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Designer Ecosystems: Incorporating Design Approaches into Applied Ecology

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Abstract

To satisfy a growing population, much of Earth's surface has been designed to suit humanity's needs. Although these ecosystem designs have improved human welfare, they have also produced significant negative environmental impacts, which applied ecology as a field has attempted to address and solve. Many of the failures in applied ecology to achieve this goal of reducing negative environmental impacts are design failures, not failures in the science. Here, we review (*a*) how humans have designed much of Earth's surface, (*b*) the history of design ideas in ecology and the philosophical and practical critiques of these ideas, (*c*) design as a conceptual process, (*d*) how changing approaches and goals in subfields of applied ecology reflect changes and failures in design, and (*e*) why it is important not only for ecologists to encourage design fields to incorporate ecology into their practice but also for design to be more thoroughly incorporated into ours.

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INTRODUCTION

The question of questions for mankind—the problem which underlies all others, and is more deeply interesting than any other—is the ascertainment of the place which Man occupies in nature and of his relations to the universe of things. Whence our race has come; what are the limits of our power over nature, and of nature's power over us; to what goal we are tending

—Thomas Henry Huxley (1863; see Ref. 1)

If the human population were evenly spread across all of Earth's ice-free land surface, there would be ~57 people per square kilometer (2, 3). At such a density, it is little wonder that the majority of earth scientists agree that our planet has entered a new epoch, the Anthropocene (4, 5). Humans directly alter more than 50% of the ice-free land area (2). We consume nearly half of terrestrial ecosystem annual biomass production (6, 7), appropriate ~50% of Earth's annual supply of renewable fresh water (8–11), alter global biogeochemical cycles (12), and cause extensive declines in biodiversity (13). This global-scale manipulation of Earth's ecosystems is the result of humanity's increasing ability to shape environmental processes for our own purposes. Such intentional control, wherein a given set of processes or patterns is altered to achieve a preferred set of conditions and outcomes, is broadly defined as design (14). In the Anthropocene, humans design most of the planet's land surface, from obvious examples such as large cities to the implicit design of forest and marine reserve boundaries (**Figure 1**).

Designs that work well on a sparsely populated planet are less appropriate in our modern, more crowded world (15). Increasingly, the science of ecology is concerned with documenting these negative consequences for organisms, communities, and ecosystems. Applied ecology (with its own subfields of conservation biology, restoration ecology, and ecological engineering) has emerged in an attempt to not just document environmental degradation but to also discover ways to either prevent new negative impacts or mitigate existing degradation.

Conventional production systems are structured to optimize the production of food, fiber, and fuel from ecosystems. The growth in intensity and extent of these ecosystem alterations, especially those that have been optimized to produce a single good or service, have collectively resulted in the growth of human welfare (16); however, these benefits have come at the cost of significant biodiversity loss, declining air and water quality, and highly altered landscape aesthetics (6, 17, 18).



Figure 1

Landscapes patterned by human decisions. (a) Cape Town, South Africa, surrounding Signal Hill and Table Mountain. (b) Rectangular agricultural ponds near Yuqiao Reservoir, Tianjin Province, China. (c) Crop fields in California, the United States. (d) Mount Taranaki, with circular boundary of Egmont National Park, New Zealand. All images from Google Earth, Digital Globe, TerraMetrics, Landsat, and CNES Astrum.

Mitigating these significant environmental costs becomes increasingly important to human health as an ever increasing proportion of our planet is under human control (19), prompting calls for alternative approaches, in a range of fields from industrial agriculture (20) to conservation (21). Leaders within each of these fields have advocated for a change in goals that more explicitly embraces our role as designers and not just protectors of natural systems (15, 20, 22–26). This change in goals is unlikely to be successful without additional changes in the approach taken by applied ecologists in developing and proposing conservation and restoration strategies.

Theories from within ecology are being applied to a range of different scales. At the most local level, restoration and conservation projects are used to improve environmental conditions project by project. These local projects can be coordinated or encouraged by policy at the program level, such as adaptive management policy. Adaptive management encourages an iterative learning and design approach to continually improve environmental outcomes (27–29). More broadly, the ecosystem service framework provides a means for encouraging conservation and restoration projects by quantifying (and often monetizing) the social benefits that ecosystems provide (30–32). These four disciplines—whether resulting from local level goals such as restoration and conservation, general strategies such as adaptive management, or general frameworks such as ecosystem services—were products of the ecological research community, and reflect a movement toward application of ecological theory in the intentional design of ecosystems. However, the specific role of applied ecology remains unclear and highly debated; i.e., should it be to promote human well-being through a better understanding of ecological processes (33) or to protect nature for biodiversity (34), or both (35)?

The concept of designer ecosystems is increasingly used to suggest a future-centric, goal-oriented approach to applied ecology with a primary focus on human well-being and working with nature in the face of rapidly changing environmental conditions (15, 24, 36–38). The concept is often met with resistance by those engaged in conservation and restoration (39–41), with the word design conveying an idea of fake nature to many (40). Several scientists in these disciplines have pointed to the construction of designer ecosystems as the only way to practically confront “novel” environmental regimes (15, 24, 26, 37, 42–44). This debate over whether we should design ecosystems or actively manage and create novel ecosystems (26) creates tension within the discipline because it requires us to address the fundamental relationship between humanity and nature, and about the role ecologists play in shaping that interaction.

Throughout this review, we differentiate management and design of ecological systems, respectively, as the actions by which we alter a system, sometimes to optimize production, such as conventional agriculture, or to minimize environmental impacts, such as conservation. Design is the broader plan where goals are set, actions are taken to achieve goals, and failures and success are studied and incorporated into the next iteration. In this framework, architecture is design and construction is management; in essence, design is strategy and management is tactics. As such, we consider adaptive management and related approaches as design processes.

The term design—traditionally associated with engineering, architecture, and industry—highlights a tension between control and wildness that has long been a part of what historically has been called ecosystem management. Roderick Nash (45, p. 27) summarizes this problem well: “A designated, managed wilderness is, in a very important sense, a contradiction in terms. It could even be said that any area that is proclaimed wilderness and managed as such is not wilderness by these very acts! The problem is that the traditional meaning of wilderness is an environment that man does not influence, a place he does not control.”

If we accept that nearly all ecosystems are altered by human activity, and the majority are actively managed (through manipulation of nutrient regimes, plant community structure, etc.), then the idea that we sometimes design ecosystems should be less troubling. We suggest that the term designer ecosystems be reserved for ecosystems in which ecological goals have been articulated explicitly, in which management actions are employed and evaluated to achieve those goals, and where both the goals and the actions are continually optimized as new information becomes available (see **Figure 2** for examples). Designer ecosystems are not equivalent to managed systems; they are the best-case scenario where intensive intervention is required, but design ideas should permeate all applied ecology with goals, actions, and information across shared ecological and design disciplines.

Here, we emphasize design instead of management for several reasons. Firstly, it more explicitly confronts the tension Nash highlights in a world where much of Earth’s extant ecosystems, production or protected, are created, maintained, and altered for and by people. Secondly, it is a more inclusive category than management and allows for a broad review of general problems and approaches to design. Lastly, it can be a shared terminology across fields that actively design landscapes, such as landscape architecture, urban planning, and engineering.

To better understand how designer ecosystems could potentially be put into practice, we review the role of design in disciplines that are closely allied with applied ecology. The relationship between ecology and design has a long history, which has been productive and indeed transformative for design-centered disciplines such as landscape architecture and ecological engineering. Design need not imply intensive manipulation with the intent of optimizing for narrow goals, nor can appropriate design ignore the ecological, cultural, and evolutionary histories that shape natural (and anthropogenic) ecosystems. Some of the recent self-identified failures in applied ecology can be attributed, at least in part, to an unwillingness to effectively apply well-established design principles to the management of ecosystems. Here, we review the following:

1. how humans have designed much of Earth’s surface;
2. the history of design ideas in ecology and the philosophical and practical critiques of these ideas;
3. design as a conceptual process;
4. how changing approaches and goals in subfields of applied ecology reflect changes and failures in design; and
5. why it is important for ecologists to encourage not only design fields to incorporate ecology into their practice, but also design to be more thoroughly incorporated into ours.



Figure 2

Designed systems versus designer ecosystems. Photos of systems designed and built by people: (a) Northumberlandia, United Kingdom; (b) Versailles gardens, France; and (c) Palm Islands, Dubai. Photos of designer ecosystems or landscapes designed as ecosystems: (d) Indian Bend Wash, Scottsdale/Tempe, Arizona (26); (e) Enset Farm, Ethiopia (25); and (f) Washington DC Middle School, the United States (example of ideas presented in 94). Photos a–c show systems that are entirely synthetic products of design, but these designs are not necessarily designed as ecosystems, whereas d–f were designed as ecosystems, taking advantage of internal ecosystem feedbacks to provide a suite of ecosystem services beyond a single primary goal. Image credits: (a) <http://www.northumberlandia.com>; (b) ToucanWings on Wikimedia Commons (Attribution-ShareAlike 3.0 Unported license); (c) Skatebiker on Wikimedia Commons (Attribution-ShareAlike 4.0 International license); (d) <http://gis.fed.maricopa.gov/raf>List.aspx> (photo provided by Amy Maxmen); (e) <http://www.newsweek.com/2014/12/26/solving-hunger-ethiopia-turning-native-crops-291558.html>; (f) Mark Storie on <http://landscapeperformance.org>.

A Designed Planet

What is engineering? The control of nature by man. Its motto is the primal one—‘Replenish the earth and subdue it’.... Is there a barren desert—irrigate it; is there a mountain barrier—pierce it; is there a rushing torrent—harness it. Bridge the rivers; sail the seas; apply the force by which all things fall, so that it shall lift things.... Nay, be ‘more than conqueror’ as he is more who does not merely slay or capture, but makes loyal allies of those whom he has overcome! Appropriate, annex, absorb, the powers of physical nature into human nature!

—Rossiter W. Raymond, US Commissioner of Mines and Mining Statistics (1913; see Ref. 41)

In many intensively altered ecosystems, such as cities, the role of humans in redesigning the landscape is obvious. At the local scale, many environments are controlled by infrastructure. Engineered infrastructure is designed to achieve one or a few specific purposes such as shelter in buildings, efficient transportation on roads, storage of water from dams, clean water through treatment plants, or the concentration and delivery of energy through power plants. These infrastructure components are then woven together into the human landscape that is the basis for modern society. Urban planners, landscape architects, transportation planners, and zoning regulations intentionally organize this landscape at a regional scale. Together, these components of modern infrastructure and the social system in which they are embedded are clear examples of systems that are designed across a hierarchy of scales for specific and direct human use.

Design at a hierarchy of scales is also central to agriculture, aquaculture, forestry, and other production ecosystems (46). The common goal in each of these resource extraction industries is to maximize the production of specific organisms, typically by controlling ecological community structure, biogeochemical cycling, hydrology, and even topography (47). Although design is accepted and emphasized as a core facet of engineering and other fields that produce or organize stable infrastructure, it is less recognized, but equally embedded, in fields that aim to improve the performance of production ecosystems. Instead, these fields have robust theory developed around effective ecosystem management; for the purposes of this review, we are not exploring these literatures for reasons outlined above regarding differences between design and management. Perhaps design is more readily appreciated in the construction of hard infrastructure that is generally stable and persistent over human life spans. Dynamically maintained systems such as production ecosystems are instead commonly referred to as management; however, production ecosystems are no less designed. Indeed, many design approaches to achieve desired outcomes include dynamical systems with varying degrees of active control (see sidebar, A Metaphor to Flight). The common ground for all human-dominated landscapes is that humans are intentionally and strategically manipulating natural processes to achieve human-desired goals. They differ in the interval between interventions.

Applied ecology is equally intentional, although immediate human needs are typically not central goals. Rather, applied ecology tends to focus on offsetting or minimizing the negative

A METAPHOR TO FLIGHT

Controlling and designing complex systems is a problem that has confronted engineers for centuries. Writing on the evolution of flight control, McRuer & Graham (158) note the following:

While the Wright Brothers are justly famed for their priority in many fields, their most notable contribution was the implicit appreciation that the secret to the control of flight was feedback.... They recognized that the frustrating search for inherent stability might well be abandoned if only the pilot were provided with sufficiently powerful controls with which to balance and steer—in other words, that the human pilot, operating on feedback signals, could use the controls to stabilize a neutrally stable or an inherently unstable aircraft.

Up to this point, many environmental and ecological engineering, restoration, and urban design projects have strived for the inherent stability that early flight engineers attempted to create. However, this one-and-done approach may not be the most appropriate for managing complex systems such as airplanes or ecosystems. Perhaps, by embracing feedback signals and dynamic controls over engineered stability as did the Wright brothers, ecosystem designers will achieve similar gains in design performance.

environmental impacts caused by infrastructure development and resource extraction. Here, we consider applied ecology to be fields that grew primarily out of ecology, including ecological engineering, restoration ecology, and conservation ecology. All of these disciplines employ ecological understanding in altering natural systems from their current state to achieve particular ends; thus applied ecology is inherently a form of ecological design. Ecological engineering is the subdiscipline that most explicitly recognizes this, with most researchers and practitioners in the field engaged in designing natural systems that can provide ecosystem services, such as wastewater treatment with constructed wetlands (48). As with other engineering fields, design is and always has been a central component of ecological engineering, embraced and researched by its practitioners (48–50).

In contrast, the field of restoration ecology—the study of repairing and managing degraded ecosystems through human intervention (24)—has among its practitioners those who reject and those who embrace design. The former posit restoration ecology as a direct response against the heavily controlled approach to ecosystem production (40, 51, 52) and hold that the primary goal of restoration is to remove the effects of human activities and re-establish a prior (prehuman) state (53). The latter propose intentional, explicit construction of designer ecosystems as a way of improving current restoration approaches (15, 38, 42, 54). Higgs and others (49) highlight these differences as “restoration 1.0,” which uses historical ecosystems as a direct template, and “restoration 2.0,” which uses historical ecosystems as a design guide (36, 49, 55). Although landscapes restored under either of these visions have clear differences in the motivations that create them, their primary structuring agent is human intent. As such, all of restoration ecology—whether restoration 1.0, 2.0, or any further iterations—is in reality a form of ecological design.

The same basic tension seen in restoration ecology is clearly reflected in current and historic debates in conservation and in Roderick Nash’s quote about the paradox of wilderness management (21, 34, 44, 45, 56). Classic conservation, in the most traditional sense, is almost exclusively focused on maintaining biodiversity (34). So-called new conservationists argue that traditional conservation is driven by an anachronistic, overly narrow goal for conservation science (57). Instead, they argue that to succeed conservation efforts must incorporate human well-being into its goals and into its models of system behavior (57, 58). By including such a broad set of conditions and goals, this so-called new conservation intentionally highlights the role of conservationists as ecosystem designers. However, even in the earliest, most traditional form of western conservation, design is a deeply embedded part of the field. From early debates about island biogeography and preserve design to intentional exclusion of people from preserves and parks, conservation has always been a design field (59). Such preserves are human constructs, intentionally isolated with the purpose of maintaining a desired, wild state that is shielded from local, regional, and global economic and social change (45).

In the context of human dominance of environmental processes, even our efforts to restore, protect, and enhance natural ecosystems are themselves exercises in design (37, 60). Protected and restored ecosystems are marked on a basic level by human intent, versions of designer ecosystems with different end goals. Many protected areas undergo active management to exclude invasive species, to replace altered disturbance regimes, and in some cases to improve the experiences of human visitors. Thus, even our attempts to minimize human control over ecosystems at small scales, even the simple act of drawing boundaries, still results in designing the environment at larger scales.

HISTORICAL ROOTS OF DESIGNER ECOSYSTEMS

With vast flows of energy man now begins to possess the ecosystems that spawned him.

—H.T. Odum (1962; see Ref. 61)

The idea that ecosystems could or should be designed for humans and nature has deep roots in the field of ecology. The analogy of ecosystems to machines has influenced ecological thinking since the term ecosystem itself was coined, with Sir Arthur Tansley (62, p. 25) stating that “all living organisms may be regarded as machines transforming energy from one form into another.” By the mid-1900s, ecosystem ecologists increasingly studied various aspects of the ecosystem “machine,” including stabilizing feedback mechanisms (63), cycling of matter and energy (64), and ecological succession (65). This increased awareness of ecosystem functioning emerged with a growing awareness of humanity’s destructive impact on nature as signaled by Rachel Carson’s (66) *Silent Spring*. By understanding and controlling the flows of energy and materials, ecosystem ecologists suggested that ecosystems could be optimized for production while minimizing the negative externalities documented by Carson and others (61, 65, 67).

Such optimistic ideas about harnessing and even improving nature were not limited to ecology and arose simultaneously in landscape architecture with the publication of Ian McHarg’s (68) *Design with Nature*, in agriculture with the creation of the agro-ecosystems journals (69), in systems engineering with the spread of ecosystem as a central design concept (70), in economics with the growth of bioeconomics (71) and, eventually, in ecological economics with the growth of ecosystem service ideas (30, 72). However, these visions of ecosystems designed with ecological theory rarely permeated into the larger applied ecology arena. One reason for this hesitancy by ecologists to work within a design framework is a long-standing philosophical divide about the role of humans in nature (73, 74). This is perhaps not surprising as ecologists are devoted to understanding the complexity of ecological interactions at all levels of biological organization, making it hard to accept the idea that we will ever have sufficient knowledge to tinker effectively with ecosystems (75). This perspective underpins the practical criticisms of the overly optimistic notions of ecosystems as deterministic, controllable machines (51, 76, 77).

The term “ecosystem design” first appears in the literature, not in a paper by ecologists, but in the title of a 1972 paper by the cyberneticists—or system engineers—Herman Koenig and Ramamohan Tummala (70, p. 449). The authors attempted to synthesize the basic principles of engineering, ecology, and economics into a coordinated analysis of the trade-offs (economic and energetic) of alternative ecosystems: “The specific objective of ecosystem design is to articulate the ecological and economic options available at the various levels of technological, spatial, and social organization so that these normative decisions reflect well-informed input. It is in this context that we use the concept of ecosystem design. Ecosystem management is used to refer to the procedures through which society selects, implements and maintains the socioecological options implicit in the design process on preferential, humanitarian, and other normative scales.”

Under their proposed framework, the production, transformation, and storage processes of designed ecosystems can be optimized, and Koenig & Tummala (70, p. 459) proposed that economic markets were the tools that could be used as a “computing mechanism for allocating the material processing capacity of the environment as a scarce resource to competing processes.” This highly technical and mathematical treatment of ecosystem functioning as commodity production functions presages much of the more recent literature promoting the ideas of ecosystem service markets (30).

The trajectories of ecosystem ecology and cybernetics, “the entire field of control and communication theory, whether in the machine or the animal” (78, p. 19), share many similarities in conceptual and mathematical model development. Ecologists interested in systems were primarily concerned with studying the flows of energy through ecosystem compartments and representing these flows rigorously and quantitatively (79). In contrast, systems engineers were interested in applying self-regulation and control theory to the management and manipulation of natural energy flows for human use. These two goals—the science and engineering—merged when ecosystem

ecologists began to apply systems energetic models directly to the management of ecosystems (28, 80). Concepts such as control theory, emergy, and efficiency are still prevalent in industrial ecology (81) and ecological engineering (48, 82), although they have fallen out of favor in less applied subdisciplines of ecology.

Ecological engineering is the discipline that most carefully maintains this cybernetic approach. The discipline of ecological engineering was first envisioned and defined by Howard T. Odum in 1962 as “the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both” (48, p. 120). From its initial conception to its modern reality, ecological engineering—as articulated most clearly by two H.T. Odum students, William Mitsch and Sven Jørgensen (82)—is the most clear application of the design ideals outlined by the Odums and systems engineers of the 1970s. Despite its broad vision of the use of natural infrastructure to achieve societal goals, ecological engineering as a discipline has primarily focused on small-scale engineering projects, such as wastewater treatment, where the outcomes of ecological interactions can be influenced to the necessary degree. However, the broader vision of large-scale ecosystem design lives on through the work of another student of H.T. Odum, Robert Costanza, and other ecological economists, who have developed the concept of ecosystem services (32, 72).

These major developments in systems ecology in the early 1960s coincided with a similar revolution in landscape architecture fomented by the very influential Ian McHarg. For the earliest landscape architects, the primary goal for designing ecosystems was to “perfect nature” for aesthetic purposes (83). Capability Brown’s (1716–1783) landscape gardening was so widespread that it became a de facto ideal for how nature should appear, so much so that nearly 250 years later, rural British natural preserves are often relics of Brown’s eighteenth century designs (84). In America, Frederick Law Olmsted’s imprint on American landscapes had a similar impact, such that landscapes that were initially recognized as highly designed have over time come to represent the idea of what nature should look like (85).

Until Ian McHarg (68) published his seminal *Design with Nature*, landscape architects rarely attempted to complement their aesthetic objectives with functional ecosystem goals (86). In his book and other essays, McHarg discussed how landscape architects can work with natural ecosystems to promote a more functional and beautiful landscape (68, 84). Other landscape architects such as John Tillman Lyle (87) helped to further McHarg’s vision of the field-producing aesthetically beautiful and functional landscapes, work that continues now with closer integration of ecological researchers and designers in urban planning and infrastructure design (97, 159, 160).

Then, as now, the idea of optimizing or improving nature was often met with both philosophical and practical critiques. The root of the philosophical problems with a designed nature is well articulated by Robert Elliot (73) in his 1982 essay, “Faking Nature.” Elliot argues that even if perfect restoration were possible, that is the ecosystem is returned exactly to its prior state, we still are left with a mere fake. He posits that even perfectly “faked nature” bears the same problem as faked art, namely that it is inauthentic and that its synthetic origin detracts from its value (73, 88). Other philosophical critiques have focused on the enabling nature of restoration, suggesting that it does little to reverse ecosystem degradation while providing the illusion that new impacts can be mitigated. In a compelling essay on this topic, Eric Katz, another philosopher, echoes Elliot’s point by stating that there are no perfect forgeries in restoration ecology (74). Katz argues that the “big lie” of restoration is that it is just another technological fix to environmental degradation, and under the guise of environmental consciousness, it allows humanity to continue to build artificial constructs for human benefit (74). Deeply embedded in these critiques is a fundamental separation of profane humanity and virtuous nature. Although ethicists and ecologists have defended ecological restoration (89, 90), Katz and Elliot’s critiques are one facet of the central argument against including design as an explicit part of restoration ecology. Doing so potentially

helps to propagate the notion that humans can design ecosystems with no loss of value from antecedent natural ecosystems. More importantly, philosophers suggest that ecosystems modified by human intent are aesthetically less valuable than authentic ecosystems (73).

Perhaps no one has described this deep philosophical problem more eloquently than Aldo Leopold, one of the fathers of conservation science. In one widely beloved essay he writes (75, pp. 146–47), “The last word in ignorance is the man who says of an animal or plant, ‘What good is it?’ If the land mechanism as a whole is good, then every part is good, whether we understand it or not. If the biota, in the course of aeons, has built something we like but do not understand, then who but a fool would discard seemingly useless parts? To keep every cog and wheel is the first precaution of intelligent tinkering.”

Leopold’s popular writings perfectly capture modern ecological thinking regarding the importance of biodiversity in sustaining the functioning of ecosystems (91) and the need for caution and extreme humility in our attempts to design natural systems. Together, the critiques of Katz, Elliot, Leopold and others stand in direct opposition to the optimistic ideal of ecosystems as controllable machines.

Further resistance to the idea of intentionally designing ecosystems arises from practical concerns about the science of ecosystem ecology and our ability to control complex systems. As a basic science, ecosystem ecology has undergone large transformations since the 1960s. These included challenges to our understanding of succession and nutrient cycling (92), critiques of energy as the central denominator for analysis and design of ecosystems (93), and a growing awareness that many ecosystems exhibit complex behaviors that are highly sensitive to initial conditions (94, 95). These dramatic shifts in our understanding of ecosystem dynamics have undercut the practical optimism that humans could successfully manipulate and control ecological systems to the degree and at the scales envisioned by early advocates of ecosystem design (76, 77). Additionally, the mere possibility of optimizing or designing ecosystems for more than one service has always been questioned (65, 96).

Both the ethical argument against increased human control of ecosystems and these practical concerns over its feasibility have limited the spread of design thinking into applied ecology. However, we are already designing many of the planet’s ecosystems. To have a positive impact on our future environment (at any scale), ecologists need to be willing to engage in discussions about how ecosystems can best be protected and managed—this means embracing our role within the design process. Thus far in the history of our field, our attempts at becoming designers as well as our critiques of the concept of ecosystem design have largely proceeded in the absence of any attempt to fully acknowledge and understand the general philosophy of design or to appreciate the tenets of design theory. In the following section, we attempt to briefly summarize both (97, 98).

THE PROCESS OF DESIGN

The engineer, and more generally the designer, is concerned with how things ought to be—how they ought be in order to attain goals, and to function.

—Herbert A. Simon (1969; see Ref. 14, p. 4)

One could describe design as a plan for arranging elements in such a way as to best accomplish a particular purpose.

—Charles Eames (1972; see Ref. 99, p. 14)

The convergent definitions of design by Charles Eames, a nonacademic furniture designer, and Herbert Simon, an economist and academic polyglot, highlight the disparate fields that utilize and inform the philosophy of design (**Figure 3**). However, despite its omnipresence and importance as

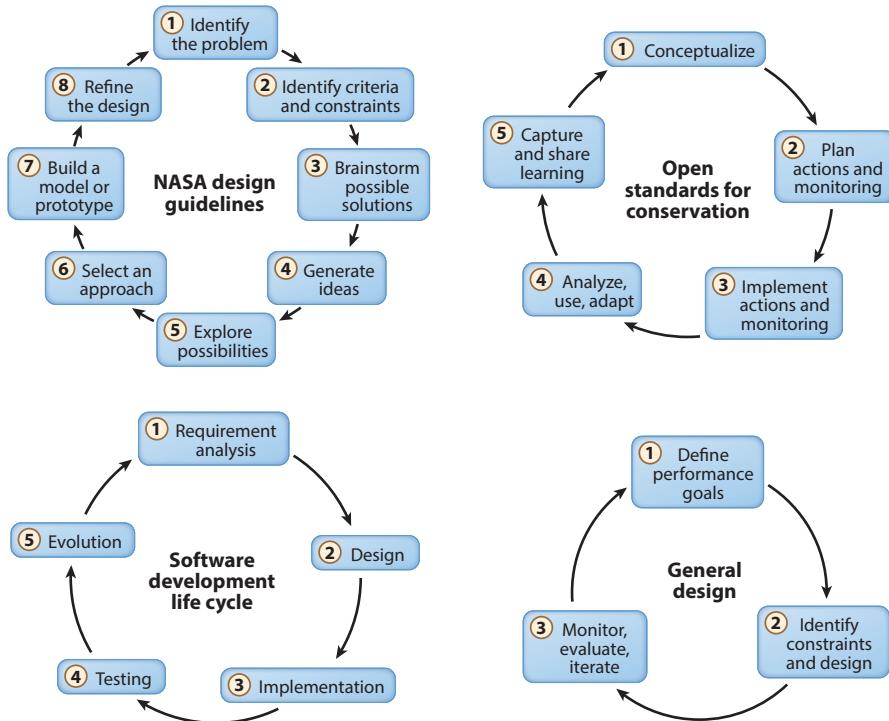


Figure 3

Disparate design fields illustrating slightly different but convergent definitions of the design approach.

a human action, ecologists have not generally worked to understand design (although see 94, 95). For example, design is not part of the standard curriculum in undergraduate or graduate ecology. However, many ecologists suggest that designers need to embrace ecology (97, 100, 102, 103) or that designers encourage ecologists to more actively engage in the design process (159, 160). For ideas in ecology to influence the design of landscapes, the exchange of ideas must be bidirectional.

In fields as seemingly disparate as algorithm development (14), furniture design (99), and architecture (87) design is explicitly acknowledged and embraced, and designers work to build functional as well as elegant and efficient products. Application of the design philosophy to ecosystems is a natural extension of a desire to build beautiful and useful software, chairs, and buildings (**Figure 4**). As a design field, however reluctant, applied ecology can be improved by more explicitly incorporating design principles and the language of design into research and practice. If we accept that future ecosystem design will occur and that decisions within the design process will be made by many stakeholders other than ecologists, we can also use our understanding of design to identify those parts in each stage of design where our expertise is best suited.

In discussing the design process for problem-solving computer programs, Herbert Simon (104) laid out the three primary objectives for any design:

1. Define performance goals;
2. identify constraints and build programs to achieve goals; and
3. monitor and evaluate the performance of the design, then iterate.

Though deceptively simple, each of these steps is vital to a successful design process and represents the distillation of many convergent definitions of design (**Figure 4**).

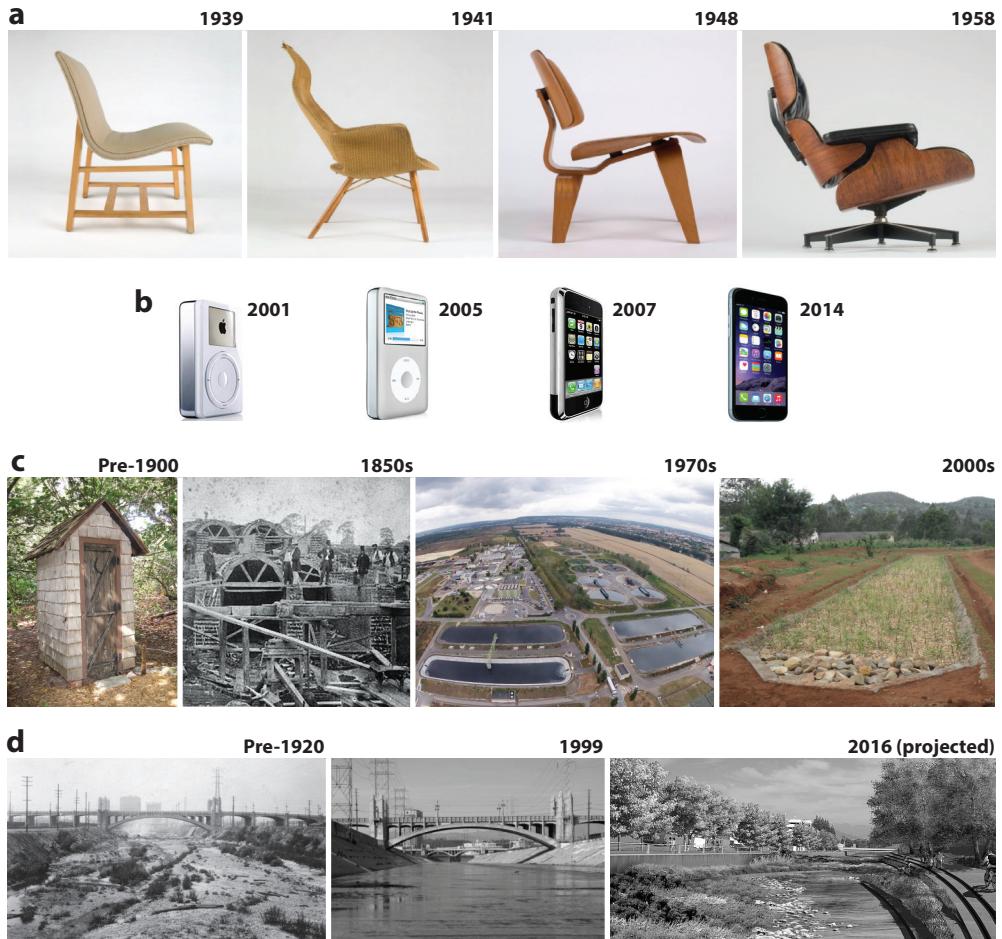


Figure 4

Figure shows the evolution of design products and the importance of iteration. (a) Evolution of the Eames chair. (b) The first iPod, the iPod (2005), the first iPhone, and the iPhone 6. (c) Outhouse, sewers of London, tertiary waste treatment (France), wetland waste treatment (Burundi). (d) Los Angeles River before channelization, after concrete channelization, and future plans for river restoration. The changing designs reflect changing systems of constraints and goals, with designs adjusted and improved according to need. Image credits: (a) © Eames Office, LLC (<http://www.eamesoffice.com>), photo by Grant Young, courtesy JF Chen; (b) <http://www.apple.com>; (c) Wikimedia Commons [left to right: Leonard J. DeFrancisci (Attribution-ShareAlike 3.0 Unported license); public domain; ToucanWings (Attribution-ShareAlike 3.0 Unported license); Sustainable Sanitation Alliance (Creative Commons Attribution 2.0 Generic license)]; (d) <http://www.larivercorp.com>.

Define Performance Goals

The setting of goals is as essential to design as the identification of questions is to science; in essence, setting goals defines the problem to be addressed, and design goals define the criteria and measures of success. In the simplest case of a design process, the designer has only to meet a single goal. A successful design would accomplish this objective function in an optimal and measurable way. However, in more complex design processes, a designer typically has multiple, potentially conflicting performance goals, making it considerably more difficult to achieve an optimal design.

In these situations, two general approaches are available to the designer: satisficing and hierarchical design.

To discuss design decisions where optimal solutions are unknowable or not worth the search cost, Herbert A. Simon (104) introduced the term satisficing. This term combines the words satisfactory and sufficient to describe situations where the search for a design that optimizes all goals is not worth the reward for finding the optimal design or where finding an optimal design is too costly. A designer, instead, satisfies by searching for the best alternative after a relatively moderate search of readily available approaches. Critically, one chooses a primary goal and optimizes for that function, leaving any secondary goals to be considered and satisfied but not optimized.

Beyond satisficing, computer scientists often use hierarchical design, which is a more robust approach to dealing with software design where the software needs to consider and meet multiple goals (105). Here, the designer ranks the most important goals for the project and then works on a design that meets goals in order of importance. This design approach works well when each goal can be cleanly separated and isolated from others or if the designer has a detailed understanding of how subsystem attributes relate and affect one another (106). But for many kinds of design problems, especially in the ecosystem context, this kind of knowledge may be limited and limiting, which is why iteration and constraint identification are vital components of the design process. In addition to design theory, formalized decision processes explored in decision science may be used to incorporate and address difficulties associated with having multiple goals and uncertainty surrounding system behavior (107, 108).

Identify Constraints and Design Programs to Achieve Goals

Design depends on constraints. At the start of any design process, the solution space is large, even with well-defined goals. Understanding and properly defining constraints restricts the suite of possible solutions. If a constraint is not included in the initial analysis, serious problems can later arise when the constraint is confronted. Designs are creative and novel in the way that they confront and work within these constraints (99, 109).

Once the goals and constraints are set, multiple alternative designs are generated that meet these goals and constraints to varying degrees. In practice, organizing and prioritizing goals, along with an extended exploration of possible and probable constraints, can occupy as much or more of the design process as developing the design solutions themselves (96). As importantly, the alternative development process may cause a reconsideration of the goals.

Monitor, Evaluate, and Iterate

Once a product (e.g., software, chair, bridge, Haber-Bosch process, or a train schedule) is created and deployed, the actual success of the product can be evaluated. Prior to deployment, goals and constraints are generated *de novo*. However, iteration (after product deployment) allows direct observation of the realities of constraints and ability to meet goals. Iteration thus provides a far more accurate picture of the constraint space and performance relationships between goals. Iteration may reprioritize or reorganize the hierarchy of goals, highlight obscure but important constraints, or elucidate previously unseen design opportunities.

An example of the power of evaluation and iterative design comes from the famous Eames chair (**Figure 1**). This chair could have achieved its primary function of supporting a seated person as a colorless wood box. However, Charles and Ray Eames redesigned the chair hundreds of times, eventually achieving an inexpensive but elegant and comfortable molded wood chair

whose innovative design has been praised and imitated for decades, earning *Time*'s best design of the twentieth century (99). Similarly, in computer science and software development, software designers have shown that iteration, monitoring, and feedback can dramatically increase success (110). In the absence of such iteration, it is only possible to perpetuate current states of knowledge, leaving little room for advancement and adaptation of designs.

What is the relevance of a famous chair design to the discipline of ecology? We include this example as perhaps the most widely acknowledged demonstration of design as an evolutionary process rather than an attempt to achieve a static endpoint. The early Eames chair looks quite clunky in comparison to its most modern iteration, just as our early attempts to design ecosystems have often proven clumsy and ineffective (**Figure 4**). It is of course far more complicated to come up with designs that can enable a landscape to support more native biodiversity or to increase its ability to sequester carbon or to produce more crops with less fertilizer—or, even more ambitiously, to do all of these things simultaneously—than it is to build a really nice chair. However, the analogy is useful in how it helps illustrate the central philosophy of design as an iterative looping process.

Becoming so-called ecosystem designers seems far less threatening when we define design (as designers have long done) as a process through which we constantly reexamine our goals and continuously optimize our approach to achieving them, as opposed to a one-time attempt to meet the goals we set today. Just as the scientific method is best drawn as a circle, so too the design process never reaches an end (**Figure 3**).

APPLIED ECOLOGY AS DESIGN?

In the most general sense, humans design ecosystems with the goal of increasing the provisioning of resources to society. The success of ecosystem designs can be seen in the rapid rise of average global human welfare, just as the failures can be seen in severe consequences to the environment (16). Indeed, one of the primary roles of ecologists, if not the central role of ecologists, has been documenting the environmental impact of traditional ecosystem design (e.g., agriculture or urbanization). However, the development and implementation of solutions to these problems have a mixed record of success (23, 111). Here, we review the self-critiques of applied ecological disciplines (primarily restoration and conservation ecology) through the lens of the stages of the design process. We consider (*a*) how applied ecology identifies goals, and how and why those goals have changed; (*b*) what constraints shape the designs of applied ecological disciplines, and how and why those constraints have evolved over time; and (*c*) the extent to which design outcomes are monitored and to which information is incorporated into future designs. Acknowledging this inherent nonstationarity of technical, social, and ecological systems and the need to manage ecosystems despite the accumulating resulting uncertainty requires us to adopt a long-term, iterative, dynamically optimizing approach. One who recognizes this will likely appreciate the appropriateness of the design process as an effective strategy for decision-making in the face of uncertainty.

Goals in Applied Ecology

Restoration ecology has had two distinct ideological histories and goals that arise from them. First, the recreation of historic ecosystems stems from an ethical fidelity to historical ecosystem pattern and process, a manifestation of Leopold's (75) land ethic. Leopold's own efforts in the 1950s at the University of Wisconsin arboretum helped start large-scale prairie and forest restoration projects, and in part led to the creation of the journal *Ecological Restoration* at the same institution (112, 113). The Society for Ecological Restoration originally defined restoration to be consistent with Leopold's land ethic: "Ecological restoration is the process of intentionally altering a site

to establish a defined, indigenous, historic ecosystem. The goal of this process is to emulate the structure, function, diversity, and dynamics of the specified ecosystem” (109, p. 340). This is a *satisficing* approach, where restoration to a past ecosystem state takes primacy, and all other goals are considered only to meet a satisfactory, sufficient standard with a modest search for better alternative solutions.

Although recreation of past ecosystems was a driving force in the formation of formal restoration ecology (36, 53, 101, 113, 114), there has always been a parallel—not mutually exclusive—goal for ecosystem restoration, restoring important ecosystem services for people (23, 113, 115). The ecosystem-service-oriented goal of restoration can be seen in history in the royal forests Europe restored to cultivate and maintain more and larger prey for the aristocracy (116); it can be seen, as well, in the United States and United Kingdom, wherein wealthy landowners hoped to improve streams on their property to promote trout fishing (117–119). When restoring for a specific ecosystem service, the design has often contained artificial structures or elements that provide the service but are not comparable to historic features of the ecosystem (e.g., lunker structures for trout habitat; see 115). Potentially, the more specific the service to be optimized, the more divergent the resulting designed ecosystem is likely to be from historical ecosystems.

These historic examples of restoration foreshadow the current shift in the goals of restoration toward enhancing a multitude of ecosystem services that can sustainably benefit people and nature alike (23). The Society for Ecological Restoration’s altered definition of restoration reflects this shift: “Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” (120). Ecosystem-service restoration arises from a generally acknowledged failure to achieve the articulated goals of recreating historic ecosystems in a world dominated by novel species interactions in ahistorical climate, biogeochemical, and hydrological regimes (15, 21, 36, 37, 42, 43, 53). Additionally, the shift in general goals reflects a problem of restoration in practice wherein goals are often not even explicitly articulated for many projects (23, 111).

In an ecosystem service framework, project goals can be both more explicit and more quantifiable (e.g., carbon sequestration in tons per square kilometer, nitrogen retention in kilogram retained per hectare, or use in visitors per month), whereas the establishment of historical baselines has always represented a challenging target. Over the past 25 years, restoration has shifted from having the goal of restoring the ecosystems that previously existed toward restoring specific functions that have been lost. More recently, some prominent restorationists have even argued for enhancement of specific ecosystem characteristics to produce a greater quantity of specific desired ecosystem functions. This shift in goals shows restoration moving toward a framework more similar to ecological engineering (*designer ecosystems* sensu 15, 49, 117). In an increasingly large number of restoration projects, recovering or restoring historic ecosystem conditions is often not the primary goal. Restoration has moved toward a hierarchical framework in which restoring historic ecosystems is a single goal rather than the only goal: A range of ecosystem functions are now equally valid priorities for design (24, 36, 37, 53).

Unlike restoration, the basic goal of conservation has changed little over the past 50 years, to preserve biodiversity (57, 121, 122). This goal unites conservationists, although some have recently argued that additional goals—such as sustaining human welfare, economies, and societies—should rather than could be included (57, 122). These additional goals are enabled by the ecosystem service framework, which explicitly estimates the instrumental value of conserving nature (31, 35, 123). Some conservationists (34, 41) reject these additional goals as a distraction and potential subversion of conservation’s core goal of preserving biodiversity for its intrinsic value (35, 124).

Our examination of the design process in other disciplines illuminates the nature of current debates in conservation biology. The controversy concerns whether the primary goal of

biodiversity conservation will be met through a clear hierarchical or satisficing design (21, 34, 44, 56, 125), although not described in these terms. Satisficing, with the preservation of biodiversity as the one clear primary goal and a set of clearly secondary nonoptimized goals, has been articulated as conservation biology (121). Hierarchical conservation designs, with a set of goals arranged in hierarchical order, have been identified as conservation science (57). The concern with hierarchical framework applied to conservation is that preserving biodiversity is at risk of potentially being lowered on the goal hierarchy, as society shifts its priorities (34). In a world where conservation science satisfies with economies taking top priority, there is real potential for biodiversity conservation to lose all priority, resulting, potentially, in net environmental loss (123, 126, 127). For example, if carbon sequestration markets dramatically outprice biodiversity conservation markets, the best action for a stakeholder satisficing may be to cultivate a eucalyptus plantation ecosystem.

Beyond restoration and conservation, researchers have argued for similar shifts in goal setting in other areas of applied ecology (106, 128, 129). For instance, in agriculture researchers have argued that pure production goals have to be compromised, to a degree, to meet broader environmental goals (20, 22, 130, 131); similar arguments have been made for urban design (132, 133), landscape architecture (87), and environmental engineering (134). Ecosystem services are a mechanism through which traditionally nonvalued functions of ecosystems can enter into goal setting. When ecosystem services are valued through an explicit market (e.g., water quality trading), the hierarchy of target services can change rapidly, such as the market value of water during a drought (22). With ecosystem services in a hierarchical framework, the general goals in applied ecology converge on multi-ecosystem service provisioning, which has been argued to be a more sustainable approach (20). As these goals have changed, the constraints facing the field of applied ecology necessarily change as well.

Constraints on Ecosystem Design

Two major classes of constraints influence the design of ecological systems. The first are local and global changes in geophysical and ecological conditions, such as shifting climate, the local or global extinction of species, and changes in the external supply of water and nutrients. The second set of constraints is in the values, knowledge, and institutions of society. Technical innovations can eliminate or reorder design constraints. Changing societal values or political leadership can rather rapidly alter the hierarchy of ecological design goals. Meanwhile, the component organisms within ecosystems are themselves constantly reorganizing and adapting to external forcing.

A central challenge of the Anthropocene is that global environmental conditions are shifting away from historical conditions toward a set of constraints that have not previously been confronted (54). As such, historical ecosystem conditions do not necessarily provide a reliable template for setting the goals for future ecosystems (36, 53). Moreover, past approaches that were successful in applied ecology may not provide comparable results under emerging and future constraints, whether water management (135), agricultural production (136), or species conservation (44). As one among many obvious examples of this problem of nonstationarity, the conservation plans for alpine pika for the next century will be very different from those of the previous, as future climate change will rapidly reduce the southern extent of their range (137). External forcing is not the only form of change; biological adaptation and artificial selection are also changing how we define the constraint space. For example, the breeding and genetic engineering of drought-resistant corn crops may reduce the challenge of water shortages in some systems (138), whereas more heat-resistant coral (139) could belie our dire projections of future coral reef degradation. Because of the trajectory and pace of global environmental degradation, any applied ecology project is

unlikely to continuously meet its originally intended goals over extended periods without active interventions (see sidebar, A Metaphor to Flight).

Local conditions may change rapidly, and in ways often not expected, so that important constraints are often unknowable until designs are implemented. Increases in impervious cover upstream of a stream restoration project (140) or changing fire return intervals as a result of development in the wildland urban interface (141) can render a previously appropriate design fruitless. A national park that was located and sized in the early twentieth century will clearly be challenged by the concentration of development at the borders in the twenty-first. This local and short-term variability is important because it creates a potential need for many distinct design solutions to any particular problem (142), and it suggests that flexibility and potential for future adaptive change must be a priority goal for projects that hope to achieve long-term ecological benefits.

One of the constraints to ecosystem design will always be our limited scientific understanding. As we learn, our strategies for achieving the same goal may change considerably. The evolution of conservation biology provides one illustration of this issue. Early conservation efforts primarily focused on ensuring an effective population size of endangered species (143, 144). As the external pressures that cause extinction were increasingly recognized as habitat loss, conservation shifted its focus to habitat conservation (145) and how to maintain viable meta-populations across networks of connected habitats (146). Most recently, conservation scientists have grown to recognize the widespread loss of entire habitat and landscape types under increased pressure from anthropogenic change, causing calls for landscape and regional conservation efforts (147). This arc of changing approaches demonstrates how when new constraints are discovered and addressed, designs necessarily adapt. However, none of the original goals or techniques are necessarily abandoned, and technology can influence the success of each. Furthermore, the various actions available for a conservation effort vary in their flexibility and spatial scale. For example, the Northwestern Hawaiian Islands Marine National Monument was in part created to protect the Hawaiian monk seal, but the population continues to decline (148). Conservationists have responded by implementing a set of population-specific conservation approaches (e.g., dehooking, disentanglement, moving seals to better habitats), which have shown success in buoying survivorship among seals (148). These more flexible measures are able to respond to local, rapidly changing constraints, whereas the rigid National Monument status provides a general, static protection.

Ecological design is affected by constraints of the biophysical and knowledge environment, both of which are changing rapidly. For many ecological design applications, these constraints shift meaningfully over the lifespan of the project, or even over the course of the design phase. Therefore, any ecosystem design is likely to require adjustments over its lifespan, and indeed the most effective ecosystem designs are likely to be those that explicitly acknowledge the lack of any definite endpoint in time.

Monitoring, Evaluation, and Iteration in Ecology

Even in a world with fixed goals and stable constraints, design begins from a position of relative ignorance. The iterative step of the design process is aimed at improving design through empirical trial and error. In ecosystems, it costs more money and takes more time to iterate on designs than in many other fields (such as software development). However, there is still a robust and well-developed theory for iteration on ecosystem designs from within ecology; this process is referred to as adaptive management.

The initial conception of adaptive management was narrowly defined to refer to the deliberate use of management interventions as experiments to identify maximum sustainable yield, primarily for fisheries (28). These efforts were a formalized way of reducing uncertainty in a

constraint space where management actions could be used as replicable experiments (28, 149). From these early efforts grew a desire to apply adaptive management more broadly as a robust way to deal with the predictable uncertainty in ecosystem behavior and as a response to management decisions, requiring a relaxation of reproducible experimentation (150, 151). Simultaneous to these changes in adaptive management approaches was a growing awareness that ecosystems could reach tipping points (94). When an ecosystem is managed assuming stationarity and only for annual maximal output, this can lead to brittleness and collapse (51). Adaptive management approaches address this nonstationarity and other nonlinear behaviors through shifts in both goals and approaches as informed by monitoring and evaluation. Early adaptive management approaches assumed that recovery from perturbations was inevitable, and thus sought to maximize particular outputs (e.g., yield). Recognition that management could erode stabilizing feedbacks led the theory of adaptive management toward cultivation of resilience (152). Methodologically, this shift required evaluation of a much broader set of potential ecosystem behaviors (153).

Despite this intellectual progress and general acceptance in the academic community, adaptive management has not permeated the practice of applied ecology extensively (150, 151). Several possibilities can explain this limited application. First, high degrees of local variation on constraints limit the ability for knowledge to be generally applied (see above). Even when knowledge is transferable across sites and disciplines can learn from local management failures, iterative design may be limited by time or resource constraints. Second, management interventions may cause changes in ecosystems with lagged responses. In such cases, disentangling causation is very difficult, and adaptive management approaches can still lead to, or even cause, negative ecosystem responses (153). Third, the goals and constraints for many ecosystem design projects change both throughout the project and during the monitoring phase; determining success with moving targets is difficult. Fourth, monitoring is an expense that can have no clear return on investment and can be seen potentially as negative if managers make poor decisions despite ample monitoring data that would implicate them (151). Finally, adaptive management initially did not include stakeholders in the goal setting or design processes (151).

Central to successful design is the need for evaluation. This is perhaps where ecological management efforts fall most short in their comparison to the ecological design ideal. The strongest self-critiques from within applied ecology have focused on the lack of monitoring and project evaluation (23, 111, 154–156). To varying degrees, this problem spans all subdisciplines of applied ecology and design in general, despite the ubiquity of monitoring and iteration as a core feature of effective design. In conservation, evaluation and monitoring are often core components of projects, but design iteration is often difficult due to political and resource constraints (155). For restoration, the problem is often much deeper. Many projects declare amorphous goals, if any, that make monitoring and evaluation nearly impossible (111). Without the full iterative component of the design process, no learning can occur and design approaches stagnate, at best, even as the goals, and the technical capacity and scientific understanding to achieve them, continue to rapidly evolve.

Here again, an analogy to a stagnant design that nearly all practitioners and researchers have encountered may prove useful. The layout of the modern computer keyboard has remained mostly unchanged since the QWERTY keyboard was first patented in 1868 (157). Many alternative letter arrangements have proven significantly easier to master and use rapidly but have not been adopted (157). Thus, we have written (and most of you are reading this manuscript) on computers whose keyboards are designed to intentionally slow down your typing speed to avoid jamming the manual typeface bars of an early nineteenth century keyboard (157). This is a great example of a once highly

successful design within an entirely failed (i.e., halted) design process. If we are too prescriptive in the range of allowable design strategies, we may prevent the innovations that are most necessary for achieving and sustaining our goals over the long term. Flexibility is difficult to incorporate into regulatory and policy structures, which is why rulemaking that emphasizes the achievement of a goal rather than management actions is more likely to have a positive, lasting impact on the environment.

CONCLUSION: ECOLOGY IN DESIGN AND DESIGN IN ECOLOGY

The point is that if we are going to design ecosystems (and we continually do so whether we care to face all of the implications or not) then it will be best to design them intentionally, making use of all the ecological understanding we can bring to bear. Only then can we shape ecosystems that manage to fulfill all their inherent potentials for contributing to human purposes, that are sustainable, and that support nonhuman communities as well. Not every landscape can fully accomplish all three of these goals, of course, and thus Odum's term, "compromise." There will always be conflicts to be resolved and priorities to be assigned. Intentional design means carrying out conscious choices. What we are trying to do, then, is to gain a measure of control, not in order to dominate nature but to participate creatively in its process.

—John Tillman Lyle (1985; see Ref. 87, p. 16)

Humans have designed a substantial portion of our planet. Our expanding population and technological innovation have created a planet that has significantly fewer species, a modified atmosphere, and dramatically altered land-use patterns creating a new epoch, the Anthropocene. To accomplish the overarching goal of applied ecology within this newly acknowledged Anthropocene it will not be enough to recognize humans as components of ecosystems. We have to acknowledge that humans are also designers of ecosystems. Resisting this idea risks the possibility of becoming increasingly irrelevant to the fields of ecosystem design that embrace it. Instead, we suggest that by understanding and appreciating what the design philosophy entails, applied ecologists can more effectively influence the way we manage ecosystems now and the way they will be managed in the future.

Historically, applied ecological research has focused on identifying and quantifying the environmental costs of other human activities. But recently, ecologists and others have called for a more active role of ecologists and ecological knowledge in design process. Achieving sustainable, multi-service ecosystem design, within applied ecology, in production ecosystems, and in urban landscapes, will inherently require ecological knowledge. To engage in the broader environmental design process (i.e., not just reserves and restoration plans, but roads, buildings and whole cities) will require a transition for applied ecologists, forcing us to expand beyond our historic strengths as the identifiers of constraints to scientists committed to devising, evaluating, and informing new solutions. The increasing disciplinary scope and geographic scale of design decisions mean that ecologists will be just one seat at the table. How can we best use that position? Over the short term, we must acknowledge the necessity of trade-offs and imperfect solutions with the goal of making sure we learn from historic failures and successes. Over the long term, design should be a component of ecological education, for academic ecologists and especially for the booming number of programs in professional environmental management. Furthermore, critiques and successes in applied ecology need to be framed through the lens of design as much as failures in design fields can be understood through the lens of ecology. Such a pedagogical shift will require discipline-wide awareness and, eventually, acceptance of the concept, process, and important role of design in applied ecology.

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