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Design principles for ecological engineering

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Abstract

The emerging discipline of ecological engineering is a response to the growing need for engineering practice to provide for human welfare *while at the same time* protecting the natural environment from which goods and services are drawn. It recognizes that humanity is inseparable from and dependent on natural systems, and that the growing worldwide population and consumption have damaged, and will increasingly stress, global ecosystems. Ecological engineering is the design of sustainable systems, consistent with ecological principles, which integrate human society with its natural environment for the benefit of both. It recognizes the relationship of organisms (including humans) with their environment and the constraints on design imposed by the complexity, variability and uncertainty inherent to natural systems. Successful ecological engineering will require a design methodology consistent with, if not based on, ecological principles. We identify five design principles to guide those practicing ecological engineering. The principles are: (1) design consistent with ecological principles, (2) design for site-specific context, (3) maintain the independence of design functional requirements, (4) design for efficiency in energy and information, and (5) acknowledge the values and purposes that motivate design.

Keywords: Ecological engineering; Ecological design; Design principles

1. Introduction

The emerging discipline of ecological engineering is a response to the growing need for engineering practice to provide for human welfare *while at the same time* protecting the natural environment from which goods and services are drawn. It recognizes that humanity is inseparable from and dependent on natural systems, and that the growing worldwide population and consumption have damaged, and will increasingly stress, global ecosystems. Sustaining human society requires engineering design practices that protect and enhance the ability of ecosystems to perpetuate themselves while continuing to support humanity.

Ecological engineering is the design of sustainable systems, consistent with ecological principles, which integrate human society with its natural environment for the benefit of both (see Mitsch

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and Jørgensen, 1989; Mitsch, 1996; Bergen et al., 1997).

Many scientists working in environmental fields are, in fact, practicing engineering as they take scientific principles and use them to address specific problems. However, very few scientists have had any engineering training, and there is little evidence of accepted engineering design methods being followed in applied ecology. Additionally, engineers are increasingly undertaking design problems in which a solid scientific understanding of natural systems is needed. We do not propose adding a little ecology to engineering, or a little engineering to ecology. Rather, we envision a new engineering discipline with ecological science as its basis. In other words, the practice of design with an appreciation for the relationship of organisms (including humans) with their environment and the constraints on design imposed by the complexity, variability and uncertainty inherent to natural systems. This approach could lead to a new paradigm for engineering design in general.

Ecological engineering has been defined in a number of ways, so we begin this paper with a look at past definitions and then propose our own definition. We discuss the current and potential scope of ecological engineering applications. Finally, we identify five design principles to guide those practicing ecological engineering. The principles are a distillation of our own ideas and those of other authors who have written on engineering and ecological design.

2. Ecological engineering defined

As a relatively new field, effort continues to be spent in defining the scope and purpose of ecological engineering. Several authors have put forward definitions for ecological engineering, and these definitions reflect the particular aspects of the practice they feel are critical. The term itself is attributed to H.T. Odum, who defined ecological engineering as "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). Mitsch and Jørgensen (1989) define the practice as "the design of human society with its natural environment for the benefit of both". This definition was slightly refined to read "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both" (Mitsch, 1996). Mitsch suggests that the goals of ecological engineering are the restoration of human disturbed ecosystems and the development of new, sustainable ecosystems that have human and ecological value. In the latter case, ecosystems are designed and created to solve human problems.

Harnessing the self-design or self-organizational properties of natural systems is an essential component to ecological engineering (Odum, 1989; Mitsch, 1996). In a constructed ecosystem, humans are likely responsible for providing the initial components and structure of the system, as well as for influencing the larger environment to which the ecosystem connects. Once created, however, nature takes over and the composition and structure become those best suited to respond to the condition imposed on the system. Humans do not need to add matter or energy to maintain a particular ecosystem state.

In Section 1, we presented a definition for ecological engineering that is a modification of Mitsch (1996), i.e. ecological engineering is the design of sustainable systems, consistent with ecological principles, which integrate human society with its natural environment for the benefit of both. This definition has a number of important elements that should be in any definition of the discipline:

1. that the practice is based on ecological science,
2. that ecological engineering is defined broadly enough to include all types of ecosystems and potential human interactions with ecosystems,
3. that the concept of engineering design is included, and
4. that there is an acknowledgment of an underlying value system.

The first point is the most fundamental. A branch of engineering can be defined by its science base, by its application, or by both. We suggest that unlike civil engineering, which is more clearly defined by its applications than the science that informs it, ecological engineering, to be truly a unique engineering discipline, must be based on ecology. Applications for ecological engineering may stretch beyond working with ecosystems and influence all engineering practice, representing a new paradigm for engineering design. However, the question of whether there is a way of practicing engineering that is significantly different from current practices, and is based on an understanding of ecology, remains. This has not been shown, but we believe the answer is yes.

The second element relates to application. While ecological engineering may represent a new paradigm for design, its most obvious application is to engineering as it relates to human interaction with ecosystems. The literature focuses primarily on created and restored ecosystems, but leaves out the broad and important area of societal interaction with *existing*, and not necessarily degraded, ecosystems.

Explicitly using the word design in our definition makes it clear that it is the primary activity of engineering. Successful engineering design requires, in part, adherence to a formal methodology. Much has been written about engineering design as it relates to engineering in general. It remains to be shown if traditional engineering practice can solve ecological engineering problems. Given that traditional practices contributed to environmental degradation, methodological issues should be considered. We will discuss design principles in more detail later.

The last element, regarding values, raises two important issues. The first is whether the definition of an engineering discipline should include a statement of values. We believe it should because it is naive to assume that we can separate our motivation for practicing engineering from our actions. Therefore, the motivations should be made explicit. Given that engineering and other professional societies generally adopt a code of ethics to guide their membership, there are precedents for the stating of values.

The second issue is, if we decide to include a statement of values in the definition, what values should we express? This is a contentious topic, but concepts such as human benefit, sustainability, and ecological health and integrity are often mentioned in the literature. For now, the statement of values in the definition of ecological engineering will be most accepted if it appeals to a plurality of value frameworks (Miller, 1995).

3. Scope of application

We have defined ecological engineering broadly and advocate its application to a number of problem areas. Potential applications include:

1. The design of ecological systems (ecotechnology) as an alternative to man-made/energy-intensive systems to meet various human needs (for example, constructed wetlands for wastewater treatment).
2. The restoration of damaged ecosystems and the mitigation of development activities.
3. The management, utilization, and conservation of natural resources.
4. The integration of society and ecosystems in built environments (for example, in landscape architecture, urban planning, and urban horticulture applications).

Methods currently exist for dealing with all the applications listed above. We feel, however, that ecological engineering can offer a unique approach to each. The first application, ecotechnology, is the most thoroughly discussed to date. Ecotechnology has been described as a means for environmental management (Straškraba, 1993) and as ecological solutions to environmental engineering problems (Mitsch, 1996). The most prevalent example of the latter is the treatment of various forms of waste products. Environmental engineering solutions to waste management focus on energy-intensive processes such as sewage treatment plants, settling tanks and scrubbers. Ecological engineering addresses the same problem with systems that rely on ecological processes that require minimal energy input from humans (essentially solar-powered).

Ecological restoration and development mitigation currently fall under the domain of applied or restoration ecology. Ecological engineering can add to these activities by providing a more formal and structured design method. Attention to the process of design in reports on applied ecology is often missing. Using repeatable design procedures in ecological restoration would facilitate learning how to improve future projects.

The third application area relates to the management of natural resources. The goal for managing existing systems would be to harvest some benefit from the ecosystem while preserving the health or integrity of the system, not compromising the production of ecological services, and not inducing unexpected changes in the system. Examples of such systems include forest and rangeland ecosystems and fisheries. In the case of forest management we may be interested in harvesting timber from an ecosystem without diminishing the ability of the forest to regenerate, to provide clean water and air, and provide habitats for a range of plant and animal species: essentially, use of the forest with minimal impact to the ecosystem. In the case of fisheries, we may want to harvest some fish without depleting stocks beyond recovery. This would signal a shift toward living off ecological 'interest' and not depleting natural 'capital' (Cairns, 1996). Our extraction level would fall within the noise level of the natural variation of the system. Moving away from spending natural capital given current and probable future pressures on ecosystems is a monumental problem.

The goal of ecological engineering is to better integrate society with its supporting environment. Creating integrated urban and other built environments is a potential application for ecological engineering. Endemic ecosystems are often completely destroyed when dense human populations arrive in an area. Increasing calls for 'greening' urban environments, allowing for more of a connection between place and nature in built environments, will require design that includes ecology and engineering. Traditional landscape architecture, urban planning, and urban horticulture approaches can be augmented by ecological engineering.

4. Ecological engineering design principles

We have mentioned a number of ideas, such as utilizing the self-designing capacity of ecosystems, which can serve as design principles for ecological engineering. To identify a more comprehensive set of principles, we have combined our own ideas with ideas from other authors who have written on engineering and ecological design. In another paper we discussed how the two design axioms proposed by Suh (1990) may be applied to forest engineering (Bergen and Fridley, 1994), and will do the same here for ecological engineering.

Odum (1992) proposed 20 ecological concepts from which design implications may also be drawn. Straškraba (1993) described seven ecosystem principles and 17 rules for practicing ecotechnology. Mitsch (1992) presented eight principles for wetland design. Todd and Todd (1994) propose nine precepts and Van der Ryn and Cowan (1996) propose five principles for ecological design. Holling (1996) also details ecosystem characteristics that have implications for design. Jørgensen and Neilsen (1996) proposed 12 principles for ecological applications to agriculture. Zalewski (2000) identified three principles for the study of ecohydrology. From the above material, we have distilled five general principles to guide those practicing ecological engineering in any context or ecosystem.

Stating first principles is a challenging exercise for an emerging field. It is an important exercise because we believe design solutions that adhere to the following principles will have the best chance of success. Successful designs, in the terminology of Suh (1990), efficiently meet their stated functional requirements without violating constraints.

What follows, while we call them principles, is more a combination of axioms, heuristics and suggestions. The boundary between some of the principles is fuzzy, implying that more work needs to be done to distill and clarify them. Most of our proposed design principles contain more than one unique idea that we have grouped together because of certain similarities. In addition, some apparent contradictions need to be resolved, arising from our attempt to merge ecology with engineering.

4.1. First principle — design consistent with ecological principles

Designs produced with regard for, and taking advantage of, the characteristic behavior of natural systems will be most successful. When we include and mimic natural structures and processes, we treat nature as a partner in design, and not as an obstacle to be overcome and dominated.

We are all familiar with the second law of thermodynamics and the concept of entropy. Perhaps the first law of biology is that life is a *negentropic* process. Life causes local decreases in entropy by producing order out of chaos. The second law is not violated because the energy expended to produce order results in more entropy overall. The practical implication, however, is that ecosystems have the capacity to self-organize. Mitsch and Jørgensen (1989) state that it is this "capability of ecosystems that ecological engineering recognizes as a significant feature, because it allows nature to do some of the 'engineering." We participate as the choice generator and as a facilitator of matching environments with ecosystems, but nature does the rest."

Self-organization is manifested through the process of succession in ecosystems. Todd and Todd (1994) discuss how as ecosystems mature, connections between components become more numerous and complex, with the system becoming more diverse and resistant to perturbation. They describe current design practices as "early successional", with simple linkages and patterns, and no room for maturation. Designs are then more susceptible to disturbance and failure. Kangas and Adey (1996) propose that mesocosms (scale range m^2 to ha) most clearly express the self-organization of ecosystems and provide experimental units that will be critical for ecological engineering and restoration ecology.

The key ecosystem attributes that allow for self-organization are complexity and diversity. Ecosystems can be complex structurally and in the temporal and spatial scales of processes. Significant ecological change is episodic, and critical processes occur at rates spread over several orders of magnitude, but clustered around a few dominant frequencies (Holling, 1996). Ecosystems are heterogeneous, displaying patchy and discontinuous textures at all scales. Ecosystems do not function around a single stable equilibrium. Rather, Holling states that, "destabilizing forces far from equilibria, multiple equilibria, and absence of equilibria define functionally different states, and movement between states maintains structure and diversity". The structure and diversity produced by the large *functional space* occupied by ecosystems is what allows them to remain healthy, or to persist.

The large functional space required for sustainable ecosystems is directly at odds with traditional engineering design practices that create systems that operate close to a single, chosen equilibrium point. Holling (1996) uses this idea to distinguish between what he terms *engineering resilience* and *ecological resilience*. Engineering resilience measures the degree to which a system resists moving away from its equilibrium point and how quickly it returns after a perturbation. Ecological resilience reflects how large a disturbance an ecosystem can absorb before it changes its structure and function by changing the underlying variables and processes that control behavior. The equilibrium conditions discussed above for ecosystems exist within the range of ecological resilience.

The distinction between the two types of resilience is important because management policies that force ecosystems to function in a state of engineering resilience lead to a loss of ecological resilience. Systems managed to produce a consistent, high yield of a single variable (such as timber or fish) lose the functional and structural diversity required to remain ecologically resilient. The system is then more susceptible to 'failure', where it may lose the ability to produce the same outputs in the future (Holling, 1996).

Diverse systems are more ecologically resilient and able to persist and evolve. Diversity can manifest in terms of the number of species, genetic variation within species, and as what Holling (1996) calls *functional diversity*. Functional diversity is another way of saying redundancy, where a number of species or processes in the system can perform similar functions. If one is impaired then others fill the void contributing to the ecological resilience of the system. The implication here is to maintain diversity in managed systems and alludes to the classic quote from Leopold (1949), "To keep every cog and wheel is the first precaution of intelligent tinkering". Protecting diversity also provides insurance against uncertainty, which we will discuss further as part of the third principle.

Another important characteristic of ecosystems is that the outputs of one process serve as the inputs to others. No waste is generated and nutrients are cycled from one trophic level to the next. The field of industrial ecology is principally based on this concept.

A final characteristic of natural systems is that they tend to function near the edge of chaos or instability (Cairns, 1996; Holling, 1996). Systems operating near the edge can take better advantage of *evolutionary opportunities*. Cairns notes that our current technological systems have co-evolved with ecosystems and that introducing chaos into one system will likely lead to chaos in the other.

Designing systems to include ecological characteristics departs from common engineering practice. Designing for ecological rather than engineering resilience means encouraging diversity and complexity and allowing systems to self-organize, mature, and evolve. How to design systems to perform like ecosystems and still function as desired is explored in the remaining principles.

4.2. Second principle — design for site-specific context

The complexity and diversity of natural systems cause a high degree of spatial variability. While the ecological characteristics discussed above are generally applicable, every system and location is different. The second principle can be stated in a number of ways, but boils down to the idea of gaining as much information as possible about the environment in which a design solution must function. Spatial variability precludes standardized designs, so solutions should be site-specific and small-scale (Van der Ryn and Cowan, 1996). Standardized designs imposed on the landscape without consideration for the ecology of a place will take more energy to sustain (see Section 4.4). Berry (1987) sums up this principle succinctly: "There are, I think, three questions that must be asked with respect to a human economy in any given place:

1. What is here?
2. What will nature permit us to do here?
3. What will nature help us to do here?"

Knowledge of the place also allows for more holistic designs. Todd and Todd (1994) refer to the Gaia hypothesis that the Earth is a complex, living organism with all its components interconnected. Ecological design considers both the upstream and downstream affects of design decisions — upstream in that we consider what resources must be imported and appropriated to create and maintain a solution, and downstream in our consideration of the site-specific and off-site impacts of the design on the environment.

In addition to the physical context of a design, knowledge of the cultural context is important. Designs are more likely to succeed and to be accepted by the local community when the people who live in a place are included in the design process. They bring knowledge of the particularities of a place and are empowered through direct participation in shaping their environment. Attention to group dynamics and conflict mediation is important for successful stakeholder participation.

4.3. Third principle — maintain the independence of design functional requirements

Ecological complexity adds high and often irreducible levels of uncertainty to the design process. Even under conditions of certainty, the amount of relevant information we possess may be overwhelming and unmanageable. We want to keep solutions simple and workable. A strategy for dealing with uncertainty is to set the *tolerances* on our design functional requirements as wide as possible.

The third principle is a restatement of the first design axiom of Suh (1990). In the realm of mechanistic engineering design, where this axiom originates, it appears very straightforward and easy to grasp. Functional requirements (FRs) are the specific functions that we wish a design solution to provide. Design parameters (DPs) are the physical elements of the solution chosen to satisfy FRs. Best designs are those that have independent (not coupled) FRs and one and only one DP to satisfy each FR. When modifying one DP affects more than one FR, a design is coupled.

In circumstances where there is functional coupling, wide tolerances on FRs can make the design essentially uncoupled. Wide design tolerances allow a larger functional range for a system while the outputs remain within acceptable ranges. This is another important aspect of designing for ecological rather than engineering resilience. Systems designed for engineering resilience often have tight tolerances.

When interacting with ecological systems, however, the concept of functional independence becomes a lot less clear. Ecosystems are complex with many levels of interconnection between components. Many elements of the system may be involved in more than one process. We must not confuse ecosystem functionality with design FRs. Ecosystems can function and provide benefits to society without human intervention. We undertake the process of design to satisfy unmet human needs, and the FRs for design follow from the statement of these needs. Ecosystem processes that presently exist that we wish to preserve while we design for unmet needs act as constraints on design. The independence principle states that we are more likely to have successful designs when we can keep the FRs uncoupled in the solution. In reality, however, it would be foolish not to take advantage of the multiple, coupled services an ecosystem can provide.

4.4. Fourth principle — design for efficiency in energy and information

The fourth principle follows from taking advantage of the self-organizing property of ecosystems. To let nature do some of the engineering means that we should make maximum use of the free flow of energy into the system from natural sources, primarily the Sun. Conversely, we want to minimize the energy expended to create and maintain the system directed, by design, from off-site sources, such as fossil fuels, large-scale hydroelectric sources, etc. While utilizing free flowing energy, however, it is important to follow where the energy would go without intervention, to make sure that it is not more critically needed downstream and that there is minimal adverse impact.

Similar to the flow of energy, the second design axiom proposed by Suh states that we want to minimize the information content of a design. The ideas and principles we have discussed so far all relate to minimizing information, or making designs simple yet successful. When we cooperate with natural processes and allow systems to self-organize, it requires less energy and information to implement and maintain a design (Kangas and Adey 1996; Odum, 1996). Meeting wide tolerances requires less information. In the case of stream restoration, high-energy inputs to control system structure or function are counterproductive to the ecological resilience and performance of the non-emphasized functions of the system. For example, the energy input needed from humans to restrict a stream channel to a confined space tends to be high and ultimately unsuccessful when a large flood occurs. A better design would recognize the expected variability in stream flows and design the system to withstand large variations in flow (wide tolerance) and still maintain its ecological and engineering functions.

Minimizing information content appears contrary to encouraging diversity and complexity in design solutions. The extra information required, however, is balanced by utilizing self-organization and wide tolerances. We can consider it an up-front capital investment in diversity to gain overall efficiency later through reduced energy requirements and a reduced risk of failure. Diversity provides insurance against uncertainty in addition to contributing to ecological resilience, as discussed in the first principle. In the case of an engineered wetland, for example, a wide range of species may be included in the initial construction, but natural processes are allowed to select those best suited for the imposed environment (Mitsch, 1996). Similarly, the first and second principles advocate an up-front investment in knowledge of the design context to minimize uncertainty and to allow less information to be transferred during design implementation.

4.5. Fifth principle — acknowledge the values and purposes that motivate design

The definition of ecological engineering we advocate states that design is practiced for the benefit of both society and the natural environment. Most engineering codes of ethics state at least that engineers have a responsibility to serve and protect society. We have explicitly broadened that responsibility to include the natural systems that support life. Regardless of specific ideology, however, design practices that acknowledge the motivating values and purposes will be more successful.

Proponents of an ecological approach to design are passionate in their arguments, relying as much on scientific observation as on ideology, morality, ethics, and spiritual beliefs. Three of the nine precepts proposed by Todd and Todd (1994) are value statements. Ecological design invites and embraces the qualitative, the uncertain, and the non-rational aspects of human nature. Goals such as connection to place, equity, sustainability, and esthetics are as important as material output.

While those writing about ecological design hold a variety of values, there is agreement at least on how to respond to risk and uncertainty. When dealing with the natural environment, many engineering decisions result from what can best be characterized as *hubris*. The term hubris seems most fitting because it implies not only overconfidence, but also that retribution may occur as a result. Herman (1996) uses the term *revenge* (after Tenner, 1991) to describe how our attempts to manage complex systems always seem to produce unexpected and unwanted side effects. Costanza (1996) warns that the worst form of ignorance is misplaced certainty.

The third principle recommends using wide tolerances under conditions of uncertainty. From a value standpoint, we also recommend adopting a precautionary approach for ecological engineering. A precautionary approach will act as a form of insurance against unpleasant surprises in the future (Perrings, 1991; Costanza, 1994; Ehrlich, 1994). Engineering would be applied sparingly, and complex solutions avoided where possible (Herman, 1996).

To avoid catastrophic failures, design solutions that are both fail-safe and safe-fail should be pursued. As opposed to traditional fail-safe approaches, safe-fail solutions acknowledge that our original functional requirements for a design may not be met or that there may be unexpected results. Failure in this case is not catastrophic. Costanza (1996) advocates selecting design alternatives that have the best worst-case outcome.

The precautionary approach has also been expressed as shifting from minimizing type-I error to minimizing type-II error (Shrader-Frechette, 1994; Lemons and Westra, 1995). It is the scientific norm to achieve high levels of confidence in a hypothesis before it is accepted (minimizing type-I error). When applied to environmental management this means that we would need almost complete certainty in a hypothesis of ecological damage resulting from engineering activity before we would accept the hypothesis. Minimizing type-II error would shift the burden of proof to the hypothesis that damage is not occurring. Shrader-Frechette (1994) spells out a number of reasons why the choice of minimizing type-II error is an ethical preference. The reasons include concepts of intergenerational equity, equitable distribution of risk, and concern for non-human species.

5. Conclusions

Ecological engineering is emerging as a distinct engineering discipline. As a new field, there is danger of confusion from multiple and competing visions of what ecological engineering is, and of the scope of its application. We have attempted to provide an inclusive and broad definition, and suggest potential applications where an ecological approach to engineering design can augment the efforts of other professionals to solve complicated and pressing problems.

Ecological engineering represents the marriage of ecology and engineering design, and as such can perhaps have its greatest contribution in changing how design is practiced in all disciplines. From the literature and from our own work, we have proposed five design principles for ecological engineering. Each principle needs to be more fully developed through further research, interdisciplinary dialogue and experimentation. Some of the most pressing research issues, we believe, are:

- identifying the most important ecological principles to mimic and harness in design;
- reconciling ecological resilience with engineering resilience;
- reconciling functional requirements, tolerances, self-organization, and succession;
- exploring the relationship between energy, information, and complexity;
- figuring out how best to deal with uncertainty;
- determining what values should motivate design;
- developing ecological engineering curricula; and
- establishing professional certification.

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