecology of post-mining landscapes. Ecol. Eng. 17 (special issue), 87–330.

Jones, C.G., 2012. Grand challenges for the future of ecological engineering. Ecol. Eng. 45, 80–84.

Kangas, P., 2004. Ecological Engineering. CRC Press, Boca Raton, FL.

Lefeuvre, J.C., Mitsch, W.J., Bouchard, V. (Eds.), 2002. Ecological engineering applied to river and wetland restoration. Ecol. Eng. 18 (special issue), 529–658.

Leopold, A., 1972. In: Leopold, L.B. (Ed.), Round River. Oxford University Press, Oxford, UK, 286 pp.

Ma, S., 1985. Ecological engineering: application of ecosystem principles. Environ. Conserv. 12, 331–335.

Ma, S., Yan, J., 1989. Ecological engineering for treatment and utilization of wastewater. In: Mitsch, W.J., Jørgensen, S.E. (Eds.), Ecological Engineering: An Introduction to Ecotechnology. John Wiley & Sons, Inc., New York, pp. 185–217.

Mitsch, W.J., 1991. Ecological engineering—approaches to sustainability and biodiversity in U.S. and China. In: Costanza, R. (Ed.), Ecological Economics: The Science and Management of Sustainability. Columbia University Press, New York, pp. 428–448.

Mitsch, W.J., 1993. Ecological engineering—a cooperative role with the planetary life–support systems. Environ. Sci. Technol. 27, 438–445.

Mitsch, W.J., 1996. Ecological engineering: a new paradigm for engineers and ecologists. In: Schulze, P.C. (Ed.), Engineering within Ecological Constraints. National Academy Press, Washington, DC, pp. 111–128.

Mitsch, W.J., 1998. Ecological engineering—the seven-year itch. Ecol. Eng. 10, 119–138.

Mitsch, W.J., 2010. The 2010 Gulf of Mexico oil spill: what would Mother Nature do? Ecol. Eng. 36, 1607–1610.

Mitsch, W.J., Jørgensen, S.E., 1989. Ecological Engineering: An Introduction to Ecotechnology. John Wiley & Sons, Inc., New York, 472 pp.

Mitsch, W.J., Yan, J., Cronk, J., 1993. Ecological engineering—contrasting experiences in China with the West. Ecol. Eng. 2, 177–191.

Mitsch, W.J., Mander, U. (Eds.), 1997. Ecological engineering in Central and Eastern Europe: remediation of ecosystems damaged by environmental contamination. Ecol. Eng. 8 (special issue), 247–346.

Mitsch, W.J., Day Jr., J.W., Wendell Gilliam, J., Groffman, P.M., Hey, D.L., Randall, G.W., Wang, N., 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River Basin: strategies to counter a persistent ecological problem. BioScience 51, 373–388.

Mitsch, W.J., Jørgensen, S.E., 2003. Ecological engineering: a field whose time has come. Ecol. Eng. 20, 363–377.

Mitsch, W.J., Jørgensen, S.E., 2004. Ecological Engineering and Ecosystem Restoration. John Wiley & Sons, Inc., New York, 411 pp.

National Research Council, 1992. Restoration of Aquatic Ecosystems. National Academy Press, Washington, DC.

Odum, H.T., 1962. Man in the ecosystem. Proceedings of Lockwood Conference on the Suburban Forest and Ecology, Storrs, CT. Bull. Conn. Agric. Station 652, 57–75.

Odum, H.T., Siler, W.L., Beyers, R.J., Armstrong, N., 1963. Experiments with engineering of marine ecosystems. Publ. Inst. Marine Sci. Univ. Texas 9, 374–403.

Odum, H.T., 1971. Environment, Power, and Society. John Wiley & Sons, Inc., New York.

Odum, H.T., 1983. Systems Ecology. John Wiley & Sons, Inc., New York (reprinted in 1994 by University Press of Colorado, Niwot, CO).

Odum, H.T., 1989. Ecological engineering and self-organization. In: Mitsch, W.J., Jørgensen, S.E. (Eds.), Ecological Engineering: An Introduction to Ecotechnology. John Wiley & Sons, Inc., New York, pp. 79–101.

Odum, H.T., 2005. Environment, Power, and Society for the Twenty-First Century: The Hierarchy of Energy. Columbia University Press, New York, 432 pp.

Odum, H.T., Odum, B., 2003. Concepts and methods of ecological engineering. Ecol. Eng. 20, 339–361.

Pedersen, M.L., Andersen, J.M., Nielsen, K., Linnemann, M., 2007. Restoration of the Skjern River and its valley: project description and general ecological changes in the project area. Ecol. Eng. 30, 131–144.

Peterson, S.B., Teal, J.M., Mitsch, W.J. (Eds.), 2005. Delaware Bay salt marsh restoration. Ecol. Eng. 25 (special issue), 199–314.

Society of Ecological Restoration, 2004. The SER International Primer on Ecological Restoration. SER Science and Policy Working Group, http://www.ser.org/content/ecological_restoration_primer.asp.

Straskraba, M., 1993. Ecotechnology as a new means for environmental management. Ecol. Eng. 2, 311–331.

Teal, J.M., Weinstein, M.P., 2002. Ecological engineering, design, and construction considerations for marsh restorations in Delaware Bay, USA. Ecol. Eng. 18, 607–618.

Wang, R., Yan, J., Mitsch, W.J. (Eds.), 1998. Ecological engineering in developing countries. Ecol. Eng. 11 (special issue), 1–313.

Zalewski, M., 2000. Ecohydrology—the scientific background to use ecosystem properties as management tools toward sustainability of water resources. Ecol. Eng. 16, 1–8.