zq35

VOL 1 | 2024

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Cover art
Cover: Cerrado | Photo: Daniel Mira, 2024 | pp. 2-3/pp. 88-89: La Gomera impressions | Photo: mini_malist (I'm not back), 2017 | Flickr cc

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Web
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ISSN
1927-8314

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Editorial

One of the most exciting aspects of bio-inspired design is the creation of new conceptual paradigms in research, design and manufacturing. Some of these paradigms can leave us breathless and can renew our hope in progress for mankind. New ways of thinking can be developed from many different activities, from observation to experimentation to user experience. In this issue we share several examples of people who have looked a little differently at the challenges before them and come up with surprising new insights

Shoshannah Jacobs et al, in *Can Manufactured Ecosystems fully replace ecosystem services?* explore what would be required to replace the current ecosystem services that Nature provides with synthetic versions and invite our readers to join them in this investigation.

Hassan et al, at the Bio-inspired Systems Laboratory at Texas A & M University examine natural models for resilient and sustainable engineering systems in *Nature as a Blueprint for Resilient and Sustainable Engineering Systems*. They use Ecological Network Analysis to review system level engineering, citing foci on detritivores, predator/prey pathway redundancies, and actor nestedness.

In her article about Leafcutter Ants, *The Collective Ant Brain*, Margie Patlak blends personal experience and research for her study of an area of fascination for her, the collective behavior and emergent properties of ant colony behavior.

Our *Robotany* article highlights the Mazzolai research group at the Italian Institute of Technology in Genoa, Italy, and their plant-inspired and ground-breaking work on robotics with a twist. They study and mimic the way plants grow, react and respond to external stimuli in order to advance new ways of thinking about what it means to move.

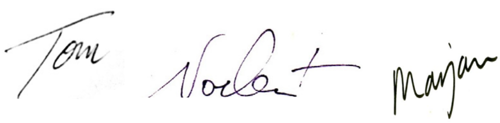
In our interview and portfolio, *Art-thinking: Rediscovering the Connection with Nature through Poiésis*, artist Daniel Mira asks that we look at the world through a novel lens. Inspired by the Cerrado, or Brazilian Savannah, and Goethe, he sees poiesis (creation or formation) as a way of reconnecting with Nature. Directly experiencing phenomena in the savannah, he has translated these into a typology of forms and feelings for the public: dot, line and plane; polarities; intensifications.

Finally, we are pleased to announce the launch of a ZQ Letters section on the Zygote Quarterly website. We start with Pete Foley's comments on the Lucchesi/

Ogden interview in *ZQ34* based on Foley's observations on the current Las Vegas water management. Please share with us your perspectives on recent issues, connections among past articles, and short explorations of issues relevant to *Zygote Quarterly*. Your letters will be published after a short review separate from regular issues. If you have any ideas for ZQ Letters, please contact us at info@zqjournal.org.

We hope the stories in this issue prompt you to think a little differently about the world around you and how the study of Nature can enrich all our lives.

Happy reading! ×



Tom, Norbert, and Marjan

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Leafcutter ant forager (*Atta* sp.) bringing home a fern fragment with a minor "hitchhiker" ant that defends against parasitiod flies on the returning journey.
Photo courtesy of Peter R. Marting

Article

The Collective Ant Brain

Margie Patlak

The Collective Ant Brain
Margie Patlak

When I was a small child my center of gravity was closer to the ground, making me more attuned to happenings there. Perhaps that's why I loved watching ants in action. Placing obstacles in their way, I tried unsuccessfully to disrupt their relentless conga lines to food sources. And I watched with big eyes and a little person's envy as they carried large burdens: food crumbs and insects much bigger than themselves. I often saw them carting away their dead brethren, which I found touching.

On rainy days I couldn't observe the ants and instead spent hours drawing detailed imaginings of their colonies underground, replete with ants cooking in kitchens, ants watching tv in living rooms, ants sleeping in bedrooms, even ants corralled in cribs. I could only view them through the restrictive lens of my own human experience. Once I entered my teen years, I outgrew this fascination with the ant world and started to see these insects more as annoyances than marvelous beings underfoot.

That changed decades later when I visited the Peruvian Amazon.

In a steaming jungle, after craning my sweaty neck to glimpse all those fast-moving feathered jewels flying above me, I happened to look down on the ground. There I was startled to see a train of leafcutter ants parading chartreuse shards of foliage above rust-colored soil while winding their way around our feet. These ants in televised nature shows had charmed me for years, but I didn't fully appreciate how they existed beyond the screen until that moment. Feeling like someone who has spotted a movie star in the flesh walking down the street, I shouted out to my husband "Oh my God, look!," pointing to the minute celebrities underfoot.

These tropical superstars were not gathering leaf fragments to pad their nests, nor could they directly eat the bits of green, but rather had much more sophisticated uses for them. After these foraging leafcutter ants cut and carry leaves back to their nests, gardening leafcutter ants chew those leaf fragments into a mulch fertilized with their own feces. This mulch supports a fungus totally dependent on the ants' tending and grows nowhere else in nature outside of leafcutter ant colonies. I knew there were some animals so domesticated they can't survive without the care of their human tenders, but never imagined there were fungi totally dependent on ant farmers!

The leafcutter ants' farming operation also includes other specialists, in addition to the foragers and the farmers: those that harvest and distribute the fungus to colony

A leafcutter ant (*Atta* sp.) with a leaf fragment.
Photo courtesy of Peter R. Marting

Leafcutter ant forager (*Atta* sp.) returning with a fern fragment | Photo courtesy of Peter R. Marting

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members, those called “supersoldiers” whose bulging heads and strong and sharp jaws defend the farm and nearby terrain from outside intrusions, and, perhaps the most incredible specialty of all, tiny bodyguards for the foraging ants, which are continually besieged by parasitic gnats. These poor ant foragers are unable, while carrying their fungal fodder, to prevent gnats from laying eggs on their necks, eggs that hatch into worms, worms that burrow into their heads and feast on their brains. This is dining that doesn’t bode well for the ants. So, to defend the foraging ants from these swarms of gnats, smaller ants from the colony accompany the larger ones on their foraging trips. During the return home to the nest, these tiny ants ride the leaf shards, kicking away any gnats that come close with their hind legs like two-year-olds having temper tantrums.

Leafcutter ants began farming millions of years before humans. Just as the steady source of grains and other domesticated crops enabled humans to multiply their numbers exponentially, the fungal crops that the leafcutter ants farm made them one of the most successful ants in the tropics. They are so numerous there in the Amazon that we could see ant highways

How do leafcutter ants cut leaves off of trees?
Video still: Antlab, 2020 (https://www.youtube.com/watch?v=yqdD4lc20Wk)

their teeny tiny feet had collectively worn into the forest floor. The mother queen of the colony can give birth to as many as 200 million workers—half the size of the U.S. human population! Due primarily to the prolific leafcutter ants, there are a million times more ants than humans in the world, and all the ants living on Earth weigh about as much as all humans. Even in our densest cities, like New York, there are more ants than people.

One leafcutter ant colony can strip a tree of its leaves or destroy a family garden overnight, such that the early Portuguese settlers in the Brazilian Amazon were said to say "either Brazil will conquer the ants, or the ants will conquer Brazil". Seeing the long stream of leafcutter ants below us, each carrying a bit of foliage, I could understand the sentiment.

Although we didn't get to see them, the leafcutter ants' own settlements are awe-inspiring: huge underground cities extending as far as 15 feet below ground. Their complex labyrinth comprises thousands of chambers interconnected by intricate tunneling. The ants constantly carry nesting matter from the bottom of their nests up to the surface, replacing it with fresh nesting material. This turnover dries out the more humid interior of the nest, preventing unwanted mold formation and providing air conditioning for underground cities far more sophisticated than any of the juvenile drawings I made of ant colonies.

Leafcutter ants aren't the only ant species showing such sophisticated cooperative behaviors. There are thatching ants of the Pacific Northwest: ant cowboys that herd aphids to new grazing grounds so they can gather up and feed their young the nutrient-rich honeydew the aphids excrete while sucking on plant stems. And when water levels rise around the nests of fire ants in the southern United States, they join their bodies together to create living rafts which float until water levels subside and they can find drier ground. Army ants of Central and South America form living bridges by linking legs and jaws when they encounter a stream or deep crevice. There are also the marvelous tropical weaver ants who stitch their nests in the tree canopy by shuttling silk-producing aphids back and forth from leaf to leaf. "Such tool use may be explained away as a series of simple behaviors strung together to create the appearance of careful planning and rational thought, but it gives one pause with respect to our place in the universe," noted entomologist May Berenbaum in her book *Bugs in the System*.

Leafcutter ant worker (*Acromyrmex* sp.) attempting to retrieve a large seed | Photo courtesy of Peter R. Marting

The Collective Ant Brain

Margie Patlak

A new leafcutter foundress queen (*Atta sexdens*) beginning her nest excavation
and a leafcutter ant worker (*Acromyrmex* sp.)
Photos courtesy of Peter R. Marting

It gives me more than pause and instead totally flummoxes! How can ants' pinhead-sized brains foster such seemingly complex behavior akin to ours?

By working together.

Although volume-wise it is a million times smaller than the human brain, an ant colony of more than one million individuals, common in nature, could collectively have more brain cells and thus more computing power than the human brain, noted ant researcher Ewa J. Godzińska. In other words, each individual ant has a tiny brain. But these brains linked together can function like a nervous system to accomplish great feats.

Ant expert Dr. Deborah Gordon of Stanford University also notes that ant behavior is carried out without any central control. Although ant colonies have queens that lay all the eggs, these queens do not rule over anything beyond the reproductive success of their colonies, she stressed in a March 2014 TED talk, "There's no management. No ant directs the behavior of any other ant." Then how do millions of ants in a colony organize themselves so effectively when I could not even get my small family to mobilize for our next activity when on vacation? It boggles my mind.

Dr. Gordon thought so, too, and embarked on a quest to figure out how ants can accomplish such astonishing feats of cooperative and seemingly intelligent behavior without a boss telling them what to do. She has spent 20 years studying the behavior of the same colonies of harvester ants in an Arizona desert to better understand how these ants carry out their complex operations, including gathering and storing seeds, tending their young, and maintaining their nest.

Gordon has been meticulous, if not obsessive, about these ants. She has used Japanese markers to label each individual insect among her cadre of more than 10,000 ants. Gordon has poked fiber optic tubes into the ants' nests so she can observe their behavior and count how many ants were doing various tasks. I was fascinated watching her video of returning foraging ants being greeted by their nest mates, who high-fived them with their antennae. It was a window into a hidden world right under our feet that I could have previously only imagined.

For example, at any given time, about half the ants in the colony are loafing around and can be put to work doing whatever tasks need to be done. When Gordon blocked the nest entrance of colonies with bunches of toothpicks, more ants rallied

A new leafcutter queen (*Atta sexdens*) looking for a good site to start a colony | Photo courtesy of Peter R. Marting

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to the nest maintenance task, pushing the toothpicks to the outer edge of the nest mound. But this made less ant power available for food foraging. If she put out a pile of tasty millet seeds in front of the nest, the opposite happened. How did the ants assess who was doing what in order to rally to the cause? Did they count how many of them were doing each task? Sort of.

She has also discovered that the aroma (chemical signature) that accrues on ants foraging differs from that of those maintaining the nest. Ants use their antennae to detect those distinctive odors, tapping each ant they encounter with their smelling appendages like blind people tapping what's around them with their white canes. "The ant uses the pattern of its antennal contacts, the rate at which it meets ants of other tasks, in deciding what to do," Gordon said in her March 2014 TED talk. "The pattern itself is the message."

A busy trail of *Atta cephalotes* leafcutter ants at La Selva, Costa Rica
Photo: Alex Wild, 2020 | Antwiki

Gordon notes that the human brain works in remarkably similar ways as this ant information network. Imagine ants as individual brain cells called neurons. It takes a buildup of electrical signaling from your multiple neurons relaying information on what's in the pantry and fridge to trigger you to go grocery shopping. Similarly, an ant may decide to go foraging based on how many contacts it makes with foraging ants returning to the nest. No one neuron decides to trigger the behavior, just like no one ant decides how many foragers to send out of the colony. Control is collectively distributed over the entire ant colony rather than centralized in a select cadre. There is no boss. All the more than 14,000 known species of ants live in colonies but there isn't a leader among them. Instead they have the equivalent of a collective brain.

That collective ant brain is not only adept at dividing up the number of ants devoted to various tasks according to need, but at efficiently exploring and bringing back to their nests new food sources using the shortest possible paths. The first foraging ants to leave a nest in search of food take rather random and rambling paths. But once they nab some food, they then return to their nests using the shortest routes possible, all the while laying down pheromone trails that attract other ants. Because the roundabout route pheromones evaporate before the shorter route pheromones, subsequent foraging ants are more likely to take the shorter routes in their own expeditions and be more efficient.

Recognizing the usefulness of mimicking such efficient ant foraging behavior when designing the quickest routes to deliver goods to multiple stores from central warehouses, the Swiss company AntOptima developed a computer modeling program that deploys digital ants to determine optimal daily delivery plans for the trucks of a major Swiss supermarket chain. In a test of this program involving distributing 52,000 pallets to 6800 stores over a period of 20 days, the computer program took only 5 minutes to find a distribution solution that human planners took more than three hours to develop. Marco Dorigo and Gianni Di Caro at the Dalle Molle Institute for Artificial Intelligence in Lagano, Switzerland developed a similar program to efficiently route information through mobile communication networks, such as those the armed forces use.

Ants may also help us improve space exploration, with decentralized ant-inspired robot swarms using a computer program developed by Qi Lu, Melanie Moses, and Joshua Hecker at the University of New Mexico. Gordon explained that, rather than deploy a single rover to comb the surface of another planet, it might make more sense to explore a new territory the way foraging ants do with multiple interacting rovers (ant equivalents) simultaneously roaming an area.

Meanwhile, back on Earth, with the rise of smart city initiatives, ant algorithms may play a critical role in optimizing traffic flow, public transportation, and other urban logistics. "Using only simple interactions, ant colonies have been performing amazing feats for more than 130 million years." Gordon advises, "We have a lot to learn from them." ×

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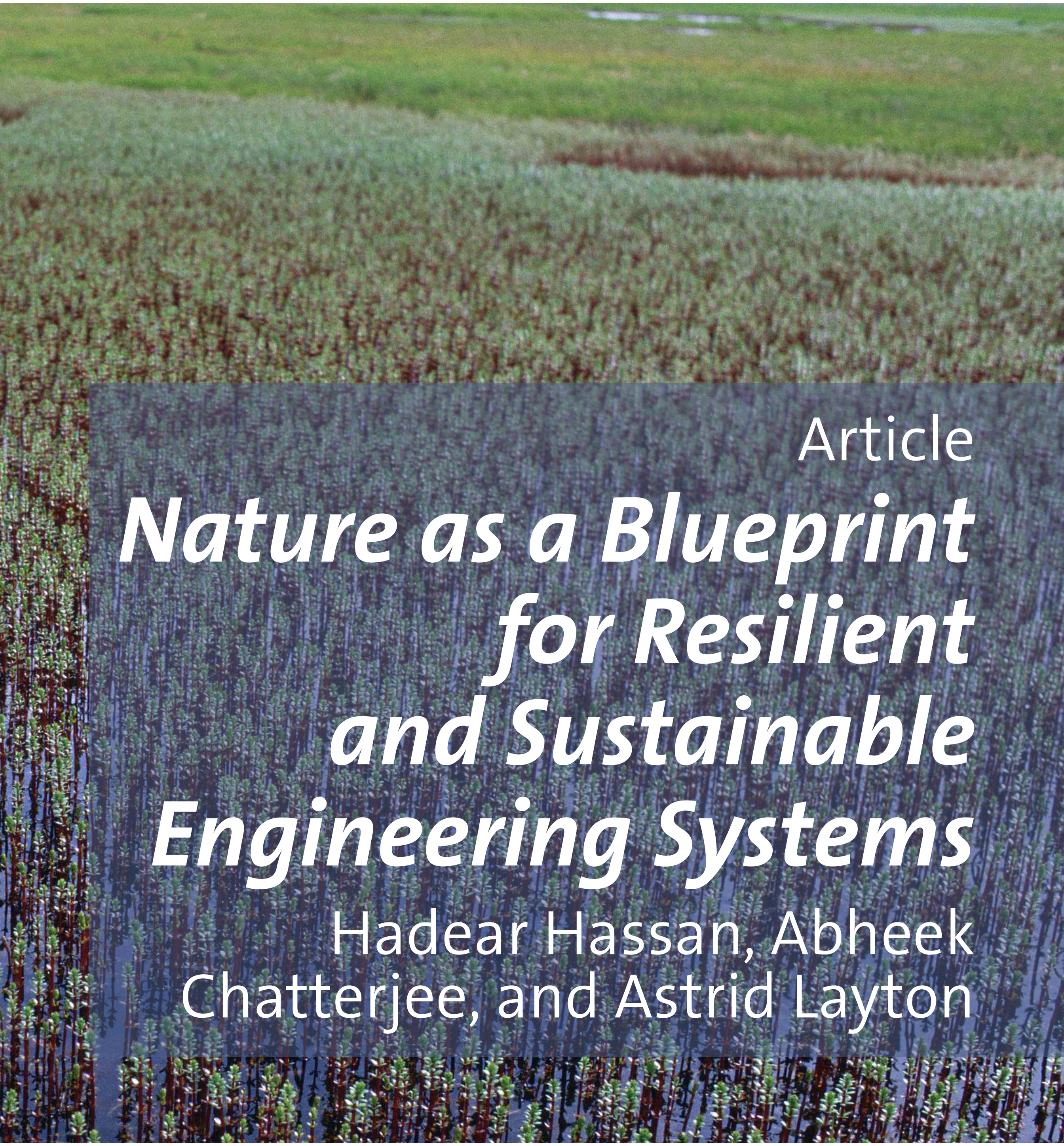
Tundra wetland with plants reflected in water
Photo: John and Karen Hollingsworth, U.S. Fish and Wildlife Service, 2013 | Wikimedia Commons



Article

Nature as a Blueprint for Resilient and Sustainable Engineering Systems

Hadear Hassan, Abheek Chatterjee, and Astrid Layton

Nature as a Blueprint for Resilient and Sustainable Engineering Systems

Hadear Hassan, Abheek Chatterjee, and Astrid Layton

Systems form the backbone of our daily existence, providing the essentials we rely on. Whether it's the water flowing through our taps, roads for our travels, or any of the products we use, they all depend on human-designed systems. Their effectiveness hinges on their design; poorly crafted systems can result in many negative outcomes. For instance, in North America water networks suffer significant losses, with estimates that 20-50% of water is wasted due to leaks [1]. Similarly, poor transportation networks create unbearable traffic: the average U.S. driver in 2022 spent approximately 51 hours stuck in traffic [2]. Manufacturing systems are responsible for emitting one-fifth of global carbon emissions [3], adding to global environmental degradation. These types of challenges however can be addressed through *thoughtful system design*.

Adding to the complexity, however, this *thoughtful* system design must also simultaneously address system resilience and sustainability. (For this article, sustainability is defined by the Brundtland Report as the ability to meet current needs without compromising the needs of the future [4].) An environmentally friendly system that doesn't consider resilience may not survive the next hurricane. Without resilience, sustainability is, well, *unsustainable*. A system that doesn't consider long-term resource availability and environmental and social costs may accomplish its tasks but may lose access to resources in the future. The consideration of one without the other can no longer produce a "good" system. While researchers are actively developing tools and knowledge to better support the inclusion of sustainability or resilience early in the system design process, these remain more common as late-stage "if possible" add-on goals.

Nature's long-surviving ecosystems show us a way to design systems that are **both** sustainable and resilient. An ecosystem is made up of species that operate with a focus on their own survival rather than the collective good of the system. These same species, however, also play crucial roles in maintaining ecosystem-level resources, resulting in a network that simultaneously maximizes system-level value extraction and individual species' survival. Additionally, these ecosystems have evolved to survive unexpected disturbances, many of which have significant overlap with the types of disasters we as humans also deal with (floods, droughts, fires, etc.). Learning, understanding, and translating principles of ecosystems' sustainability and resilience into engineering system design offers a route for human systems to balance the management of shared resources with individual (e.g., community, company, household) needs. Studying how biological systems operate sustainably while being adaptable to disruptions, and how those two characteristics can support each other, can glean valuable insights for human systems. This is especially interesting because sustainability and resilience are traditionally studied separately - a practice that neglects their interconnectedness. Nature, with its robust and sustainable complex systems, offers a model for integrating these two goals. Embracing a systems-oriented approach inspired by nature can help humans navigate the convergence of sustainability and resilience.

Biological ecosystems and human-engineered networks are both systems that exchange materials and/or energy; the interactions and structures that emerge from the material and energy transfers among the constituent systems within human-engineered networks are akin to predator-prey relationships or trophic level exchanges in biological ecosystems. Our research team in the Bio-inspired Systems Lab (BiSSL) works on quantitatively transferring these types of principles from biological ecosystems to enhance the design of human-engineered systems. The research done in BiSSL aims to address challenges in engineering systems, leading to cost savings, enhanced efficiency and resilience, and reduced environmental impact. We are working towards translating biological system concepts into practical design tools and guidelines for human systems, fostering their tangible implementation. One example is the use of Ecological Network Analysis (ENA), a mathematical framework ecologists use to study the structural and functional characteristics of biological ecosystems. Applying ENA to human-engineered systems has paved the way for innovative "inspired by nature" advancements in system-level sustainability and resilience. This article provides an overview of three ecological strategies (resource cycling, the Window of Vitality, and actor nestedness) used by our team to examine engineering systems.

One of the aspects we study is *resource cycling in ecological food webs and the significance of detritivore/decomposer species*. Resources in biological ecosystems circulate in a way that minimizes waste and maximizes value retention within a system's boundaries. Detritivores, or species that feed on dead organic matter (detritus) and reintroduce nutrients into the ecosystem, play a critical role in enabling this high resource value utilization. Ecosystems have evolved to maximize the number of species a set amount of resources can support,

Mycena interrupta, Myrtle Forest, Collinsvale, Tasmania, Australia | Photo: JJ Harrison, 2010 | Wikimedia Commons

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sustainably developing the overall system. Tundra ecosystems, for example, have bacteria and fungi that play a key role in decomposing dead plant matter and releasing nutrients into the soil, facilitating plant growth in these cold, nutrient-poor environments [5]. Our examination of industrial networks applies this ecological concept to human-made systems. A detritivore-type actor refers to entities actively engaged (both receiving and producing) in waste or byproduct management activities such as composting, recovery, reuse, and recycling, those involved in agricultural practices such as farming, landscaping, and greenhouse operations, and in general process low-quality materials/energy in a way that makes it available again by the rest of the network [6]. Using ENA metrics coupled with average biological ecosystem values to design a carpet recycling network found that the bio-inspired approach could outperform traditional cost and emissions considerations [6]. Enhancing cycling in particular by adjusting user-producer links within a human network shifts the network towards the value retention characteristic of natural ecosystems [7]. Active detritivore-type actors in human networks can notably enhance sustainability and resilience by promoting value retention and diversification of resources. They can also move resource availability to more local sources. For example, from 2016-2019 the US received 90% of its lithium needs from international sources [8], considered by some a national security issue [9]. Lithium, however, is a mineral that could be extracted in large quantities from used batteries that are disposed of inside the US, creating a US-based source of this critical mineral. These types of findings instill optimism for developing economically and ecologically sustainable and resilient human systems, with potential applications across scales from industrial water systems to city economies. The integration of ENA into human network design offers a quantifiable approach to bolster sustainability and resilience, aligning human systems with the effectiveness and adaptability observed in biological ecosystems while improving economic profitability (a goal of circular economy [10], which has been gaining traction recently).

Another aspect studied in BiSSL is the ecological finding that long-surviving biological ecosystems have evolved to have their predator-prey interactions uniquely balance pathway constraints and redundancies, called the *ecological "Window of Vitality"* (explained in Fig. 1). Ecologists hypothesize that this balance supports both effective resource utilization for growth and development under normal conditions and the system's ability to survive, adapt, and recover from unexpected disruptions. [11]

Our work demonstrates the utility of the ecological Window of Vitality for the design of human systems across various domains, including power grids, water infrastructure networks, manufacturing systems, and supply chains. Traditionally designed power grids, for example, tend to produce much more rigid (or pathway-constrained, Fig. 1-right) systems than biological ecosystems, falling well outside of the ecological DoSO range. Incorporating biologically-inspired redundancy moves these systems into the Window, resulting in grids that better adjust to network demands when unexpected disturbances of any type occur. The approach also highlights that the strategic and informed use of biological system principles can enhance resilience without significant costs; resultant benefits such as a 40% decrease in real power lost are achieved with only a marginal 5% cost increase compared to traditional methods

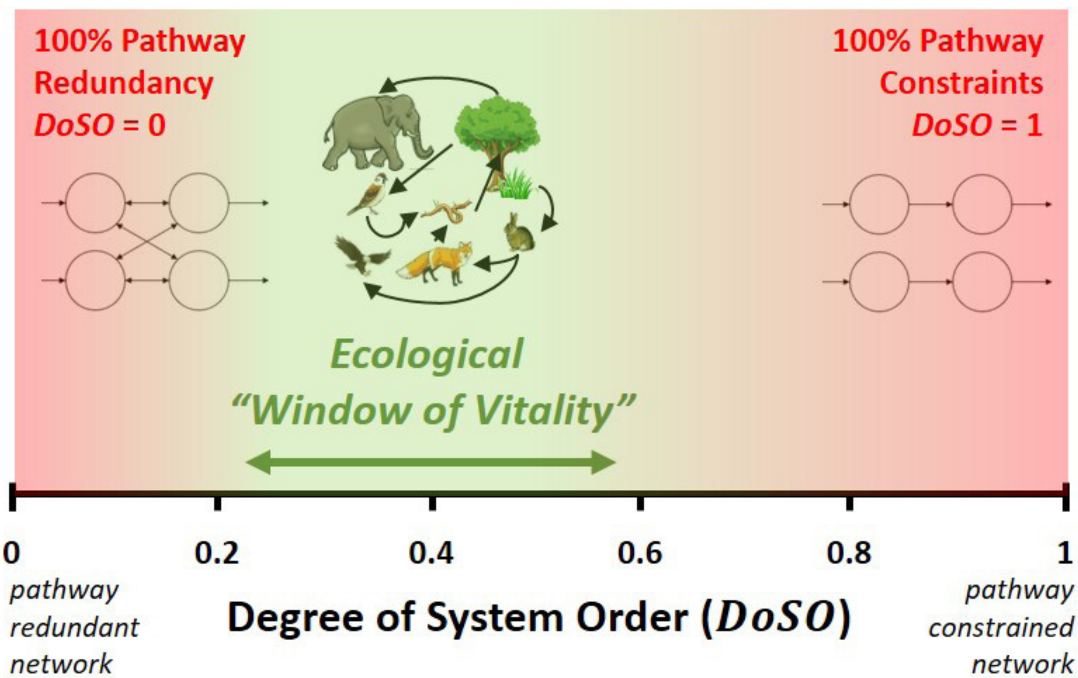

Figure 1. Relative pathway constraints (or redundancy) in a flow network is measured using the ENA metric Degree of System Order (DoSO) [12]. Highly pathway-redundant networks (left, DoSO ~ 0) have multiple options for flow routing and highly pathway-constrained networks (right, DoSO ~ 1) have few. Long-surviving biological ecosystems avoid both extremes and are found in a unique DoSO range that supports their survival through disturbances as well as their normal growth and development.

[13]. This principle of balancing pathway constraints and redundancies can also support supply chains' achievement of 'balanced resilience' [14]. Resilience in the supply of critical resources, such as food and medicine, is a key part of the UN's Sustainable Development Goals. We've shown that ecology-inspired supply network designs both significantly reduced revenue loss and improved demand satisfaction under disruptions [15, 16]. Unlike traditional approaches that depend on anticipating specific disruptions, the ecological Window of Vitality seems to provide a threat-independent means to evaluate engineered networks for their ability to both sustainably grow and survive.

Mutualistic biological systems, such as plant-pollinator networks, have been found to use a unique hierarchical organization of partnerships known as nestedness (Fig. 2). This system structure sees some species forming multiple partnerships with other species in the network while others form partnerships with subsets of the partners of the more connected species, creating a hierarchy of interactions ranging from "generalists" to "specialists." Ecologists have suggested that this hierarchical structure may enable greater resource utilization and prevent cascading disruptions to the ecosystem in case of certain disruptions [17]. BiSSL has investigated the value of this ecologically nested structure in the context

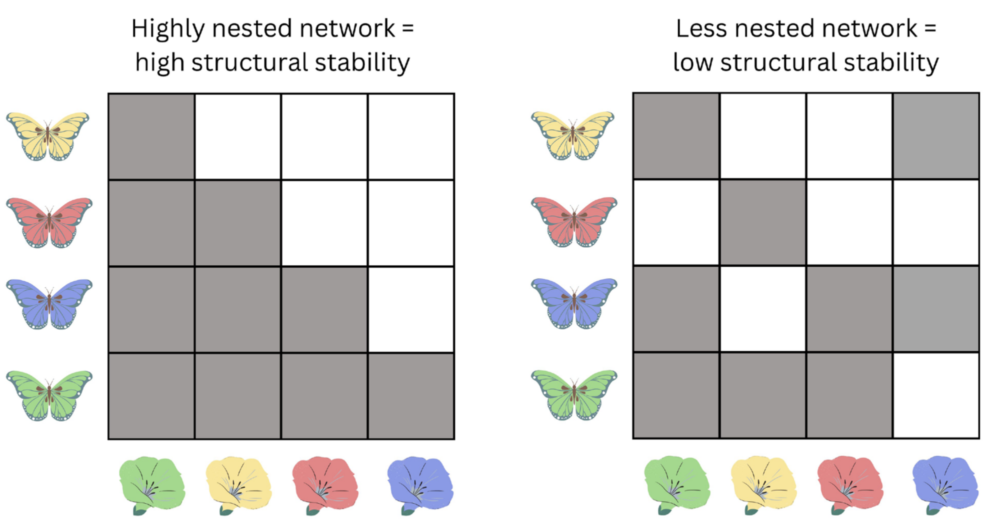

Figure 2. Rohr et al. [19] propose that a highly nested network, like the fully nested one shown on the left, signifies strong structural stability. This allows species to coexist across wider ranges of growth rates, as seen by the pollinator-plant interactions noted with gray shading. Conversely, a less nested network (right) indicates weaker structural stability. Figure modified from [20].

of symbiotic industrial networks, where an ecologically nested structure utilizes a combination of high-throughput firms with multiple resource flows and partnerships with many - if not all - co-located firms while specialized firms requiring specific resources have selective partnering with only those highest-throughput firms. Strategically placing connections in an industrial water network to follow an ecologically-similar nested architecture resulted in more effective resource utilization, decreased raw material consumption, and financial gains [18]. The more nested industry architectures also had improved responses to disturbances. The quantitative nature of nestedness and other bio-inspired system characteristics investigated in BiSSL enables us to directly address under what conditions benefits can be expected and under what conditions the approach isn't worthwhile, for example from an economic perspective. The industrial water network study for example found that when the industries were close or moderately dispersed and/or resources were high to moderately expensive, increasing nestedness improved cost and resource use outcomes. When resources were cheap the approach wasn't worthwhile.

Our research in BiSSL highlights how adopting characteristics from biological ecosystems can enhance both sustainability and resilience across various engineering system scales. The resultant bio-inspired systems achieve cost savings, improve the effective use of their resources, improve their resilience to unexpected disturbances, and reduce any created environmental burdens. The longer-term objective is to seamlessly integrate these biological system-level characteristics into the design of human systems, creating practical and implementable design tools and guidelines. By learning from nature, we are uncovering insights on how to design systems that can support us for years to come.

BiSSL's upcoming initiatives focus on further understanding and integrating these and other biological system principles into engineering design, leveraging our success thus far. Next steps include delving deeper into how these principles can be practically applied across diverse systems with the development of accessible tools and guidelines for engineers and designers to guide not only new system designs but also modifications and recovery efforts. Through collaborations within academia, industry, and the public, we aim to promote the widespread adoption of these sustainable engineering practices. ×

Simbiosis mutualisme | Photo: Misdi ketambe, 2018 | Wikimedia Commons

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Nature as a Blueprint for Resilient and Sustainable Engineering Systems
Hadear Hassan, Abheek Chatterjee, and Astrid Layton

Hadear Hassan
Hadear Hassan is currently pursuing her Ph.D. in the J. Mike Walker '66 Department of Mechanical Engineering at Texas A&M University. She received her bachelor's degree in mechanical engineering from Texas A&M University in 2021. Hadear's research interests are focused on advancing the fields of smart and sustainable manufacturing, with a particular emphasis on energy using bio-inspiration at a systems level and innovation diffusion. In addition to her research pursuits, Hadear is also deeply invested in engineering education. Hadear has been awarded the J. Mike Walker '66 Impact Award and the 2023 Association of Former Students Distinguished Graduate Student Award for Excellence in Teaching and is also an Associate Fellow in the Center for the Integration of Research, Teaching, and Learning (CIRTL) Academy for Future Faculty (AFF).

Dr. Abheek Chatterjee
Dr. Abheek Chatterjee is a Postdoctoral Associate at the University of Maryland, College Park, researching macro-economic models regarding the Circular Economy transition. Abheek received his Ph.D. in Mechanical Engineering from Texas A&M University in 2022. His Ph.D. research investigated novel ecology-inspired principles for resilient and sustainable System of Systems design. During his Ph.D., Abheek was a Graduate Teaching Fellow for the Texas

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Dr. Astrid Layton
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We would appreciate your feedback on this article:

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Article

Can Manufactured Ecosystems fully replace ecosystem services?

Shoshanah Jacobs et al.

Can Manufactured Ecosystems fully replace ecosystem services?
Shoshanah Jacobs et al.

by Shoshanah Jacobs, Elizabeth Porter, Dave Dowhaniuk, Mark Lipton, Dawn Bazely, M. Alex Smith, Nikoleta Zampaki, Peggy Karpouzou, Marjan Eggermont, Michael Helms, Mindi Summers, Andria Jones, Christina Smylitopoulos, Heather Clitheroe, Adam Davies, Marsha Hinds Myrie, Daniel Gillis, Claudia Rivera, Karina Benessaiah, Kristina Wanieck

Imagine a straight path. Behind you is the natural world of a distant past, a pre-industrial biosphere, where ecosystem services provide clean air, fruits and vegetables, building materials, a sense of inspiration and connection to the land, and more. Immediately around you, within the urban sprawl and big box stores, small devices are integrated into the natural systems. You don't notice them initially: microdrones whirl and buzz above flowering vegetable crops alongside the dwindling number of natural pollinator species. A water purification plant operates a short distance behind you. In front of you, an airplane flies low, releasing oak e-seeds, fertile acorns attached to humidity-sensitive coiled wood fibers that bury themselves into the soil when it rains. There are no squirrels or other small mammals to bury seeds in front of you. To your left, looming over an industrial 'park,' is a gleaming multi-armed tower releasing silver iodide to form rain clouds over nearby farmland. As you walk forward along the path, you notice that the landscape now has more tech than trees. Your path ahead extends to a bare horizon in the distance, unrecognizable. Human-made technology dominates this landscape. There are few elements of nature you once embraced. This could be another planet.

Now, imagine a clock face where, 60 minutes ago, life on Earth began. Biological paradigm shifts dominate the hour: DNA, multicellularity, and social behaviour. Humans joined the hour only 175 milliseconds ago. The telegraph, photograph, and locomotive led to human-driven technology 0.18 milliseconds ago. Just 0.09 milliseconds ago, the talking picture. Human-driven technologies are in their early stages of development in the context of biological evolution.

We ask you to imagine because our path is not predetermined. Forecasting our climate future, however, leads us to conclude that we must start planning a climate adaptation strategy now. We do this work reluctantly and hope that it will not be required. Our international Manufactured Ecosystems team (https://www.manufacturedecosystems.com/) was recently awarded a New Frontiers in Research—Exploration grant that funds high-risk and high-reward research to ask, 'What is required to replace ecosystem services with technology?' We are a team of researchers

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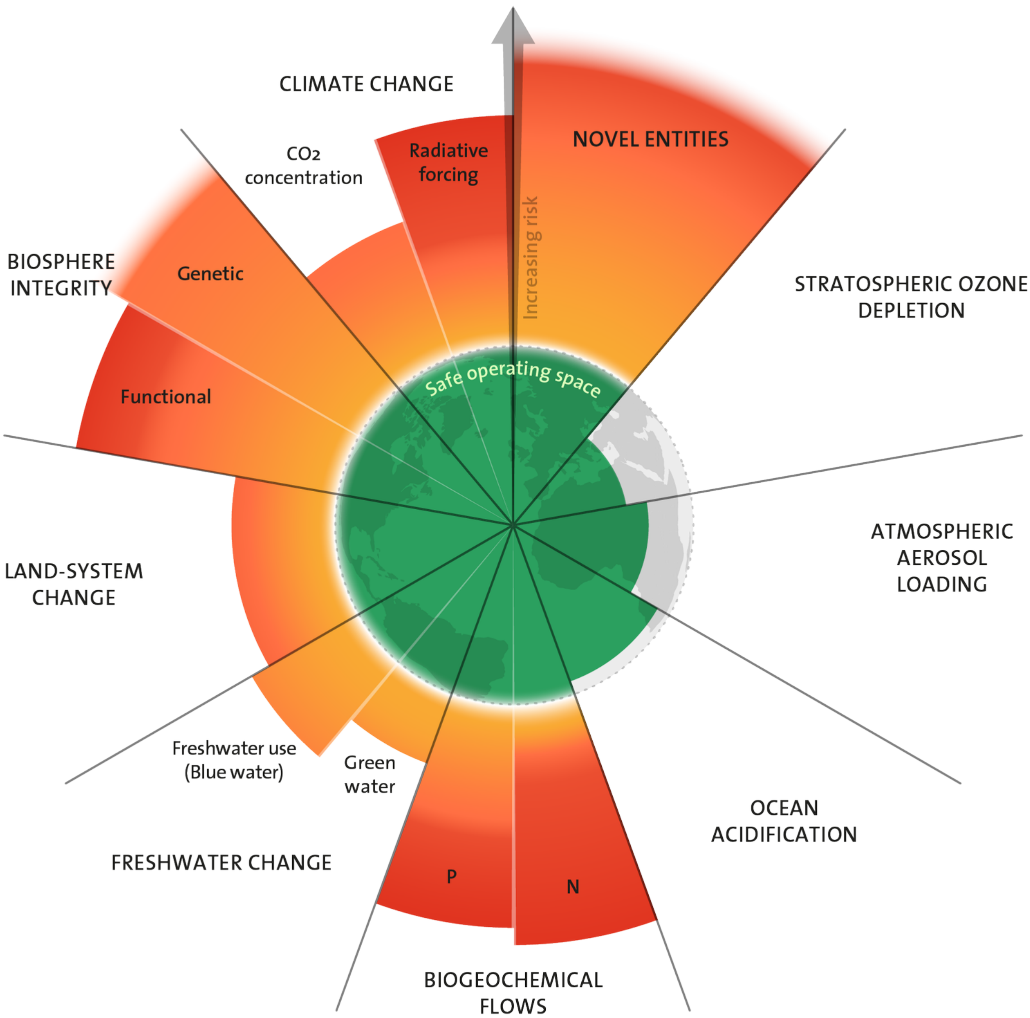
Can Manufactured Ecosystems fully replace ecosystem services?
Shoshanah Jacobs et al.



The 2023 update to the Planetary boundaries. Licensed under CC BY-NC-ND 3.0. Credit: "Azote for Stockholm Resilience Centre, based on analysis in Richardson et al 2023".

from six countries and many disciplines recognizing the need for a whole system approach to technological and environmental innovation by exploring the potential for nature-based knowledge, techno-knowledge, and imagined knowledge to forecast the future of climate adaptation.

Manufactured Ecosystems - could we build them?

In September 2023, the Stockholm Resilience Centre updated findings on "nine processes that regulate the stability and resilience of the Earth system."[1] Crossing planetary boundaries increases the risk of system-wide environmental failures. Of the nine boundaries assessed, including freshwater use and CO2 concentration, human activity has caused us to cross six (Richardson et al., 2023), increasing the likelihood of a climate crisis if we do not rapidly change human consumption behaviour. In other words, we will lose many of the services that ecosystems provide to sustain human life and well-being. The natural world's contributions to our survival and identity as a species are priceless. Attempts to enumerate the value of tangible ecosystem services fall in the trillions of dollars (Costanza et al. 1997). While we could theoretically replace many ecosystem functions, we may never replace the joy a toddler gets from chasing butterflies and small mammals that have become extinct. A faltering planet brings immeasurable changes to what it means to be human and to life on Earth.

As we ponder this strange world of more tech than trees, we should soberly contemplate the need to develop new technologies to support, enhance, and perhaps replace ecosystem services so that we might extend our very survival. The questions now are, "*Are ecosystem services replaceable with technology?*" and "*What are the implications of technological ecosystems?*" Dr. Alastair Fitter asked these questions in a widely read 2013 article. Dr. Fitter wrote that if there is currently no existing technology to serve an ecosystem function, then "it is not likely to be available in the next 50 years that could operate at an appropriate temporal or spatial scale." This dire thinking may not be inevitable. Ten years ago, RoboBees[2] had yet to exist. Microplastic-digesting bacteria[3] were still a thing of science fiction. These technologies, emerging in only the last microseconds of our evolution, hint at a path down which we can design nature-inspired technologies to support large-scale implementation for climate adaptations. We have a long way to go; the clock is ticking, and the motivation is great.

1. https://www.stockholmresilience.org/research/planetary-boundaries.html
2. https://doi.org/10.1038/s41586-019-1322-0
3. https://www.science.org/doi/10.1126/science.aad6359.

Can Manufactured Ecosystems fully replace ecosystem services?

Shoshanah Jacobs et al.

To explore what a manufactured ecosystem might look like, the Manufactured Ecosystems team looks to four sources of knowledge: nature, human-driven technology, imagination, and *each other*. *Nature*, the biological world, has been evolving for billions of years, adapting to circumstances and context facilitated by an uneven distribution of resources and an abundance of time. The ecosystem services we must seek to replace due to human-induced climate change were built in nature, so we begin by understanding the mechanisms underlying their functioning. The discipline of biomimetics guides us in learning about variations across scales, and this understanding of scale is a critical element in studying the biological complexity of mechanisms. For example, photosynthesis, the production of sugars from sunlight, occurs at a molecular scale in plants. In contrast, water purification is achieved by multiple forms of filtration at a community scale through a wetland ecosystem of interacting plants, bacteria, fungi, and animals. Although working at very different scales, both are essential ecosystem services. Scales and ecosystems also encourage us to think of projects beyond straight lines - there are few straight lines in nature. Yet the linearity of how we think and manage projects threatens our ability to achieve the level and scale of innovation required to modify the course of the climate crisis.

Human-driven technology is driven by short timelines and a need for efficiency. Technology does not play well with nature's level of complexity, multi-functionality, and repurposing. It conflicts with nature-based ways of knowing and doing. For example, human technology often solves problems by adding more energy or substance to increase efficiency. At the same time, nature takes information, structure (Vincent et al. 2006), and time to move towards solutions that tend to be locally adapted and multi-functional. But what we learn from engineering design practices is to be intentional with our adaptation goals. These practices give us the gift of fast-tracking toward a solution that fits human needs. Our team is curating a collection of existing technology from around the world that can be helpful in our Manufactured Ecosystem. Our work addresses the challenges of transdisciplinary literature and patent searching using a two-step, two-scale approach. We begin by using broad search terms likely to include many less relevant documents (such as Soil Formation AND Technology). Then, we use non-metric multidimensional scaling (NMDS) to visualize abstracts based on vocational linguistic similarity and eliminate those irrelevant to the search. What we

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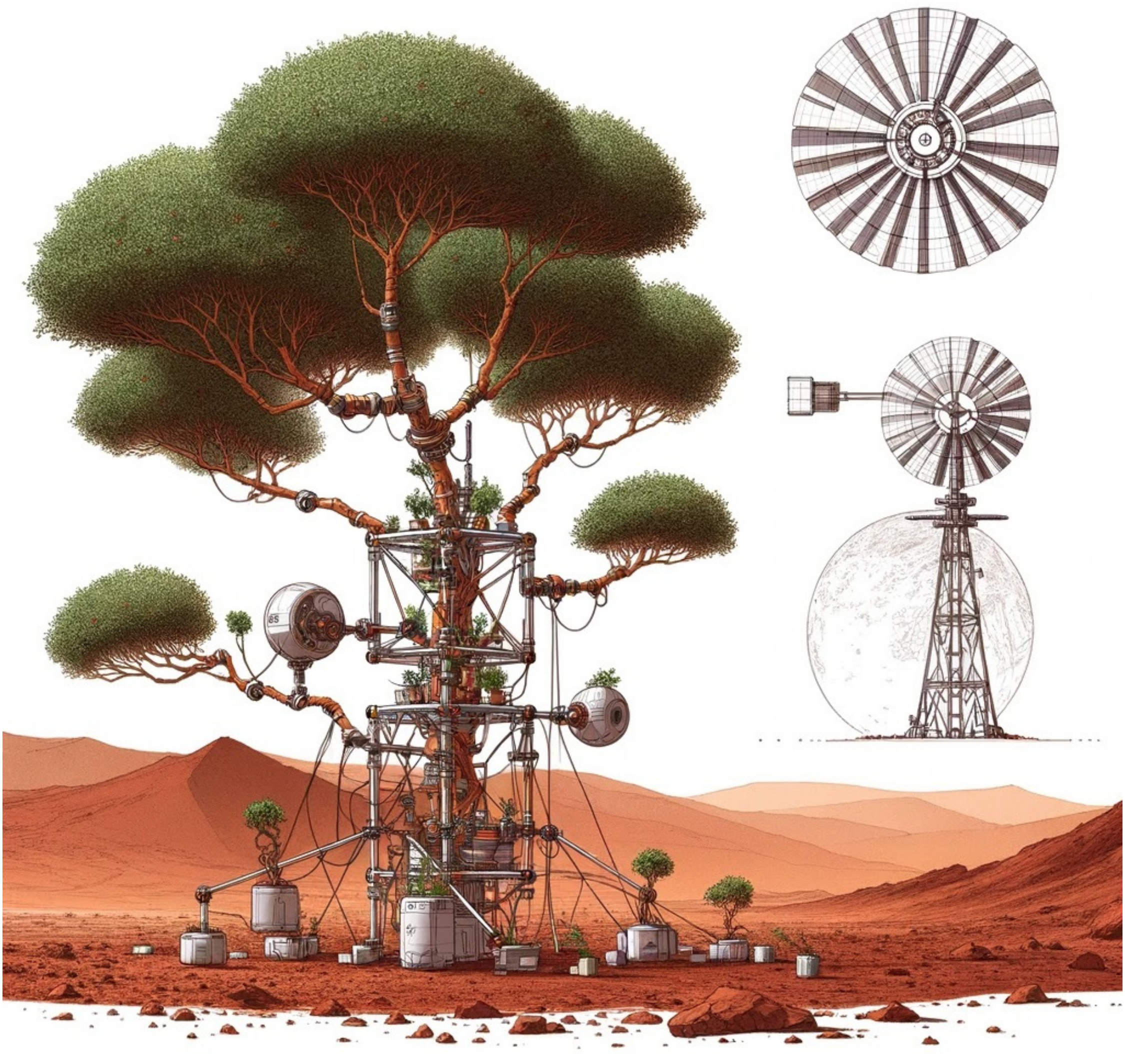
have learned is that often, 'new ways' are much older than we think.

Human technology's rapid explosion begins in people's *imaginations*. It is an untapped source of knowledge, especially in STEM fields. Various narratives of Manufactured Ecosystems are found in diverse research disciplines, from the natural sciences (hypotheses, proposals, theoretical frameworks, and commentaries) to the humanities (literary texts, artworks, music, and digital art). Manufactured Ecosystems can be found in the modern literature of the 20th-21st century, specifically in Cli-fi and Solarpunk. Other humanities fields, such as Arts, Media Studies, and Education Studies explore manufactured features and functionalities within ecosystems and how manufactured ecosystems affect our welfare and support sustainable practices. We have learned that any technological innovation succeeds or fails in context. Our humanity will determine our future.

Finally, we learn from *each other*. In a society that looks increasingly to Generative AI, we must resist the pressures for faster, cheaper innovation and build intentional ways of strengthening our ties to each other. As experience shows us, faster and more affordable are rarely better. Our many academic, industry, government, and community silos drive wedges between our collective knowledge, hindering the achievement of synergies such that we lack significant and sustainable social climate innovations. Our university textbooks teach us that the technological skeptic (one who prioritizes conservation and restoration) is in irreconcilable conflict with the technological optimist (one who looks to technology to solve future problems) (Costanza 2001). Yet, in our present reality of "there is no Planet B," we must reconcile divergent views, make new connections (Burrows et al. 2022), reinforce positive existing connections, and create transdisciplinary pathways within our social and educational institutions. Sociologists Ray and Anderson (2001) interviewed US citizens with widely opposing political affiliations to identify common ground, the first step in reconciliation. They found that there is always some common ground, even between skeptics and optimists. We cannot succeed unless we learn from and about each other - our modes of relationality must change.

Biomimetics – a dominant tool

Biomimetics becomes our dominant design tool in a landscape full of machines and robots. To replace natural systems with technology, we must first know how nature



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works. What is learned from biomimicry, bioinspired design, and our attempts to implement nature-based solutions will be essential for our innovation journey. Transdisciplinarity unlocks new directions for (re)designing research and development systems (see Costanza et al. 2017) for the complex tasks ahead of us. To support, enhance, and replace ecosystem services, all ways of knowing should inform what we learn about the natural mechanisms that provide essential services. From there, we can abstract that information and, in collaboration as a transdisciplinary team, use this knowledge and our anxieties about the impending climate apocalypse as an energy source for equitable and sustainable innovation. Through ongoing collaboration, we look to venerable seeds of wisdom, in situ sources of knowledge; "necessity is the mother of invention."

Join us - You are welcome here!

The Manufactured Ecosystems team is branching out and inviting you to join. 2025 will see the assembly of transdisciplinary working groups, including writers, scientists, and artists. Based on timeliness, reliability, urgency, and scope, we selected six ecosystem services: biodiversity, pollination, cultural services, soil formation, photosynthesis, and climate regulation. The teams will focus on one relevant technology for each ecosystem service. We are exploring the limitations of our existing technology, our contextual influences on the effectiveness of human innovation, and the narratives we might use to change the course of environmental degradation. If a technological innovation begins in the imagination, so can environmental protection. In addition to documenting our work in research articles and conference presentations, we will publish a literary anthology and commission works of art for a Manufactured Ecosystems Exhibition. The ideas developed in these works will solidify the team membership necessary to raise funds to design new technologies. ×

To learn more about our projects, visit www.manufacturedecosystems.com and https://www.manufacturedecosystems.com/our-team

We would appreciate your feedback on this article:

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All story images courtesy of Daniel Mira

Portfolio

Art-thinking

Daniel Mira

Art-thinking

Daniel Mira

Art-thinking: Rediscovering the Connection with Nature through Poiésis

"We are layers of sensitivity and ancestry involved in the experience of existence."

Daniel Mira, a recent PhD in Art-thinking, brings a new perspective to poiésis[1] as a way of reconnecting with nature. In his research, he delves into the layers of sensitivity and ancestry that surround the experience of human existence, proposing a holistic vision that challenges prevailing utilitarian thinking.

According to Mira, this view echoes the thinking of Goethe and other natural phenomenologists, who see experience as a connection between rational knowledge and wisdom. When immersed in natural phenomena, we reach a state of awareness and presence to live in the now and intuitively access the experience of being.

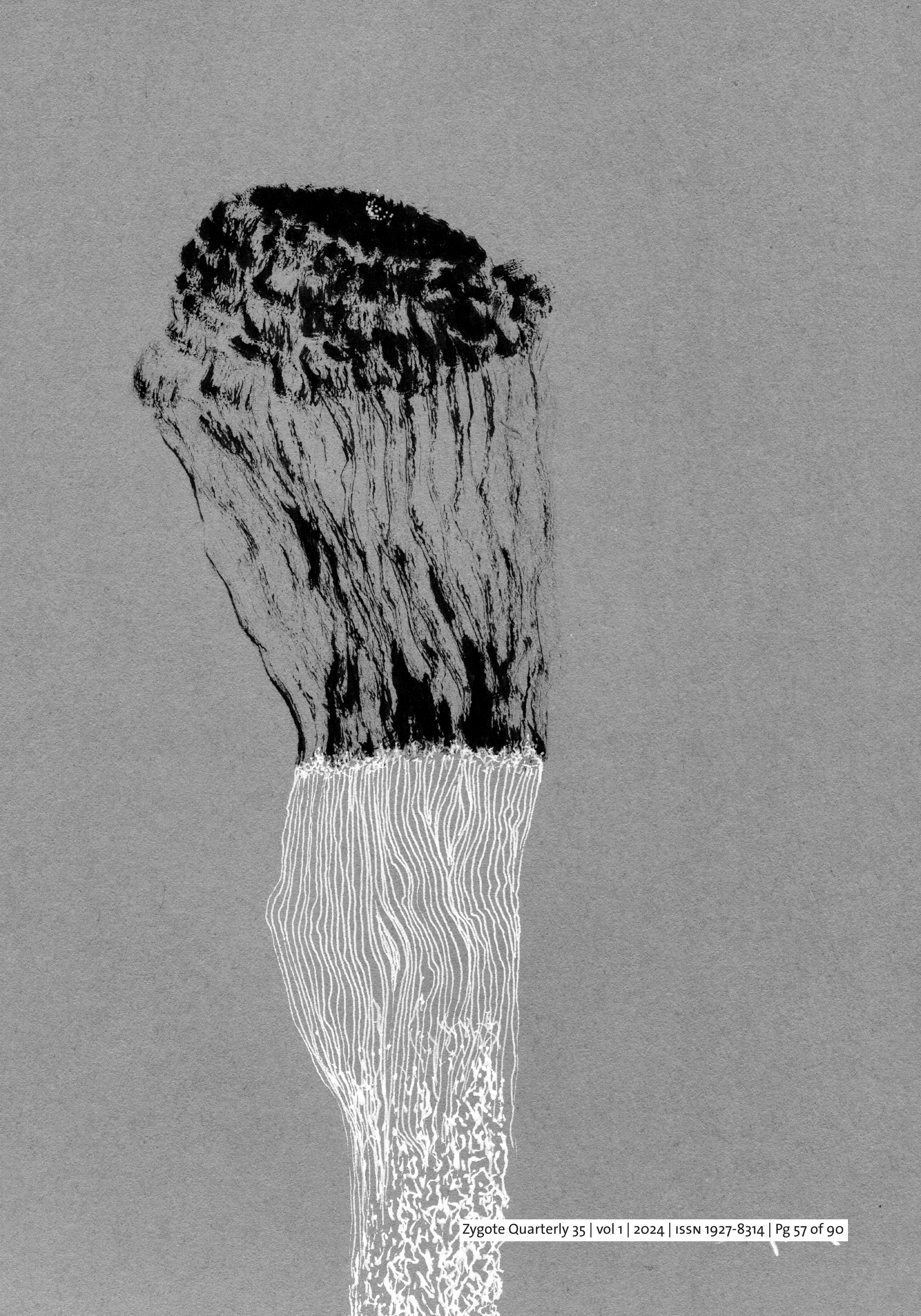
Drawing on the concepts of Humberto Maturana and Francisco Varela, Mira points out that life is autopoiesis[2], expressing itself from its ancestry and constantly adapting to the needs of the environment. However, he criticizes the materialistic and anthropocentric modernity that distances us from this understanding. This entangles contemporary society in a logic that justifies our existence as parasites on the planet when our decisions are guided by quantitative metrics and selfish needs, seeing nature as a resource to be exploited.

He argues that science's excess of analytical logic weakens other approaches and, to sustain itself, structures a series of utilitarian dogmas. In contrast, he proposes a return to poetic thinking that sees nature as a living being to be shared and experienced. Inspired by Eastern traditions and native Brazilian communities that recognize life and movement in all things, Mira advocates a deep connection with unity and immanence.

It goes back to natural philosophy, when there was still an integration of human beings and nature, creating a vision full of myth, imagination, and appreciation for life. For Mira, the recovery of this union between sensitive (poetic) and logical thinking is essential for an integral existence and the realization that humanity, as part of nature, can live in autopoiesis, contributing to life and generating abundance.

His approach to his work is regenerative art based on bio- and ethno-inspiration. His goal is to create an expression that highlights the poiesis of nature as an inspiration for contemporary thinkers, designers and artists. Through shared imaginaries, we can generate a future committed to the systemic balance of all life forms in their essential and existential interrelationships.

1. The process of emergence of something that did not previously exist.
2. A system capable of producing and maintaining itself by creating its own parts.
Definitions: https://en.wikipedia.org/wiki/Poiesis| https://en.wikipedia.org/wiki/Autopoiesis



Art-thinking
Daniel Mira

Could you tell us how you get your inspiration from nature?

In this context, I am currently inspired by the biomes of the Neotropics, in particular the Cerrado (Brazilian Savannah) as a bio-inspired entity of longstanding ancestry. Located in the center of Brazil, this savanna biome contains the greatest savanna biodiversity on the planet. Its autopoietic dynamics and strategies for sustaining life are unique. Considered the oldest region on the continent, its nature thrives on ancestry, where every being has been searching for new ways to exist for thousands of years.

Who or what inspired you? How did you nourish yourself for this process?

My methodology was to experience the botanical life of the Cerrado phenomenologically. I organized my observations into three groups: dot, line, and plane; polarities; and intensifications. The aim was to experience these patterns and, instead of intervening in the phenomenon, to compose with it. A

great support for my research came from the dialogue with the traditional communities living there. In these conversations, I integrated the imagery resulting from my observations with the imagery of these communities, creating a sensitive and poetic relationship of new compositions.

Experiencing the Botanical Life of the Cerrado: A Poietic Methodology

Based on his observations, Mira has proposed compositions that respond to the sensitive relationships he has developed with the place. Each series of works seeks to portray deeper layers of recording and perception of nature, avoiding a process of rational cataloging of life. Within this approach of observing, feeling, and manifesting, the proposition of art-thinking emerges as a way to give art a regenerative purpose, transforming it into a vector for reconnecting with nature.

Art-thinking
Daniel Mira


Art-thinking
Daniel Mira

Art-thinking
Daniel Mira

Art-thinking

Daniel Mira

Dot, line and plane

Art-thinking

Daniel Mira

Polarities

Inspired by Goethe's quotation, "The particular always leads us to the universal, and the universal to the particular. Both interact in every observation and interpretation," Mira seeks an experiential understanding of the polarities present in the territory.

In his works, he observes that the forms of the landscape, seemingly segmented and separated, reveal an integration between opposites when carefully observed. He says that listening to the needs of the context, through active listening to the community and to nature, has facilitated the (re)integration and expansion of the imaginaries of what we, as city dwellers, understand as poetic thinking.

For him, the act of seeing and experiencing in an attempt to integrate polarities is essentially a learning point. His work not only captures these observations but promotes a sensitive and poetic relationship with the environment, reflecting a profoundly regenerative artistic vision:

Us and the object

Light and Darkness

Body and Soul

Two souls

Mind and Matter

Thought and expansion

Ideal and Real

Sensitivity and Reason

Imagination and Intellect

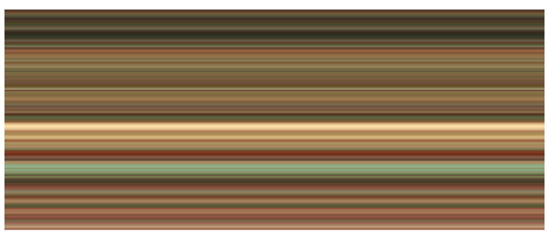
Being and desire

Two halves of the body

Right and Left

Breathing

- Goethe



Art-thinking
Daniel Mira

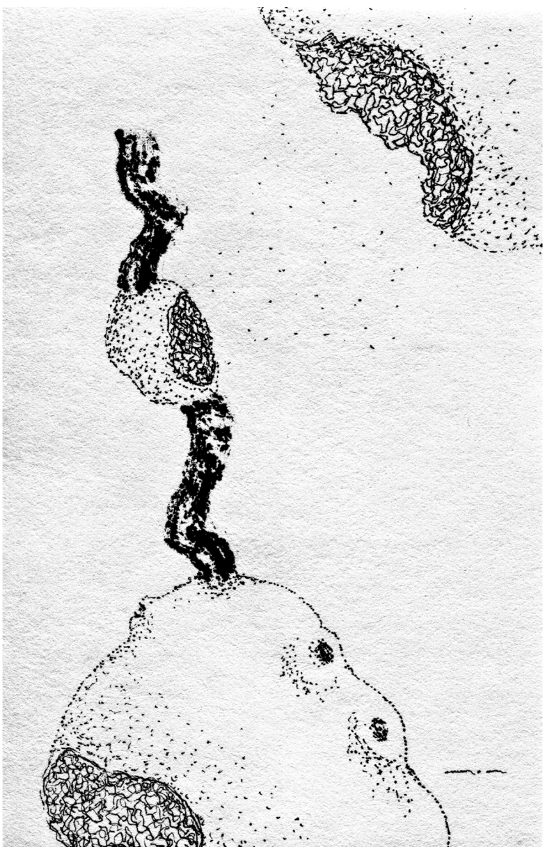
Community leader Dona Santa, seed collector of the Cerrado group in distress

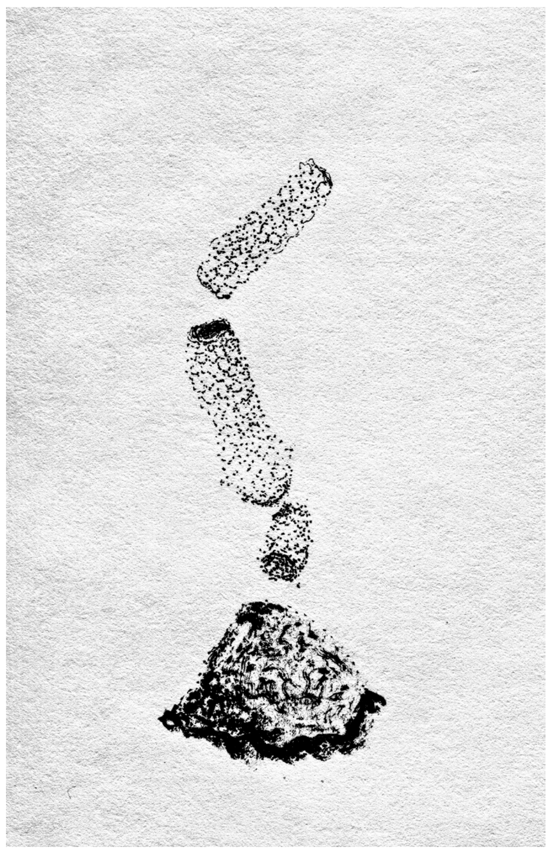
Community leader Sr. Valdo, seed collector of the Cerrado group in distress

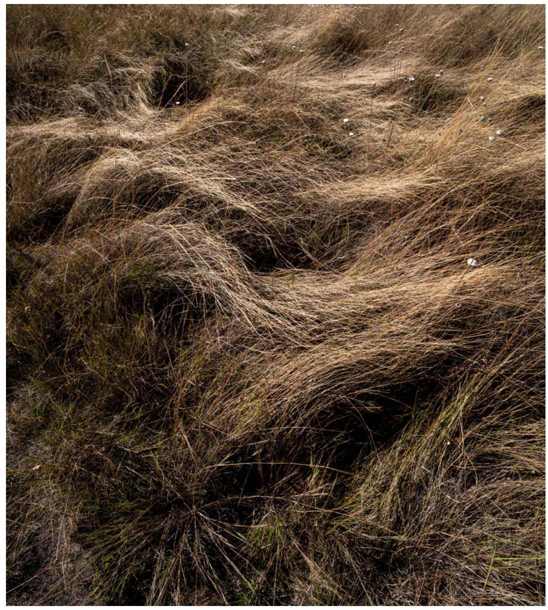
Art-thinking
Daniel Mira

Intensification
In his exploration of poiesis as a method of reconnecting with nature, he addresses not only the theme of polarities, but also intensification, which he defines as a natural dynamic imbalance. This unstable movement is essential to the expression of life in nature and demonstrates that autopoiesis results from the interaction of the polarities of past and present, ancestry and present. In this context, each organism is simultaneously active and receptive, living in relational symbiosis with its environment.

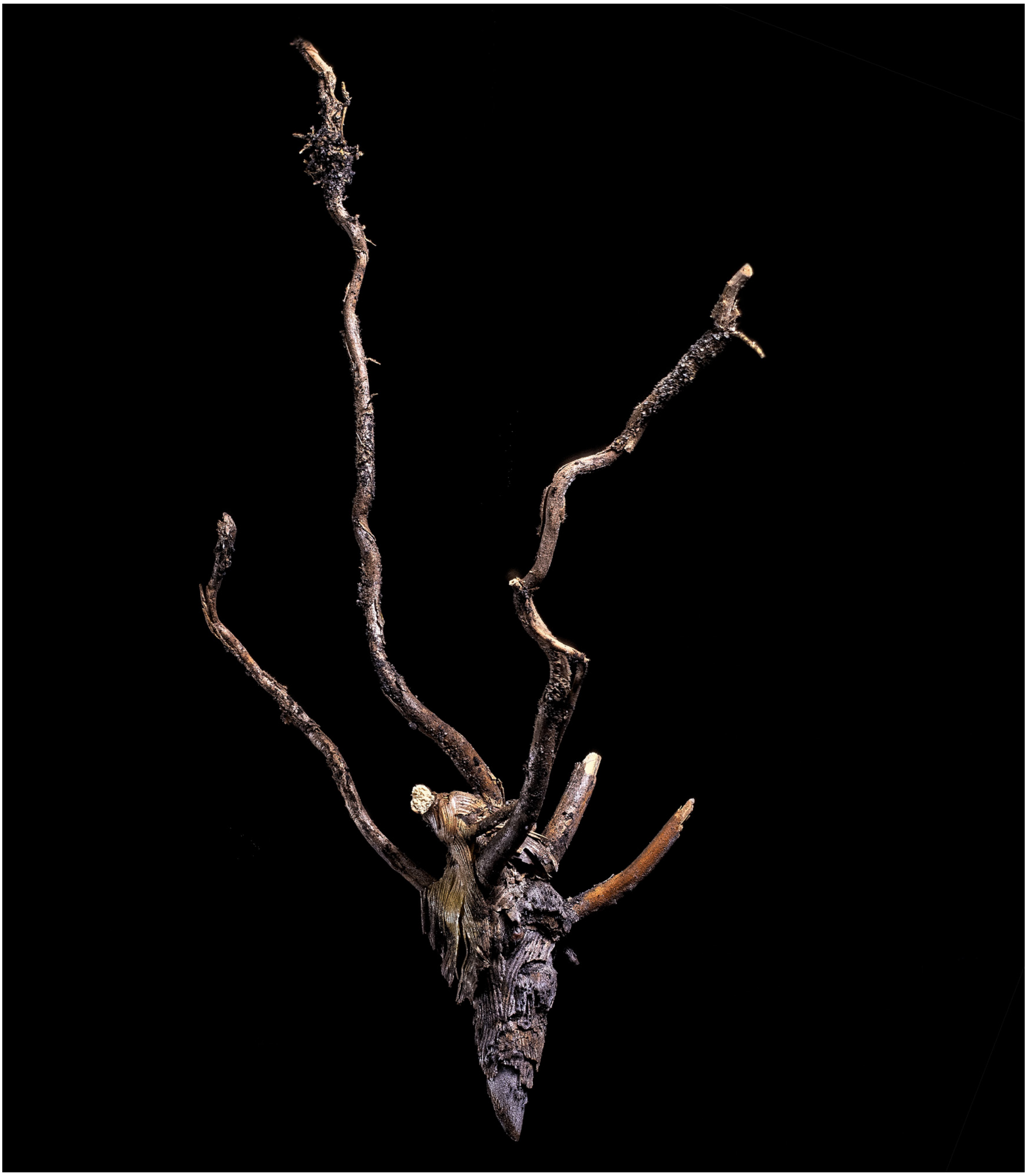
For him, the experience of natural phenomena implies the perception of the dynamics of polarities, which manifest themselves through intensification or movement.







Art-thinking
Daniel Mira



Art-thinking

Daniel Mira

What are you working on at the moment? Do you have any interesting projects you can tell us about?

I'm currently working on the exhibition "ME DEIXE EXISTIR" (Let Me Exist), which originates from my doctoral thesis "The (auto) poiésis of the Brazilian Cerrado: Artistic Research through Natural Phenomenology". This exhibition is the confluence of my perceptions throughout my career as a thinker and artist, where the natural phenomenological experience regenerates fundamental aspects of our existence. The exhibition includes several immersions in the Cerrado with the traditional communities that inhabit it. My poetic deductions are intuitions and reflections on the dimensions of life that dwell within and without me.

What was the last book you liked?

My current main influences are biologists like Lynn Margulis, artists like Andy Goldsworthy and Richard Long, as well as the Amerindians of Jaider Esbell and the wild cycle of Ana Dantes and Ailton Krenak.

What is your vision of perfect happiness?

In all that I have explained and experienced, my relationship to happiness is a logical and poetic flow that recognizes and meets the needs of life without qualifying experiences as good or bad. For me, happiness is the clear perception of the flow of life, whether it is positive or negative, difficult or easy, happy or sad.

If not an artist, who/what would you be?

I don't think my profession defines who I am, but if I hadn't done something in the visual arts, I would have done it in some other poetic work. My way is to experience the way, the poetic experience as a way of life, whatever its expression. ×

Daniel Mira is an art thinker. He works as an artist, researcher and creative entrepreneur. He graduated in art from the University of Brasilia, specializing in Visual Poetics, with a master's degree in Design and a doctorate in creative processes inspired by nature from the University of Brasilia. He works in the context of "poietic" research centered on nature, approaching the intersection between the sensible and the logical in the formation of human thought and its expressions. As context, he immerses himself in Brazilian biodiversity, orienting his creative themes towards life-centered expressions, as the path to regeneration in cultural, social and innovation spheres.

He is the CEO of NOUS Ecossistema which includes the NOUS Institute that he founded in 2007, the NOUS School, and a regenerative design consultancy that promotes actions in the areas of Humanities, Nature and Culture. He has been teaching as a university professor for over fifteen years, coordinating communication actions for the cause through projects such as the Humanizate extension center. He has been sharing his creativity in the areas of visual arts, photography, art curation and visual design for over 20 years. He has worked with the Brazilian government, museums and various cultural institutions. In his artistic career, he has exhibited his work in Brazil, New York, Barcelona, Berlin and Slovenia.

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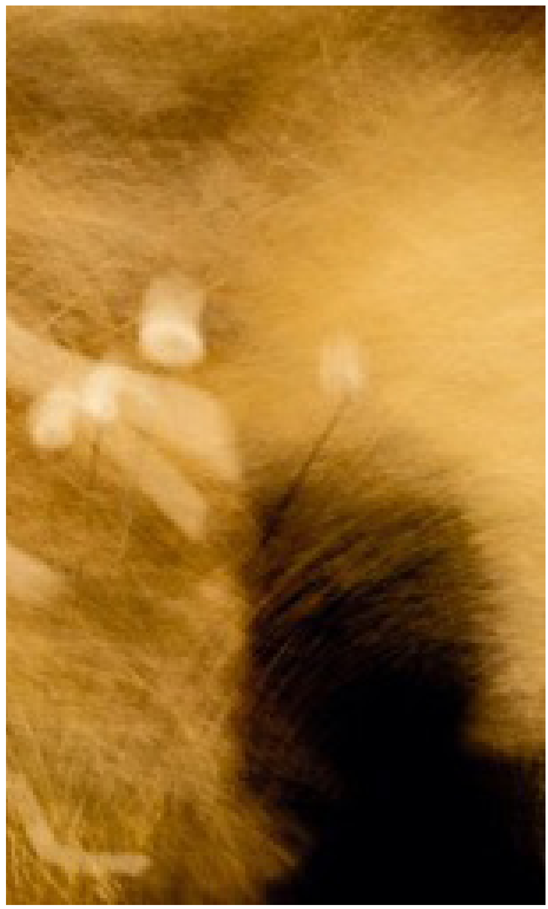

green tendril
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Article

Robotany: a new way to move

Tom McKeag

Robotany: a new way to move

Tom McKeag

If you are a bioinspired designer and wish to imitate living things to advantage, one of the first questions you might ask yourself is “What is Life?” No, this won’t be an existential question (you may put that one off, like the rest of us, until it’s too late), but rather a technical one. What defines Life anyway? You might note some of Life’s attributes, such as growth and change, movement, reproduction, responsiveness and adaptation, and indeed, most definitions of Life include the ability to perform these and other functions. Biological life can be defined specifically, however, by these essential four constituent molecule types: nucleic acids, proteins, fats and carbohydrates.

Still, when it comes to emulating functional performance, attributes or characteristics are the handle that one grasps when searching for solutions from the natural world. For example, in order to do something defined as “work”, some “thing” needs to be moved. How, then, does Nature move something? An overwhelming field of possibilities opens up to the designer and must be tamed. And so, the sorting begins. Whatever one’s selection criterion (outcome, material, kinetics, information, or energy, say), the designer must study the subsequent phenomenon to a degree that informs a judgment about translatability. Can one translate that phenomenon, and its constituent events, into synthetic models using the methods and materials at hand (or in promising view) in our built world?

The field of robotics has dipped deeply into the well of natural examples, and practicing designers have, no doubt, wrestled with all of these basic steps to varying degrees. The understandable trend has been to the study of the animal world for autonomous motion; biomechanics is a long-established field of study in its own right, and animals are universally and ubiquitously mobile. Other forms of life move, however, and at different linear scales. Could there be inspiration lurking in the overlooked drawers of Nature’s Cabinet of Wonders? How different would the translation be? Looked at from another angle, how different would the biotic functional toolkit be? What would be its additional value?

There are several functional capabilities that living beings possess that give Nature the decided advantage over any man-made imitation. Real-time cellular production, for example, really is a handy skill to have, and every one of us has it, except, I suppose, single-cell organisms. Adaptive growth, repair of damage, and sending bits of ourselves, in the form of DNA, across time are some of the fundamental and essential results.

tendril | Photo: john moore, 2009 | Flickr cc

Robotany: a new way to move

Tom McKeag

Plants are particularly expert at adaptive growth. Lacking the mobility of animals, they have evolved to adjust to their surroundings, and have developed several strategies triggered by this environment. Heliotropism is a familiar example. Indeed, plants not only adapt to their environment, but control it as well; spreading chemical compounds, luring pollinators (or, in some cases, tasty victims), and fundamentally changing the soil, air, moisture and temperature around themselves. Though rooted in one place, they are highly dynamic; growing, attaching themselves to surfaces and morphing their shapes to avoid or approach changeable conditions. As circumstances change, the plant must differentiate its cell production, creating new cells where needed for structural strength, or direction change, or repair. These activities model the same basic capacities of a responsive robot: a control mechanism, sensors, and mechanisms for reaction (effectors). In the plant, however, these capacities are initiated at the cellular scale and below, and are part of a complex system of biochemical reactions; the parameters of time, linear scale, materials and energy are wildly different from the modus operandi of most man-made robots. Translating these wondrous skills into a useful machine for human use is a great challenge.

Dr. Barbara Mazzolai and her research team at the Italian Institute of Technology in Genoa, Italy, have taken up that challenge. They are focused particularly on climbing plants. These plants have evolved to compete with other plants by concentrating their material and energy on fast growth and reaching for sunlight, while reducing their investment in robust stem structures. Instead, they have developed sensing mechanisms that detect external supports, and various mechanisms for climbing: twining, tendrils, spines and rootlets being chief among them.

The Mazzolai team has designed a machine based on a climbing plant and named it “FiloBot”. It has the capacity to grow, attach to, or wind around objects and respond to external stimuli. They have adapted additive manufacturing technology (Fused Deposition Modeling or FDM) to provide real-time production of material in response to the environmental clues picked up by its sensors. This enables the machine to move through complex environments, cross gaps, and seek and attach itself to supports. All of these skills would be most useful in robotic search and rescue, for example.

The robot employs sensors to guide the melting of a spool of plastic in order to “grow” and morph its shape. Brightness and orientation control the temperature of the melt; lower temperatures producing faster, more brittle new material, while higher temperatures result in slower, stronger additions to the "plant". The melted filament is extruded in a circular fashion, thus enabling directional change depending on the density of deposited material. The researchers claim that the machine can print new material at a rate of between 2 and 7 millimeters per minute.

The FiloBot comprises a mechanism that mimics a plant's apical meristem, that region of cells capable of division and growth in the root and shoot tips of plants. It contains the controller and the feeding, heating and plotting units, along with a Bluetooth connection to a Graphical User Interface (GUI). Seven sensors input data into the controller. This apical growing mechanism extends from a pre-printed precursor structure by printing new layers of filament. The precursor structure contains the power lines, battery and cooling fans. A separate spool of filament unrolls passively as drawn by the feeder motor.

Getting the additive manufacturing to work within this small machine was a major challenge. Bed and extruder temperature, plotting speed, environmental temperature

Meet FiloBot: the self-building, vine-like climbing robot
Video: The New Scientist, 2024 | https://www.youtube.com/watch?v=t3aerY5gcSk

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and moisture were key performance issues. The group labored within the many material constraints associated with 3-D printing. The team tested five commercially available filament stocks, and each had decidedly different benefits and drawbacks and, therefore, effects on the other performance issues. Polylactic acid, or PLA, for example, was relatively stiff, putting stress on the feeder motor, and required higher melt temperatures, although its deposition was smooth and quick and it is biodegradable. The choice of a stock material, with its individual mechanical properties, had a significant impact on printing parameters and control strategy, to the point of requiring custom settings for each operation.

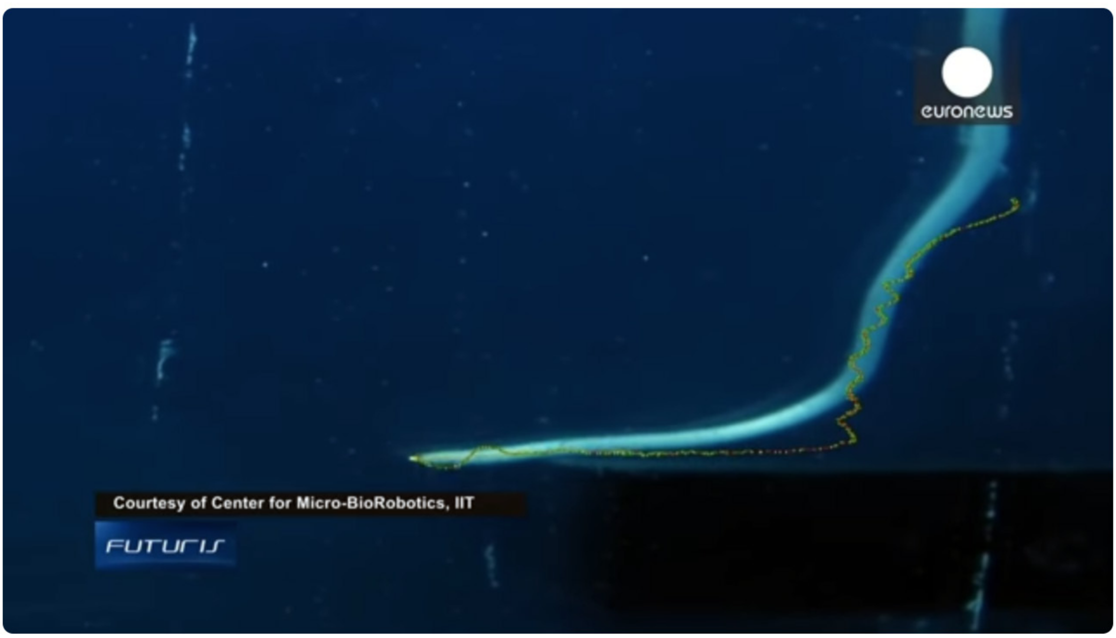
Similarly, the group worked to design an optimum extruder length that would allow curving deposition. If the extruder was too short, it would limit the extruder speed and growth rate. If the filament curvature was too high, then it would stress the feeder motor. The team compromised with a length of 14 mm and an internal curvature of 9 mm. Throughout the research, design and testing, temperature (and the resulting viscosity of the deposited material) was crucial to performance.

The innovation here is in stretching the functional expectations of additive manufacturing in order to mimic a fundamental advantage that the natural world has over the synthetic one: adaptive, responsive, real-time growth. One might see other, fundamental functional possibilities: damage repair by a system of "hot" growth nodes within a network framework comes to mind immediately.

FiloBot is part of a continuum of research into plant-growth-as-movement applicable to robotics, starting in 2012, with the development of the "Plantoid", a seed and root-inspired device that mimics the sensing, anchoring and searching growth of roots. This device has been called the first plant-inspired robot device, and also employed FDM.

Mazzolai's Bioinspired Soft Robotics Laboratory has also been working on other plant-inspired projects, expanding the scope of plant mimicry by including such components as a plant-inspired energy source and additional climbing tactics for growing robots. They have developed prototypes of tendrils that are powered by osmotic action and are reversible. Osmosis, the net movement of water across a semipermeable membrane, is a key mechanism in plants and is powered by the difference in concentrations of substance on either side of the membrane. Made from polyethylene terephthalate (PET), the robot mimics a plant's modulation of turgidity (and therefore stiffness) in different parts of its stem, allowing it to curl around an object. They are also developing a reversible micro-hook attachment device. Their work on a so-called "biohybrid" energy source focuses on a plant's conversion of mechanical to electrical energy via tribo-electrification. The tribo-electric effect happens when the contact between two material surfaces redistributes electrons, setting up positive and negative polarities, and therefore an electrical charge. Combing one's hair or shuffling over a carpet will create this effect, popularly known as "static electricity".

The researchers in Genoa are part of a larger community convened in 2019, under the GrowBot project and funded by the European Union FET Proactive Emerging Paradigms and Communities Research and Innovation Action grant agreement. This multidisciplinary, multi-organization, multi-national project is focused on developing low-mass and low-volume robots capable of anchoring themselves, negotiating voids, and more generally climbing. The objective is to provide robotic capabilities that conventional wheeled or legged robots cannot provide.



A Robot That Grows Like Plant Roots - Futuris
Video: Euronews Next, 2015 | https://www.youtube.com/watch?v=iqKRNKCmzhE&t=43s

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PLANTOID

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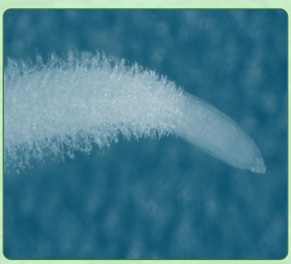
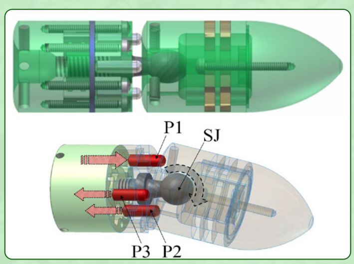
Innovative Robotic Artefacts Inspired by Plant Roots for Soil Monitoring

The plant roots as a model for **Collective Adaptive Behaviour** and as a source of inspiration for **Soft Robotics**

- The plant root system morphologically adapts to the environment to explore it with a number of rich sensorized probes
- Plants represent an excellent paradigm in terms of energy efficiency, low speed, strong actuation, and low power consumption
- Plants show adaptively variable growth and development during their lifetime

The **PLANTOID** project aims at taking inspiration from the smart, effective, and efficient strategies of plant roots to develop a new generation of robot and ICT technologies in sensing, actuation, and distributed adaptive intelligence for tasks of soil exploration and monitoring





The PLANTOID Collaborative Project

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Whether inspired by the way roots search for nutrients, or tendrils wind around supports, or leaves convert small packets of energy, the Mazzolai lab and their colleagues have been expanding our knowledge of how the plant world works, as well as how its strategies might work for us. Their quest for fundamental, nature-based capabilities and the translation to our technology is inspiring in itself. ×

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ISSN 1927-8314