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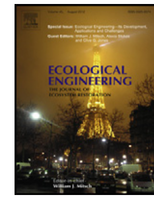

Ecosystem health and ecological engineering

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ABSTRACT

Ecosystem health is a desired endpoint of environmental management and should be a primary design goal for ecological engineering. This paper describes ecosystem health as a *comprehensive, multiscale, measure of system vigor, organization and resilience*. Ecosystem health is thus closely linked to the idea of sustainability, which implies the ability of the system to maintain its structure (organization) and function (vigor) over time in the face of external stress (resilience). To be truly successful, ecological engineering should pursue the broader goal of designing healthy ecosystems, which may be novel assemblages of species that perform desired functions and produce a range of valuable ecosystem services. In this way ecological engineering can achieve its goals, embedded in its definition as the "design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both." It allows the benefits of ecological engineering practices 'to both humans and the rest of nature' to be assessed in an integrated and consistent way that will allow us to build a sustainable and desirable future.

1. Ecosystem health

A basic question in ecosystem management is: "management for what goal?" or "what do we mean by a healthy ecosystem?" The default endpoint has often been restoration to a past state in which there was presumably little or no human influence on the ecosystem. For example, the National Research Council's (1992) definition of restoration as "returning a system to a close approximation of its condition prior to disturbance, with both the structure and function of the system recreated" implies that the state "before disturbance" is the preferred state. This default definition of ecosystem health (while appealing due to its apparent conceptual simplicity) has proven to be both unrealistic and unworkable (Rapport, 1989a,b; Costanza et al., 1992; Rapport et al., 1998a,b).

Humans have been important components of ecosystems for millennia, and they (like any large and abundant omnivore) have always radically altered the systems of which they have been components (Flannery, 1994; Redman, 1999; Diamond, 2005). For example, Flannery (1994) argues that the original Australian aborigines caused the extinction of many species of megaherbivores and replaced (in many areas) what was originally a high diversity closed woodland ecosystem which did not burn and where most nutrient cycling was through herbivores, with a lower diversity open woodland ecosystem which cycled nutrients through almost annual fires, which were set and controlled by the aboriginal humans. What is the "natural" or "pre-disturbance" system to serve as the restoration endpoint in cases like this? The pre-aboriginal closed woodland or the post-aboriginal open, fire-adapted woodland, which existed for 10,000 years, or some other state? This question is not answerable from a purely "objective" point of view, and must also include consideration of social goals (Costanza et al., 1992).

Societal goals for ecosystem management have come to focus on the concepts of health, ecosystem services, and sustainability (Lubchenco et al., 1991). How do we harvest from, and otherwise utilize ecosystems, while maintaining their health and integrity and the array of non-use services that they also provide (Costanza et al., 1997a) into the indefinite future? This does not mean that all ecosystems should (or could) have high levels of direct human interaction. A sustainable system at the landscape and larger scales will most likely involve a range of human interactions from very intense agro and urban systems to highly protected areas. Determining the optimal structure of this mix is one of the most important ongoing research problems facing us today.

Social goals for sustainable ecosystem management are thus centered on maintaining the "ecological health" of the system. Ecosystem health is a relatively new approach to environmental management (Costanza et al., 1992). The concept of health implies "well-functioning" and clearly the well-functioning of the Earth's ecosystems is a major concern and a major societal goal (Belsky, 1995). The goal of finding the means to protect the health and integrity of the Earth's ecosystems was one of the major principles to emerge from the United Nation Conference on Economic Development and Environment (United Nations, 1992). A healthy

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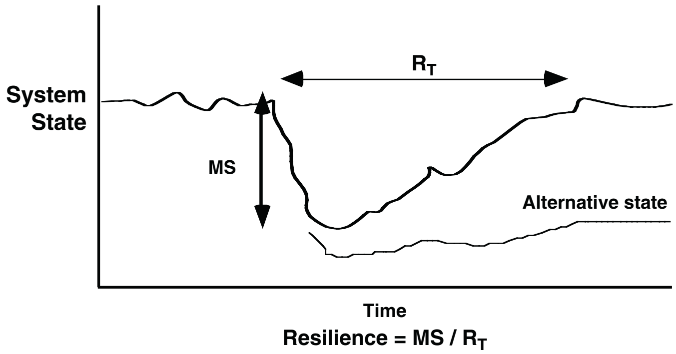

Fig. 1. The two components of resilience (return time – R_T, and maximum stress – MS, and how they can be integrated into a single quantitative measure.
From Mageau et al. (1995).

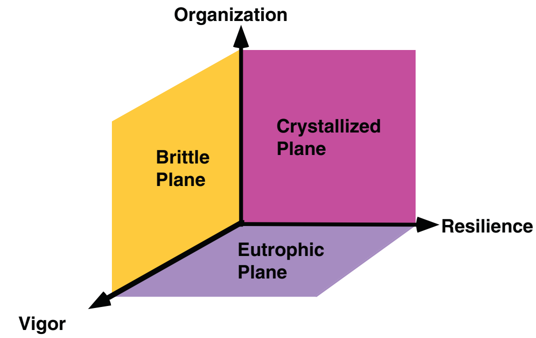

Fig. 2. Hypothetical relationship between vigor, organization, and resilience. From Costanza (1992).

ecosystem may be defined in terms of three main features: vigor, resilience, and organization (Costanza, 1992; Mageau et al., 1995). In terms of benefits to the human community, a healthy ecosystem is one that provides the ecosystem services supportive of the human community, such as food, fiber, the capacity for assimilating and recycling wastes, potable water, and clean air.

While the concept of health applied to the level of ecosystems and landscapes is of relatively recent origin (Rapport et al., 1981, 1998a,b; Rapport, 1989a,b) it has become a guiding framework in many areas, particularly in the evaluation of the large-marine ecosystems (Sherman, 1995), agroecosystems (Gallopin, 1995; Wichert and Rapport, 1998), desert ecosystems (Whitford et al., 1996) and others (Rapport, 1989a,b).

To appreciate the ecosystem health concept, one must begin by acknowledging that humans are a major component organism in many (if not most) ecosystems today – although the degree of human interaction varies widely. The human part of the ecosystem includes the humans themselves, their artifacts and manufactured goods (economies), and their institutions and cultures. It is both this larger ecosystem (including humans) whose health we need to assess and the smaller scale subsystems of which it is composed.

Based on a survey of health concepts in many fields, Costanza (1992) developed the following three general categories of performance that are usually associated with "well-functioning" in any complex living system at any scale (Fig. 1):

1. The *vigor* of a system is a measure of its activity, metabolism or primary productivity. Examples include metabolic rate in organisms, gross and net primary productivity in ecological systems, and gross national product in economic systems.
2. The *organization* of a system refers to the number and diversity of interactions between the components of the system. Measures of organization are affected by the diversity of species, and also by the number of pathways and patterns of material and information exchange between the components.
3. The *resilience* of a system refers to its ability to maintain its structure and pattern of behavior in the presence of stress (Holling, 1973). A healthy system is one that possesses adequate resilience to survive various small scale perturbations. The concept of system resilience has two main components: (1) the length of time it takes for a system to recover from stress (Pimm, 1984); and (2) the magnitude of stress from which the system can recover, or the system's specific thresholds for absorbing various stresses (Holling, 1973) Fig. 1 shows these two components combined into an overall definition of resilience as the ratio of the maximum stress the system can withstand without flipping to a new state (MS) divided by the return time.

Ecosystem health has thus been defined as (Costanza et al., 1992):

An ecological system is healthy and free from "distress syndrome" if it is stable and sustainable, i.e. if it is active and maintains its organization and autonomy over time, and is resilient to stress.

This definition is applicable to all complex systems from cells to ecosystems to economic systems (i.e., it is comprehensive and multi-scale) and allows for the fact that systems may be growing and developing as a result of both natural and cultural influences.

One possible overall system health index (H) based on these ideas has also been proposed (Costanza, 1992 – Fig. 2):

$$H = V \times O \times R$$

where H is the system health index, also a measure of sustainability; V is the system vigor, a cardinal measure of system activity, metabolism, or primary productivity; O is the system organization index, a 0–1 index of the relative degree of organization of the system, including its diversity and connectivity; R is the system resilience index, a 0–1 index of the relative degree of resilience of the system.

This formulation allows a comprehensive index incorporating the three major components outlined above. In essence, it is the system vigor or activity weighted by indices for relative organization and resilience. In this context, eutrophication is unhealthy in that it usually represents an increase in metabolism that is more than outweighed by a decrease in organization and resilience. Artificially eutrophic systems tend toward lower species diversity, shorter food chains, and lower resilience. Naturally eutrophic systems have developed higher diversity and organization along with higher metabolism and are therefore healthier.

Fig. 2 shows these three system characteristics arrayed as a three-dimensional graph, with the planes associated with the absence of any one component labeled. For example, systems with vigor and resilience but low organization would approach the "eutrophic plane" as described above. Systems with low resilience would approach the "brittle plane" – they may be very organized and productive, but subject to collapse due to their lack of resilience. A fire-climax forest that has been allowed to grow too dense due to fire suppression is one example. Finally, systems with low vigor may be organized and resilient, but are close to the "crystallized plane" – approaching an abiotic system with little "life" involved.

A healthy living system in this framework is one that balances all three characteristics.

A healthy system must also be defined in light of both its context (the larger system of which it is a part) and its components (the smaller subsystems that make it up – see below). Ecosystem health can and must be assessed for systems that both include and exclude humans.

Ecosystem health as a design and management goal can be contrasted with the more typical goal of ecological restoration – a return to some prior state of the system with lower human impact. As we have discussed, the ‘prior state’ goal is arbitrary and unrealistic, since humans have been an integral part of ecosystems for eons and the concept automatically precludes the possibility of a healthy ecosystem that includes humans. It also does not necessarily lead to ecosystems that produce the range of goods and services valuable to humans.

2. Is ecosystem health an accepted concept?

The definition of ecosystem health I have proposed is certainly not the only one possible and there has been substantial debate over the years about the idea. For example, Suter (1993) argued that “Ecosystems are not organisms, so they do not behave like organisms and do not have properties of organisms such as health.” It is certainly true that ecosystems are not organisms and definitions of ecosystem health based on a direct analogy are not appropriate, as I have pointed out above. The point is that both organisms and ecosystems are complex, living systems and complex living systems *do* share many properties. Homeostasis is not one of them, but that is not a reason for discarding ecosystem health as a useful concept. Rather, it is an argument for developing a more sophisticated concept of health – one that will benefit human health assessment as well. The definition I have proposed incorporates a much broader definition of health that is potentially applicable and useful across all complex living systems.

Another objection to the concept of ecosystem health is that it is a “normative” concept that implies specific societal goals, rather than an “objective” scientific concept. This is certainly true, but many see that as an advantage and an essential characteristic of the health concept rather than a problem, as part of a “functionalist” philosophy (Callicott et al., 1999). The fact is that there is always some implied goal that drives environmental decision-making. The advantages of using the health concept to describe this goal are the implication of a set of interacting components in a complex living system. The concept of health and its assessment and improvement are complex and multidimensional. I have tried to clearly describe a version of the health concept that might be applicable to all complex living systems at multiple scales, and that helps get us out of the bind of only using some arbitrary prior state of the system as the definition of “healthy” in environmental decision-making.

Ecosystem health has become a very active area of research and dialog. A search in the ISI Web of Science with the topic “ecosystem health” found a total of over 3000 articles with over 20,000 citations as of March 2012. Over 600 of these articles have been published in the journal *EcoHealth*, which has become a primary venue for ongoing discussion of the concept of ecosystem health and its applications. The EcoHealth Alliance (http://www.ecohealthalliance.org/) and EcoHealth: the International Association for Ecology and Health (http://www.ecohealth.net/) are active organizations in this area.

In the remainder of this paper I link the concept of ecosystem health with sustainability and ecosystem services. A healthy system should sustainably provide a range of ecosystem services, but one needs to better define sustainability and ecosystem services in order to make the connection clear. Finally, I make the link to ecological engineering – that ecosystem health (in the way I have defined it) should be a primary design goal for ecological engineering.

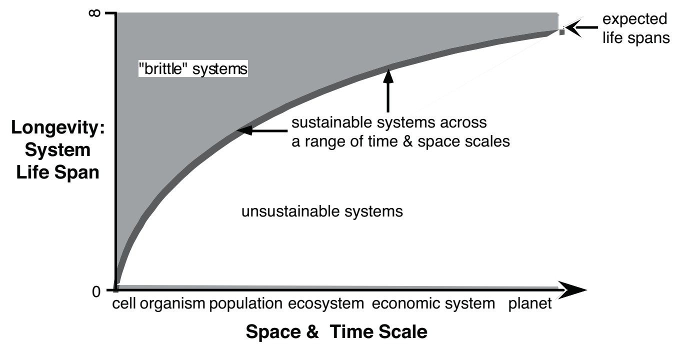

Fig. 3. Hypothetical relationship between sustainability (as longevity) and scale. From Costanza and Patten (1995).

3. Defining sustainability

There has been a huge amount of discussion in the literature over the years about how one “defines” sustainability, sustainable development, and related concepts (cf. Pezzey, 1989; World Commission on Environment and Development, 1987; Costanza, 1991). Many argue that the concept is useless because it cannot be “adequately defined.” Most of this discussion is misdirected because it: (1) attempts to cast the problem as definitional, when in fact it is a problem of prediction, and (2) fails to take into account the many time and space scales over which the concept must apply (Costanza and Patten, 1995).

Defining sustainability is actually quite easy: a sustainable system is one which survives for some specified (non-infinite) time. The problem is that one only knows one has a sustainable system after the fact. Thus, what usually pass for definitions of sustainability are actually predictions of what set of conditions will actually lead to a sustainable system. For example, keeping harvest rates below rates of natural renewal should, one could argue, lead to a sustainable natural resource extraction system – but that is a prediction, not a definition. We only know if the system actually is sustainable after we have had the time to observe whether the prediction holds. Usually there is so much uncertainty in our ability to estimate natural rates of renewal and our ability to observe and regulate harvest rates that a simple prediction such as this is, as Ludwig et al. (1993) correctly observe, always highly suspect.

Likewise, sustainable economic development can only be observed after the fact. Most “definitions” of sustainable development, encompassing elements of: (1) a sustainable scale of the economy relative to its ecological life support system; (2) a fair distribution of resources and opportunities between present and future generations, as well as between agents in the current generation, and (3) an efficient allocation of resources that adequately accounts for natural capital, are thus really “predictors” of sustainability and not really elements of a definition. Like all predictions, they are uncertain and are subject to much discussion and disagreement.

The second problem is that when one says a system has achieved sustainability, one does not mean an infinite lifespan, but rather a lifespan that is consistent with its time and space scale. Fig. 3 indicates this relationship by plotting a hypothetical curve of system life expectancy on the *y* axis vs. time and space scale on the *x* axis. We expect a cell in an organism to have a relatively short lifespan, the organism to have a longer lifespan, the species to have an even longer lifespan, and the planet to have a longer lifespan. But no system (even the universe itself in the extreme case) is expected to have an infinite lifespan. A sustainable system in this context is thus one that attains its full expected lifespan in the context of the systems it is related to in scale.

4. Natural capital and ecosystem services

"Ecosystem services" (ES) are the ecological characteristics, functions, or processes that directly or indirectly contribute to human well-being – the benefits people derive from functioning ecosystems (Costanza et al., 1997a; MEA, 2005). Ecosystem processes and functions may contribute to ecosystem services but they are not synonymous. Ecosystem processes and functions describe biophysical relationships and exist regardless of whether or not humans benefit (Boyd and Banzhaf, 2007; Granek et al., 2010). Ecosystem services, on the other hand, only exist if they contribute to human well-being and cannot be defined independently.

The ecosystems that provide the services are sometimes referred to as "natural capital," using the general definition of capital as a stock that yields a flow of services over time (Costanza and Daly, 1992). In order for these benefits to be realized, natural capital (which does not require human activity to build or maintain) must be combined with other forms of capital that *do* require human agency to build and maintain. These include: (1) built or manufactured capital; (2) human capital; and (3) social or cultural capital (Costanza et al., 1997b).

These four general types of capital are all required in complex combinations to produce any and all human benefits. Ecosystem services thus refer to the relative contribution of natural capital to the production of various human benefits, in combination with the three other forms of capital. These benefits can involve the use, non-use, option to use, or mere appreciation of the existence of natural capital.

The following categorization of ecosystem services has been used by the Millennium Ecosystem Assessment (MEA, 2005):

(a) *Provisioning services* – ecosystem services that combine with built, human, and social capital to produce food, timber, fiber, or other "provisioning" benefits. For example, fish delivered to people as food require fishing boats (built capital), fisherfolk (human capital), and fishing communities (social capital) to produce.
(b) *Regulating services* – services that regulate different aspects of the integrated system. These are services that combine with the other three capitals to produce flood control, storm protection, water regulation, human disease regulation, water purification, air quality maintenance, pollination, pest control, and climate control. For example, storm protection by coastal wetlands requires built infrastructure, people, and communities to be protected. These services are generally not marketed but have clear value to society.
(c) *Cultural services* – ecosystem services that combine with built, human, and social capital to produce recreation, esthetic, scientific, cultural identity, sense of place, or other "cultural" benefits. For example, to produce a recreational benefit requires a beautiful natural asset (a lake), in combination with built infrastructure (a road, trail, dock, etc.), human capital (people able to appreciate the lake experience), and social capital (family, friends and institutions that make the lake accessible and safe). Even "existence" and other "non-use" values require people (human capital) and their cultures (social and built capital) to appreciate.
(d) *Supporting "services"* – services that maintain basic ecosystem processes and functions such as soil formation, primary productivity, biogeochemistry, and provisioning of habitat. These services affect human well-being *indirectly* by maintaining processes necessary for provisioning, regulating, and cultural services. They also refer to the ecosystem services that have not yet been, or may never be, intentionally combined with built, human, and social capital to produce human benefits but that support or underlie these benefits and may sometimes be used as proxies for benefits when the benefits cannot be easily measured directly. For example, net primary production (NPP) is an ecosystem function that supports carbon sequestration and removal from the atmosphere, which combines with built, human, and social capital to provide the benefit of climate regulation. Some would argue that these "supporting" services should rightly be defined as ecosystem "functions," since they may not yet have interacted with the other three forms of capital to create benefits. We agree with this in principle, but recognize that supporting services/functions may sometimes be used as proxies for services in the other categories.

This categorization suggests a very broad definition of services, limited only by the requirement of a contribution to human well-being. Even without any subsequent valuation, explicitly listing the services derived from an ecosystem can help ensure appropriate recognition of the full range of potential impacts of a given policy option. This can help make the analysis of ecological systems more transparent and can help inform decision makers of the relative merits of different options before them.

Scientists and economists have discussed the general concepts behind natural capital, ecosystem services, and their value for decades, with some early work as far back as the 1920s. However, the first explicit mention of the term "ecosystem services" was in Ehrlich and Mooney (1983). More than 2400 papers have been published on the topic of ecosystem services since then.[1] The first mention of the term "natural capital" was in Costanza and Daly (1992).

One of the first studies to estimate the value of ecosystem services globally was published in *Nature* entitled 'The value of the world's ecosystem services and natural capital' (Costanza et al., 1997a). This paper estimated the value of 17 ecosystem services for 16 biomes to be in the range of US$16–54 trillion per year, with an average of US$33 trillion per year, a figure larger than annual GDP at the time.[2]

In this study, estimates of global ecosystem services were derived from a synthesis of previous studies that utilized a wide variety of techniques to value specific ecosystem services in specific biomes.[3] This technique, called "benefit transfer," uses studies that have been done at other locations or in different contexts, but can be applied with some modification. Such a methodology, although useful as an initial estimate, is just a first cut and much progress has been made since then (cf. Boumans et al., 2002; USEPA Science Advisory Board, 2009)

More recently the concept of ecosystem services gained attention with a broader academic audience and the public when the

[1] According to a search of the Institute for Scientific Information "web of science" database, accessed February 22, 2011. This database includes only a subset of scientific journals and no books, so it represents only a subset of the literature on this topic.

[2] Some have argued that global society would not be able to pay more than their annual income for these services, so a value larger than global GDP does not make sense. However, not all benefits are picked up in GDP and many ecosystem services are non-marketed, so GDP does not represent a limit on real benefits (Costanza et al., 1998).

[3] See Costanza (1998) for a collection of commentaries and critiques of the methodology.

Millennium Ecosystem Assessment (MEA) was published (MEA, 2005). The MEA was a 4-year, 1300 scientist study commissioned by the United Nations in 2005. The report analyzed the state of the world's ecosystems and provided recommendations for policymakers. It determined that human actions have depleted the world's natural capital to the point that the ability of a majority of the globe's ecosystems to sustain future generations can no longer be taken for granted.

In 2008, a second international study was published on The Economics of Ecosystems and Biodiversity (TEEB), hosted by the United Nations Environment Program (UNEP). TEEB's primary purpose was to draw attention to the global economic benefits of biodiversity, to highlight the growing costs of biodiversity loss and ecosystem degradation, and to draw together expertise from the fields of science, economics, and policy to enable practical actions moving forward. The TEEB report was picked up extensively by the mass media, bringing ecosystem services to a broad audience.

Natural capital and ecosystem services are key concepts that are changing the way we view, value, and manage the natural environment. They are changing the framing of the issue away from "jobs vs. the environment" to a more balanced assessment of all the assets that contribute to human well-being. Significant transdisciplinary research has been done in recent years on ecosystem services, but there is still much more to do and this will be an active and vibrant research area for the coming years, because better understanding of ecosystem services is critical for creating a sustainable and desirable future. Placing credible values on the full suite of ecosystem services is key to improving their sustainable management. Hundreds of projects and groups are currently working toward better understanding, modeling, valuation, and management of ecosystem services and natural capital. The new Ecosystem Services Partnership (ESP – http://www.es-partnership.org/) is a global network that helps to coordinate these activities and build consensus.

5. Engineering healthy ecosystems

Ecological engineering has been defined as "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both" (Mitsch and Jørgensen, 1989). Based on the foregoing discussion, a version of this definition might read: "The design of healthy ecosystems, which may be novel assemblages of species that perform desired functions and produce a range of valuable ecosystem services sustainably."

What does this mean in practice? It represents a significant change in the usual goals of ecological restoration, for example, away from "restoration to some prior state untouched by humans" to "restoration to a new, possibly unique, state that is healthy in a broader sense of having an optimal balance of vigor, organization and resilience, and that may include a broad range of human interactions." There is growing recognition that many current ecosystems are "novel" and require novel approaches to their management (Seastedt et al., 2008).

This opens up a range of new possibilities for ecological engineering and a range of research questions in the combined fields of ecosystem health, ecosystem services, and ecological engineering. Some potential research areas include:

1. Development of several alternative operational indicators of the three major components of ecosystem health – vigor, organization, and resilience (VO&R) – preferably ones that can be sensed remotely and/or mapped spatially (Mageau et al., 1995, 1998).
2. Development of better tools and models for measuring, valuing and mapping ecosystem services of value to human society (Costanza et al., 1997a).
3. Testing the hypothesis that a healthy ecosystem in terms of its VO&R is one which also produces high levels of ecosystem services using (1) statistical analysis of sites for which we have measured both VO&R and ecosystem services and (2) integrated landscape simulation models at several scales which include both indicators of VO&R and ecosystem services.
4. Development of measures of system sustainability based on relative longevity (Costanza and Patten, 1995).
5. Testing the hypothesis that a healthy ecosystem in terms of its VO&R is one which is more sustainable. Since sustainability is inherently a temporal measure that implies longevity three complementary approaches may be necessary: long-term historical analysis, integrated landscape simulation models (that are capable of exhibiting *un*sustainable behavior), and mesocosm experiments. While all of these approaches have limitations in testing the ecosystem health – sustainability hypothesis, taken together they provide a powerful suite of tests.

6. Conclusions

- Ecosystem health, as described here, can serve as a design goal for ecological engineering at multiple scales. This approach is comprehensive and multi-scale and can motivate the protection, restoration and design of ecosystems that contribute to human well-being in a sustainable way.
- Healthy ecosystems provide a range of ecosystem services. A focus on the design, protection, and restoration of healthy ecosystems will help to sustainably provide the ecosystem services that underlie all human well-being.
- Ecological engineering has a huge role to play in this approach. It is the "how" part of the equation and the suite of tools and techniques to build healthy ecosystems. Remember too, that this view of ecosystems includes humans as an integral component. Therefore, ecological engineering is about not only designing wetlands for waste treatment, but also designing linked systems of humans and the rest of nature at multiple scales.
- Ultimately, we have to design a new socio-ecological system to create a sustainable and desirable future. Our current socio-ecological regime and its set of interconnected worldviews, institutions, and technologies all support the goal of unlimited growth of material production and consumption as a proxy for quality of life. However, abundant evidence shows that, beyond a certain threshold, further material growth no longer significantly contributes to improvement in quality of life. Not only does further material growth not meet humanity's central goal, there is mounting evidence that it creates significant roadblocks to sustainability through increasing resource constraints (i.e., peak oil, water limitations) and sink constraints (i.e., climate disruption). Overcoming these roadblocks and creating a sustainable and desirable future will require an integrated, system level redesign of our socio-ecological regime focused explicitly and directly on the goal of sustainable quality of life rather than the proxy of unlimited material growth (Beddoe et al., 2009). This transition, like all cultural transitions, will occur through an evolutionary process, but one that we, to a certain extent, can control and direct. We cannot predict the future, but we can design and create a more sustainable and desirable future. Ecological engineering based on the concepts of ecosystem health, ecosystem services and sustainability can and must play a significant role in that evolution.

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