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NOTE AND COMMENT

Designing sustainable systems using nature's toolbox

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Abstract

Supporting the Earth's human population without destabilizing planetary processes is the central challenge of sustainability science. Key to achieving this goal is designing systems that are robust and resilient to dynamic and unpredictable conditions. Bioinspiration leverages naturally evolved solutions to address such challenges, yet a solution derived from one-to-one correspondence between a natural and artificial challenge can be limited in its broader application. Here we advocate for an approach to nature-inspired design that forgoes mimicking specific solutions in favor of identifying general design features that enable natural systems to function. These features are not specific to any naturally evolved solution and so have the potential to be broadly applied across human-engineered systems to enhance resiliency in ways that do not compromise ecosystem functioning, thereby contributing to sustainable development. As an illustrative example, we show how a well-known bioinspired algorithm that mimics the collective action of ant colonies can be understood in terms of fundamental design features and how these features can in turn be better harnessed to benefit diverse sustainable design initiatives.

Keywords Sustainable design · Bioinspiration · Nature-inspired design · Complex systems · Resilience · Robustness

Introduction

A central challenge of sustainability science is how to meet the needs of Earth's increasingly large human population without destabilizing the ecosystem processes upon which life depends (O'Neill et al. 2018; Raworth 2012). Key to these efforts is developing systems that are able to function across a broad range of operational conditions and that exhibit robustness and resilience to environmental, economic, or social disruption (Folke 2016). Indeed, a core focus of the UN 2030 Agenda's Sustainable Development Goals (SDGs) is developing robust and resilient systems for resource distribution (water: SDG 6; energy: SDG 7), public transportation (SDG 11), and trade (SDGs 9 and 12). Such systems are rarely designed de novo but are constrained by pre-existing infrastructure; economic, social, and political systems; and the social-ecological contexts in which they will operate. Moreover, interdependencies within and among complex systems (ecological, social, or artificial) can cause localized disruptions to have cascading impacts throughout the entire system (Folke 2016; Inoue and Todo 2019). Identifying and implementing features that can buffer the stability of complex designed systems to maintain desirable conditions in the face of uncertainty and disruption is therefore an important goal for sustainability science.

Biological systems face analogous challenges and have evolved mechanisms that allow them to function in a robust and resilient manner across dynamic and unpredictable conditions (Kitano 2002). While evolution does not necessarily select for efficiency, it does select against fragility, leading to examples of emergent solutions across different taxa and different temporal and spatial scales that display flexibility and durability in the face of disturbance (Fefferman 2019). Bioinspiration seeks to leverage these proven solutions to address analogous challenges in human-designed systems

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(Benyus 1997; Fayemi et al. 2017). For example, the capacity of ant and honeybee colonies to collectively solve challenging, multi-parameter problems based on local decision-making by individual workers has generated bioinspired advances that have revolutionized certain subfields of engineering and computer science, including robotics, cybersecurity, and network protocols (Dorigo et al. 2021; Fefferman 2019; Korczynski et al. 2016; O'Shea-Wheller et al. 2021).

There are many examples of naturally evolved solutions for promoting robustness and resilience in complex systems that could likewise be leveraged in sustainable design. Indeed, sustainability thinking has been a driving force behind many biomimicry efforts (Benyus 1997). Optimization algorithms inspired by distributed decision-making in insect colonies have benefited the planning and design of transportation networks (SDG 11) and renewable energy systems (SDG 7) (Ibarra-Rojas et al. 2015; Karaboga et al. 2014; Yu et al. 2012; Zheng et al. 2013). Principles derived from termite mounds have led to the development of energy-efficient architectural cooling systems (SDGs 7 and 11) (Paar and Petutschnigg 2017; Radwan and Osama 2016). Adaptive management approaches for livestock seek to promote grassland conservation and restoration by mimicking the movements of large, free-ranging herds (SDGs 2 and 15) (Teague et al. 2011). As these examples illustrate, biomimicry and related approaches have proven successful in a diverse range of applications and fields (Lepora et al. 2013). However, focusing on case-by-case identification of natural solutions that are directly analogous to a specific design challenge can potentially limit the broader applicability of many bioinspired efforts, as designed solutions may not perform well under challenges that are not also mirrored in the inspiring system. Here, we propose a complementary approach that focuses on abstracting general tools used by nature that contribute to system robustness and resilience, rather than reproducing specific solutions. In other words, by probing the design elements that make biological solutions successful, we can apply them in purposeful nature-inspired design.

To illustrate the utility of this perspective, we present as a case study a widely employed nature-inspired algorithm [ant colony optimization (Dorigo and Stützle 2004)]. We show how the success of this algorithm, which emulates ant foraging behavior, can be more generally understood in terms of design features that are observed repeatedly across naturally evolved systems and in a broad range of environments. We then discuss the benefits that these design features confer to naturally evolved systems and provide initial recommendations for how they may be purposefully leveraged to support sustainability transformations.

Ant colony optimization

Inspired by the ability of foraging ants to collectively identify the shortest path between their nest and a food source (Beckers et al. 1992), ant colony optimization (ACO) is a general method for solving combinatorial optimization problems (Dorigo and Stützle 2004). The set of possible solutions to a specific problem is mapped onto a graph, where the nodes are components of candidate solutions and the edges between nodes are probabilistically traversed by agents (i.e., ants) searching for solutions (i.e., finding food) (Fig. 1a). For example, in designing a public transit network, the nodes and edges can respectively represent stops and routes (Yu et al. 2012). Agents that locate higher quality solutions reinforce traversed edges to increase the likelihood that future agents will select those routes and associated nodes, mimicking the deposition of pheromone trails by ants (Fig. 1b). As a result, although the initial sample of possible solutions is randomly determined, the algorithm converges across iterations on higher quality solutions, as agents are more likely to select and reinforce those edges.

ACO was designed to mimic a specific natural solution: the deposition and following of trail pheromones by ants. However, the algorithm's success can be more generally understood as stemming from two features that are not specific to the trail-following paradigm. First, the algorithm combines independent local samples to produce accurate

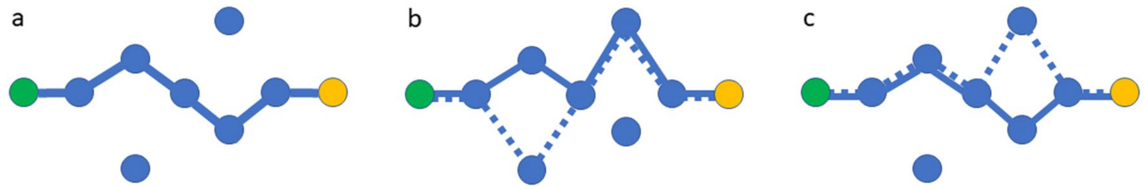

Fig. 1 **a** A set of nodes representing components of potential solutions to an optimization problem. Here, the edges connect the components of the globally optimal solution traversing from a start node (green) to an end node (yellow). **b** Agents probabilistically select paths that indicate candidate solutions. Paths associated with higher-quality solutions are reinforced (indicated by solid edges), making it more likely that subsequent agents will also select those paths. Note, the globally optimal solution in **a** has not yet been located. **c** Agents following the best candidate solution identified in **b** continue to explore alternative options. In this way, the globally optimal solution (indicated by solid edges) is located and reinforced

system-level decisions in a process referred to as 'distributed decision-making.' Although each agent evaluates only its own solution, it communicates high-quality solutions to other agents via trail reinforcement. This increases the likelihood that subsequent agents will locate this solution and, ultimately, for the system to converge on high-quality solutions. However, if agents were strictly bound by the earlier decisions of others, globally optimal solutions could be ignored in favor of the best solution initially identified, discouraging improvement by later agents. To avoid convergence on a suboptimal solution, ACO has agents select edges probabilistically, allowing continued exploration of alternative solutions (potentially incorporating elements of the current best-known solution; Fig. 1c). This probabilistic search feature (one of a suite of features referred to as 'error convergence mechanisms') enables agents to conduct local searches centered around a known solution. Ant colony optimization can thus be understood as a process by which local information is probabilistically sampled and aggregated across agents to produce a globally optimal (or near optimal) solution. Such an approach rapidly eliminates poor solutions from consideration, while simultaneously avoiding an exhaustive search.

ACO has been employed in diverse applications relevant to SDGs, including transportation network design, congestion control, and economic/environmental dispatch problems (Kar 2016). Yet despite its success, ant colony optimization is limited in the problems to which it can be applied, as these problems must match the structure imposed by the trail-following paradigm. However, distributed decision-making and error convergence are not specific to trail-following in ants. By understanding how these and other design features observed in biological systems support system functioning, we can apply them in purposeful design without being constrained by needing to mimic the precise structure of any particular biological solution. In other words, solutions can be designed by focusing not only on what is observed in nature, but on why those solutions have evolved.

A sampling of nature's toolkit

Here we examine in greater detail how the two design features identified above ('distributed decision-making' and 'error convergence') can promote the resilience and robustness of complex systems, whether natural or artificial. With each mechanism, we consider how insights derived from natural systems may inform sustainable design initiatives and provide initial recommendations for their application. It is important to note that these are not the only features employed by natural systems (Table 1; see also the electronic supplementary material) but serve as illustrative examples of the potential utility of this approach.

Distributed decision-making

Leveraging localized decision-making in the design of systems, including energy grids (SDG 7), transport systems (SDG 11), and supply networks (SDGs 9 and 12), can reduce the burden of gathering, storing, and processing system-wide information and allow collective decision-making to be more responsive to local conditions [e.g., during disaster relief (Kruke and Olsen 2012) or adaptive management of ecosystem resources (Armitage et al. 2009)]. Distributed decision-making systems produce successful global outcomes by leveraging complementary sets of information held by decision-makers and enabling them to respond to local conditions rapidly and effectively. Yet designing distributed decision-making systems is not trivial. Important considerations include understanding the information that

Table 1 Examples of design features observed in natural systems

Design feature	Definition	Benefits	Potential applications
Proximate cues	Observable signals that indirectly reflect critical information about a system	More accessible and cost-effective to monitor	Identification of indicators to evaluate SDG progress
Distributed decision-making	Local decisions and/or knowledge is combined to generate accurate global decisions	Greater responsiveness to local conditions Reduced burden of gathering and/or evaluating information	Real-time control for public transit systems Increase stability of distributed supply chains
Predictable patterns in connectivity	Network structure describing paths of potential transfer/contact among discrete elements or agents	Focuses on roles rather than individuals	Flexible and adaptive command and communication
Error convergence	Mechanisms for managing or exploiting errors in observation, decision-making, or communication	Reduced potential for catastrophic outcomes Increased efficiency of local search for global solutions	Reduce risk of market destabilizations

is needed by actors or system components to enable local decision-making and how it can be acquired. Does effective decision-making require communication among actors? If so, how should communication networks be structured to promote effective coordination while remaining robust to disruption (Brintrup et al. 2017; Gallos et al. 2017; Pinter-Wollman et al. 2011)? By studying evolved distributed decision-making systems, it may be possible to extract elements that can be employed in human-engineered systems to facilitate information-sharing, enable flexibility in decision-making, and enhance robustness and resilience under uncertain and dynamic conditions.

An illustrative example of the power of distributed decision-making in nature is the foraging behavior of honeybee colonies (Fig. 2a). A honeybee colony collectively allocates thousands of foragers among multiple flower patches spread across 100 km^2 in proportion to the quality of those patches (Seeley 1995). It achieves this despite a continually changing floral landscape and without any individual forager knowing the value of any other site beyond the one it is exploiting at that moment. This colony-level decision is managed through a robust process involving a unique form of communication known as the waggle dance, by which a honeybee informs others of the location (both direction and distance) of a valuable resource (von Frisch 1967). Waggle dances not only transmit information about resource locations, but also regulate how foragers are distributed across resources in the following manner. Foragers who dance to direct other bees to a particular site decide whether or not to dance based on direct indicators of resource quality (e.g., nectar sweetness, distance from the hive) and on the ability of the colony to process the increased nectar flow from additional dance-recruited foragers (Seeley 1992, 1994). Dancing therefore acts as an integrative cue that reflects the relative value of the advertised foraging patch to the colony, with foragers dancing more vigorously and for longer for patches judged to be of higher quality (Seeley 1994). These longer and more vigorous dances attract more followers than shorter, less vigorous dances. Consequently, high quality sites elicit robust, long-lasting dances with a strong likelihood of attracting and recruiting nestmates to those sites (Seeley 1995). In this way, decision-making by individual foragers about the production of waggle dances leads to decision-making at the colony level about where to forage, such that the colony collectively prioritizes high quality food resources.

The robustness of distributed decision-making in the honeybee foraging system is due to several elements, including independent evaluation of options, amplification of high-quality alternatives, and negative feedbacks that ensure that a resource does not attract more foragers than it can support. Such features, either together or independently, can likewise be employed to promote sustainability, resilience, and robustness in human-engineered systems. An industrial ecosystem, for example, can be viewed as a distributed system in which the overall system dynamics emerge from the decisions and behavior of individual businesses, each acting on varying subsets of information (Pathak et al. 2007). Drawing on knowledge of how distributed decision-making systems function in nature could aid in identifying and addressing obstacles that limit the transition of industrial systems from a linear model (i.e., ‘take, make, waste’) towards a circular industrial ecosystem that limits waste production by retaining, reusing, and repurposing resources and materials as long as possible (Ryen et al. 2018; Tate et al. 2019). Although seemingly obvious, a relative dearth of businesses undertaking processes that support circularity (e.g., dismantling products, reclaiming/recycling materials) indicates that these processes are evaluated as less profitable than continued extraction and use of raw materials from the environment. Yet recognition of this fact also highlights that an industrial system can be primed to shift towards circularity if processes that support circularity are made relatively more attractive, due to individual businesses discovering and exploiting the resulting novel opportunities.

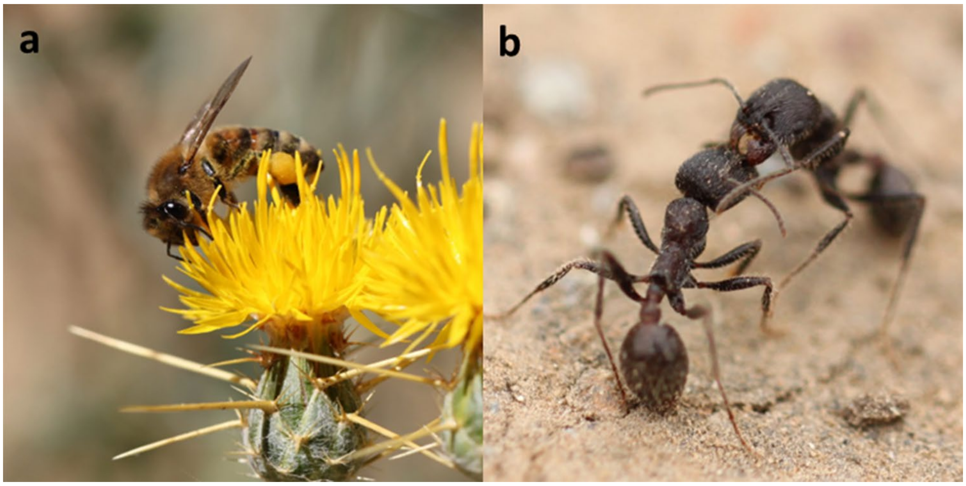

Fig. 2 **a** Honeybee (*Apis mellifera*) foraging on a flower. **b** An interaction between two *Veromessor andrei* harvester ant workers. Photos by Noa Pinter-Wollman

Proposed measures to achieve this include the development of secondary material banks and material passports that provide information on and access to reclaimed or recycled materials, coupled with changes to production design to enable easier decomposition of products at the end of their lifespan so that materials can be reclaimed for further use (Ryen et al. 2018; Tate et al. 2019). Implementing systems that enable information-sharing and coordination of material flows among businesses can likewise serve to amplify profitable opportunities for utilizing secondary materials. Indeed, some businesses have adopted such a role themselves, serving as information and material brokers within a broader industrial ecosystem (Tate et al. 2019).

Error convergence

Even with access to high quality information, errors in observation, decision-making, communication, or prediction inevitably occur. Understanding the mechanisms by which biological systems manage or even exploit such errors may yield insights that can facilitate purposeful implementation of error convergence features in designed systems. Determining whether errors are self-correcting or self-compounding is critical. For instance, within supply networks, demand forecasts often over- or undershoot production relative to actual demand (Datta and Christopher 2011). In a phenomenon referred to as the ‘bullwhip effect’, as one moves upstream from customers to suppliers, errors in forecasted demand are often replicated and then compounded at each level, leading to increasingly greater mismatches between production and actual demand (Lee et al. 2004). Such distortions contribute to supply chain inefficiencies and can have destabilizing effects on access to vital supplies (relevant to SDGs 9 and 12)—e.g., surges in forecasted demand for personal protective equipment and ventilators in response to the COVID-19 pandemic likely contributed to mismatches between regional access to medical supplies and relative need (Patrinley et al. 2020). By studying natural systems, we may better understand how to guard against or even leverage inevitable local errors to buffer the success of global outcomes and improve system-wide robustness and resilience.

As with distributed decision-making, honeybee and ant colonies provide useful examples of naturally evolved solutions for managing, or even exploiting, errors (e.g., in communication, navigation, or decision-making). For instance, honeybees that follow a waggle dance often fail to find the advertised location, yet these navigational errors are often bounded within a relatively narrow range around the advertised location (Riley et al. 2005). Such errors thus enable local searches within regions that are more likely to contain high quality resources (analogous to the probabilistic search feature employed by ACO). Social insect colonies also offer useful examples of how to mitigate against self-compounding errors within complex social systems. Within an insect colony, frequent communication among workers (Fig. 2b) means that the effects of an error made by one individual can potentially propagate throughout the colony. For example, ants alert nestmates when the colony is under attack to mount a collective colony defense, but false alarms can occur (Guo et al. 2022). What keeps these false alarm signals from propagating and leading to costly colony-level responses that pull workers away from essential tasks to a non-existent threat? In the harvester ant (*Pogonomyrmex californicus*), a combination of physical interactions and short-lived individual responses acts to rapidly curtail the propagation of false alarms (Guo et al. 2022). The widespread mobilization of unalarmed ants through interaction requires sustained efforts by alarmed ants. However, such sustained activity is unlikely to occur during a false alarm because the alarm response of each ant rapidly dissipates in the absence of reinforcement by an actual threat.

Understanding the principles that underpin the success of naturally evolved error convergence mechanisms can enable their purposeful implementation for sustainable design. One such application could be the development of decision tools to facilitate adaptive co-management of ecosystem resources (Armitage et al. 2009). A key element of adaptive co-management is enabling participants to flexibly test and use a diversity of management measures (e.g., quotas, educational programs, novel technologies) to identify those that are currently most effective within their local ecological, social, economic, and cultural contexts (Armitage et al. 2009; DeFries and Nagendra 2017), akin to a local search of an adaptive landscape. Understanding how natural systems leverage error convergence to effectively conduct such searches can aid in developing policies and tools to facilitate these efforts. For instance, as discussed above, errors in naturally evolved systems are often guided by prior information and are therefore bounded, increasing the likelihood that they will yield beneficial information that can potentially lead to higher quality solutions (Fefferman 2019). Thus, policies can be put into place that support innovation, development, and testing of novel management approaches, guided by local, traditional, and institutional knowledge, as part of a system-wide iterative and parallel search for effective management solutions. Once such a solution is located, how can it be effectively disseminated throughout the broader co-management network? Studies of social insect colonies indicate that the ability to collectively redirect efforts away from established low-quality solutions towards newly discovered higher-quality ones strongly depends on the dynamics governing communication and decision-making (Detrain and Deneubourg 2008). For example, when confronted with two foraging trails (i.e., solutions), ant decision-making can be strongly non-linear—i.e., small differences in pheromone strength between two trails can lead to large differences in relative usage (Detrain and Deneubourg 2008). Such a system makes it difficult to redirect efforts to a newly discovered resource, even when it is superior to other known options. Within adaptive co-management schemes, political, social, and institutional inertia can likewise limit participants' ability to flexibly enact policy changes in response to new information (DeFries and Nagendra 2017; Fabricius and Currie 2015). Turning to natural systems that do not face such difficulties (e.g., collective foraging in honeybees) may suggest novel organizational or management tools to counteract such tendencies and thereby promote greater flexibility and responsiveness in ecosystem management.

A new approach to bioinspired design

The promise of bioinspired design is to draw from solutions in evolved biological systems to resolve complex problems in human-designed systems in ways that support (or at least do not disrupt) ecosystem processes (Benyus 1997; Fayemi et al. 2017; Fefferman 2019). Biomimicry approaches have been successfully applied in a variety of contexts and fields, yet many previous bioinspired efforts have been unnecessarily limited by seeking one-to-one correspondences between biological systems and a particular applied challenge. We advocate for an alternative, complementary approach to nature-inspired design that uses general, fundamental principles of biological function rather than delving into specifics. Such an approach has the potential to lead to bioinspired designs that are broadly applicable and which can contribute to the robustness and resilience of human-engineered systems in ways that promote sustainable development. Here, we have highlighted some of the tools employed by nature (e.g., distributed decision-making; error convergence) that can be applied broadly to other problems. These features are certainly not the only ones (Fefferman 2019). By studying the ways in which evolved systems cope with different environmental conditions and unpredictable disruptions, we may uncover principles that can be purposefully applied in novel designs. We hope to motivate new discussions and collaborations among biologists, mathematicians, engineers, and other applied scientists that can lead to new approaches towards building a more sustainable future.

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Data availability No datasets were generated or analyzed as part of this work.

Declarations

Conflict of interest We have no conflicts of interest to declare with regard to this work.

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