

Applying Evolutionary Meta-Strategies to Human Problems



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1 Introduction

Humans are facing increasingly intricate, entwined, and encompassing problems. Climate change (Raftery et al. 2017; Mora et al. 2017), deepening planetary toxicity (Cribb 2017) affecting our intelligence (Bratsberg and Rogeberg 2018) and genetic expression (Baccarelli and Bollati 2009), and the anthropogenic Sixth Extinction (Ceballos et al. 2017) are only some of the obvious, existential threats *Homo sapiens* faces as a civilization and a species.

While engineers plan Mars colonies unlikely to be successful due to our unacknowledged ignorance of how to successfully construct ecosystems, it is time complexity scientists face a difficult truth: because the problems confronting humanity are multiscale, multidisciplinary, nonlinear, and interdependent, they fall in the wheelhouse of complexity science. Complexity science is necessary, and perhaps obligated, to address humanity's complex future.

Complexity scientists in concert with specialists provide the best chance of addressing our entangled global problems. They are experienced in high-dimensional systems and are armed with concepts that apply across scales and disciplines. They have the theoretical, mathematical, and computational skills to map real world problems onto realistic models. Complexity science offers perspectives, approaches, and models to offset the common domain- and field-specific bias of "If all I have is a hammer, everything looks like a nail."

Support: No institutional support or grant was used for this work

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Except for climate models, there have been insufficient attempts by scientists to model real-world high-dimensional systems in all their parameters. Complexity scientists, with their roots in physics and mathematics, prefer to model the least complex or realistic version possible when faced with the real-world intricacy of biology, neuroscience, and ecology, often for reasons of mathematical tractability. Accurate analysis is then hampered by these facile models because difficult or unfamiliar structures, functions, and dynamics have been left out. Due to the tendency to study models based on over-simplistic derivations of real-world systems, even experts are often seeking answers in the wrong part of the state space. Questionable conclusions are then drawn from these low-dimensional creations as nonexperts assume they map accurately to reality.

The increasing hyper-specialization of scientific disciplines into largely inaccessible “silos” also causes a lack of integration into Complex Systems (CS) science of the multitude of emergent principles seen in actual complex systems. Brains, organisms, ecosystems, biochemical networks, etc. offer their own lessons, concepts, and mathematics – but CS approaches rarely utilize them, except in a highly abstracted form such as “deep machine learning.” Yet uniting the critical lessons of true complex systems with formalizations from theoretical CS and other fields is most likely to yield principles for creating sustainable societal structures.

One major blind spot blocks success in this arena: few models of our planetary reality explicitly include *humans*, the species with the largest disruptive impact on our natural complex systems. Without understanding the roles or the impacts humanity is having, scientists (and nations) remain unaware of the effects and the problems caused by human presence and their cascaded and convergent impacts.

Currently, we have neither clear, standardized methods to delineate ecological and abiotic interactions with humans, nor standard protocols to marry theory and data with policy. In fact, scientists are often unable to even format some problems across the many disciplines involved, due primarily to hyper-specialization, preventing both insight and solutions. The resulting lack of cross-disciplinary integrators/interpreters hinders overall progress tremendously. More generally it is problematic because no one – neither science, industry, nor government – rewards truly “big picture” or “Seven Generations” (Graham 2008) thinking. Quite simply, *it is no one’s job to care about our whole world system.*

And yet is the entire planet that is in disequilibrium, and likely to destabilize most local equilibria.

What scientists *can* do is explore how evolutionarily sustainable, working complex systems (like ecologies, biochemical networks, or real neurons) map onto our human-created ones and vice-versa. Using real systems and the principles we derive from them as guides, we can more clearly grasp what we as a species have done, and learn what is necessary to construct, rebuild, and sustain functioning planetary systems.

2 A Preliminary Framework for Encapsulating Human Problems

Solving humanity's entangled multiscale problems require understanding both their genesis and their context. For that, we need clear and relatively comprehensive delineations of our systems, both natural and human-created. To correctly describe these relationships, we need tools – methods, frameworks, mathematics. Most importantly, we require the conceptual tools and cognitive scope necessary to acquire new comprehension of our planet's dynamic interdependencies, and their network solutions.

Ecological network representations are a good starting place for a particularly useful dynamic and functional description of our systems, even if they lack critical components. From early work on community ecology (Paine 1966, 1980; Cohen 1978; Ives et al. 1999, Williams and Martinez 2000) to path analysis (Shipley 1997), ecosystem dynamics (Ulanowicz 1997), and other formulations (Levins 1975; Patten 1995; Shachak and Jones 1995), ecological network models have embraced approaches from the abstract (e.g., McRae et al. 2008) to highly detailed models focused on specific relationships and aspects of functional ecological roles such as predator, prey, parasite, and pollinator (e.g., Proulx et al. 2005). The latter address functional subsets of ecosystem components and/or dynamics, for instance, food webs (Dunne et al. 2002) and pollination networks (Jordano 1987; Kaiser-Bunbury et al. 2010). While these models often tell us enough to model species and sometimes systems behavior, as each address only a subset of flow types or classes of interaction, many aspects of dynamics and informatics are unknown.

A minority of ecological network models (e.g., Odum 1983; Andrewartha and Birch 1984) have attempted to encompass whole systems, but for purposes of general prediction, action, and policy, few if any have addressed Earth's most pressing problem: humans, and the impacts of their behaviors and institutions on its species and systems.

Given ecology's nonmathematical roots, high-dimensionality, and generally empirical approach, theoretical ecology has had a difficult time parsing large-scale models, at least for our purposes. We can use knowledge from other systems to escape this limitation.

3 Mapping from Neurons to Species

Many biological networks have core similarities, although this fact is largely unexplored. Neurons have been quite well-studied, in comparison to global (or even local) eco-dynamics, though we cannot yet model more than a fraction of their behaviors. But as individual entities, the basic dynamics of neurons are

well-described by the Hodgkin-Huxley equations (Hodgkin and Huxley 1952). Together with a huge amount of data, this enables us to note core structure and function (see Fig. 1a, b). Most neurons, for instance, maintain a narrow resting membrane potential range of only 15–30 mV of their total 150 mV range of

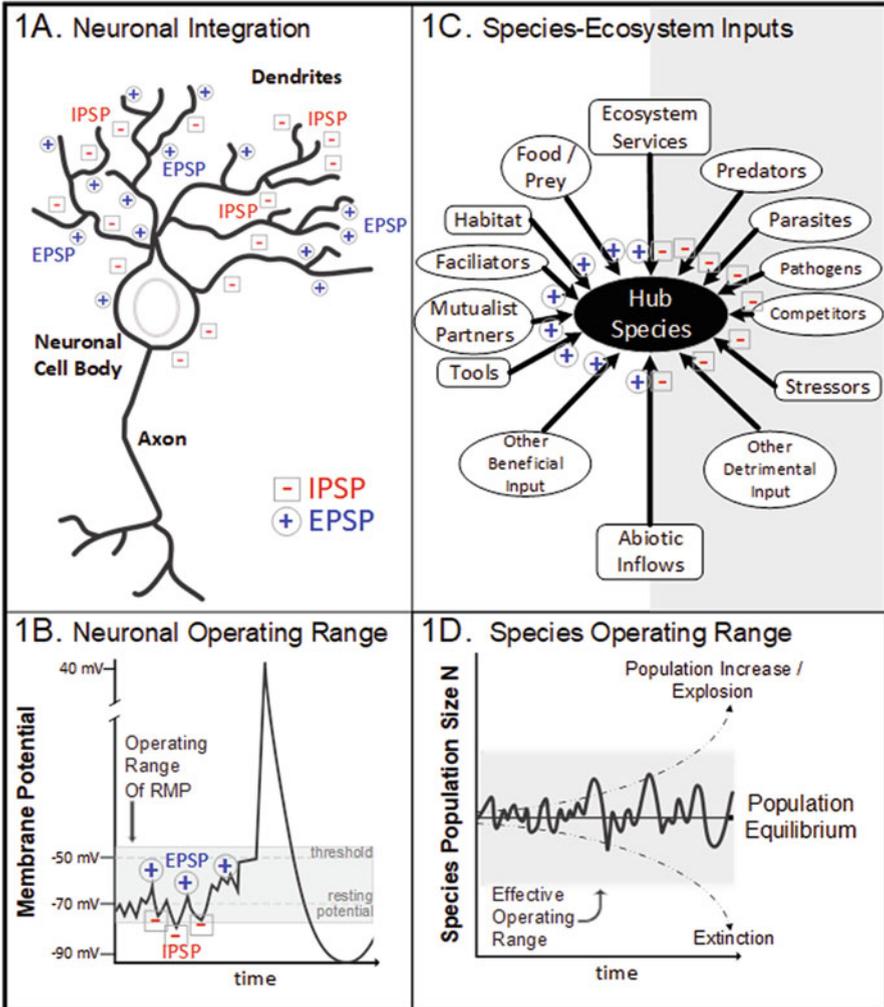


Fig. 1 Deriving concepts from one complex system for application to another. Neurons and species both have their behavior constrained within a narrow range when embedded within a network which provides them with hundreds or more inputs of many classes and dynamics. (a) Neuronal integration. Physiological dynamics of a typical neuron mean it has a resting potential (equilibrium state) of between ~ -70 mV and -55 mV. This resting potential is displaced by positive inputs in the form of EPSPs (excitatory postsynaptic potentials) which move the neuron closer to its threshold for triggering an action potential or spike or by negative inputs in the form of IPSPs (inhibitory postsynaptic potentials) which move the neuron further away from its threshold for triggering a spike. (b) Neuronal operating range.

action. Only in this narrow range does the physiology allow the integration of hundreds/thousands of positive and negative inputs to generate an action potential (spike) capable of signaling to its recipients (ibid). We can infer that as a norm, a neuron's positive (excitatory – moving the membrane potential closer to a spike) and negative (inhibitory – moving the membrane potential further from a spike) inputs are roughly balanced, to keep it within operating range.

Comparisons between real neurons and species (or other entities) in ecological networks are not spurious, as they share many key attributes:

1. Multiple kinds of input types to both neurons and species. Many different classes, pattern, and dynamical response types mean complex structure and complex dynamics are likely.
2. Highly detailed circuitry (in neuroscience, “microcircuitry”) may best describe both neural systems, comprised by circuits of classes of neurons and their dynamical relations, and ecosystems, described by circuits of classes of species and their dynamical relations.
3. Opposing positive and negative inputs to each individual entity/node/species constrain dynamical behavior to a subset of the space necessary to maintain a specific operating range. This balancing act at multiple scales is a function of sustainable network structure.
4. Individual entities, whether neurons or species, have a wider behavioral landscape outside of the network than within it; that is, network inputs act to constrain the behavior of these complex entities when they exist within their networks.

Fig. 1 (continued) Summation of both excitatory and inhibitory inputs yield constant variation around the resting membrane potential. Much lower or higher than this, physiological dynamics prevent the possibility of an action potential. In other words, to signal other cells with an action potential, a neuron must stay within a small operating range. What maintains the cell within this operating range is an ongoing relative balance of excitatory (+) and inhibitory (–) postsynaptic potentials which drive the neuron's voltage up and down within the range until it hits threshold and signals with a spike. **(c)** Simple species-ecosystem inputs. A simple visual description of an ecological network that attempts to incorporate all classes of interaction and impact that would alter the population (or other metric) of the entity-in-question or hub species, over time. Functionally beneficial (+) and detrimental (–) inputs roughly balance to create an operating range for a given “species-in-question”/entity, referred to as the hub species as we temporarily treat it as the network's central node. Note that the beneficial or detrimental nature of an input is not intrinsic, but can change if thresholds, magnitude of the flow, or other state changes occur. Water, for example, is necessary and beneficial – but too much is negative and detrimental. Specific functions govern most interactions. **(d)** Integration of the ecocircuitry at any given “hub” organism, species, or entity includes all types of biotic and abiotic interactions. Positive interactions (inputs of energy, materials, and services and information which increase the hub species' population) and negative interactions that decrease the hub species' population, must balance to produce a stable population. If negative inputs predominate over the long term, extinction results; if positive inputs predominate, the species population increases, perhaps exponentially. But species populations also must have an operating range to exist successfully in the long term – dip too low in population, and vulnerability to extinction from a freak virus or storm increases; explosive population growth, and feedback mechanisms (such as depletion of prey) endangers the population

As inputs/constraints are lost, neuron/species/entities may express previously unseen and unexpected behaviors.

While the mapping between neurons and species is not exact, these four analogous aspects of system structure and dynamics form a quite powerful mapping, one whose insights may be drawn on in constructing more realistic ecological and ecocircuitry models.

3.1 A First, Oversimplified Model of “Ecocircuitry”

We propose a theoretical framework for modeling all species, ecosystems, and connected planetary systems. The idea of *ecocircuitry* we define as a realistic ecological network that includes all classes of interaction and behavior, and specific dynamics where possible, but is explicitly extended to include:

- *Homo sapiens*, as a species, and its behaviors, actions, and institutions. This includes all human-related network presences that impact flows of energy, materials, services, and information. We include not merely the physical, such as infrastructure, government, roads, art, corporations, farming, and so on, but beliefs, knowledge, and culture.
- Abiotic input flows. All nonliving things are classed as abiotic – solar heat, rivers, rocks, clouds, weather, and geochemical cycles. Organisms need abiotic inputs (like heat, water), but those inputs have different – yet incorporable – dynamics than species do under evolutionary selection. Many human institutions can usefully be treated as abiotic agents/flows according to their desired optimization and dynamics. We outline this simplest basis for an ecocircuitry model (see Fig. 1c, d) for its illustrative principles.

Ecocircuitry network models include flows of energy, material, services, and information through many classes of inputs/outputs both biotic and abiotic. We posit that the population size of any species varies with the convergence of its network interactions. Since ecologists most often study pairwise interactions, it is difficult to grasp the large number and diversity of inputs to any species-in-question, but inferring the need to maintain a particular operating range, Eq. 1 shows that

$$f\left(\sum_{i=1}^n b_i\right) = f\left(\sum_{j=1}^m d_j\right) \quad (1)$$

the functional weighting of the sum of all beneficial (positive) inputs, b , must be approximately equal to the functional weighting of the sum of all detrimental (negative) inputs, d . The subscript i enumerates each individual input of the set of n positive inputs, while j does the same for the set of m negative inputs. All functions f

indicate generic, not specific, functions. Applications of functional weightings will be discussed in an upcoming paper.

Equation 2 thus describes the simplest approach to population change over time for the species-in-question/hub of population size N :

$$dN/dt = f \left(\left(\sum_{i=1}^n b_i \right) - \left(\sum_{j=1}^m d_j \right) \right) \quad (2)$$

where the change in the species population, dN/dt , is a function of the sum of the beneficial, or positive inputs, b , minus the sum of the detrimental, or negative inputs, d .

The hub species is simply the species that is considered the 0th order of the network for a given analysis, with its inputs being 1st order, the inputs of its 1st order inputs being 2nd order, etc. – all within an N -dimensional ecocircuitry network. Parsing the network through the perspective of a single defined “species” as the central hub allows us to grasp the details of ecological and human connectivity patterns beyond food webs, and enables examination of specific evolutionary strategies arising from either particular species interactions or more general rules that govern such interactions.

Examining ecocircuitry through multiple points of view from many individual species supports a form of parallax, necessary due to the size and complexity of these networks. Not only does this provide multiple viewpoints on the system, but it suggests that complete summations over all species’ perspectives may be necessary to accurately assess both unintended consequences and true costs and benefits.

For ecocircuits the interrelated flows of the system (energy/material/information/services) are the drivers of key metrics of “success” – whether increase in population for a species, decrease in infant mortality for a nation, increase in profits for a corporation, and so on – and are addressed in a forthcoming paper.

3.2 A Realistic Basis of Ecocircuitry: Modeling Entities from Organisms to Institutions with a Double Binary Model

Some may say that the simple ecocircuitry model is elegant – but it is too simple. It conveys well the idea of integration of inputs of varying sign or impact, but it is not correct for determining changes in species population, as it portrays only half of the flows. The reason for that is our mapping from neurons to species is useful but incomplete.

Neurobiological network models are primarily focused only on information (spike) output, so flows of materials, energy, and services are ignored in neural equations. This is a primary difference and misses not only classes of input critical to

species and ecosystem flows, but their outputs, which are losses of both positive and negative flows. These losses are not a separate and unchanging output like a spike, but rather reflect the loss of both *desired* things – like nutrients or sensors – as well as the loss of *undesired* things, like waste or toxins. An accurate network description of species population thus changes over time as flows wax and wane, requiring a more sophisticated approach that reflects dynamic structure-function relationships.

We call the incorporation of this four-part model of ecocircuitry, the double binary model (see Fig. 2). The double binary model incorporates all aspects of the simple ecocircuitry model, but the dynamics governing it reflect the reality of flows through entities more accurately. We can thus improve the simple binary model above – a balance of beneficial and detrimental inputs *only* – by adding outputs. This produces the “double binary” of both:

- Beneficial and detrimental inputs (positive and negative “gains”)
- The output of benefits and detriments (positive and negative “losses”)

In this case, it is the balance of the net positive effect (beneficial inputs + detrimental outputs) minus the net negative effect (detrimental inputs + beneficial outputs) that helps all individual entities, thus their species, and thus the system, maintain dynamic stability.

Equation 3 shows that net positive effects must roughly equal net negative effects:

$$f\left(\left(\sum_{i=1}^n b_i\right) + \left(\sum_{h=1}^q d_h\right)\right) = f\left(\left(\sum_{j=1}^m d_j\right) + \left(\sum_{k=1}^p b_k\right)\right) \quad (3)$$

The functional weighting of the sum of all beneficial (positive) inputs, b_i , plus the sum of all detrimental (negative) outputs, d_h , must be approximately equal to the functional weighting of the sum of all detrimental (negative) inputs, d_j , plus the sum of all beneficial (positive) outputs, b_k . The subscript i enumerates each individual input of the set of n beneficial inputs, with subscript k enumerates each individual output of the set of p beneficial outputs; the subscript j enumerates each individual input of the set of m detrimental inputs, with subscript h enumerates each individual output of the set of q detrimental outputs.

Equation 4 now describes the simplest realistic approach to population change over time for any “hub” species of population size N :

$$dN/dt = f\left(\left(\sum_{i=1}^n b_i\right) + \left(\sum_{h=1}^q d_h\right)\right) - f\left(\left(\sum_{j=1}^m d_j\right) + \left(\sum_{k=1}^p b_k\right)\right) \quad (4)$$

where the change in the species population, dN/dt , is a function of the sum of the net positive effect (beneficial inputs + detrimental outputs) minus the sum of the net negative effect (detrimental inputs + beneficial outputs).

The power of this approach is that it offers a proxy for the stability of an ecological network dependent on each individual species’ capacity to optimize

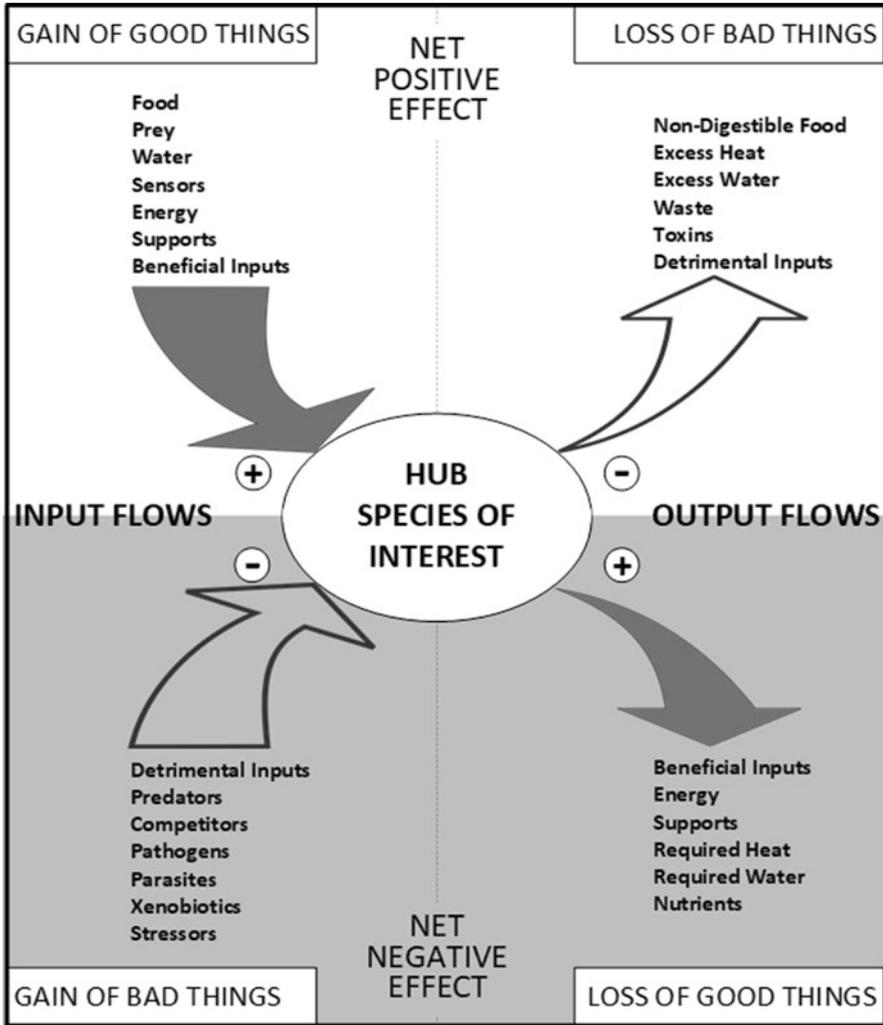


Fig. 2 Ecocircuitry: the double binary model. This ecocircuitry model consists of four quadrants with differing dynamics: two are sets of input flows (intrinsically, added to the hub entity/species-in-question), one beneficial, generating a net positive effect, and one detrimental, producing a net negative effect. The other two are sets of output flows (output, intrinsically subtracted from the hub), one being detrimental things lost, for a net positive effect, and the other beneficial things lost, yielding a net negative effect

its own network inputs by maximizing positive inflows and negative outflows while minimizing negative inflows and positive outflows. Its predators and other interaction partners simultaneously seek to optimize their own network flows. Species networked together in both support and opposition can effectively balance the positive and negative inputs to each species over the long term. Over a densely

linked network of species, these coupled dynamics result in a system of adaptive “checks and balances” that tends to homeostatically maintain ecosystem structure and function, often despite frequent and substantial perturbations.

Therefore, neither ecological networks nor the evolutionary strategies they produce is a matter of simple accounting. Rather than merely a “pollinator,” a hummingbird is a multifaceted entity that is predator, prey, mutualist, competitor, and many more things – depending on its interactor. What is valuable to one organism – e.g., dung to the dung beetle – may be useless or even negative to the organism that released it. Thus, the network should be viewed through “the eyes” of many species to begin to grasp the multifaceted ecosystem we live in. An insistence on using a single currency in ecocircuitry (as with “money”) means a myriad of weighting functions and their interactive impacts will likely be missed as we look through any single lens. An insistence on viewing our system only through the eyes of *Homo sapiens* is equally short-sighted. “Getting rid of all vermin” means one thing to a human with a house, and something different to an ecosystem for which that entity serves multiple purposes.

3.3 Core Evolutionary Strategies and Meta-Strategies: Manipulating the Ecocircuitry

General evolutionary strategies emerge from this model, and intrinsically map to the handling of beneficial and detrimental inputs and outputs. Van Valen (1973) and successors have famously described the “Red Queen” evolutionary dynamic, in which any given species must constantly adapt that they may persist against other, coexisting species that are engaged in similar optimization processes. The connectivity of species in ecological networks and the resulting convergent input to each species implies that all species also continually evolve strategies for manipulating their ecological network inputs. Such strategies may also illuminate evolutionary vs. developmental patterns of gene flow, particularly environmental-epigenetic interactions and resulting natural selection.

Gremillion and Brown (2001) outline core strategies used by any species to optimize its flows:

- (i) Altering the number of flows or connections
- (ii) Altering the magnitude of flows
- (iii) Decreasing the variance of all flows

Thus the core evolutionary strategies as shown in the simple model are quite straightforward *optimizations* in many dimensions:

1. Increase the number and magnitude of beneficial connections. For example, increase nourishment through foraging, locate assistive medicines, and plant nonlocal crops.

2. Decrease the magnitude and/or number of detrimental/connections. For example, kill predators, fight pathogens, and decrease stressors.
3. Decrease the variance of all flows. As variability itself induces instability, it can lead to temporary or permanent vulnerability to extinction. The best example is that of *storage* – which reduces vulnerability to changing conditions; e.g., hibernation, squirrel nut storage, and from grain silos and cisterns, to libraries as stable, external cognitive storage.

3.4 *Meta-Strategies*

Evolutionary meta-strategies are *strategies for managing the core evolutionary strategies* – managing the number, magnitude, variance, and type of inputs and outputs to the organism, entity, or species in question. A human in ancient Sumeria, for instance, would insure the number of his beneficial inputs is increasing, by using meta-strategies of language and mathematics to explicitly track them. To speed up the output of negative pathogens, human meta-strategies include growing herbal medicines, using chemistry to produce pharmaceuticals, building hospitals. Many, many more such things are meta-strategies. It is on the shoulders of these inventions, insights, and constructions that humanity has built civilization.

There is a vast and uncounted array of such meta-strategies – in part because new ones are constantly being invented. Money/currency, for instance, was invented a long time ago. Banking *systems* took much longer; credit cards another 500 years after that; Bitcoin, the first cryptocurrency, was only invented in 2009. And that is just skimming one class of meta-strategy. A brief and quite incomplete list of some types of meta-strategies may be illustrative:

- Defense: from sharpened sticks and stone axes to predator drones and missiles
- Food/prey: fire, cooking, beneficial spices, stoves and kitchen gadgets, recipes, and gear
- Energy: use of wood, passive solar, fossil fuels, hydro, geothermal, active solar, wind, tidal
- Teaching: stories, apprenticeships, guilds, formal education, hyperspecialized experts
- Water: from baskets to vases to irrigation to plumbing, wells, and vast infrastructure
- Cognitive meta-strategies: concepts, language, money, printing, science, and computation

Corporations and businesses, governments, schools, bureaucracies, and newspapers – even social manners, cultural norms, and languages, in their cognitive-shaping capacities – all impact input/output flows through their cognitive effect on decisions and actions.

But what clearly differentiates a strategy from a meta-strategy?

Say you are a foraging creature. You find a new berry in the forest; you eat it – that is a core strategy: increase your number of positive inputs. But your reaction tells you it is poisonous. If you are a regular forest critter, you never look at that berry again; it is useless for purposes of your core evolutionary strategies. If you are a human, however, you gather that berry, cook it down, and coat your arrows with it. You have now effectively laid the “poison” meta-strategy onto the “throwing spear” meta-strategy, for amplified success in both hunting and protection.

Indirect approaches like this often have multiple benefits: they extend distance from threat, physical or otherwise (many fighting implements do this); they provide leverage through distance; and they are amplifiers of power and capacity to enable needed adaptation, in the same way the Colt 0.45 pistol in the Old West was called “the Equalizer” (Moss 2016). Similarly, the poisoned berry amplifies the lethality, and therefore the operative range of the arrow, as well as broadening the effective target area.

But *Homo sapiens* is hardly the only species to implement innovative meta-strategies, just the most obvious one. We now know a great number of species are tool-users – and tools are the basic meta-strategy. Beyond this, ants keep other ants as slaves (Wilson 1975) and engage in agriculture (Mueller et al. 1998). The externalization of labor and assurance of food sources through cultivation are two meta-strategies used often by *Homo sapiens*. Eco-engineering species like beavers and termites as well as builders of nests and structures are using meta-strategies in combining biotic and abiotic materials to enhance their survival and reproduction. Even coyotes following humans into populated areas, where a fertile foraging ground is available, is a meta-strategy, for it does not use a direct signal to find food, but an indirect one: where humans move is indicative of an abundance of largely uncontested food, in centralized garbage cans.

Once some portion of ecocircuitry is formulated in the double binary model, specific useful evolutionary strategies become clear. Here we outline four examples of meta-strategies that can help generate understanding and solutions, to illustrate potential classes of application.

3.5 Applying Evolutionary Meta-Strategies

Meta-strategies are the water we swim in unknowingly, built on the insights and integration of past and present. Everyone uses meta-strategies many times a day, whether a refrigerator or a meditation technique, a TV show or formal manners, for these and many more form the network of strategies in which humans have become ecological specialists at being *generalists* – of learning, generalizing, and

specializing – though the creation of tools and infrastructure are not just for action but for observation, analysis, or playing. *Meta* here can imply meta-meta-meta-meta: layers and levels of utility, benefit, advantage, making the world one in which complexity can be handled more easily if we peel back levels rather than ignore them. A few examples below help illuminate the scope and application of the meta-strategy concept.

4 Meta-Strategy: Perceiving Higher-Order Impacts Through Darwinian Algebra

One of the major problems in ecology and other real-world systems is the complexity of the network itself, and our inability to see, with straightforward logic, far out into the network. This means that humans seeking to understand ecological networks (including *Homo sapiens*) are not easily able to assess the consequences of their actions on the systems in which they play such a powerful role, save for their closest connections and obvious impact.

Thus, humans are rarely able to determine the net effects, beneficial or detrimental, of our manipulations of the ecocircuitry, whether in draining a swamp or in large-scale spraying of mosquito pesticides. Nor do we really try: the combinatorics and higher-order interactions are too complex without a relatively intuitive and logical framework, method, or training.

An ecocircuitry formulation allows us to use the properties of the network, creating a kind of commutative “Darwinian algebra.” For instance, we all can grasp the meaning of “the enemy of my enemy is my friend” – either because of personal example or because it is a logical axiom of $[-] [-] = [+]$. Using such notation, we can look at interactions at increasing distance and still derive the sign of the impact on the hub species as shown in Fig. 3. While the actual strength or weighting of an input is clearly important, a first approximation of the *sign* of higher-order impacts – negative or positive – is most critical, as it enables us to track the unexpected relationship of cats to clover (see Fig. 3).

This small slice of Darwin’s local ecocircuitry shows how a more functionally inclusive and realistic incorporation of multiple kinds of inputs/outputs can illuminate higher-order interactions – generally termed “indirect” in ecology – of facilitation and interference. Figure 3 does not, of course, show the summation of all inputs/outputs at each stage in isolating this part of the red clover ecocircuitry; but it does give us a means to look far out into the network for cascade effects, unintended consequences, costs or benefits, or even interactions between multiple distant indirect inputs or outputs. We can then generate methods by which we may better sense and measure these interactions, invaluable as typically, these are quite difficult as both a network problem and as a practical ecosystem issue.

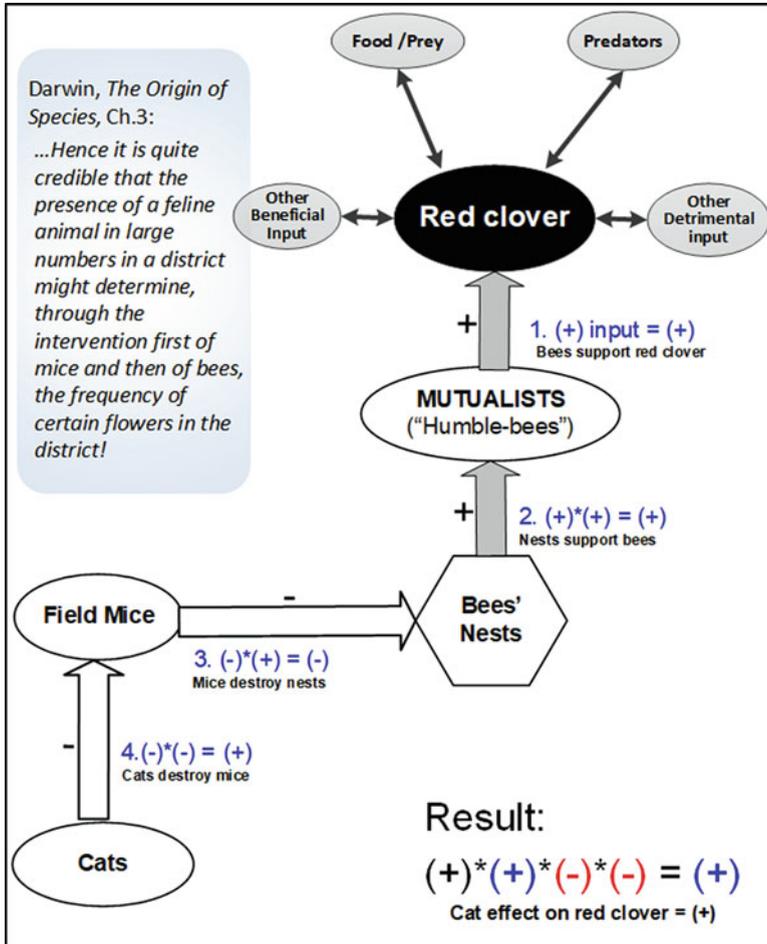


Fig. 3 The enemy of my friend’s enemy is my friend: Darwinian “algebra” explains how cats are the friends of red clover. Starting from the species-in-question (hub), Red clover. Its necessary pollination by humblebees (1). The supportive structure of humblebees’ nests – which thereby support clover as well (2). Field mice destroy the nests of the bees which pollinate the clover and are therefore its enemy (3). Cats, in this ecosystem, prey on mice and are thereby functional facilitators of clover (4). (Quote: p. 72 of the 2nd edition of Darwin’s *Origin of Species* [1859])

5 Meta-Strategy: Language Shapes Acceptance of Climate Change

“Evolutionary meta-strategy,” as we coin it, is meant to be fairly encompassing. It includes not only physical expressions of action like trade, art, engineering, agriculture, transport, etc., but also psychological and cognitive meta-strategies such

as education, belief structures, and language. The latter leads directly to a multitude of additional strategies such as writing, printing, universities, and science, but also socio-political manipulation and propaganda.

Arguably the most successful capture of real-world complexity is climate change modeling. Brown and Caldeira (2017) found in that arena that the more real system structure/dynamics are included, the more predictive the models. But more facts have not changed all minds. The issue of climate change, intersecting as it does with human nature and cognition, clarifies how correct use of cognitive-*linguistic* meta-strategies could change perception, belief, decision-making, and thus policies. Possible solutions to the dangers of climate change in the United States are currently stymied by “climate change deniers.” Examination of this phenomena shows it may be purely a cognitive/linguistic effect, underscoring the need for *strategic* use of meta-strategies.

The initial proclamation of “global warming” led to assumptions that such warming could be ameliorated by turning up the air-conditioning, while record low winter temperatures were interpreted to contradict the entire idea. When terminology switched to “climate change,” deniers comforted themselves with the truths that “change happens” and “climate’s always changing,” irrelevant as those facts are to anthropogenic climate change. In both cases the “linguaging” used conveyed the *cause* of many problems to professionals, but lack of context meant no alarm for deniers. Indeed, both original terms sound, to those without context, as though the problem is overstated.

Analysis of this situation through the eyes of meta-strategy can be summed up by the Einstein quote: “Language is an implement of reasoning, in the tool sense of the word.” For “climate change,” it shows us that the terminology used must instead be indicative of the *effect and its impact* – as impacts are what evolutionary strategies optimize.

We propose substituting the term “extreme climate instability” for its cognitive and emotional connotations as it is far more difficult to shrug off or deny. “Extreme climate instability” indicates both a severity not indicated by previous terms and introduces the concept of climate “instability,” a far more alarming concept than change and highly indicative of a far larger scale of weather and even social uncertainty. Moreover, “instability” actually matches the weather (climate) being seen by the average person, so that personal experience and scientific labeling are coherent, not at odds. This is using a meta-strategy to convey contextualized information on which individuals are more motivated to act and thus forestall disaster.

6 Meta-Strategy: Honeybees and the Cause of Colony Collapse Disorder (CCD)

Honeybees (*Apis mellifera*) must apply the core evolutionary strategies to numerous input flows, for their set of potential and realized interactions with other species includes mutualistic pollination relationships with dozens of species of flowering plants (Wilson 1971; Seeley 1997); many nectivorous competitors (Nabhan and Buchmann 1997); and diverse predators, parasites, and diseases (Gould and Gould 1988; Schmid-Hempel 1998).

A large number of causes have been proposed to cause CCD (Steinhauer et al. 2018). Figure 4 shows that massive changes in the ecocircuitry of honeybees have recently occurred in both the number and magnitude of all types of flow, virtually all of them antithetical to the honeybee's self-optimization (Stone et al. 2017). Largely due to *Homo sapiens*, these changes occur in virtually every arena of the circuit. Beneficial inputs (e.g., habitat and plant species for nectar and pollen) are diminished by human activity, while the loss of detrimental things (e.g., toxins) is diminished; detrimental inputs (e.g., pollutions) are increased, while the loss of positive things (e.g., energy, nutrients) is increased. These changes yield an increase in net negative effects and a decrease in net positive effects. Taken together, this degree of negative *convergent causation*, wherein a number of interacting components together produce nonlinear (and often unpredictable) effects, could likely result in colony collapse.

Yet it is possible that the search for a single cause has led to our inability to effectively act. Due to its multicausal nature, we are far less likely to identify *the* cause of CCD. But by believing there to be a single cause, we continue to seek one, and this has prevented us from recognizing that it is the combined negative effects of anthropogenic action, including, as just one factor, the creation of honeybee monocultures brittle to environmental variance, that has enabled this crisis.

While we seek a solitary cause to CCD, when it is far more likely to be the result of multiple convergent causes, we will not find “the answer” nor stop the unnecessary demise of one of our most important pollinators. To halt CCD, many of humanity's net negative effects on *Apis mellifera* may have to be stopped or remedied, at many points of the honeybee's ecocircuitry.

7 Meta-Strategy: *Homo sapiens* Shapes Entire Networks to Attack Its Enemies

Many of humanity's meta-strategies revolve around *defense* – against predators, parasites, pathogens, and competitors. Unlike the teeth and claws of predators, mankind's weapons have been consciously constructed. Over time *Homo sapiens'* meta-strategies around defense have shown numerous themes and patterns. For example:

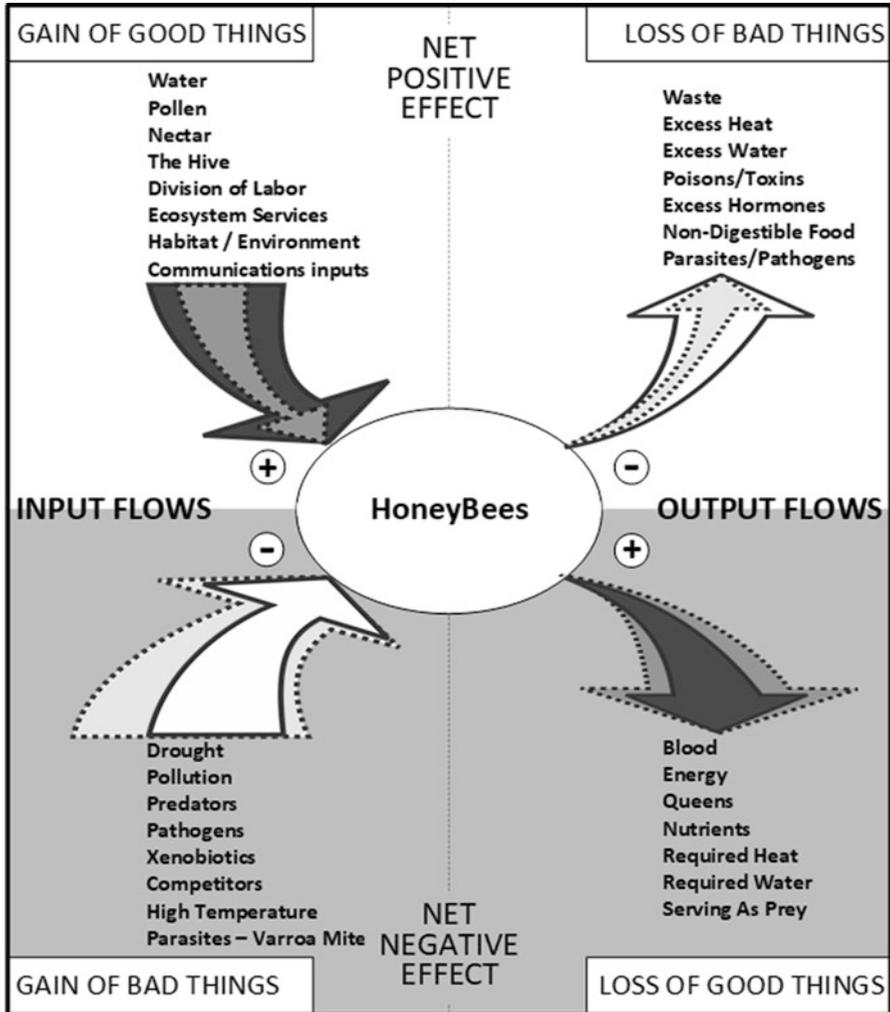


Fig. 4 The ecocircuitry of honeybees in colony collapse disorder. Solid-lined arrows show the normal, balanced flow of inputs and outputs to the honeybee, *Apis mellifera*, while dotted lines show the impact of *Homo sapiens*. Like all species, honeybees try to optimize their own flows, but the status of their inputs and outputs shows that humans have had impacts on most of these flows that are the opposite of that desired for optimization: decreased positive inputs like habitat, nectar and pollen plant species, coupled to increasing negative inputs like xenobiotic pesticides and noise stressors. On the output side, the rejection/loss of negative things like the Varroa mite is decreased due to inhibited immune system function (Evans et al. 2006), while the loss of positive things – nutrients stored in their honey, communication signals interfered with by EMF – creates a net negative effect

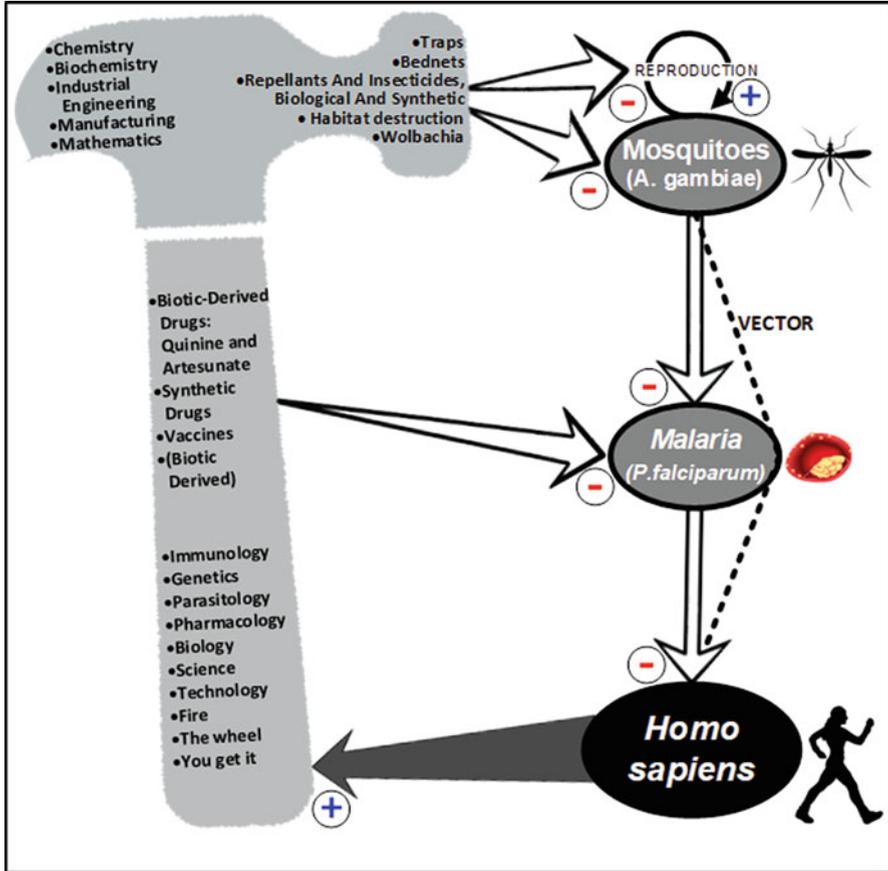


Fig. 5 *Homo sapiens* uses foundational meta-strategies to attack malaria and its vector. Illustration of how humanity has built specific strategies for our defense against known enemies as well as invisible pathogens up from foundational meta-strategies like chemistry and manufacturing. We coordinate ever higher and higher-order meta-strategies in an attempt to completely destroy these enemies

- Introduced distance – spears, catapults, guns, missiles, drones – up to and including physical removal from the site of danger.
- Increased weapon power/effectiveness/leverage – poisons, explosives, projectile rifling.
- Mobility – horses, ships, combat vehicles, airplanes.
- Infrastructure – fortifications, roads, armies/navies, weapons factories, supply chains.
- “Defense” to the point of extinction of the threatening species. While humans have not yet completely extinguished mosquitoes or malaria, Fig. 5 shows many of the ways that we are trying to do so – and the degree to which we will use

huge swathes of our ecocircuitry to try effectively fashioning global-scale threats to other species. Humans have made a great number of species, from wolves to smallpox, go extinct. Other species do not preemptively remove all members of a species it fears – but the efficiency of this defensive strategy has made this not just possible but standard for humanity.

8 Conclusions

Our planet is at an inflection point – a crossroad of direction, potential, and choice. Such transitions are vulnerable: once the giant boulder is rocking, it may be persuaded along many different paths. Ecocircuitry models may provide that direction via a system analysis that incorporates human behavior and institutions into ecological networks encompassing all aspects of the physical world.

Given that humans, their institutions, and their created entities are now essentially the primary “selective agent” for virtually every species on planet Earth, human connectivity and impact on our global ecological networks can no longer be ignored. Indeed, *Homo sapiens* must be explicitly incorporated, for any solutions based on modeling without them are addressing a system that does not currently exist.

Our aim is to actualize the “web of life” – Darwin’s “entangled bank” – as a useful framework, analytic tool, and dynamical model. A description simple enough to be easily comprehensible, yet sufficient to capture the real complexity of the structure/dynamics of human-connected ecologies, from local ecosystems to the planet. A tool that provides the ability to identify patterns, dynamics, and blind spots, and allows researchers to conceive and visualize new *kinds* of solutions.

The massive amount of data emerging on ecosystems and their component entities, flows and dynamics, coupled to new “big data” mining techniques, highlights two specific needs. First, the necessity to organize this data into coherent structures that allow human understanding of their complexity; and second, to create generalizable models that can integrate relevant but currently siloed knowledge across all of our planet and species, including *Homo sapiens*.

Our model posits an overarching extension of ecological models to (1) include multivalent sets of dynamical flows (energy, materials, services and information); and (2) delineate the interactions between species/ecosystems, abiota (all nonliving things, from weather to water) and the human sphere, including its entities, systems, and impacts, from cars to constructs.

Taken together, we define these things as Earth’s ecocircuitry. Optimization imperatives emerge when viewed through this lens: species have generated a vast host of complex evolutionary strategies to manage, manipulate, safeguard, and signal their I/O flows to maximize the beneficial, minimize the detrimental, and stabilize what exists. With all metrics (whether Darwinian, money, status, etc.), these

optimization imperatives point to classes of evolutionary strategy, and further to network-manipulating meta-strategies whose principles can be consciously applied to our planet's problems.

The ecocircuitry model itself *is* such a meta-strategy – a cognitive tool. Humanity and presumably successfully sustained life is supported by huge numbers of meta-strategies of all kinds. With the development of certain “portal” meta-strategies such as language, teaching, and other information sharing, one species, *Homo sapiens*, has illustrated their iterative potential.

Yet a crucial point is that not only have humans used these evolutionary meta-strategies to become who we are, to develop our civilizations and our understanding of reality, but that *we do not recognize them as such*. Critical tools we take for granted – reading and writing, mass printing, libraries and universities, even education, science, and complex systems science itself – are all functional meta-strategies. Yet we do not recognize or understand these strategies as agents of active global change, even as they reshape the world around us.

Thus we can no longer silo concepts and useful models within specialized disciplines, for we run the risk of science – and humanity – using a pixel-by-pixel process on problems requiring *big picture* breadth and depth. Let us gain parallax through multidisciplinary perspectives to generate more accurate, insightful models for solving real-world complex problems, rather than low-dimensional models that will not map to reality sufficiently to be either correct or useful.

We thus urge complexity scientists to go beyond their primary training in nonlinear dynamics, physics, or mathematics, to study natural (neural, biochemical, ecological, physiological) complex systems. The complexity of the latter outpaces simplistic nonlinear-dynamical approaches and places those systems in the wrong part of the state space to find real-world solutions. Instead, complex systems science can and should extract core principles from natural complex systems, and use them to build accurate, integrative models more suitable for both understanding and decision-making.

More specifically, complexity scientists should be challenged to take on cross-cutting problems in collaboration with policy experts, thinkers, and the public, for our current political approach appears incapable of solving the very real and devastating threats which face us. We can – and should – train specialists to be generalists and remind complexity scientists that true complexity does not collapse to $F = ma$, nor is the best system description the most mathematically tractable one. We can – and should – learn to extract principles from specific real systems and apply them generally. And perhaps most importantly, we could – and should – reward big picture, long-plan, interdisciplinary problem solving rather than persist in the short-term approach of “publish-or-perish.”

Perhaps most importantly, let us cease using poorly parsed, low-dimensional models too simplistic to apply to the hard problems, and embrace the high-dimensional interdisciplinary modeling that may be less easily done, but is most urgently needed.

When humans accept their effects on – and responsibility to – our global network, we can choose to use evolutionary meta-strategies such as a nuanced description

of Earth's ecocircuitry, to understand and illuminate *Homo sapiens'* roles in the network of Earth's global ecology. We can then recognize our place and "ecological function" in the planetary system and the impacts our population, behavior, and institutions have within and upon it. Only then can we be empowered to rebuild our vulnerable and damaged networks into more resilient sustainable ones.

It is up to us to solve the problems of our planet with all possible useful strategies, as conscious beings capable of both analyzing the complex networks we exist within, and of taking action to mitigate destructive practices. Responsibility for the future of Earth lies firmly in the hands of *Homo sapiens* – and especially in the hands of those scientists who have the capacity to understand, model, and illustrate both problems *and* solutions. It is time for a conformation change in science that supports our informing the lay public in a clear and unbiased way of the perils and possibilities before us, and together determining how humanity, its tools and its capacities can become the network solution. Complexity science wedded to principles of biology/ecology, economics, evolution, and behavior may offer one of the tools we need to change our present negative trajectory.

Acknowledgments The author would like to thank E. Todd Hochman for his interdisciplinary brainstorming and assistance in graphics design; Professor James H. Brown for his in-depth collaboration on the initial model; Professor Astrid Kodric-Brown for her valuable collaboration on information flows and honeybee systems; John Smart, for his beneficial comments; the Hitchings-Elion Fellowship that funded some of the initial neuroscience thinking that led to this model; and the Department of Biology, UNM, ABQ for their essential support.

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