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Perspective

Ecological Engineering and Sustainability: A New Opportunity for Chemical Engineering

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Introduction

In its short history, chemical engineering has moved far beyond the bulk production of commodity chemicals that first motivated the discipline's development. The concept of "unit operations" enabled chemical engineers to "see" the underlying similarity of, for example, separating alcohol from water in a fermenter, and separating gasoline from diesel in a refinery. The identification of the fundamental unit operations allowed chemical engineering to focus on the processes as opposed to the product, which in turn has enabled the discipline to move into a multitude of new directions.

The application of chemical engineering principles to biological processes at the cell-to-tissue scale has been particularly successful, leading a number of prominent departments to change their names to include some variant of "Biological." Yet the emphasis of the research in these departments has largely remained focused on the smallest biological scales, missing the opportunity to tackle the most complex and interconnected biological system on Earth—the biosphere.

As the Biosphere 2 project (see sidebar for details) clearly demonstrated, current ecological knowledge does not enable us to "engineer systems that provide humans with life-supporting systems that natural ecosystems produce".[1] Indeed, a number of fundamental questions regarding the biosphere's structure, stability and response to perturbations still remain open. However, just as new technologies are enabling molecular and cellular biology to evolve from a mostly observational science to a quantitative, predictive one, ecology is now at a crucial turning point in making a similar transition. In this perspective, we argue that chemical engineers are well positioned to contribute significantly to the transition occurring in ecology, and that ecological knowledge is of fundamental importance to chemical engineers interested in sustainability research.

Our article is organized as follows. First, we provide an overview of reasons that have kept chemical engineers from greater involvement in ecological research. We then review recent research, with particular emphasis on the structure of ecological networks and the development of general theories for food-web structure and food-web dynamics. Finally, we discuss a recent study of contaminant transfer in an invaded food web, for which the integration of chemical engineering tools with traditional ecological and environmental analyses proved essential.

The biosphere: An "ecological plant"

Consider a large chemical plant (Figure 1a). A typical plant may contain a number of reactors, separation units such as distillation columns, heat exchangers, and miles of pipes to enable transfers between the different units. To the untrained eye, the chemical plant appears exceedingly complicated; yet analysis of this system is well within the bounds of traditional chemical engineering and indeed provides the foundation of its core curriculum.

Now consider a new "chemical" plant, one in which the units are the species found in a given ecosystem (Figure 1b). The pipes in this "ecological plant" represent predator-prey interactions between these species, and serve to transfer bio-

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Biosphere 2

Biosphere 2 is a 3.14-acre structure in Oracle, Arizona, originally built to be an artificial *closed* ecological system. The objective of the Biosphere 2 project was to explore the interactions between the Earth's (Biosphere 1's) various biomes, and to determine our ability to engineer a viable and self-sufficient ecological system. Construction of the complex, which started in 1985, took 6 years to complete and cost an estimated $200 million.

Biosphere 2 comprises a 1,900 square meter rain forest, an 850 square meter ocean with a coral reef, a 450 square meter mangrove wetland, a 1,300 square meter savanna grassland, a 1,400 square meter fog desert, a 2,500 square meter agricultural system, a human habitat with living quarters and office, and a below-ground level technical facility.

The first long-term closed mission in Biosphere 2 lasted from September 26, 1991 to September 26, 1993, and eight individuals were enclosed inside. The mission experienced a number of critical problems such as a large number of species extinctions and water systems overloaded with nutrients that then polluted the aquatic habitats. More critically, the crew experienced persistently decreasing oxygen levels. The starting oxygen concentration of 21% had, by January 1993, dropped to 14%, a level typically found at an elevation of 17,500 feet. The project required multiple injections of oxygen in order for the crew to remain the full 2 years.

Even with its large budget, the Biosphere 2 project demonstrated our inability to engineer a self-sustaining system able to provide food, water, and air for eight individuals over the course of 2 years. In fact, "several visiting ecologists doubted that a viable closed habitat to support human life could have been assured, even had the best ecological knowledge of the time been brought to bear."[1]

mass and energy throughout the environment. At least on an abstract level, it seems hard to justify why the study of these two systems would require distinct conceptual approaches. Remarkably, ecosystems have not been significantly studied by chemical engineers, even though chemical engineering conceptually spans the entire range of energy, mass and time scales relevant to ecosystem dynamics. One of the reasons for this neglect may be the traditional view that ecological systems cannot be engineered nor can a general understanding or theories be developed. As we will see later, this assumption is slowly being eroded.

Ecological Engineering and Sustainability

Humankind's actions have had a staggering effect on the natural behavior and balance within the biosphere. This effect can be most directly observed through the extinction of species. Extinctions can greatly alter an ecosystem's biodiversity; they can affect ecosystem stability, its resilience to environmental change, and its resistance to invasion of exotic species.[2]

Climate change, habitat destruction, invasive species, and unsustainable practices are taking their toll on the Earth's biosphere. Significantly, these matters are nowadays on the mind of many because of the tremendous impact they will have on the future of human civilization. So it does not come as a surprise that chemical engineering is moving to address some of the challenges and opportunities created by these issues.

Surprisingly, while environmentally-oriented research has gained a significant foothold in chemical engineering, ecologically-focused research has largely been ignored. If one considers, however, important and timely ecological problems such as contaminant accumulation in predator species (including humans), the continued spread and ecological impacts of invasive species (including diseases and their vectors), and the loss of diversity associated with global climate change, it becomes clear that understanding mass and energy balances, kinetics, and transport phenomena is critical.

The lack of a quantitative and predictive discipline of ecological engineering means that policy makers face a number of decisions where they must weigh social and economic factors, but cannot estimate ecological consequences based on solid scientific knowledge. The lack of understanding of the long-term consequences of policies affecting the environment is one of the reasons we have allowed the toll on the Earth's biosphere to reach its current critical situation. It is, thus, crucial that chemical engineers bring their knowledge to bear on the maturation of ecological engineering. It is thus crucial that chemical engineering bring their knowledge to bear on the maturation of ecological engineering.

Threats to the Biosphere

Climate change[3] and atmospheric pollution[4] are examples of well-known problems to chemical engineers and areas where they have contributed significantly. We next review some threats where chemical engineers have not been involved, but could be.

Species Loss

There may be as many as fifty million different species of plants and animals on Earth.[5] About two-thirds of these species live in the tropics, largely in the tropical forests.[5] Recent studies show that about 30–50% of plant, amphibian, reptile, mammal, and bird species occur in just 25 hotspots that occupy no more than 2% of the terrestrial land mass.[6] It is believed that fish and other marine organisms are similarly concentrated.[7]

The concentration of natural species demands that hotspots be managed with particular attention and caution.[8] Unfortunately only about one half of the original 16 million square kilometers of tropical rain forests remain,[9] and clearing eliminates about 0.2 million square kilometers every year.[10,11] Between 2000 and 2005, roughly 2.4% of the global rainforest cover was removed.[12] This and other factors, such as increasing population and global warming, place us in the midst of the sixth largest extinction event in natural history.[13]

The impact of diversity loss extends far and wide. Many drugs were and are discovered via testing against libraries of natural compounds. Population diversity also provides bene-

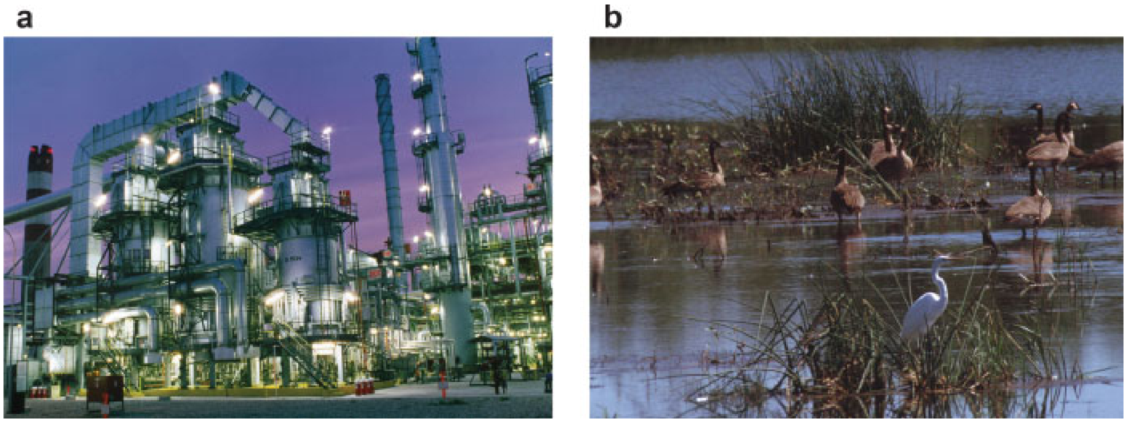

Figure 1. Chemical plants.

(a) Petroleum refinery, and (b) Ecological system. The mass and energy transfer required for the processing of crude oil is both well-studied and well-characterized. In contrast, the processes occurring in the ecosystem are far from being well-characterized, even though they are similarly founded upon mass and energy transfer for proper function. (Photo a courtesy of Emerson Process Management; photo b courtesy of USDA NRCS.)

fits, such as greater resistance of crops, cattle, and supporting species against disease.

Invasive Species

Although direct species extinctions (e.g., through habitat destruction) take place on far shorter time scales than evolution and introduction of new species into a habitat,[13] species invasions can have effects that, in the long-term, are as far-reaching and dramatic — including extinction of native species. Estimates of the overall cost of invasions by exotic species in the United States alone range up to $137 billion annually.[2] The fear of new invasive species is such that in the fall of 2004, a federal task force announced funding for a $9.1 million permanent electrified barrier on a waterway near Chicago to prevent the invasive Asian carp from continuing its migration from the Mississippi River toward Lake Michigan. The Asian carp is characterized by a voracious appetite and could potentially wreak havoc upon the Great Lakes' ecosystems and their $4 billion-a-year sport-fishing industry.

Contaminant Accumulation

The presence of contaminants in the environment has been recognized as an important ecological perturbation since before the publication of *Silent Spring* in 1962 brought to public light the effects of DDT on bird populations.[14] Much of the research effort has been focused on persistent chemicals that pose a threat even in environments far from emission sources, from organic contaminants and methyl mercury showing up in the fish we eat,[15,16] to the accumulation of persistent organic pollutants (POPs) in marine mammals in remote polar regions.[17] More recently, attention has turned to the presence of pharmaceuticals and other endocrine-disrupting (hormonally active) chemicals in the environment.[18] Chronic exposure to these chemical stressors has far-reaching implications for both human and wildlife populations, affecting reproduction, development and, ultimately, longevity on both an individual and population scale.

Food Web Structure

Unit operations for ecology

Before the birth of unit operations, the different chemical industries were thought of as following different sets of principles. It was the concept of unit operations that allowed chemical engineering to focus on the process rather than the product. In ecology, research is for the most part still restricted to the study of one to a few species within an ecosystem. The reach of such studies is naturally limited because it is unclear how directly knowledge gained about one ecosystem extends to different ecosystems. A lingering question is whether it will ever be possible to develop general theories of ecology which apply to many systems, beyond their specific identifying characteristics — that is, do ecological "unit operations" exist that will allow us to simplify the analysis of these complex systems?

Recent research on food-web structure is providing a definite answer to this important question. The central hypothesis of this line of research is the following. Despite all the aspects unique to each ecosystem, there exist a number of universal features that hold for a large number of ecosystems. This hypothesis is based on the principle that there are emergent properties in complex systems that arise from constraints acting upon the system.[19] For example, species' bioenergetic constraints may determine aspects of ecosystem structure such as number of autotrophic species and of top predators.

The recent incorporation of tools from fields outside ecology — including statistical physics and chemical engineering — has helped uncover phenomenological "laws"; that are obeyed by empirical food webs that differ in such crucial aspects as the population and type of species present, assembly history, and environment type.

Food Web Theory

The first attempts at developing a theory of ecosystem organization start with the concept of ecological niche.[20] Unfortunately, niche was initially defined as the region in an *n*-dimen-

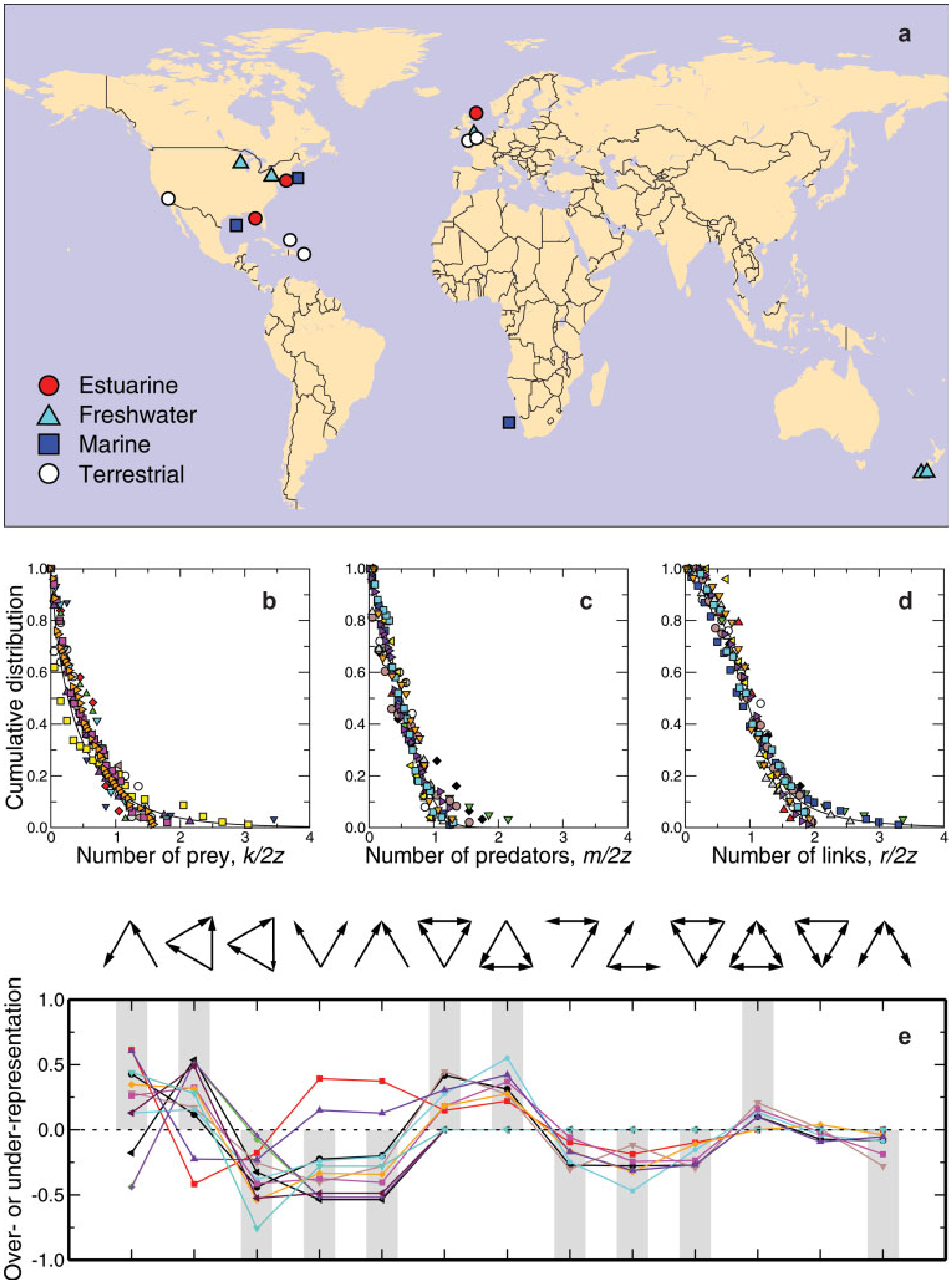
a
Estuarine
Freshwater
Marine
Terrestrial
b
c
d
Cumulative distribution
Number of prey, k/2z
Number of predators, m/2z
Number of links, r/2z
e
Over- or under-representation

Figure 2.

sional space occupied by a species in a specific ecosystem. The value of n was never specified, and so neither could the exact meaning of the dimensions be specified. Prompted by the work of Joel Cohen,[21] there was an effort to make the theory falsifiable by providing a more concrete definition of ecological niche. Specifically, niche space becomes 1-D (one-dimensional), with the dimension thought of, for concreteness purposes, as the mass of a representative individual of the species. This conceptual breakthrough led to the development of several computational models[22–25] that are able to accurately reproduce the structure of many complex empirical food webs (Figure 2a).

While these models share several significant assumptions, they differ in other aspects. Thus, it was not possible to determine which specific assumptions are required in order to predict the properties of the empirical food webs and which assumptions are ancillary. In an effort to shed new light on the factors behind the success, or failure, of food-web models, Stouffer et al. performed a systematic study of several food-web models.[25] Their analysis demonstrated that, to successfully explain many statistical properties of empirical food webs, a food-web model must satisfy two critical conditions. First, the species must be rankable or orderable. Second, predators consume an exponentially-decaying fraction of species with rank equal to or lower than their own.

Most importantly, this study found evidence that the distributions of the number of prey, number of predators, and number of trophic interactions in empirical food webs obey universal functional forms (Figure 2b). Importantly, the observed patterns cannot be explained by systematic errors in data collection because the data were collected by different investigators utilizing different protocols.

This result is consistent with the hypothesis that ecosystems display "universal" patterns in the way trophic relations are established despite apparent fundamental differences.[25,26] More recently, it was demonstrated that these patterns are also obeyed by food webs assembled from the fossil record.[27] This remarkable result strongly suggests that the mechanisms that are responsible for shaping the structure of food webs today have remained unchanged across geological time scales.[27]

The distribution of, for example, number of prey per species describes a global aspect of food-web structure. However, the regularities uncovered for food web structure hold even at finer levels of description. For example, Camacho et al.[28] and Stouffer et al.[29] examined the over- and under-representation profiles of unique 3-species subgraphs in model-generated and empirical food webs (Figure 2c). Their analysis unveiled the subgraphs that appear more and less frequently than expected by chance. They found a conserved profile of over- and under-representation across the same diverse set of empirical food webs. Again, the implication here is that food-web structure is explained by universal constraints that act upon the system and not by the presence or absence of different species, different levels of biodiversity, or habitat.

Food-web dynamics and stability

The emerging consensus regarding the *structure* of the network of predator-prey interactions[30] suggests that the opportunity to advance our understanding of ecosystem *dynamics* and *stability* is now at hand. The implications of this structure, however, have yet to be uncovered. As an example, it is unknown whether the structure tends to make food webs more or less stable, either in their resistance to perturbations or in biodiversity maintenance and species' abilities to persist.

Let us also recall that, for an ecosystem to be viable, the food web relies upon efficient transfer of mass and energy. One wonders then whether or not the distributions of numbers of prey, predators, and links serve to optimize this transfer. It was similarly observed that the local structure of food webs, as embodied by food-web motifs, is conserved across diverse communities. While this was related to the mechanism of prey selection,[29] it is unclear whether the arrangement of this local structure also serves to optimize some transfer process.

Modeling Bioaccumulation Using Food Webs

One of the most obvious and perhaps better known "unit operations" acting on the biosphere is the global distillation phenomenon, sometimes known as the grasshopper effect. First described by Wania and Mackay in 1995, this effect helped explain how persistent organic pollutants — semivolatile substances with long environmental lifetimes — were being measured in high-concentrations in marine mammals and in humans living in high-latitude (polar) environments, despite being far from any large emission source.[31–34] This phenomenon also contributes to a global fractionation effect, whereby chemicals released into the environment are redistributed along a latitudinal gradient according to their volatility and their retention in environmental media and in organisms.

This "retention tendency" was successfully modeled using a concept dear to chemical engineers: fugacity. The fugacity formalism, used to describe equilibrium partitioning, was first applied to contaminants in the environment by Mackay and Paterson,[35] and has now been successfully used to describe

Figure 2. Phenomenological "laws" of food-web structure.

(a) Location of the most well-studied empirical food webs. Note that they range from marine to terrestrial; (b), (c), and (d), cumulative distributions of numbers of prey, predators, and links per species for empirical food webs. It is visually apparent that the different food webs appear to obey the same functional form, shown by the solid lines, which is a hallmark of universality,[25,26] and (e) over- and under-representation of food-web motifs in empirical food webs. Across the x-axis we show the 13 unique food-web motifs comprising three species.[29,39] Each motif represents the predator-prey interactions of a triplet of species, and in the figure the vertices represent species and the arrows point in the direction of mass and energy transfer, from prey to predator. A value on the y-axis greater than zero implies the corresponding subgraph appears more frequently than expected at random while a value less than zero implies less frequent appearance than expected by chance. As in b, c, and d, we find striking agreement with the theoretical predictions indicated by the gray bars. (Panels b–e modified from Stouffer et al.[25] and Stouffer et al.[29]).

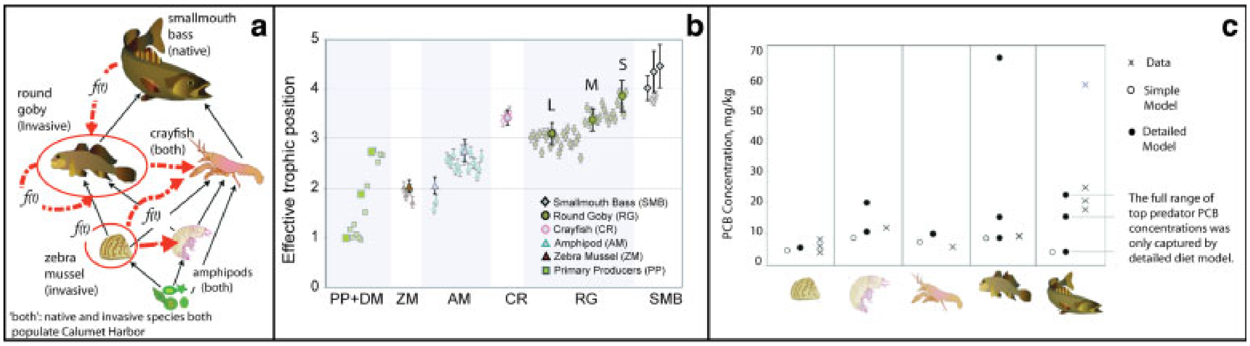

Figure 3. Simple, but not trivial, food webs produce complex ecological outcomes.

(a) Food web of Calumet Harbor, in Lake Michigan. This food web is dominated by only a few, mostly non-native, species (see legend). A simple structure appears to result when considering only binary links between predators and prey (links exist or do not exist). However, when recycling of non-prey food items are considered in the food web (e.g., feces, fish eggs; red arrows), as well as the dependence of diet on season and species age (links marked with *f*(*t*); e.g., fish diets often change dramatically from the juvenile to the adult stage) it is apparent that the dynamics are substantially more complex (Modified from Ng et al.[38]). (b) Modeling of the trophic structure of the Calumet Harbor food web. It is typically thought that the top predators in an ecosystem have the highest ^{15}N ratio. Therefore, nitrogen stable isotope analysis is routinely used to estimate a species' trophic level. In Calumet Harbor, however, it was found that the round goby, a prey of the smallmouth bass, occupied an *effective* trophic level as high as the bass through consumption of "recycled" nutrition sources such as fish eggs. This can be attributed to changes in diet and behavior from small (S) to medium (M) to large (L) size gobies. Ng et al.[38] used a stochastic model of individual species' behavior, and classical ecological techniques such as stomach contents and stable isotope analyses to develop a detailed diet model for the Calumet Harbor species that could explain the trophic position data,[38] and (c) effect of trophic structure on contaminant accumulation. The diet model developed in b was coupled to a bioaccumulation model to predict PCB levels in Calumet Harbor's species. The high levels observed in the top predator (smallmouth bass) and in the round goby are of concern to human populations with high rates of fish consumption. (from Ng et al.[38]).

the accumulation of contaminants in global, regional, and local environments and in the biotic sphere from food webs to within individual species' digestive tracts.[35–37]

More recently, Ng and coworkers[38] have combined techniques from a number of disciplines to describe contaminant accumulation in a food web that was far from "natural." They coupled a fugacity-based bioaccumulation model with stochastic modeling techniques more typically employed in statistical physics, and with fundamental ecological tools such as stomach contents and stable isotope analyses. This allowed them to develop a food-web-based bioaccumulation model that captured the complexity of contaminant-biota interactions in a food web affected by multiple human-induced stressors (Figure 3).

Their model was based on a southern Lake Michigan food web that had been subject to chronic anthropogenic impact, resulting in an ecosystem with low diversity. Although on the surface the structure of the food web seemed very simple, the interactions among these species are surprisingly complex (Figure 3a). These interactions among species and among populations within a single species led to the emergence of complicated patterns in the trophic hierarchy and in contaminant accumulation, as measured by nitrogen stable isotopes (Figure 3b) and PCB concentrations (Figure 3c).

Ng et al. were able to successfully model these patterns by integrating multiple tools in the development of a detailed diet model for one particular member of the food web: the round goby, an invasive forage fish. Stomach contents analysis, a traditional tool in ecology, was used to resolve the round goby diet on a lifetime (ontogenetic) scale, while a stochastic consumption model captured consumption of seasonally available prey on a much finer scale. Using stable isotope measurements to calibrate this diet model, they were able to construct a food web description that captured the critical links on these multiple time scales in order to successfully predict patterns of contaminant accumulation. Their model shows how inclusion of greater detail at the species level, and integration of these techniques across disciplines, can help to explain environmental signals that at the food-web scale may seem hopelessly complex.[38]

Discussion

In early 2004, President Bush announced a renewed effort for space exploration. Noteworthy among the proposals was a return to the Moon by 2018. Beyond missions to the Moon, NASA officially announced in December 2006 that it was planning to build a permanent moon base. The objective is to have the base fully functional by 2024. The Moon base would serve many purposes, including serving as a test bed for a more ambitious goal, announced in September 2007, of putting a man on Mars by 2037.

These objectives are laudable and will represent tremendous achievements for engineering and science. However, if we consider our inability to successfully engineer the Biosphere 2 project, much progress remains to be made if we hope to succeed. Indeed, maturation, if not outright creation, of a discipline of ecological engineering must be a top priority if we are to achieve the stated goals.

The emergence of ecological engineering as a mature and successful discipline will not be easy. First, we must make significant progress in taking ecology from an observational science to a predictive one. Consider again the issue of invasive species in the Great Lakes. There is much speculation regarding the impact of introduction of the Asian carp, yet there exists no robust means to predict what the effects will truly be. An experimental test of such a scenario is environmentally unwise; thus, the development of theoretical and computational means to model such processes provides the strongest opportunity to transform the predictive capabilities of ecology.

Ecosystems are complex systems. We cannot hope to understand their working principles by studying the components in isolation, just as we cannot optimize the output of a chemical plant without a systems perspective. Clearly, it is in our best interest to keep the biosphere operating properly. However, before we reach a point where we can effectively manage fisheries (food production), prevent accumulation of toxins (quality control), or reduce indiscriminate species extinctions (operate sustainably), we must develop unifying frameworks in the same manner as nearly a century ago chemical engineering conceptually unified the study of different industries. The question is, are we open to the challenge?

Acknowledgments

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