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PhD Preliminary Examination

PhD Cognate Area 1

**A review of ecological engineering principles.**

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**Table 1.** A summary table of ecological engineering principles categorized into the three basic categories. Specific design principles are adapted from *Mitsch and Jørgensen 2004.*

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| --- | --- | --- | --- |
| **Principle Number** | **Specific Design Principles** | **Basic Principle** | **Specific example** |
| **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*) |
| **2** | Energy input to the ecosystem and available storage of matter are limited. | Energy signature | Solar energy is the dominant form of energy |
| **3** | Ecosystems are open and dissipative systems. | Energy signature | Input energy is crucial. |
| **4** | Attention to the limited number of factors is most strategic in preventing pollution or restoring ecosystems. | Energy signature  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 |  |
| **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 | Control for the rate of application of sludge. |
| **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 |  |
| **15** | Ecosystem and species are most vulnerable at their geographic edges. | Self-organization  Preadaptation |  |
| **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*) |

1. **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. A need for ecology to be more prescriptive rather than descriptive lead to the development of the field of ecological engineering around 40 years ago, with rapid acceleration 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 (H. T. Odum 1962). Odum highlighted the field as, “the study and practice of solving problems with technological designs.” (H. T. Odum and Odum 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.” (H. T. Odum and Odum 2003; E. P. Odum 1989). In fact, harnessing the self-organization properties of natural systems is a critical component of ecological engineering (H. T. Odum 1983; Mitsch 1996). There is no doubting Odum’s contribution to the field though we must acknowledge that around the same period Ma Shijun 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, and 2) the transformation, decomposition, concentration, and regeneration of substances based on multi-layer trophic structures (Kangas 2004). 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 gave way to the establishment of the journal of *Ecological Engineering* around 1992 (Mitsch 1998). Various principles, corollaries, and basic concepts have been developed for the field; however, I believe they can summed up into three main categories including energy signature, self-organization, and preadaptation (Kangas 2004; Mitsch and Jørgensen 2004; H. T. Odum and Odum 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). Synonymous with ecotechnology, a more widely-accepted definition however was given by Mitsch and Jørgensen (1989) stating that ecological engineering is “the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both.” A slightly upgraded definition often used today describes ecological engineering as “the design of human society with its natural environment for the benefit of both” (Mitsch and Jørgensen 2004). Similarly, the Chinese approach using Ma's (1988) definition has since defined ecological engineering as “a specially designed system of production process in which principles of the species symbiosis and the recycling and regeneration of substance sin an ecological system are applied with adopting the system engineering technology and introducing new technologies and excellent traditional production measures to make a multi-step use of substance.” Unlike the engineering-focused definition, it is evident that most other descriptions of the field more closely focus on the concept of unity between nature and society. The term ecological engineering has sometimes been deems controversial (Kangas 2004) because, unlike engineering that seeks to fit its design onto nature, ecology seeks to protect nature from human impact (Hall 1995). However, engineers and ecologists must celebrate the union between the two fields by combining the strengths of both disciplines to create new frameworks to solve a variety of environmental problems. Mitsch and Jørgensen (2004) summarize the goals of ecological engineering 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.

***Ecological engineering vs. restoration ecology vs. environmental 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). Thus, like ecological engineering, the design of an ecosystem is at the heart of restoration. Concepts of ecological engineering and restoration are interrelated though restoration lacks two key foundations of ecological engineering which are: 1) emphasis on self-design ability of the ecosystem, and 2) constructing approaches on a theoretical base and not just an empirical (Mitsch and Jørgensen 2004). Environmental engineering on the other hand 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.

1. **Basic principles of ecological engineering**

***Self-organization***

Perhaps the most crucial of the three main principles, self-organization lays at the core of ecological engineering. 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 (H. T. Odum 1988). In other words, self-organization is the notion that species are continually added and removed from the system, trophic and non-trophic interactions change in dominance, and the environment itself also changes. 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.” This is evident when we examine how the survival and persistence of species introduced into an ecosystem have more to do with nature than humans. Through the concept of self-design, we view nature as a partner as opposed to a force to overcome or dominate (Bergen, Bolton, and L. Fridley 2001). Many systems are organized into hierarchies – the organization can be controlled through external/imposed organization or by self-organization (Pahl-Wostl 1995). Self-organization in biological systems allows for the amplification of the production process through internal feedbacks. Undeniably, however, the degree of self-design 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 for the influx and efflux substances such as phosphorous, nitrogen, and mercury (Mitsch and Gosselink 2000; St. Louis et al. 1994). Ecological succession is the manifestation of self-organization (Todd and Todd 1994). As diversity rises, stability increases and the system becomes more resilient to disturbance and perturbation. Hence, an ecologically-engineered ecosystem that greatly focuses on the concept of self-design is ultimately some of the most successful.

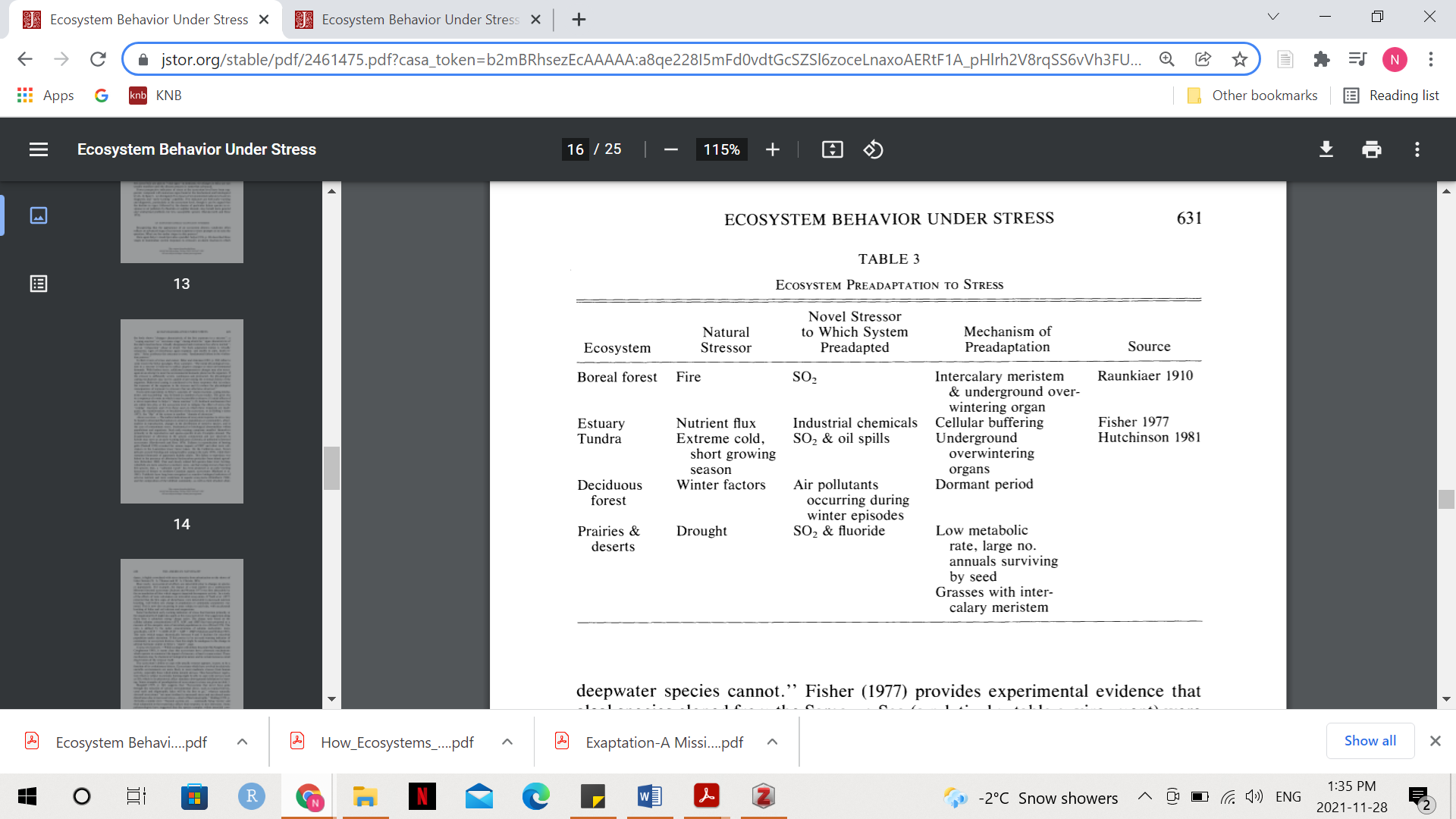
**Figure 1.** Spectrum of ecological engineering examples, showing relative sustainability potential, reliance on self-design and required human engineering from *Mitsch (1998)*.

***Energy signature***

Energy, defined as the ability to work, is the central concept of thermodynamics. Different systems can have different energetic inputs, including solar, wind, rain, waves, etc. The interaction between these energies performs different types of work; thus, as Kangas (2004) states it, “….each energy signature causes a unique kind of system to develop.” Energy signature is directly-related to self-organization because self-organization hierarchies lead to various energy cascades (H. T. Odum 1988). *Emergy*, a term popularized by H.T. Odum and suggested by Scienceman in 1983 (Brown and Ulgiati 2004), has been used to quantify different units of energy into one such that we can compare and contrast the energetics of a system.” Emergy is energy that is required to generate flow or storage (H. T. Odum 1988) and maximum emergy is when all products and by-products are sent back into the system to reinforce source input and augment efficiency. I define emergy as the energy available to generate flow and feedback in a system such as that products and service 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. For example, fossil fuels, minerals, and water have more emergy than sunlight because “Sunlight is a dilute energy, and the costs of concentrating are have been already optimized and yield maximized by the millions of year of natural selection for this maximization” (H. T. Odum 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 has been subtracted (Brown and Ulgiati 2004)). Solar energy should thus be the dominant energy in an ecologically-engineered system as it is the most sustainable energy source. Furthermore, energy signatures can also be altered through pulsing and disturbance (W. E. Odum, Odum, and Odum 1995). Nature is in fact homeorhetic as opposed to homeostatic (E. P. Odum 2002), meaning there is stabilized flow as opposed to a steady-state. Nature’s pulsing contributes to the flow of energy through greater productivity, biological activity, and chemical cycling (Mitsch and Jørgensen 2004). Equilibrium thermodynamics allows for the explanation of ecosystems to perturbations (Ruth 2008). Pulsing and disturbance can be incorporated in 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.

***Preadaptation***

In essence, adaptations allow species to cope with the pressures that nature imposes on the ecosystem. Ecological niche is an important concept when we discuss adaptations. The ecological niche theory comprises organismal habitat and the use of resources in relation to 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. In a way then, preadaptation can essentially be understood as adaptations or “preexisting features” that allow organisms to be suitable to new situations (Kangas 2004). These can be an adaptation that have accumulated in one system without anticipation of subsequent uses, though may improve functionality in a different system (Dew 2007). Some biologists argue however that the term is contradictory to evolutionary principles because the process of natural selection does not involve planning for the future. In 1982 Gould and Vrba introduced the term "exaptation” in place of preadaptation and defined 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 which mimic natural stresses” (Rapport, Regier, and Hutchinson 1985). Table 1 provides some of the preadaptation in natural systems.

**Table 2.** Ecosystem preadaptation to stress from *Rapport et al. 1985*.

The discussed principles are the foundational basis of ecological engineering. Ecological engineering projects should have a design that maximizes energy signature, encourages the use of preadapted species to promote a successful design, and most importantly takes advantage of the self-organization properties of natural systems. In the following section, I will further break down each principle and provide real-life case studies to further illustrate each point.

1. **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 probing. I have attempted to the best of my ability to categorize each of these 19 principles into the three main categories discussed above (Table 1). 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. 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: wave energy.

1. ***Energy inputs to the ecosystem and available storage of matter are limited.***

The dominant energy form of a system should be solar energy. Any form of energy trying to imitate solar energy in any or another (i.e. fossil fuels) is simply unsustainable. This is related to the notion of conservation of mass and energy: energy cannot be created nor destroyed, instead only converted between one form and another.

1. ***Ecosystems are open and dissipative systems.***

Ecosystems obey the laws of thermodynamic. Because the entropy or 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.

1. ***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).

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

Just like in 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.

1. ***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. 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.

1. ***Design for pulsing systems whenever possible.***

Ecosystems that have regular pulsing patterns often have greater productivity, biological activity, and chemical cycling. 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.

1. ***Ecosystems are self-designing systems.***

Unlike traditional engineering that does not like anything left up to nature, ecological engineering takes advantage of the self-design properties of nature. Self-design in a system means that the system is able to “…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.

1. ***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 principles of ecological engineering. The creation of large agricultural spaces can have substantial biodiversity loss (Pe’er et al. 2011). Ecotones, defined as shifts between biomes 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.

1. ***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.

1. ***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 neighbouring 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 of microbial growth (Brix 1997).

1. ***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. As discussed above, the use of sludge in agriculture must be done in such a way that the nutrients are fully absorbed by the system they are applied to, in order to account for transition processes.

1. ***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).

1. ***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 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.

1. ***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. Planning should avoid the use of biological components at the lower and upper end of the spectrum.

1. ***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 in 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.

1. ***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 are able to lower nutrient pulsing (P-PO4) from rural areas to about 120 μg/l which avoids toxic algal blooms (Wolanski et al. 2004).

1. ***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 are, but instead the entire catchment, including the upstream, middle stream, and downstream (Chou, Lin, and Lin 2007).

1. ***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 in fact be reversed; however, only locally not universally. Structures can include organisms. 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).

1. **Conclusion**

Over the last four decades, ecological engineering has provided with a more prescriptive regimen of ecology rather than a descriptive one. With its overreaching goal of designing to follow the laws of life rather than opposing them, ecologically engineering views biology and nature as the model for life (Todd and Todd 1994). Since its developmental days in the ’60s (H. T. Odum 1962), the field has presented three main principles to better illustrate the application of ecological theories (Kangas 2004). Often looked upon as the union between man and nature for the mutual benefit of both, three basic principles including energy signature, self-organization, and preadaptation are at the heart of ecological design (Kangas 2004; Mitsch and Jørgensen 2004; H. T. Odum and Odum 2003; Mitsch 1998). 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, Kangas, and Mulbry 2011), and have shaped the manner in which we view agricultural land (Pe’er et al. 2011; Bagreev, Bandosz, and Locke 2001; Asbjornsen et al. 2004). In a way, ecologically engineering is an acid test for many ecological theories because it provides us with the opportunity to examine the “correctness” of the theories that have been put forward in scholarly publications over the last 100 years. Further research should examine to the application of ecological engineering not only for the purpose of ecosystem restoration or the “re-building” nature but also for the development of living technologies that will be key in the creation of eco-cities and urban spaces in the future.

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