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A Review of the Roots of Ecological Engineering and its Principles

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ABSTRACT

The wide definition of ecological engineering, a vast, multidisciplinary field, is the application and theoretical understanding of scientific and technical disciplines to protect natural habitats, as well as man-made and natural resources. The following two ideas are central themes in ecological engineering: (1) restoring substantially disturbed ecosystems as a result of anthropogenic activities and pollution, and (2) the synthesis of sustainable ecosystems that have ecological and human value by heavily relying on the self-organization capabilities of a system. Given the current paradigm of anthropogenic disturbances, the ideas and approaches of ecological engineering will be key in the creation of ecosystem resilience, eco-cities, and urban spaces. This review aims to discuss the roots of this discipline, draw comparisons to similar fields, including restoration ecology and environmental engineering, and offer a discourse of its basic principles with relevant examples from the literature. The aim is to bridge the gap between ideas such as energy signature, self-organization, and pre-adaptation to sustainable business and circular economy for a future that combines the natural environment with human society for the mutual benefit of both.

Keywords: ecological engineering, restoration, environmental engineering, ecological engineering principles, self-organization, self-design, circular economy, energy signature.

INTRODUCTION

Historical background

The need for a domain of ecology that integrates human society with the natural environment for the mutual benefit of both has always been present; though, perhaps more today than ever before due to anthropogenic pressures on natural systems. A need for ecology to be more prescriptive rather than descriptive led to the development of the field of ecological engineering around 40 years ago with rapid acceleration in the extent of publications in the last 15 years [Mitsch 2012]. Often regarded as the founding father of the field, Howard T. Odum has been credited with coining the term ecological engineering in the '60s [Odum H.T., 1962]. Odum highlighted the field as, "the study and practice of solving problems with technological designs" [Odum H.T. and Odum B., 2003]. He placed great emphasis on defining the practice as a union between the economy of society to the environment, "by fitting environmental technology with ecosystem self-design for maximum performance" [Odum H.T. and Odum B., 2003; Odum E.P. 1989]. Harnessing the self-organization properties of natural systems is a critical component of ecological engineering [Odum H.T., 1983; Mitsch 1996]. Self-organization refers to the ability of biological and natural systems to change, and most importantly, regulate their internal structure and operations [Tzafestas 2018]. Around the same period as Odum, Shijun Ma was developing similar ideas on the opposite side of the world. In his 1985 paper, he discusses similar ideas that can be summarized into two basic functions of the community dynamics: (1) the general eco-balance resulting from the harmonization of well-coordinated structure with functions in the ecosystem, (essentially explained as self-organization further in this review) and (2) the transformation, decomposition, concentration, and regeneration of substances based on multi-layer trophic structures (energy signature in this review) [Shijun

1985]. These two fundamental functions are the basis of the dynamic processes in ecosystems. Given his contribution to the field, he has been referred to as the "father of ecological engineering in China" [Mitsch and Jørgensen 2004]. Efforts by Odum, Ma, and others founded the *Journal of Ecological Engineering* around 1992 [Mitsch 1998]. Ecological engineering is a diverse, multidisciplinary field that can be broadly defined as the theoretical and applied knowledge of scientific and technical disciplines for their use in the protection of natural environments, in addition to natural and anthropogenic resources [Kostecka 2019]. The following section will dive deeper into the definition of ecological engineering. Various principles, corollaries, and basic concepts have been developed for the field; however, I propose that there are three main categories including energy signature, self-organization, and preadaptation [Kangas 2004; Mitsch and Jørgensen 2004; Odum H.T. and Odum B., 2003; Mitsch 1998]. These concepts will be discussed in detail later on in this review, following an introduction to the field.

A closer look at defining ecological engineering

Definitions of ecological engineering generally focus on the engineering aspect of the coined term or the close relationship between society and the natural environment. If we focus on the engineering facet of the term, its definition is "to use ecological processes within the natural or constructed limitation of natural systems to achieve engineering goals" [Etnier and Guterstam 1997]. Ecological engineering is synonymous with ecotechnology, and a widely-accepted definition of the field describes it as "the design of human society with its natural environment for the benefit of both" [Mitsch and Jørgensen 2004]. Table 1 summarizes some of the other synthesized definitions of ecological engineering and lists their source. The term ecological engineering has sometimes been deemed controversial [Kangas 2004] because, unlike engineering which seeks to fit its design onto nature, ecology seeks to protect nature from human impact [Hall 1995]. However, we must recognize that this is a multidisciplinary field; hence, engineers and ecologists must celebrate the union by combining the strengths of both disciplines to create new frameworks to solve a variety of environmental problems. Fields of science that are multidisciplinary, such as biomedical engineering and biostatistics, can have novel and direct benefits in finding solutions to a complex and diverse set of problems [Disis and Slattery 2010]. Expanding the Mitsch and Jørgensen's [2004] definition provided above, the goals of ecological engineering can be summarized into two main points: 1) restoring substantially disturbed ecosystems as a result of anthropogenic activities and pollution, and 2) the synthesis of sustainable ecosystems that have ecological and human value. This essentially

Table 1. A list of the various definitions/descriptions of ecological engineering found in the literature are given alongside the author's name(s), as well as the number of times they have been cited. Adapted from Schönborn and Junge (2021)

Year	Author	Definition/description	Cited
1989	Busch et al.	By ecotechnology (German:Ingenieurökologie), we understand the engineering implementation of ecological knowledge and principles.	2
1989	Mitsch and Jørgensen	The design of human society with its natural environment, for the benefit of both.	478
1993	Straškraba	Ecotechnology is defined as the use of technological means for ecosystem management based on deep understanding of principles on which natural ecological systems are built on the transfer of such principles into ecosystem management in a way to minimize the costs of the measure and their harm to the global environment.	67
2001	Bergen et al.	The design of sustainable systems, consistent with ecological principles, which integrate human society with its natural environment for the benefit of both.	325
2003	H.T. Odum and B. Odum	Ecological engineering is the study and practice of fitting environmental technology with ecosystem self-design for maximum performance.	70
2003	Mitsch and Jørgensen	The design of sustainable ecosystems that integrate human society and its natural environment for the benefit of both.	332
2008	Gosselin	Practical ecological engineering is… "the conception, implementation, and monitoring of the ecological component of planning and/or management projects, for the benefit of human society, including its environmental expectation"; Scientific ecological engineering is "the scientifically development of tools, methods and concepts for direct use in the practical ecological engineering."	44

means that the goal of ecological engineering is taking advantage of the "self-engineering" and "self-regulating" powers of nature to restore disturbed ecosystems with initial help from humans for the set-up, to ignite the natural flow in processes. This way humans can benefit from nature and nature can benefit from humans.

Ecological engineering vs. restoration ecology vs. environmental engineering

Fields such as restoration ecology and environmental engineering share overlapping ideas and techniques with ecological engineering but differ in some fundamental aspects. Herein, I contrast the differences and similarities between environmental engineering, restoration ecology, and ecological engineering. In broad terms, restoration ecology can be viewed as "the science of habitat and biodiversity recovery" [Young 2000]. Restoration ecology can be applied along a continuum to re-construct devastated sites and to manage relatively unmodified sites [Hobbs and Norton 1996]. This means entire site restoration or relatively limited modifications or involvement in ecosystem maintenance. Like ecological engineering, the concept of design is at the heart of restoration. Concepts of ecological engineering and restoration are interrelated; however, restoration lacks two key foundations of ecological engineering which are: (1) emphasis on the self-design ability of the ecosystem, and (2) constructing approaches on a theoretical base and not just an empirical [Mitsch and Jørgensen 2004]. Conversely, environmental engineering is a field that involves the integration of scientific principles for environmental pollution control and management [Weiner and Matthews 2003] using tools such as scrubbers, flocculation tanks, and sedimentation basins. The greatest difference between ecological and environmental engineering is that the former takes advantage of the self-design capacities of ecosystems, whereas the latter heavily incorporates the use of devices and technologies to contain pollutants. In summary, though these fields differ in certain fundamental principles, the combination of their various conceptual and practical frameworks complement one another to guide management, repair environmental damage, and promote ecosystem resilience in today's rapidly changing world.

BASIC PRINCIPLES OF ECOLOGICAL ENGINEERING

Self-organization

Perhaps the most crucial of the three main principles, self-organization lies at the core of ecological engineering because the greatest emphasis of the field is placed on the spontaneous emergence of spatio-temporal patterns that form from the interaction of local elements within the system [Isaeva 2012]. Self-organization is a concept of self-development where species relations and networks are developed over time and selectively reinforced as more energy becomes available, to feed products into the system for production [Odum H.T. 1988]. The theory states that species are continually added and removed from the system, trophic and non-trophic interactions change in dominance, and the environment itself also changes. Hence, it is the dynamic emergence of natural order from the shared behaviour of individual agents [Saha and Galic 2018]. Mitsch and Jørgensen [2004] have taken the definition one step higher and defined the term self-design as, "the application of self-organization in the design of an ecosystem". Through the concept of self-design, nature is viewed as a partner as opposed to a force to overcome or dominate [Bergen et al. 2001]. Many systems are organized into hierarchies – the organization can be controlled through external/imposed organization or by self-organization of the natural system [Pahl-Wostl 1995]. Self-organization in biological systems allows for the amplification of the production process through internal feedback. In ecological engineering, we rely on the self-organization of nature's hierarchies to restore systems, rather than imposing organization. Undeniably, however, the degree of self-organization varies in the varieties of sub-fields of ecological engineering. Fields such as soil bioremediation are closer to practices of environmental engineering as reliance on human-made structures is more present (Figure 1). This is contrary to practices such as wetland restoration where enhanced aquatic chains, processes, and plant species can control the influx and efflux of substances such as phosphorous, nitrogen, and mercury [Mitsch and Gosselink 2000; St. Louis et al. 1994]. Ecological succession, the process by which the structure of a community evolves over time, is the manifestation of self-organization [Todd and Todd 1994]. As diversity rises, stability increases and the system becomes more resilient to

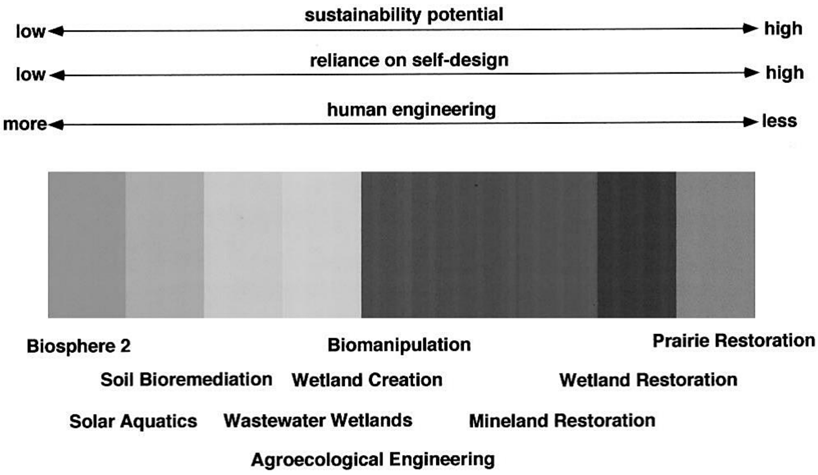

Figure 1. Spectrum of ecological engineering examples, showing relative sustainability potential, reliance on self-design, and required human engineering adapted from Mitsch (1998)

disturbance and perturbation. Hence, ecologically-engineered ecosystems that greatly focus on the concept of self-design are ultimately some of the most successful. Thus, self-organization is at the core of many biological processes ranging from the molecular (for instance, the blood pH buffer system) to species level (sucession) and a variety of environmental and ecological disciplines rely on this property of nature to a certain degree.

Energy signature

Energy, defined as the ability to work, is the central concept of thermodynamics [Fanchi and Fanchi 2017]. Different systems can have different energetic inputs, including solar, wind, rain, waves, etc. The interaction between these energy types performs different types of work; thus, as Kangas [2004] states, "…each energy signature causes a unique kind of system to develop." The varieties of ecosystems that exist across the globe illustrate the mixture of the different types of energy sources that exist. Energy signature is directly related to self-organization. This is because self-organization hierarchies lead to various energy cascades [Odum H.T. 1988]. In order to quantify different units of energy into one such that we can compare and contrast the energetics of a system the term *Emergy*, popularized by H.T. Odum, was suggested by Scienceman in 1983 [Brown and Ulgiati 2004]. Emergy is energy that is required to generate flow or storage and maximum emergy is when all products and by-products are sent back into the system to reinforce source input and augment efficiency [Odum H.T. 1988]. Emergy is a complex concept, but here I define emergy as the energy available to generate flow and feedback in a system such that products and services are directly or indirectly made available. Unlike energy, emergy takes economy, resources, politics, and most importantly, the importance of circularity in environmental processes into account [Chen et al. 2017]. Circular economy (opposite of linear economy) is an idea derived from various scientific fields and can be loosely defined as an economic system with a cyclical flow of materials from production to consumption to reduce the negative environmental impacts and promote environmental sustainability [Korhonen et al. 2018]. As an example, fossil fuels, minerals, and water have more emergy than sunlight because "Sunlight is a dilute energy, and the costs of concentrating have been already optimized and yield maximized by the millions of years of natural selection for this maximization" [Odum H.T. 1972]. Sunlight is a powerful energy source because, unlike fossil fuels that have high societal, environmental, and economic costs, sunlight has a very high net energy [true value to society after the costs of getting and concentrating the energy have been subtracted [Brown and Ulgiati 2004]. Solar energy should be the dominant energy in an ecologically-engineered system; thus, to evaluate resources, goods, or services qualitatively, solar emergy (sej) is used as the unit [Amaral et al. 2016]. This is related to the concept of *transformity* which is the solar emergy required to provide a joule of product or service (sej/J). Energy signatures can also be altered through pulsing and disturbance [Odum et al. 1995]. Pulsing, a form of natural disturbance, can be incorporated into ecological engineering design (for example, by adding fertilizer that has nutrients, turbulence, adding a source of water, adding herbicide, etc.) [Kangas 2004] to encourage the progress and development of the ecosystem in a particular manner. Pulsing contributes to the flow of energy through greater productivity, biological activity, and dissolved nutrients [Winemiller et al. 2014]. In summary, the term emergy allows us to compare between work done by different forms of energy whilst factoring in environmental impact and economic circularity. Emergy allows us to examine the true nature of goods, services, and resources so we can make more sustainable decisions. Work in different systems is done through a variety of energy signatures, and emergy enables us to make a leveled comparison between them.

Preadaptation

Adaptations are important because they allow species to cope with the pressures that nature imposes on the ecosystem. Ecological niche is a central concept when we discuss adaptations. The ecological niche theory comprises organismal habitat and the use of resources concerning biotic interactions [Begon and Townsend 2020; Bowman and Hacker 2021; Slagsvold and Wiebe 2007]. Hutchinson [1978] argues that a species' ecological niche is the sum of its total adaptations. Adaptations dictate which resources such as food, cover, and space can be utilized by a species. Preadaptation is functionally best defined as adaptations or "preexisting features" that are a by-product of other evolutionary processes or were selected for reasons other than their today's apparent function [Larson et al. 2013]. These can be an adaptation that has accumulated in one system without anticipation of subsequent uses, though may improve functionality in a different system [Dew 2007]. In 1982 Gould and Vrba introduced the term "exaptationbut available for useful cooptation in descendants, then an important concept has no name in our lexicon (and unnamed ideas generally remain unconsidered" in place of preadaptation and defined it as "…such characters, evolved for other usages [or for no function at all], and later "coopted" for their current role…" An example of exaptation is seen in feather and flight-sequential exaptation in bird evolution. The Black Heron of Africa (*Egretta ardesiaca*) uses its wings to fly like most birds today; however, interestingly it also uses it to cast a shadow on the water to better see its prey/food. This is a developed characteristic behaviour with previous genetic dispositions. Selecting species with preadaptations better suited to the emerging conditions of an ecosystem is key in ecological engineering. Preadapted species to systems with high stress are more likely to resist moderate stresses from human activity, especially those that mimic natural stresses [Rapport et al. 1985]. Despite its relevance, the term exaptation has not been popularized. This is because the formal definition does not contrast the term from adaptation since many traits used for a specific function were likely modified from a pre-existing form for a different purpose than the one they have today. Adaptation can be viewed as a more guided process of natural selection of a characteristic used today, whereas exaptation has more to do with the usefulness of a trait later on by chance (Table 2). Exaptation aids in expanding the term preadaptation with more specific examples in an attempt to highlight some of the slight differences between preadaptation and the more classic term adaptation.

The discussed principles are the foundational basis of ecological engineering. Projects for ecological engineering should have a design that takes advantage of the self-organization properties of natural systems, maximize energy signature, and encourages the use of preadapted species. Ecological engineering projects should harness the circularity of environmental processes. In the following section, I will further break down each of the basic principles discussed above into the specific 19 ecological design principles and provide real-life studies to further illustrate each point.

Table 2. Summary of adaptation and exaptation adapted from Dew et al. (2004). The term aptation refers to characters currently subjected to selection, regardless of whether they originated directly from the selective process (adaptation) or for a purpose other than their intended one (exaptation)

Process	Definition		Usage
Natural selection processes shape a characteristic for current use	Adaptation	Aptation	Function
A characteristic previously shaped for another function is co-opted for a new use	Exaptation		Effect
A character whose origin cannot be ascribed to selection processes is co-opted for use			

Ecological design principles

The following section aims to break down the three main principles discussed into 19 guiding principles that best attempt to represent 60 years of ecological engineering. I attempt to categorize each of these 19 principles into one or more of the three main categories discussed above (Table 3). Principles are mostly adapted from Mitsch and Jørgensen [2004] and Todd and Todd [1994]. Real-life examples are provided to demonstrate some of these principles.

1) Ecosystem structure and function are determined by the forcing function of the system.

Anthropogenic forcing functions can determine the overall trajectory of the ecosystem.

Table 3. A summary table of ecological engineering principles categorized into three basic categories defined by Kangas 2004. The 19 Specific design principles are adapted from Mitsch and Jørgensen 2004. This synthesis attempts to categorize each specific principle to fit into one or multiple categories of the three basic categories. Representative study(ies) that illustrate the specific principle is also provided

Principle number	Specific design principles	Basic principle	Representative publication(s)
1	Ecosystem structure and function are determined by the forcing functions of the system.	Energy signature	Wave as a forcing function in coral reefs (Bradbury and Young 1981; (Williams et al. 2013)
2	Energy input to the ecosystem and available storage of matter are limited.	Energy signature	Solar energy is the dominant form of energy (Amaral, Martins, and Gouveia 2016)
3	Ecosystems are open and dissipative systems.	Energy signature	Input energy is crucial (Kangas 2004)
4	Attention to the limited number of factors is most strategic in preventing pollution or restoring ecosystems.	Self-organization	Limiting nutrients in lakes (Correll 1999; Rabalais 2002)
5	Ecosystems have homeostatic capabilities in soothing out and depressing the effects of strongly variable inputs.	Self-organization	Forest moderating a range of environmental conditions (Asbjornsen et al. 2004)
6	Match recycling pathways to the rates to reduce the effect of pollution.	Self-organization	Control of the input of sludge as fertilizer (Bagreev, Bandosz, and Locke 2001)
7	Design for pulsing systems wherever possible.	Energy signature	Algal Turf Scrubbers (ATS) (Adey, Kangas, and Mulbry 2011)
8	Ecosystems are self-designing systems.	Self-organization	Eutrophication in wetlands (Sánchez-Carrillo et al. 2010)
9	Processes of ecosystems have characteristics in time and space scales that should be accounted for in environmental management.	Self-organization	Ecotones to separate agricultural land (Pe’er et al. 2011)
10	Biodiversity should be championed to maintain an ecosystem’s self-design capacity.	Self-organization Preadaptation	Mixed-crop cultivation (Ghahremani et al. 2021)
11	Ecotones, transition zones, are as important for ecosystems as membranes are for cells.	Self-organization	Littoral zones with macrophytes (Brix 1997)
12	Coupling between ecosystems should be utilized wherever possible.	Energy signature Self-organization	Circularity and coupling in ecosystems (Ochoa-Hueso et al. 2021)
13	The components of an ecosystem are interconnected, interrelated, and form a network, implying that direct as well as indirect effects of ecosystem development need to be considered.	Self-organization	DDT biomagnification in fish (Deribe et al. 2013)
14	An ecosystem has a history of development.	Preadaptation	Comprehensive Everglades Restoration Plan (CERP) (Paudel et al. 2020)
15	Ecosystem and species are most vulnerable at their geographic edges.	Self-organization Preadaptation	Climate buffer zones in forests (Biringer and Hansen 2005)
16	Ecosystems are hierarchical systems and are parts of a larger landscape.	Self-organization	Hierarchical components as ecological indicators of an ecosystem (Jørgensen and Nielsen 2013)
17	Physical and biological properties are interactive. It is important to know both physical and biological interactions and to interpret them properly.	Energy signature Self-organization	Macrophytes lowering nutrient pulsing to control for algal blooms (Wolanski et al. 2004)
18	Ecotechnology requires a holistic approach that integrates all the interacting parts and processes as far as possible.	Energy signature Self-organization Preadaptation	River remediation focusing on the entirety of the catchment (Chou, Lin, and Lin 2007)
19	Information in ecosystems is stored in structures.	Preadaptation	Size of an organism (Mitsch and Jørgensen 2004)

Forcing functions can be defined as forces that may interact with the various biotic and abiotic components of a system that originate outside of that system and are not under its control [Bradbury and Young 1981]. For example, the structure of a coral reef can be a direct consequence of the forcing function of wave energy which is a disturbance that can result in less hard coral cover in some reefs [Williams et al. 2013]. Thus, forcing functions can be energy forms that guide/influence the spatial arrangement of ecosystems.

2) Energy inputs to the ecosystem and available storage of matter are limited.

The dominant energy form of an ecologically-engineered system should be solar energy. Any form of energy trying to imitate solar energy in any form or another (i.e. fossil fuels) is either unsustainable or less sustainable than solar energy. Solar energy is the dominant form of energy in ecologically engineered systems and is used as the measure of emergy (sej/J) which takes circular economy and environment into consideration when calculating the true value of the energy [Amaral, Martins, and Gouveia 2016].

3) Ecosystems are open and dissipative systems.

Ecosystems obey the laws of thermodynamics. Because the entropy (disorder) in a system is always increasing, ecosystems rely on a steady input of energy from outside to carry out functions needed for maintenance and survival. Interactions between energy inputs such as solar, wind, and waves create unique energy signatures able to carry out different types of work within a system [Kangas 2004].

4) Attention to the limited number of factors is most strategic at preventing pollution or restoring ecosystems.

Ecological homeostasis can depend upon many factors; though, one is usually the most limiting. Ecosystem restoration should focus on the most appropriate limiting factor. For example, for lake restoration, it might be the availability of nutrients such as phosphorous or nitrogen [Correll 1999; Rabalais 2002], that can dictate the growth of aquatic vegetation, algae, and microbes. Limiting factors can influence self-organization through their availability in the formation of self-controlled hierarchical pathways.

5) Ecosystems have some homeostatic capability that results in smoothing out and depressing effects of strongly variable inputs.

Just like living organisms, ecosystems have ecological buffering capacities. For instance, forests can moderate environmental conditions like microclimate [Asbjornsen et al. 2004]. However, buffering capacities have a threshold that environmental managers need to respect, otherwise, the system may suffer greatly and even collapse as it exceeds the self-organizing/soothing capability of the natural system.

6) Match recycling pathways to the rates of the ecosystem to reduce the effect of population.

Substances must not be applied to an ecosystem faster than the rate at which they are used because otherwise, they can run off into other nearby systems and negatively impact species. Sludge can be used in agriculture as a form of fertilizer [Bagreev, Bandosz, and Locke 2001]. Though, if the rate of application of sludge is higher than its utilization by the landscape, a large amount of sludge can seep through to lakes, streams, and groundwater near the agricultural system. If the rate of substances is greater than the rate at which they are recycled, energy and nutrient balances can become disturbed which can, in turn, affect internal feedback loops.

7) Design for pulsing systems whenever possible.

Ecosystems that have regular pulsing patterns often have greater productivity, biological activity, and chemical cycling [Mitsch and Jørgensen 2004]. Nature is homeorhetic as opposed to homeostatic [E.P. Odum 2002], meaning there is stabilized flow (homeorhetic) as opposed to a steady-state (homeostatic). Pulsing contributes towards the homerhetic properties of nature. In the Gulf of Mexico, the need to improve hypoxic water quality has led to the invention of an ecologically-engineered system that pulses wastewater over a sloping surface attached to filamentous algae (Algal Turf Scrubbing or ATS) [Adey, Kangas, and Mulbry 2011]. The algae use photosynthesis to remove nutrients such as phosphorous, nitrogen, and carbon dioxide from water, in turn injecting oxygen into the water. Pulsing can affect energy signatures and can be used to guide the formation or the progress of an ecosystem in a particular matter.

8) Ecosystems are self-designing systems.

Ecological engineering takes advantage of the self-design properties of nature. Self-design in a system means that the system can "…implement sophisticated regulations before violent fluctuations or even chaotic events occur"

[Mitsch and Jørgensen 2004]. For instance, wetlands designed to remove excess nutrients from streams and lakes have a self-design ability to regulate eutrophication levels accordingly. Eutrophication in wetlands takes advantage of the self-design abilities of the ecosystem by accelerating processes of primary productivity and net accumulation of organic matter, whilst enhancing organic matter decomposition, microbial activity, and soluble nutrients in sediments [Sánchez-Carrillo et al. 2010].

9) Processes of ecosystems have characteristic time and space scales that should be accounted for in environmental management.

Space scales and the concept of the right time are important to consider because the creation of large land such as agricultural spaces can have substantial biodiversity loss [Pe'er et al. 2011]. Ecotones, defined as shifts between biomes horizontally through space [Neilson 1993], have the potential to reduce biodiversity loss by providing a space for animals and plants to find their ecological niche in the grand sea of agricultural land. Ecotones promote species interactions and provide available sources in the system for self-organization to take place.

10) Biodiversity should be championed to maintain an ecosystem's self-design capacity.

Biological diversity increases the self-design and buffering capacities of an ecosystem. For example, cultivated, mixed-culture crops have a greater soil microbial population, better soil carbon profile, and lead to greater crop yields [Ghahremani et al. 2021]. Additionally, they are also less vulnerable to disturbance. Biodiversity in crops mimics the diversity of natural ecosystems. This promotes the creation of species networks and interactions; hence, promoting the self-organizing properties of this system.

11) Ecotones, transition zones, are as important for ecosystems as membranes are for cells.

Transitional zones are crucial as they can absorb undesirable changes before they reach a neighboring ecosystem. For instance, Littoral zones with macrophytes stabilize surface of the beds, provide good conditions for filtration [stop contamination], prevent vertical flow systems from clogging, insulate the system against frost during winter, and provide a great surface area for microbial growth [Brix 1997]. Ecotones build ecosystem resilience which is key for successful self-organization.

12) Coupling between ecosystems should be utilized wherever possible.

Ecosystems are open systems and interconnected. This means that changes in one can have local, regional, and global impacts. The use of sludge in agriculture must be done optimally that the nutrients are fully absorbed by the system they are applied to, in order to account for transition processes [Wang et al. 2008]. Coupling ecosystems promotes circularity and efficiency in energy transfer and material, in turn maximizing the internal feedbacks of self-design and decreasing unwanted transition processes [Ochoa-Hueso et al. 2021].

13) The components of an ecosystem are interconnected, interrelated, and form a network, implying that direct as well as indirect effects of ecosystem development need to be considered.

An effect on one part of the ecosystem is bound to have an effect, which may be even more pronounced, on another part, either indirectly or directly. It is thus key that management considers these indirect and direct effects. In the famous case of DDT in pesticides, high levels of biomagnification can occur in fish that may be used for human consumption [Deribe et al. 2013]. Contaminations in one ecosystem can disturb matter and function elsewhere.

14) An ecosystem has a history of development.

Ecosystems do not develop overnight. The components of an ecosystem have been carefully crafted over decades to cope with the problems nature imposes on them. Hence, the restoration success of ecologically-engineered ecosystems should not be measured immediately. Ecological development should be given adequate time before the evaluation of success. The Comprehensive Everglades Restoration Plan (CERP) was developed by the United States Army Corps of Engineers (USACE) and the South Florida Water Management District (SFWMD) was approved in 2000 to restore the Everglades wetland and water system in Florida. Nearly 20 years later, the project is still ongoing and evaluation studies continue to take place [Paudel et al. 2020]. Preadaptations stored in the memory of the ecosystem can aid in accelerating the development process.

15) Ecosystems and species are most vulnerable at their geographical edges.

Creating an ecosystem should contribute towards the buffering abilities of species in the middle range of their environmental tolerance. Thus, planning should avoid the use of biological components at the lower and upper end of the spectrum. For instance, climate buffering zones in forest restoration can protect species and reduce genetic loss by providing an area of a natural, healthy forest system [Biringer and Hansen 2005]. Buffer zones promote the natural self-organization of biological systems through space and resources.

16) Ecosystems are hierarchical systems and are part of a larger landscape.

Each part of an ecosystem plays a different role in the food chain and the biogeochemical processes. Populations interact in a network through biotic and abiotic relationships in a synergistic manner that augments the utilization of matter, energy, and information [Jørgensen and Nielsen 2013]. Thus, ecological hierarchies can be used as ecological indicators of the functioning of an ecosystem.

17) Physical and biological processes are interactive. It is important to know both physical and biological interactions and to interpret them properly.

Physical properties must be integrated with biota dynamics to achieve "new operational strategies" [Harper, Zalewski, and Pacini 2008]. For example, toxic algal blooms may be avoided by establishing macrophytes in an aquatic ecosystem. Macrophytes can lower nutrient pulsing [$P\text{-}PO_4$] from rural areas to about 120 μg/l which avoids toxic algal blooms [Wolanski et al. 2004]. Control of nutrient pulsing is a way of guiding the energy signature of the ecosystem, as well as ensuring nutrient inputs are not high enough, which would otherwise disturb the ecosystem's internal feedback cycles.

18) Ecotechonology requires a holistic approach that integrates all interacting parts and processes as far as possible.

Ecosystems are more than their parts. Therefore, management must consider the interaction between the various parts. For instance, remediation of rivers should not only focus on one area, but instead on the entire catchment, including the upstream, middle stream, and downstream [Chou, Lin, and Lin 2007]. A holistic approach views nature as an entity that is not separate from humans and incorporates ideas from all three categories discussed above: energy signature, self-organization, and preadaptation.

19) Information in ecosystems is stored in structures.

When energy is inputted into a system, structures are built to try and move away from entropy. In a way, entropy can be reversed locally, but of course not universally. Structures can include organisms. The size of organisms can tell us about "important features of life, such as the rate of development, speed, of movement, and the range of areas they inhabit". [Mitsch and Jørgensen 2004]. Preadaptations, as discussed above, can be viewed as information stored in structures that are used today, but not for the function they were originally intended for.

CONCLUSION AND FUTURE DIRECTIONS

Over the last four decades, the field of ecological engineering has attempted to be a more prescriptive branch of ecology rather than a descriptive one. Ecological engineering views biology and nature as the model for life [Todd and Todd 1994], with the overreaching goal of designing to follow the laws of life. Over the years, ecologically-engineered ideas have been incorporated into the creation of wetlands as a purification system [Brix 1997; St. Louis et al. 1994], been used as an inspiration in the creation of pulsing systems [E.P. Odum 2002; Adey et al. 2011], and have shaped the manner in which we view agricultural land [Pe'er et al. 2011; Bagreev et al. 2001; Asbjornsen et al. 2004]. In a way, ecologically engineering is a pragmatic test for many ecological theories because it provides us with the opportunity to examine some of the theories that have been put forward in scholarly publications over the last 100 years. However, it is crucial to remember that natural systems are ever-changing and dynamic and that living systems cannot be defined with certainty. Hence, ecological engineering should focus on understanding the organizational properties of the system and strive to incorporate resiliency into the system as a resilient ecosystem will naturally adapt itself to changing external inputs [Parrott 2002]. Additionally, to accomplish the wide use of ecological engineering, the field needs to form relationships not only with other scientific fields but also with the social sciences and business. Social and political interactions impact the environment and vice versa [Jones 2012]. Thus to create and implement effective designs, a relationship between ecological engineering and social and political sciences is key. Over the last few years, we have seen the emergence of studies examining sustainable business, circular economy, and the environment; though, there is still much more to research for examining the human-natural earth systems. We live in times of environmental uncertainty and this uncertainty is increasing rapidly. The role of nature-based solutions for a circular economy has the potential to guide us toward new technologies and a wealth of new approaches [Schönborn and Junge 2021]. Green technologies such as solar cells, wind generators, and harnessing thermal energy are some of the products of such research over the last decade. In the future, the focus of ecological engineering will be on nature-based climate adaptations, resilient landscapes, sustainable crop productions, and applying the frameworks of ecological engineering to circularity in production. For instance, nature-based green areas are a great way to enhance the resilience of cities in light of climatic changes [Alexandri and Jones 2008]. Aside from their climatic benefits, green roofs also offer great promise for sustainable crop production in urban communities [Walters and Stoelzle Midden 2018]. Ecological engineering techniques, including planting crop protégé species in tandem with nurse plants, can mediate the performance of protégé plants thus enhancing biodiversity conservation and increasing the success of urban crop production [Rolhauser et al. 2023]. This practice can also be applied to make the ecosystem biodiversity more resilient to land-use changes. Furthermore, throughout much of history, our focus on solving environmental problems has been very linear. For example, the historical development of engineering solutions for wastewater treatment in Europe focused on linear steps, with the final disposal of the water into rivers and landfills [Lofrano and Brown 2010]. However, more recent advances in wastewater treatment, specifically treating microplastics, focus on the sustainable detection and removal of microplastics using technologies such as filters such as that the water can be fed back into the system for usage again, promoting circularity. Future directions will surely continue to focus on the concept of circularity in areas including mitigating plastic production and microplastic control, as well as textile and garment production. These

Table 4. Definitions table for keywords and key ideas discussed in this review

Keyword	Definition
Self-organization	The concept of self-development where species relations and networks are developed over time and selectively reinforced as more energy becomes available, to feed products into the system for production. Responsible for hierarchical organizations in nature.
Ecological engineering	1) Restoring substantially disturbed ecosystems as a result of anthropogenic activities and pollution, and 2) the synthesis of sustainable ecosystems that have ecological and human value by heavily relying on the self-organization capabilities of a system.
Environmental engineering	A field that involves the integration of scientific principles for environmental pollution control and management using tools such as scrubbers, flocculation tanks, and sedimentation basins.
Restoration ecology	The science of habitat and biodiversity recovery whose techniques can be along a continuum to re-construct devastated sites and to manage relatively unmodified sites.
Ecological succession	Processes by which the structure of a community evolves over time.
Energy	Ability to do work. A central topic in thermodynamics.
Energy signature	When all forms of energy in a system, including wind, solar, water, etc. combine to create a unique form of energy able to do work.
Emergy	The energy available to generate flow and feedback in a system such as that products and services are directly or indirectly made available, measured in sej. Emergy takes economy, resources, politics, and most importantly, the importance of circularity in environmental processes into account.
Pulsing	A form of natural disturbance that contributes to the flow of energy through greater productivity, biological activity, and dissolved nutrients
Circular economy	An economic system with a cyclical flow of materials from production to consumption in order to reduce the negative environmental impacts and promote environmental sustainability.
Adaptation	The process by which species become more suited to their environment or a character that is well-suited to the current environment of the living species.
Preadaptation/Exaptation	A character evolved for other usages (or for no function at all), and later “coopted” for its current role.
Aptation	A character currently subjected to selection, regardless of whether they originated directly from the selective process (adaptation) or for a purpose other than their intended one (exaptation).
Homeostasis	A steady state in a process in living things and the environment.
Homeorhesis	A steady flow in a process within a system that returns to a trajectory rather than a steady state.

technologies and other novel approaches will be key in the creation of ecosystem resilience, eco-cities, and urban spaces.

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