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Engineering role models: do non-human species have the answers?

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Abstract

A shift from traditional engineering approaches to ecologically-based techniques will require changing societal values regarding 'how and what' is defined as engineering and design. Non-human species offer many ecological engineering examples that are often beneficial to ecosystem function and other biota. For example, organisms known as 'ecosystem engineers' build, modify, and destroy habitat in their quest for food and survival. Similarly, 'keystone species' have greater impacts on community or ecosystem function than would be predicted from their abundance. The capacity of these types of organisms to affect ecosystems is great. They exert controlling influences over ecosystems and communities by altering resource allocation, creating habitats and modifying relative competitive advantages.

Species' effects in ecosystems, although context-dependent, can be evaluated as 'beneficial' or 'detrimental'. The evaluation depends on whether effects on other species or ecosystem function are more or less desirable from a given perspective. Organisms with beneficial impacts facilitate the presence of other species, employ efficient nutrient cycling, and are sometimes characterized by specific mutualisms. In contrast, many cases of detrimental engineering are found from introduced (i.e., exotic) species and are characterized by a loss of species richness, a lack of nutrient retention and the degradation of ecosystem integrity. Species' impacts on ecosystems and community traits have been quantified in ecological studies and can be used similarly to understand, design and model human engineering structures and impacts on the landscape. Emulation of species with beneficial impacts on ecosystems can provide powerful guidance to the goals of ecological engineering. Using role model organisms that have desirable effects on species diversity and ecosystem function will be important in developing alternatives to traditional engineering practices.

Keywords: Ecosystem engineers; Biomimicry; Ecosystem function; Keystone species; Exotic species; Species diversity; Sustainability

1. Introduction

When one seeks alternative approaches in one's life (e.g., chosen career, culinary repertoire), it is good to have positive role models. Seeing an alternative model, particularly one performed in an appealing or successful way, helps us to overcome the inertia of the status quo. In one of his final books, the late Dr. Eugene Odum gave us an appropriate role model candidate when he wrote that "in nature there are a lot of answers about what we should be doing in society. Nature has been here longer than humans and has survived a lot of

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catastrophes" (Odum, 1998). Likewise, engineering's role models, we would argue, should also logically come from the natural world. The motivation and goal of the engineering work that lies ahead for humans should be based on examples that include non-human species and natural ecosystems.

Engineering has provided the infrastructure of human progress. High technology engineering projects (e.g., superhighways, dams, skyscrapers) and engineered processes (e.g., wastewater treatment) can be viewed as works exemplifying the goals and progress of current industrialized society. However, many of our current engineering practices also contribute to urban sprawl, loss of biodiversity via habitat destruction, unsustainable use and conversion of resources and degradation of essential services that functional, healthy ecosystems provide. Role models in the natural world can show us alternative engineering and design practices that maintain a high quality of life for humans, as well as ensuring the existence and habitat of other species.

The developing field of ecological engineering must demonstrate that its goals and designs can provide desirable alternatives to traditional practices. The field needs to create exemplary projects that serve to illustrate the relevance of these concepts to fulfill the design's objective, while preserving ecological integrity. For example, the Olentangy River Wetland Research Park at Ohio State University (http://www.swamp.ag.ohio-state.edu; Mitsch et al., 2002) and the "living machines" developed by Todd and Todd (1994) for water purification and food production are examples of this ideal. These works integrate ideas of nature and design to create processes that use natural components to be functional and yet also to affect positive impacts in the environment. Specifically, the inherent energy and activities of living systems and organisms are harnessed, in contrast to traditional engineering methodologies that employ external energy and potentially toxic (e.g., chlorination) methods. These works and others (see Todd, 1988; Todd and Todd, 1994; Mitsch et al., 1998, 2000) are already serving as an alternative paradigm to traditional engineering practices. Still, there is the potential to influence the development of the field of ecological engineering in a more comprehensive way.

The focus of this paper is to show the benefits of studying the characteristics, functions and impacts of non-human species and to apply these concepts to the field of ecological engineering. Fortunately, there are an estimated 5–30 million other species on the planet (Wilson, 1988) that can provide us with different models of how to integrate human populations with the matter and energy flux of ecosystems. Particularly useful in assessing species' effects is the illuminating literature on organisms as ecosystem engineers (Lawton and Jones, 1995; Jones et al., 1994) and keystone species (Power et al., 1996; original usage by Paine, 1969). Such organisms have disproportionately large environmental impacts relative to their abundance and profoundly affect the communities and ecosystems they inhabit. Also noteworthy, as we look to nature for role models, is the literature that deals with biomimicry, which underlies "innovation inspired by nature" in materials science, medicine, and in identifying energy alternatives (Benyus, 1997). Examination of attributes and effects of other species, particularly in their engineering activities, can be compared with human endeavors and will hopefully inspire future ecological engineering activities.

2. How can ecosystem engineers and keystone species help us to understand more about ecological engineering?

The concept of viewing organisms as ecosystem engineers was put forward in the early 1990s by Jones et al. (1994), who elucidated the roles of particular organisms in creating, modifying and maintaining habitats in ecosystems. Ecosystem engineering is demonstrated by many different types of organisms. For example, alligators create habitat for other species by the wallows they maintain. Under dry season conditions, alligator-wallows are often the only wet areas where aquatic species can find refuge (Finlayson and Moser, 1991). The physical disturbance created by elephants greatly alters vegetation patterns, affecting the food supply and population dynamics of other organisms (Naiman, 1988). The effects of ecosystem engineers can be as small and difficult to detect as algal–herbivore control of rock weathering or as large and obvious as the effects of forests on climatic patterns (Jones et al., 1994). Engineering activities of non-human species can affect habitat and resources for other species.

Species can also be identified as a 'keystone' to the community or ecosystem they inhabit, having impacts disproportionately larger than their abundance. Many organisms that are considered ecosystem engineers can also be characterized as keystone species (Power et al., 1996). Characteristics of keystone species would be useful to consider in ecological engineering. They could be utilized in systems where they would provide 'more bang for the buck' than other non-keystone species. Further, the effects of all species, and notably keystone species, are dependent on environmental context (Power et al., 1996). For example, the organism that was first shown to have keystone importance in marine intertidal systems (the starfish *Pisaster ochraceus*; Paine, 1969), has been shown to have much weaker effects in more highly disturbed coastal environments (Menge et al., 1994). The concepts of keystone species and ecosystem engineers give us non-human role models of other species that have community and ecosystem-scale influences. They also show us that species' effects depend on a particular environmental context.

The effects of humans and other species in communities and ecosystems can be quantified. In the ecological literature, such effects have been measured, for example, as community importance (CI), as the change in a community or ecosystem trait per unit change in the abundance of a given species (Power et al., 1996). Experimentally, measurements of CI are made by removing species and measuring the response of a chosen trait or traits (e.g., nutrient cycling, species richness, etc.). Interaction strength (Paine, 1992) is a related measure, but CI is determined in intact communities, whereas interaction strength is determined on a sub-set of interacting species. These metrics have allowed quantification of species impacts in ecosystems and on populations of other species. We suggest that similar metrics could be adopted and used in ecological engineering to determine the effects of particular engineering designs, or to determine ecosystem impacts of human modifications.

As we consider effects of species in ecosystems below, we use the terms 'beneficial' and 'detrimental' to characterize desirable or less desirable (from a given human perspective) effects of species on populations, communities and ecosystems. It is important, however, to point out that the beneficial or detrimental effects of species are contextual, because species' effects are variable in space and time. Compared to traditional engineering, which frequently seeks to create a fixed object to last a set number of years, ecological engineering must incorporate the plasticity of natural, living systems. Natural role models, such as the beaver, show that this resilience and adaptability to variable conditions by changing objectives is desirable and fundamentally different than traditional engineering approaches (Allen et al., 2003). However, the variability and context-dependency of species' effects offers some of the greatest challenges to utilizing natural systems in ecological engineering.

Nevertheless, natural systems are not entirely unpredictable and it is from natural systems that all goods and services ultimately derive. These services include important processes of soil formation, decomposition of organic matter, filtering capacity, recycling of nutrients, and regulating local and global climate patterns. Goods include the production of healthy, functioning populations, such as fisheries and forests. Ecological engineering can similarly aim to provide goods and services from natural systems. Identifying traits of organisms that have been shown to have large and beneficial effects in ecosystems will help us better emulate those impacts. While species' effects are dependent on temporal and spatial change, they nonetheless are useful in ecological engineering. Thus, further study should be encouraged to identify species characteristics and their range of responses that yield results that are beneficial to humans and ecosystems.

3. Allogenic and autogenic engineers: potential human analogs

Ecosystem engineers can be classified as either autogenic or allogenic engineers (Jones et al., 1994). Autogenic engineers, such as corals or trees, change the environment via their own physical structures. Allogenic engineers, such as woodpeckers or beaver, change the environment by transforming living and non-living material from one physical state to another, using mechanical, chemical or other means.

The beaver, particularly the North American beaver (*Castor canadensis*), is the quintessential example of an allogenic ecosystem engineer. It creates wetlands and modifies entire landscapes through damming and foraging activities. In the process, it increases nutrient retention and habitat heterogeneity (Naiman et al., 1988). In their native ecosystems these engineering activities increase plant and animal diversity (Pollock et al., 1995; Wright et al., 2002) and make ecosystems more resilient to disturbance (Naiman et al., 1988).

Human-built structures are also examples of allogenic engineering. Role models in nature, like the beaver, demonstrate the potential synergy and mutual benefit that can be developed between humans and ecosystems via the discipline of ecological engineering. Human allogenic engineering (e.g., building homes, offices and dams) or our management of the autogenic engineering features of other species (forest stands, coral reefs) need to examine and utilize the beneficial attributes that natural species and ecosystems provide.

4. Beneficial engineering: positive natural role models

The presence or activities of some organisms can be viewed as beneficial to other populations. Corals create such a beneficial environment. Through their autogenic, three-dimensional reef structure, they create a highly diverse and productive ecosystem. Out of the 34 animal phyla found on earth, 32 can be found on coral reefs, whereas only 9 phyla are found in tropical rainforests (Porter and Tougas, 2001). Most corals are a mutualism between animals, cnidarians, which lay down a skeleton of calcium carbonate and symbiotic algae, called zooxanthellae. Zooxanthellae make homes in coral tissue, benefiting the cnidarian and giving some corals a golden or greenish color.

The physical presence of corals modulates current speeds and siltation rates, and the structures they create support a diversity of other organisms, such as algae, mollusks, annelids, fishes, sponges, reptiles and mammals. The distribution and abundance of many of these taxa depends on the presence of corals (Sebens, 1994). The physical structure of coral reefs not only provides habitat for other species, but also facilitates nutrient cycling, by slowing down the transport of nutrients and particles. Consequently, the high diversity and productivity of coral reefs can be achieved in extremely low nutrient environments.

Interestingly, it is increased nutrient concentrations in coastal waters that are some of the largest threats to coral reefs (Richmond, 1993); reef systems are adapted to and utilize low nutrient input. The reefs, which are presumed to be the longest-lived ecosystems in the world (on the order of 400 million years) give us a lesson for our own survival. The inclusion of other life forms, rather than their exclusion, can be a key to long-term success and survival. Coral organisms and the reefs they create provide complex physical and biological systems that in turn produce mutualisms, resilience, high productivity and species diversity.

Another example of an autogenic engineer with an ecological impact that facilitates other species and ecosystem stability is the ribbed mussels (*Geukensia demissa*) that are found in New England salt marshes (Bertness, 1997). The integrity of the New England salt marsh ecosystem heavily depends upon the physical structure provided by these native mussels, via their association with other species, such as the salt marsh cordgrass (*Spartina alterniflora*). The mussels attach themselves to the roots of the cordgrass with strong filaments, called byssal threads. The attachment of the mussels stimulates the cordgrass to produce more below ground roots. This arrangement adds stability to the salt marsh ecosystem by increasing the cohesiveness of cordgrass beds, promoting resistance to tidal erosion, and providing habitat for additional species such as fiddler crabs and other biota (Bertness, 1997). Thus, the physical matrix created by mussels and cordgrass promotes the existence of many other species.

Allogenic engineers are those organisms that change the physical state of materials in the ecosystem and thus affect resource flows to other organisms. Earthworms are noteworthy allogenic engineers. Their burrowing activities and cast construction alter the mineral and organic composition of soil, accelerate nutrient cycling, and facilitate drainage of soils, ultimately affecting plant population dynamics and community composition (Hendrix, 1995). Earthworms have a positive impact on many other classes of soil organisms. Litter transformers such as mites, nematodes, collembolans and isopods depend on earthworm engineers to maintain soil structure in which pore spaces are an appropriate size. Soil micropredators (e.g., nematodes, flagellates) depend on the earthworms to stimulate the microflora, bacteria and fungi, on which they feed (Lavelle et al., 1997). Earthworms also stimulate soil bacteria in a mutualistic relationship wherein they ingest soil bacteria that then help them degrade recalcitrant organic matter. The bacteria get transported to new substrates and benefit from intestinal mucus from the earthworms as an organic food resource (Lavelle et al., 1997). This beneficial engineer is highly successful, perhaps in part because of the mutualistic relationship it has with bacteria.

Studies that have quantified earthworm effects illustrate their facilitation of other organisms. Areas of high earthworm densities were compared to areas of lower density in tropical pastures. Researchers found higher earthworm density increased densities of springtails (*Collembola* spp.), which are important litter transformers in soil ecosystems, as well as other taxa (Loranger, 1995; cited in Lavelle et al., 1997). Termites, another common organism that structures the soil ecosystem, also promote species richness. Construction of termite mounds can result in greater local plant diversity because specific plant assemblages are typically found in association with the mounds (Wood and Sands, 1978).

5. Detrimental engineering: a characteristic of non-native species?

As stated above, detrimental or beneficial effects of engineering are contextual and depend on one's objective. However, much evidence suggests that many exotic, non-human species can have large detrimental effects on ecosystems via their engineering activities. For example, in North America the exotic zebra mussel (*Dreissena polymorpha*) has had dramatic effects on ecosystems via its intense filtering capacity. *D. polymorpha* is one of the best known 'newly arrived' exotic species in the United States. It was introduced from Eurasia into the Great Lakes from ballast water in the early-1980s and by the mid-1990s had spread to lakes and streams along the Mississippi drainage and throughout northeastern North America.

Zebra mussel impacts largely occur through their ability to reduce phytoplankton from surrounding water via high rates of filter-feeding that deplete food available to other organisms. The filtering has both a 'mechanical' and a 'feeding' component. Much of what is filtered passes through undigested in feces or pseudofeces. The pelagic food resources are thus deposited to the benthos, thereby changing food webs and energy flows. The magnitude of the reduction in edible particles that results is great enough to shift several other ecosystem characteristics and functions. For example, lakes and rivers with zebra mussels have experienced 50–75% declines in phytoplankton and small zooplankton biomass and similar declines in filter-feeding zooplankton and native bivalves (Strayer et al., 1999).

While a few organisms benefit from the shelter and surface area provided by the zebra mussel shells, overall species richness is reduced in systems that zebra mussels have colonized (Strayer et al., 1999). Increased dissolved nutrient concentrations are also typically observed in areas that have been colonized by zebra mussels. Following invasion of zebra mussels to the Hudson River, for example, dissolved phosphorus concentrations almost doubled (Strayer et al., 1999). Increased nutrient concentrations were posited as likely due to the reduction in organisms that would otherwise retain and recycle those nutrients, such as phytoplankton and zooplankton. Thus, the system became less nutrient retentive following zebra mussel invasion and re-engineering of the system.

Feral pigs are another example of organisms with the potential to be detrimental engineers. They can have pervasive effects on non-native environments. Through their rooting activity, pigs disrupt plant roots, underground stems and soil invertebrates, sometimes resulting in plant death, root death, and decreased rates of nitrogen retention (Mack and D'Antonio, 1998). They reduce soil arthropod abundance, increase nutrient leaching, and decrease plant diversity.

The effects of feral pigs on the succession of soil arthropod assemblages was determined following pig removal in Hawaii Volcanoes National Park. After 7 years of recovery, soil microarthropod densities and the number of springtail species doubled compared to a control plot that was accessible to pigs (Vtorov, 1993). Feral pigs also increased nutrient loss from soils. Singer et al. (1984) found that nitrate concentrations in soil water from shallow wells and from stream water was higher in or downstream from plots that supported pig populations compared to other plots where pigs were not present in the Great Smoky Mountains National Park (USA). Two small mammal species, the red-backed voles and short-tailed shrews, were also almost completely absent in pig influenced areas, and there were reductions in soil organic matter in areas with pigs, relative to inaccessible areas.

6. What kinds of engineering should we mimic?

It may not be a coincidence that examples of beneficial engineering cited above come from natural systems whose biotic assemblages have co-evolutionary histories. Alternatively, in many cases where ecosystem engineering resulted in detrimental impacts on other species or on ecosystem function, an exotic species was the perpetrator. However, not all exotic species evince pervasive and damaging impacts in non-native ecosystems. In fact, the majority of all introduced, exotic species fail to establish themselves permanently (Lawton and Brown, 1986). The danger lies in such species as exotic ecosystem engineers that then become invasive and whose ability to affect ecological change extends across broad landscapes. The role of exotic species in ecosystem engineering is now so pervasive on a worldwide-scale that it is definitely detrimental and has been identified as one of the major components of global ecological change (Vitousek et al., 1997).

Germane to this discussion is the fact that an ecosystem engineer that is native and beneficial to one area may be destructive when introduced to a new ecosystem. Such is the case of the North American beaver. As illustrated above, many studies have shown how beaver fundamentally affect the function of ecosystems they inhabit in the Northern Hemisphere, largely in beneficial ways. They create greater habitat heterogeneity, make the system more resilient to disturbance and increase plant and animal diversity at the landscape-scale (Pollock et al., 1995; Naiman and Rogers, 1997; Naiman et al., 1988; Wright et al., 2002). However, when beaver have been introduced to non-native habitats in southern South America, their consequences are not so clearly beneficial to other organisms or the ecosystem.

In South America, the ecological role of the beaver must be re-evaluated due to differences in vegetation, evolutionary history and community assemblage. Southern South American forests are relatively simple, species-poor ecosystems, which also makes them particularly susceptible to invasion by introduced species (Meffe and Carroll, 1997). Without predator controls and with ample habitat, the beaver populations, which began with only fifty individuals, expanded explosively to reach unprecedented densities and occupied nearly every watershed in the region in only a few decades (Sielfeld and Venegas, 1980; Lizarralde, 1993). Also, the region's vegetation has not evolved defensive or reproductive strategies to handle extensive herbivory by beaver (Riveros et al., 1995). Consequently, *C. canadensis* has been described as a plague at the southern tip of South America (Lizarralde, 1993), but a beneficial keystone species in North America (Naiman et al., 1988). This illustrates the point that engineering practices must be contextual and take into account local, native conditions.

Many traditional human engineering endeavors more closely resemble the effects of exotic, rather than native species. For example, increases in urban land cover within catchments result in the reduction of species richness in streams (Roy et al., 2003), as well as altering many other structural and functional stream characteristics (Paul and Meyer, 2001). There are countless such examples of human modification of the environment having detrimental effects on species diversity, abundances or ecosystem functions. Indeed, these effects are exemplary of the state of our world. Much current ecological work is aimed at describing such relationships and cataloging the negative impacts of humans on the ecosystems on which they depend. However, scientists and engineers must go beyond these first small steps of documenting degradation to determining and demonstrating better ways to use and harness resources. Ecological engineering can involve management of the positive autogenic and allogenic engineering capabilities of species, as well as the study and mimicry of such effects in human engineering endeavors.

7. Beneficial ecosystem engineering characteristics

Some of the characteristics of beneficial engineering by non-human species outlined above include:

1. The *presence of mutualisms* is often an inherent part of native ecosystem engineering. These included the symbiotic relationships in coral (symbiotic algae and cnidarians), the cordgrass/ribbed

mussel mutualism and the earthworm/symbiotic gut flora mutualisms.

2. Beneficial engineering also results in one organism *facilitating the presence of other species* (reef organisms, soil arthropods by earthworms, and beaver-associated wetland plant species). Conversely, detrimental engineering results in reduced abundance of other species or species richness losses (feral pig effects on soil arthropods, zebra mussel effects on aquatic species, exotic beaver effects on South America riparian forests). Well-engineered systems tend to be *speciose*, unlike monocultures.
3. Well-engineered systems were characterized by *efficient nutrient cycling, a high degree of materials recycling, retention and resilience*, such as we see in coral reefs and earthworm activities. On the other hand, activities by exotic zebra mussels and feral pigs resulted in the release of nutrients from their respective systems. Currently, increased nutrient runoff results from many kinds of human land disturbance, which is a clear indication that such systems are poorly engineered and managed.
4. Non-human ecosystem engineers are also *flexible and adaptable* to fluctuating environmental conditions. Their engineering activities respond to external conditions and have the ability to change and be modified as the objective changes over the lifetime of the ecosystem engineering activity. This inherent uncertainty in natural systems also challenges us to improve our predictive capabilities concerning species' effects on ecosystems as a contribution to their future use in ecological engineering.

8. Conclusions

Many human engineering activities are detrimental to other species and whole ecosystems because, like some exotic ecosystem engineers, human activities largely do not take into account the conditions to which the local ecosystem has evolved. In essence, modern societies often are not adapted, and therefore in a sense not native, to their environment. Rather, humans modify the environment to fit their lifestyles by many status quo engineering practices. One goal of ecological engineering should be to shift human impacts on ecosystems to a more natural response that takes into account local, native conditions. In addition, techniques used in the study of non-human species, particularly in quantifying their effects on ecosystem processes and other populations, could be employed in ecological engineering studies. For example, evaluation of the keystone importance of species involves measurement of community importance (Power et al., 1996). Similarly, ecosystem engineering designs (via either modeling or in situ evaluation) could be evaluated using the same technique. Specifically, a given design could be tested based on its effects on community or ecosystem traits.

The attributes of non-human engineering given here were distilled from a small number of examples, but they have been selected to suggest guiding principles for human endeavors towards positive environmental impacts. The real-world implementations of these concepts already are beginning to take place. For example, William McDonough, an architect and industrial designer, uses the principles of equity, ecology and economy to create a "new industrial revolution," the very foundation of which is to behave native to a place. He posits that engineering and design should seek to eliminate the concept of waste, to measure prosperity by the amount of natural capital created or conserved and to rely on natural energy flows (McDonough, 1992; McDonough and Braungart, 1998), just as natural ecosystems function. Others have championed the idea of emulating the wisdom found in natural systems for use in such disparate arenas as wastewater treatment (Todd, 1988) and business transactions (Benyus, 1997). Bergen et al. (2001) also suggests design principles that include species and ecosystem traits. Ecological engineering is a field critical to the encouragement of the widespread use and mimicry of natural systems to provide goods and services to humans.

The growth and success of this field is critical to human survival and quality of life. We currently experience the consequences of human 'non-native' behavior in the form of global climate change, increases in UV-B radiation, desertification, chemical contamination and biological extinctions. Today we are searching for ways to re-adapt our society and ourselves to be members of the ecosystems in which we exist. We are searching for two things: (1) information about ecosystems; and (2) ways to utilize that information in decision-making and planning. Ecological engineering can act as a bridge between knowledge acquisition about ecosystems (ecology) and how to implement that information (engineering and design). There are fortunately many lessons to be learned from the natural world about how to fit our impacts into healthy, functioning ecosystems. We must create a new paradigm that includes integration of human resource use into, while perhaps mimicking, natural systems. The research, demonstration, teaching and implementation that can occur via ecological engineering will hopefully help to create such a paradigm.

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