Philosophical Lens

ECO-AUGMENTATION: SHAPING THE FUTURE OF SOCIAL-ECOLOGICAL SYSTEMS

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THE FUTURE OF SOCIAL-ECOLOGICAL SYSTEMS

The current state of the planet, marked by climate change and biodiversity loss, is one of humanity's most urgent challenges, further exacerbated by a projected population increase to nearly 10 billion by 2050. Scientific and technological advancements are vital for monitoring and mitigating these dynamics toward solutions for humanity to coexist with a changing planet in a sustainable way. In this spirit, the third platform of GESDA's Science Breakthrough Radar® provides an overview of trends and breakthrough anticipations in Eco-Regeneration and Geoengineering at 5, 10 and 25 years,[1] encompassing critical strategies such as decarbonisation to reduce greenhouse gas emissions, Earth systems modeling to understand interactions within the planet's systems, Ocean stewardship to manage and protect environmental resources, Solar radiation modification to offset global warming and Future food systems to ensure nutritional security for all. Amidst these comprehensive efforts to sustain the planet's health while adapting to accelerating global change, the 2024 Philosophy Lens zeroes in on eco-augmentation.

GESDA on Eco-Augmentation

Coined by GESDA in the context of its second High-Level Anticipation Workshop,[2] eco-augmentation can be defined as "human deliberate and strategic interactions with nature for more resilient and sustainable social-ecological systems". Thus defined, eco-augmentation is intended to fill a gap as a platform for the sciences that navigate the fine balance between repairing and enhancing natural systems to interface their views and build synergies with a focus on three primary dimensions:

- "Reading and writing ecosystems," which refers to the advanced technologies in synthetic biology, genetic editing and ecological modeling used to monitor, understand and manipulate ecological systems;
- "Transitioning ecosystems," which refers to a constant state of flux, influenced by new species, extinctions and environmental changes in ecosystems that must be understood and managed to maintain good functioning despite alterations; and
- "Hacking co-evolution," which refers to the evolutionary dynamics between human societies and natural ecosystems, whose processes can potentially be steered towards beneficial outcomes.

Central to eco-augmentation then are questions combining normative and descriptive aspects, such as: Why should we augment nature and ecosystems, more specifically? How should this be done? For whom is this augmentation intended? Which understanding of nature are we adopting as we set to augment it? And, crucially, how shall we construe eco-augmentation objectives when enhancing social-ecological resilience and sustainability contrasts with "less desirable states" of diminished capacity to sustain natural resources and provide ecosystem services?

These considerations, in turn, probe into the intrinsic, relational and instrumental values of nature underlying eco-augmentation, proposing various approaches such as conservation, restoration and (re-)creation of (novel) ecosystems. They also concern the perspectives of different stakeholders, whether ecocentric, biocentric, zoocentric or anthropocentric, and the nature of the ecosystems involved — be it inclusive or exclusive, dynamic or static. Altogether, these dimensions form the conceptual landscape of eco-augmentation to investigate in this year's edition of the Philosophy Lens (Table 1).

TABLE 1. Eco-augmentation's conceptual landscape[3]

WHY?	Intrinsic		Relational	Instrumental
HOW?	Conservation/Preservation		Restoration/Rehabilitation	(Re-)creation
FOR WHOM?	Ecocentric	Biocentric	Zoocentric	Anthropocentric
WHICH NATURE?	Exclusive, Static		Inclusive, Dynamic	
WHAT TARGET?	Stability		Resilience	

GESDA's Fundamental Questions

In surveying the conceptual landscape of eco-augmentation, the Philosophy Lens will focus on three fundamental questions that drive GESDA's anticipation of scientific and technological advancements in its aim to develop inclusive and global solutions for a sustainable future:

- Who are we, as humans?
- How can we all live together, as societies?
- How can we ensure the well-being of humankind and the sustainable future of our planet?

The Philosophy Lens will use these three fundamental questions to guide us in analysing the key notions at stake in the definition of eco-augmentation — namely, humans, nature and their interactions.

Environmental philosophy will play an instrumental role in our analysis. Characterised as a hybrid discipline that draws from the philosophy of science, epistemology and ethics to examine fields that range from conservation biology to synthetic biology via restoration ecology,[4] it will provide us with the necessary tools and frameworks to unpack "eco-augmentation".

GESDA's Value-Neutral Approach

In the background of our reflections, a critical research-practice gap remains in effectively linking conceptions of nature, humans and human-nature relationships with ecosystem planning, management and governance to catalyse meaningful action toward resilience and sustainability. Our definition of eco-augmentation is ultimately expected to also bridge this gap by being practically actionable by academic, diplomatic, philanthropic and citizen communities.

Along the way, critical issues will include conceptualising resilience and sustainability, identifying key processes and principles for transition and generating interdisciplinary knowledge to advance these goals.[5] Our approach toward these goals will be honest knowledge-brokering.

In the spirit of honest knowledge-brokers, we will aim to map the ground of the central notions at stake in the definition of eco-augmentation — humans, nature and their interactions — while always striving for value neutrality. And by value neutrality, we are not implying that these notions can be value-free; rather, while acknowledging the value-ladenness of each without yet taking a stance, we will seek to open the solution space of action and opportunities for society and decision-makers, enabling them to "use the future to build the present" — as per GESDA's motto.

HUMANS & NATURE

Unpacking eco-augmentation starts with examining the roles and identities of humans within the Anthropocene and the evolving concept of nature. By asking "Who are we, as humans?" and "What is nature?", we will come to understand how our perceptions and interactions with nature shape possible environmental futures and the relevance of eco-augmentation in this pursuit.

Who Are We, as Humans?

Eco-augmentation is deeply rooted in the context of the Anthropocene, where humanity's transformative impact on the environment prompts a reassessment of who we are, as humans and what it means to be a human — following GESDA's first fundamental question.

The Anthropocene

Introduced by Crutzen and Stoermer in 2000,[6] the Anthropocene encapsulates a multifaceted concept — scientific, political/moral and ideological. Scientifically, the Anthropocene acknowledges the quantitative impact humans have on the environment, which is evident in measurable changes such as global warming and biodiversity loss. Politically and morally, it raises awareness of our role and responsibility in these changes, underscoring the need for mitigation efforts. Ideologically, it challenges us to rethink our relationship with nature, moving beyond traditional human-nature and technology-nature dualisms, toward an understanding of the intricate entanglements between nature, technology and humanity.

Thus operating as a "trading zone" between the natural sciences, social sciences and humanities, the Anthropocene fosters cross-disciplinary collaborations, which span different timescales: Earth systems science takes it to look to the future, focusing on humanity's environmental impact to develop normative recommendations; geological and stratigraphic sciences delve into the past to find evidence of it as an official geological timeframe (Box 1); and the social sciences and humanities weave it together into geo-biological, civilisational and political dynamics.[7]

BOX 1. Geological Anthropocene

The Anthropocene Working Group (AWG) was established in 2009 as a task group of the Subcommission on Quaternary Stratigraphy (SQS) — a component body of the International Commission on Stratigraphy (ICS) responsible for the International Chronostratigraphic Chart (ICC), which serves as the basis for the Geological Time Scale (GTS).[8] The AWG was tasked with examining the Anthropocene for potential inclusion in the GTS, which requires a chronostratigraphic and geochronological unit defined by a globally synchronous base. In 2024, the AWG's proposal to formally include the Anthropocene in the GTS as a new chronostratigraphic unit with a series/epoch status was rejected by the SQS, with subsequent ratification by the ICS Executives, members of the seventeen sub-commissions of the International Union of Geological Sciences (IUGS).[9]

An alternative proposal suggests treating the Anthropocene as a geological event, similar to the Great Oxygenation or the Cambrian Explosion, rather than a formal epoch.[10] This approach would better capture the spatial and temporal heterogeneity underpinning anthropogenic global environmental changes, aligning more closely with the diverse disciplines engaging in human-environment interactions. Importantly, it wouldn't require formal stratigraphic approval while still maintaining the scientific assessment of humanity's transformative impact on Earth.

Against the Anthropocenic backdrop, three main issues resonate with eco-augmentation: environmental transformations, science-technology-nature integration and epistemic inclusion. While eco-augmentation recognises the critical role of technoscientific knowledge systems alongside other bodies of knowledge, understanding that both human and nonhuman actors transform environments, it promotes breaking down the barriers between science, technology and nature, toward a holistic view of environmental stewardship. Specifically, eco-augmentation involves reimagining human-nature relations through technology and, therefore, mandates re-evaluating technology as a driver in ecological and evolutionary biological processes, within a "pluriverse" construed as a plural space in which different cultures and modes of living coexist.[11] This will be a recurring theme in our analysis of "eco-augmentation".

Human Transformative Power

The Anthropocene setting hinges on the transformative power of humans — although that power may vary significantly based on individual and group demographics. As humans in the Anthropocene, we are, to varying extents, technology-powered transformative agents with unprecedented abilities to shape and sustain new social-ecological environments. Coupled with the evolutionary advantages of a cultural species backed by the use of symbolic language and the alleged privilege of reflexive consciousness, Anthropocenic transformations position us in principle as the Earth's "ultimate ecosystem engineers",[12] endowed with exceptional adaptability and agency, for better or worse.

For the better, we can hope to leverage our increasing awareness and understanding of the human transformative impact to repurpose our self-serving "geobiophysical" power toward resilient and sustainable futures. For the worse, the Anthropocene's complexities, entanglements and uncertainties can also be viewed as an evolutionary self-destructive "success story", a large-scale evolutionary trap that may extend beyond our ability to aim for desirable outcomes.[13] Awareness of our impact alone is indeed insufficient for effective and responsible action and reliance on techno-solutionism — the belief that technological solutions alone can fix the planetary polycrisis — may prove inadequate if not outright hubristic. We will return to these considerations at the end of our journey in the land of eco-augmentation.

For now, a critical dilemma emerges for what it means to be a human in the Anthropocene: should we, as humans, harness or restrain our transformative nature? Our specific self-production mode — that is, how we actively shape our existence — could indeed serve as either a model to emulate or a cautionary tale to avoid replicating. Addressing this dilemma is crucial to handling our transformative power with humility in our approach to eco-augmentation.

Future Anthropocene

Conflicting ideologies vie for the future Anthropocene. This ranges from ecomodernist techno-utopism, which posits the merging of Earth and the technosphere into an engineered planet to address environmental challenges and drive sustainable development, to convivialist degrowth, which calls for scaling back human impact and fostering community-oriented ways of living.

While the controversial notion of a "Good Anthropocene" might currently seem like an oxymoron in this context, it can nonetheless serve as a valid future project or aspirational goal. Initiatives like the "Seeds of Good Anthropocene" represent pathways to transformative change in human-nature relationships for a better future in the Anthropocene, envisioning a world that is more just, prosperous and ecologically diverse.[14]

Beyond universalist assumptions that consider human societies as ahistoric and homogeneous, achieving this vision will require understanding who we are as humans-in-nature from a cross-cultural perspective and tailoring eco-augmentation endeavors to the spatial and temporal heterogeneity of anthropogenic changes. As we will see, this will be key for a sustainable "living-together" in eco-augmentation.

What Is Nature?

In eco-augmentation, humans are "humans-in-nature" who cannot be characterised without delineating nature at one stroke, a concept imbued with various meanings and values across cultures and times. Redefining "nature" will therefore be a strong leverage in fostering more resilient and sustainable environmental practices in the Anthropocene.

The Origins of "Nature"

The term "nature" originates in literate, urban contexts.[15] Despite the vast number of studies dedicated to protecting it, it lacks a clear and precise definition but instead holds various conflicting meanings. Even within the natural sciences concerned with eco-augmentation, the meaning of nature diverges significantly, contrasting fixed, dynamic and analytic visions of nature across the fields of conservation biology, restoration ecology and molecular biology, respectively. This is because, as Lévi-Strauss famously noted, "the scientist never carries on a dialogue with nature pure and simple,"[16] but rather always with historical and sociocultural constructions thereof.

Recognising the anthropological frames that influence how we perceive and relate to nature is thus another essential step in eco-augmentation. In doing so, two intertwined dimensions of nature's characterisation must be kept in mind distinctly: a descriptive dimension, which concerns how nature is epistemically construed and a normative dimension, which addresses why nature matters ethically. Together, these two dimensions are crucial for a comprehensive understanding of what we are interacting with, and why, in eco-augmentation.

Nature across Cultures

Conceptualisations of nature vary widely across different cultures, generally clustering into three main perspectives: an inclusive universe where humans are integral parts of nature, an exclusive environment where humans are seen as separate from nature and a deified nature imbued with spiritual dimensions.[17] The notion of a non-human or human-independent nature, where humans are either dominating or experiencing a humbling absence of control, remains largely a Western exception,[18] contrasting with the more prevalent anthropogenic nature, which is viewed as a meaningful, integrative space co-shaped by human activity. Similarly, most cultures tend to see nature as dynamic and active (*natura naturans*), whereas the static and passive view of nature (*natura naturata*) is predominantly a Western concept influenced by Abrahamic religions and the idea of creation in the hands of God.[19]

These varying perspectives significantly intersect with how different societies, including technoscientific ones, value nature. The values ascribed to nature cover a spectrum from intrinsic values, where nature is valued for its own sake (that is, regardless of its utility or meaning to humans), to instrumental values, where nature is valued for its utility to humans, via relational values, which emphasise the meaningful relationships between humans and nature (Box 2). Understanding these diverse cultural conceptualisations and values is again essential when engaging in eco-augmentation practices.

BOX 2. Intrinsic vs. instrumental values

Intrinsic values that recognise nature's inherent worth independently of human perspective present a twofold paradox. Conceptually, they are impossible as they require a "view from nowhere," whereas any valuation depends on a situated valuer, except for those endorsing extreme moral realism. Pragmatically, such values are self-defeating since they presuppose some form of disinterestedness that would cancel any obligations from humans.[20] Besides, shortcomings of intrinsic values also arise from their lack of straightforward operationalisability, making them difficult to apply in environmental decision-making contexts — even if, as one might argue, unquantifiable values can be rationally deliberated upon.[21]

In contrast, instrumental values can facilitate the necessary trade-offs involved in environmental decision-making by allowing for the comparative evaluation of competing claims through their straightforward operationalisation into quantified metrics. Ultimately, however, eco-augmentation may benefit from moving beyond the intrinsic-instrumental values dilemma, adopting mixed strategies that integrate both types of values, or else focusing on a relational view of values along the lines of the IPBES Values Assessment framework (2022).[22]

Technologisation of Nature

The non-human and sometimes furthermore static and passive view of nature is reinforced by the Western technoscientific epistemology based on an observer/observed or subject/object dichotomy. Within this framework, dominant representations of nature include: nature-habitat, as illustrated by protected wetlands, where it serves as an environment where living organisms coexist and interact; nature-poiesis, seen in processes like reforestation, where nature is viewed as an immanent principle of generation; and nature-artifact, exemplified by urban gardens where nature is designed as a product after a technical ideal.[23]

These representations underpin the evolution from a nature that is merely interfered with to one where technology is employed to transform life itself and rescue natural organisms and ecosystems, through a series of stages marked by intensifying technology-powered anthropogenic and anthropocentric alterations.[24] In this process, technology becomes the primary driver in shaping nature through its imposition of “second nature” onto nature that humans control and dominate, whereas uncontrolled nature, in contrast, is perceived as uncanny and threatening.[25]

This transformation has led to what some describe as *lumpennature*, where independent, unaltered nature no longer exists.[26] It also forms the background of contemporary dominant environmental policies, whose shortcomings must be overcome in the context of eco-augmentation.

Future Nature

Policy frameworks have long rested on a monocultural dichotomy-based conception of nature, distinguishing sharply between human and non-human, cultural or artificial. Enshrined in illusions such as the US-Anglo-centric idea of “pristine wilderness” and often driven by colonialist ambitions, as when settlers perceived the lands as terra nullius requiring industry to become productive, they perpetuated the myth of a fragile “balance of nature” to protect, despite a lack of empirical evidence to support such views.[27]

Although the debate might not yet be finally settled in the scientific literature, stability is increasingly recognised as flawed.[28] Like cybernetic models that organise networks homeostatically, stable systems are often incapable of adapting to change. Instead, constant evolution and change are the norm in natural systems, leading to replacing the outdated notion of balance with the “flux of nature” toward unpredictable uncertainties,[29] aptly captured in the above notion of “transitioning ecosystems” — a key dimension of eco-augmentation.

In eco-augmentation, new conceptions of nature are therefore needed. Documents like the IUCN PAMC (1994/2008) and the UN MEA (2003/2005),[30] nowadays supplanted by the IPBES reports (2019/2022),[31] already highlighted the importance of including cultural diversity and moving beyond dichotomy-based thinking. Beyond the Anthropocene, then, that already transcends the human-nature dualism, it becomes necessary to challenge not just the dichotomy but the very idea of nature and humanity as separate entities, emphasising their common fate as intertwined forces.

Shifting from stability to resilience thinking will also be crucial in managing uncertainties about unpredictable futures in an era where perturbations, including anthropogenic ones, are normalised. Unlike the single, stable equilibrium of vulnerable systems where change has potentially dramatic consequences, resilient systems embrace unstable equilibrium comprised of multiple equilibria, where disturbance is an opportunity for adaptation and transformation amidst ongoing change. At the heart of human-nature interactions, eco-augmentation will thus focus on maintaining dynamic processes between elements rather than striving for a steady state.

ENSURING THE FUTURE OF OUR PLANET

Once we adopt a notion of humans and nature as complex networks of social-ecological processes, we must next turn our attention to their relationships. For eco-augmentation, the question is then "How can we ensure the well-being of humankind and the sustainable future of our planet?" Exploring the dynamics of social-ecological systems, deliberate and strategic human-nature interactions and the development of resilient and sustainable ecosystems, will pave the way to a harmonious coexistence between humanity and nature in eco-augmentation.

Social-Ecological Systems

Social-ecological systems are the privileged target of eco-augmentation. In line with the "human-in-ecosystem" critique of the human-nature dichotomy,[32] they capture the coupled dynamics of human societies and ecosystems, treating them as complex adaptive systems, where evolutionary, ecological and sociocultural processes interplay.[33]

Social-Ecological Co-Evolution

From an evolutionary perspective, social-ecological systems are characterised by emergence, whereby self-organisation among heterogeneous components leads to new system-level properties, behaviours and capacities resulting from complex causality. This perspective sees co-evolution as a process of reciprocal adaptation based on feedback between sociocultural and environmental elements, generating novel emergent outcomes. "Feedback" in this context refers to the process where changes in one part of the system (either the sociocultural or environmental aspect) influence and cause changes in another part, either positive or negative, which in turn can loop back to affect the original part. Evolutionary fitness in social-ecological systems will then manifest as differential resilience and persistence of functionally integrated yet heterogeneous ensembles.[34]

Thus characterised, social-ecological co-evolution encapsulates the potential for mutual adaptability and individual transformability of ecological and human social ensembles, fostering resilient and sustainable social-ecological systems in the face of ongoing change. Contrary to a teleological, mechanistic, or deterministic process aiming for an optimal stable state, it is open-ended, organic, non-deterministic, self-organised and inherently unpredictable. A key driver for such co-evolution is social-ecological niche construction.

Social-Ecological Niche Construction

Many organisms transform their environment in a self-serving manner, thereby conversely influencing selection pressures. In the eco-augmentation context, social-ecological niche construction theory helps capture the underlying dynamics of human-nature co-evolution by emphasising the causal interrelationships between sociocultural and environmental processes across three interconnected dimensions (Figure 1):[35]

- Social-ecological causation, which focuses on the symmetric dynamics of niche construction, where sociocultural systems impact ecological systems via social-ecological systems and natural selection, impacting the other way around;
- Social-ecological inheritance (that is, the transmission of environmental and cultural legacies across generations), which encompasses parallel inheritance mechanisms within ecological, social-ecological and sociocultural systems; and
- Cross-social-ecological indirect effects, which consider how distant niches influence one another globally.

These three dimensions further highlight ethical considerations of interspecies, intergenerational and intragenerational justice, respectively, which are centrally at stake in eco-augmentation.

FIGURE 1. Ecological, social-ecological and sociocultural systems co-evolution
[Insert figure 1 from Dorninger, et al. (2023: 3): https://royalsocietypublishing.org/cms/asset/40d9033b-1568-4cfd-b3d4-8bd314285e84/rstb20220431f01.jpg]

As human societies intensely modify natural environments to enhance their utility and reduce selective pressures, an increasing disconnection between human activities and self-constraining environmental feedback may result in modifications of human environments independent of adaptive needs or pressures. Such outgrowing niche construction processes can lead to "runaway effects", where cultural practices for ecosystem engineering (such as livestock husbandry) enhance selection for traits adaptive to engineered ecosystems (like sedentism or lactose tolerance), generating even greater dependence on cultural niche construction.[36]

From an Anthropocenic perspective, this potential to break feedback loops is again ambivalently a co-evolutionary success, demonstrating human adaptability and agency and a failure, leading to self-destruction and social-ecological lock-ins that exacerbate the said interspecies, intergenerational and intragenerational injustices, underscoring the need for direct experience of feedback to build resilient and sustainable social-ecological systems.[37] Eco-augmentation will have to steer around these many pitfalls and challenges.

Hacking Social-Ecological Dynamics

To address these pitfalls and challenges, reorienting self-serving niche construction onto other-serving practices that integrate the future well-being of the planet with immediate human interests is necessary. Sociocultural niche construction can follow pathways of disruptive upscaling, downscaling, or stabilising changes, whether positive or negative.[38] The crux will lie in designing intentional "regenerative niche construction" to counterbalance or mitigate anthropogenic destructive processes and guide disruptions toward more resilient and sustainable social-ecological systems despite the inherent uncontrollability and unpredictability of sociocultural and ecological evolutionary processes.[39]

To this end, building on the principles of social-ecological systems theory discussed earlier appears particularly suited. This solution-and-action-oriented interdisciplinary approach emphasises the social evolvability of science and technology as pivotal in achieving global sustainability and resilience, advocating for better-designed interventions to facilitate intentional, beneficial change. Hacking of social-ecological co-evolution will then involve identifying targets for changes that hold the potential for high-level transformative impacts.[40]

By purposefully engineering self-reinforcing social-ecological feedback loops that target detrimental lock-ins and self-destructive processes to steer away from them, we can hope to prioritise resilience and sustainability to address the Anthropocene polycrisis, akin to leveraging positive runaway processes. Here, building and maintaining the adaptive and transformative capacities of transitioning social-ecological systems — that is, social-ecological co-evolvability — will be essential to promote resilient and sustainable social-ecological systems.

Deliberate & Strategic Interactions

At the core, eco-augmentation consists of strategic and deliberated human-nature interactions. Various options and shifting paradigms of such interactions must be navigated as we envision building resilience and sustainability into social-ecological systems.

Interaction Management Strategies

Conservation, preservation, restoration and rehabilitation represent some of the most common strategies for managing human interactions with nature, each grounded in distinct views, ideals and objectives. Conservation, for instance, typically adopts a "hands-off" approach, viewing nature as intrinsically valuable and deserving of protection for its own sake. Preservation, on the other hand, allows for limited intervention aimed at sustaining species, habitats, or natural resources for the long-term benefit of all. Restoration efforts, in turn, focus on structural goals, typically aiming to recover a particular species or ecosystem composition; whereas rehabilitation targets functional goals, seeking to restitute ecosystem functions, processes, or services, regardless of the original compositions.

These approaches reflect a spectrum of human deliberate and strategic interactions with nature intensities, from minimal interference to more active measures — with the role of humans evolving from mere observers to active participants, partners, stewards and engineers,[41] or even humble gardeners facilitating non-dystopian anthropogenic environmental changes.[42] All are ever-more attuned to the specifics of social-ecological systems toward resilience-driven interactions.

Historical Fidelity & Ecological Integrity

Be it as conservation, restoration, or even recreation, two criteria typically guide ecosystem management strategies: a reference state criterion involving historical fidelity to some idealised past condition and a dynamic criterion referring to ecological integrity as good ecosystem functioning.[43] The former is challenged by the feasibility of accurately knowing the past and implementing management plans based on that knowledge. This difficulty in achieving historical fidelity further increases with the degree of path dependence at stake in the reference state under consideration (that is, how much the order and timing of events from the reference state influenced the system's current state), calling for more extensive knowledge and micromanagement accordingly.[44]

On the other hand, the dynamic criterion, focusing on good ecosystem functioning, typically emphasises resilience and sustainability. This criterion shifts the perspective from past-focused to future-oriented considerations, addressing how ecosystems can adapt and transform to continue to function effectively amidst changing conditions. Nevertheless, it also faces challenges, particularly in operationalising what constitutes good ecosystem functioning. Backward-looking interpretations of ecological integrity often fall back on historical fidelity, while forward-looking interpretations struggle with incorporating path-dependence complexities, making it difficult to predict or plan for future ecosystem states without a deep understanding of the system's history.

Toward Resilience-Driven Interactions

In response to the unpredictability inherent in emergent social-ecological systems, experimental, iterative and flexible forms of interactions are increasingly implemented, gradually reducing uncertainties. This trend is shifting away from "relentless usufruct ideologies" where humans possess, dominate and exploit nature as they wish, to more dynamic and flexible ecosystem management practices centered on learning, exploration and experimentation.

Unlike command-and-control, equilibrium-centered, mechanistic approaches based on the traditional human-nature dichotomy and leading to vulnerable ecosystems, such as in mainstream geoengineering, this new paradigm aligns with the above resilience-driven, geofunctional view of Earth systems as globally-integrated and causally-interconnected social-ecological systems. In this context, the increased technologisation of resilience-driven interactions blurs the lines between fixing damaged nature and enhancing a deficient original state beyond its own capacities with more beneficial structural or functional characteristics (like the species or ecosystem composition and ecosystem functions, processes, or services alluded to above, respectively). Such a continuum compels us to reframe ecosystem management strategies as involving a kind of replacement, transformation, or reconstruction[45] — in short, "recreation".

An "anything-goes" concern then arises in such historically unconstrained ecosystems resulting from artificial recreations, where human deliberate and strategic interactions with nature might lead to the degradation of natural ecosystems insofar as certain ecosystem services are maintained.[46] Setting appropriate human-nature interaction values in the absence of historical benchmarks will be the key challenge for the eco-augmentation of these novel ecosystems.

Resilient & Sustainable Systems

Several values can guide us in (re-)creating (novel) ecosystems that will form resilient and sustainable social-ecological systems — the goal of eco-augmentation. Altogether, they converge toward renewed planetary thinking, in which humans are part of a larger web of life.

Human Natural Values

While "all ecosystems can be considered 'novel' when placed in the appropriate temporal context," [47] the current era is notable for their increasing appearance rate. Novel ecosystems, defined as "ecosystems that [completely] differ in composition and/or function from present and past systems,"[48] typically due to human activity, offer in this regard a unique opportunity to rethink human-nature interactions within eco-augmentation. Specifically, the so-called "anything-goes worry" associated with these historically unconstrained ecosystems can be addressed by appropriately choosing a flexible set of values in place of the reference state criterion that bears on ecological integrity as the dynamic criterion.[49]

Serving as proxies or surrogates for the impossibility of historical fidelity, human natural values aim to promote the resilience and sustainability of non-human biotas and the non-anthropogenic aspects of physical environments.[50] Ecosystem services and biodiversity are paradigmatic examples of such values (Box 3), while their appropriate choice ultimately aims to align human-nature interactions with the broader goal of well-functioning ecosystems.

BOX 3. Ecosystem services & biodiversity

Until recently, ecosystem services have been the dominant paradigm in ecosystem management strategies (e.g., UN MEA 2005).[51] Characterised by the direct or indirect benefits humans derive from ecosystems, they position nature as a service provider at the nexus of anthropocentric and instrumental valuation frameworks rooted in the human-nature dichotomy — although a broader interpretation can include benefits to non-human species. They have three main applications:[52] a functionalist, consequentialist and comparabilist approach that compares the values of services in cost-benefit analyses for decision-making; a functionalist, consequentialist and incommensurabilist approach that values invaluable services through decision-making based on multi-criteria assessments and deliberative processes; and a non-functionalist and non-consequentialist heuristic approach that highlights the fundamental dependency of humans on nature's sustaining and nurturing capacities.

Biodiversity, on the other hand, is a descriptive and normative concept altogether endowed with both intrinsic and instrumental value. This ambivalence is rendered in the "rivet popper argument",[53] which originally posited that protecting biodiversity is essential for maintaining ecosystem services (and ecosystems, more generally) crucial to human well-being — with the caveats that the diversity of functions, rather than taxa, is what matters and that not all ecosystem functions provide direct services. The ecosystem services argument for biodiversity has struggled due to its inherent functionalism, requiring proof that biodiversity optimally supports important functions, which has led to three significant issues: a lack of empirical evidence directly linking biodiversity to ecosystem services, a scale mismatch between local ecosystem services and global biodiversity changes and the potential for human technologies to optimise ecosystem services more effectively than biodiversity alone.[54]

Due to such shortcomings, ecosystem services have commonly been superseded by the Nature's Contribution to People (NPC) framework since the IPBES Global Assessment report (2019),[55] which refers to "both positive and negative contributions to good quality of life for which nature is a vital, but not necessarily the sole, contributing factor," encompassing material goods, cultural values and ecosystem services. Unlike traditional frameworks, NCP integrates Indigenous, Local and Traditional Knowledge (Box 4), highlighting the non-material and relational aspects of human-nature interactions.

Resilience & Sustainability

Resilience and sustainability are the expected outcomes of well-executed eco-augmentation based on appropriately chosen anthropogenic natural values, such as ecosystem services or biodiversity, in cross-scale functionally integrated ecosystems. Resilience, in general, is concerned with how systems persist amidst change and comes under two primary types (Table 2).[56] Engineering resilience, on the one hand, measures the return time of a system to a steady state after perturbation, emphasising recovery and constancy within a single stable equilibrium context. Social-ecological resilience, on the other hand, describes a system's ability to absorb perturbations, emphasising "robustness" alongside the capacity for continuous development within multi-stable equilibria (or "unstable equilibrium") contexts.[57] Social-ecological resilience is the type of resilience at stake in eco-augmentation dealing with the creation of novel ecosystems through strategic and deliberate human-nature interactions from a social-ecological systems perspective.

In contrast to perfectly optimised systems that collapse under change due to a lack of adaptability,[58] social-ecological resilience is facilitated by a heterogeneous diversity of functional groups with high variability and redundancy, which enhance a system's self-organising capabilities to maintain its functions and structure while undergoing change.[59] Combining present-focused adaptability with future-oriented transformability,[60] this concept of resilience is intrinsically tied to iterative temporality, where future states are seen as variations of past or present conditions, emphasising the system's ability to change through recurring patterns rather than progressing along a linear, historical path[61] — which will prove critical from an ecosystem management perspective, as we will see.

TABLE 2. Resilience typology[62]

TYPES	FEATURES	FOCUS	CONTEXT
Engineering resilience	Return time, efficiency	Recovery, constancy	Vicinity of a stable equilibrium
Social-ecological resilience	Interplay disturbance and reorganisation	Persistence/Robustness, adaptability/transformability,	Multiple equilibria, integrated cross-scale system dynamics

Turning to sustainability, as originally defined by the Brundtland report (Article 27), is about meeting "the needs of the present without compromising the ability of future generations to meet their own needs."[63] This concept has both weak and strong versions, with the former allowing for the functional replacement of entities and the latter demanding the conservation of individual entities. In both cases alike, however, since it narrowly centers on interhuman relationships across time only and treats nature as a uniform non-human entity, this traditional anthropocentric construal of sustainability is bound to fail in meeting its goals.[64] Several criticisms have ensued, acknowledging that moving toward a new construal of sustainability was therefore needed, as prominently reflected in the UN Sustainable Development Goals (SDGs).[65]

Among these new construals, multispecies sustainability emerges as the most fitting approach for eco-augmentation targeting social-ecological systems, particularly when constrained by human natural values that serve as proxies in lieu of unattainable historical fidelity. By valuing relationality with the environment and interconnectedness across life forms, multispecies sustainability aims to meet the interdependent needs of all species, viewing non-humans as actors with agency (and not resources) whose interests must be negotiated and compromised with to ensure the well-being of both current and future generations across the spectrum of life forms.[66]

Beyond Centric Thinking

In this line, eco-augmentation, defined as human strategic and deliberate interaction with nature for more resilient and sustainable social-ecological systems, invites us to move beyond centric thinking. Moving beyond centres starts with asking "who places what at the center of what (and what else is therefore excluded…),"[67] which reveals hierarchical dualisms that reflect or reproduce domination ideologies rooted in culturally relative blind universalism — and extending from Earth-centrism to anthropocentrism, with ecocentrism, biocentrism and zoocentrism in between.

Along these anthropocentric/non-anthropocentric polarities, the challenge is both epistemic and moral, holding in our inescapable human condition in the things we know and value, respectively (cf. the paradox of intrinsic values [Box 1]). Alternatives such as anthropomorphising non-human entities or de-anthropomorphising humans are both fraught with scientific and philosophical complexities.[68] Nevertheless, acknowledging that the way people treat each other influences how they treat the rest of nature and vice versa, calls for expanding kinship to all living beings by recognising non-human agency to sustain mutually beneficial evolutionary feedback.[69]

Accordingly, multi-perspectival planetary thinking is needed for consistent, effective and responsible eco-augmentation, shifting away from any centric view to relational habitability of the Earth where humans are mediators within complex networks of interdependent relationships, both synchronically and diachronically.[70] In this renewed planetary thinking, eco-augmentation will materialise environmental justice — whether interspecies, intergenerational, or intragenerational (Figure 1) — in such a way that human natural and cultural values can only be pursued together.[71]

LIVING ALL TOGETHER

As all the components, dimensions and relationships concerned with eco-augmentation have been covered, our remaining question is "How can we all live together?" in eco-augmentation, with a focus on the technosphere and sociosphere that make our collective life in societies. Diving into the interplay between these two spheres will set a way forward to integrate technological advancements and sociocultural values into resilient and sustainable futures.

The Technosphere

The technosphere encompasses the technological environment created by humans, shaping and sustaining new social-ecological systems. From this perspective, a key challenge for living together in eco-augmentation is conceptualising technology in human-nature interactions for more resilient and sustainable social-ecological systems. Tackling this challenge within the Anthropocene demands a double shift beyond traditional dualisms revolving around technology, highlighting the ambivalent nature of technology for a technologised humanity.

Natural-Technological Hybrids

As we anticipated above, within the Anthropocenic technosphere, technology is not merely a human construct; humans, conversely, are also products of technological evolution. Likewise, in eco-augmentation, nature serves as a model for technology, whereas technology shapes our understanding of nature.[72] In other words, for eco-augmentation technologies to be deployed in deliberate and strategic human-nature interactions, nature cannot be reduced to an object of knowledge anymore but should instead also be treated as a model to mimic.

Mimicking nature can consist of transferring nature-based general design principles to technical domains (inspiration), abstracting and translating nature-based functional principles into requirements for technical applications (imitation), or merging nature into technical design and vice versa to replicate the functional principles of the natural model (integration). Nature, in this mimicking relationship, can serve as a model technically, providing insights for better technology design, or ethically, guiding us to make technology more compatible with life on Earth (Table 3).[73] Ultimately, always treating nature as an ethical model at the same time, not just a technical one, will prove essential to prevent its further exploitation by anthropocentric biomimetic technology.[74]

TABLE 3. Mimicking nature[75]

MODEL	INSPIRATION	IMITATION	INTEGRATION
TECHNICAL	**Nature** as a source of ideas for innovative functions. **Mimesis** as inspiration from broad functional principles.	**Nature** as a repository of innovative designs to study. **Mimesis** as the abstraction and translation of precise functional principles for technical purposes.	**Nature** as a realm offering unique properties that can be harnessed. **Mimesis** as functional incorporation of biology and technology to replicate and enhance biological capabilities.
ETHICAL	**Nature** as a source of ideas for sustainability. **Mimesis** as inspiration from broad functional principles for ecological sustainability.	**Nature** as a model and measure for sustainable innovation. **Mimesis** as the abstraction and translation of precise functional principles for ecological sustainability.	**Nature** as endowed with an instrumental and intrinsic value of ecosystems. **Mimesis** as the functional integration of biology and technology to obtain services and regenerate ecosystems.

This approach, while balancing the potential for symbiotic interaction between nature and technology — whether fixing or enhancing — against the risks of domination and exploitation, moves from the traditional hylomorphic view, which sees humans providing knowledge and nature supplying material, to a "biomimetic epistemology" where nature becomes a source of knowledge, offering working principles.[76] When materialised, it results in a new ontological category, beyond dualisms: mirroring the resilient and sustainable social-ecological systems they originate from, natural-technological hybrids will be self-organised, adaptive and transformable, endowed with autonomous agency and independence together with an element of unpredictability and uncertainty — thus necessitating socially responsible implementation.[77]

Technologised Humanity

The reciprocal mimesis between technology, humans and nature operating with eco-augmentation in the Anthropocene emphasises some converging principles and dynamics that present the technosphere with autonomous agency and independence. Such anthropomorphising technological determinism, in turn, may lead to disempowering human agents who then come to overlook their responsibility, as critically alluded to before, in designing technological innovations that shape the social and natural worlds.[78] Retaining ownership and control over technology within the technologised nature and humanity of the technosphere will therefore be crucial to fostering resilience- and sustainability-driving technologies in eco-augmentation.

Unfortunately, those in charge of the technosphere in the Anthropocene can too often be likened to Homo Prometheus, skilled in technical arts but lacking the political expertise necessary to integrate technology into the art of living well with other communities. Illustrated in the above command-and-control, equilibrium-centered, mechanistic approaches to human-nature interactions, a narrow-minded technosolutionism ensues that concentrates on using technology to address emerging problems without altering the underlying paths that cause these issues. As a result, it perpetuates a cycle of technological fixes rather than fostering systemic change.

This scenario aligns with the idea of a "technological pharmakon", where planetarised humanity, threatened by its technological creations, is also destined to remedy this situation through the very same technology.[79]

Technological Pharmakon

The dual role of technology acting as both disease and cure necessitates further careful examination of its distinctiveness compared to nature. Unlike the self-production of autotelic nature, where means and ends are conflated in a feeling of oneness, technology involves hetero-production, characterised by a separation between means and ends, driven by specific purposes. Moreover, human natural-technological hybrids displayed in eco-augmentation differ from animal tools in scale, impact and potential non-species-centric applications. Crystallising unprecedented risks and opportunities, they associate the promising impact of altering "the fabric of non-human life" with the threat of unintended detrimental and potentially irreversible consequences. This perspective, while echoing Mill's assertion that "arts are but the employment of the powers of nature for an end,"[80] captures the naturalness of human artificial interventions in the anthropogenic adagio "nature is us".[81]

When thinking of eco-augmentation technology within a planetary context and as a planetary phenomenon, the hyper-control that technologised humanity has reached thus reveals itself as not being under control, somehow intrinsically. Yet, by failing to acknowledge and understand human controlling limitations, humans, however empowered, will lose the possibility of exerting control responsibly.[82] A crucial aspect of navigating technology-powered human-nature interactions in eco-augmentation will then involve determining when, where and how to draw the line between humility and hubris — while recognising that what was once considered hubris can become normalised over time.[83]

In this picture, anthropogenic — yet non-anthropocentric — technologies should be used to protect the planet. New forms of effective social governance of eco-augmentation technologies will be necessary in the sociosphere for repurposing them toward acentric, pluralist ends in a planetary era, ensuring their alignment with more resilient and sustainable futures.

The Sociosphere

Achieving resilient and sustainable futures presupposes radical transformations in the sociosphere, powered by new future imaginaries and adaptive technoscientific governance. As it culminates in global inclusive diversity, the novel sociosphere will overcome the science-society-policy divide with effective eco-augmentation.

Futuristic Imaginaries

We need new imaginaries prompted by aspirational narratives for more resilient and sustainable futures to guide us in reconstituting the living environment and adapting to the Earth's degraded state.[84] Besides technology-driven transitions at stake within the technosphere, these narratives must also critically involve transitions driven by values change and local adaptation. Participatory methods, such as constraint-based scenario planning, can help us here foster the capacity of societal imagination for shaping the future.[85] While focusing on unknowable contingencies when exploring alternative futures, these methods improve decision-making under uncertainty by appropriately identifying resilient and sustainable policies. Balancing cross-scale back-and-forth between top-down and bottom-up scenarios will be crucial for this process.

Small, concrete, local changes are often more feasible, controllable and predictable than large-scale transformations. They afford a logic of tests or experiments particularly apt for eco-augmentation, whereby the failure of a prototype necessitates only minor strategy adjustments rather than major structural changes within an iterative relationship to temporality.[86] Initiatives like the aforementioned "Seeds of a Good Anthropocene" showcase examples of such innovations and experiments, identifying features of a better future and processes for inducing fundamental changes in human-environment relationships through bottom-up efforts.[87]

Yet, these scenarios, although relevant locally, are difficult to upscale coherently. Combining them with top-down scenarios, which provide useful abstract, global frameworks for comparing worldviews but struggle to downscale to local implementation, is therefore essential for crafting compelling aspirational narratives toward better futures — especially, if we want these narratives to drive eco-augmentation governance effectively.

Technoscientific Governance

Governance of eco-augmentation for more resilient and sustainable social-ecological systems in the Anthropocene requires rethinking policy decision-making and action to manage change proactively rather than merely reacting to it. Accelerating global changes, coupled with the unpredictability and uncontrollability of social-ecological systems dynamics, generate conflicting timeframes that require both short-term adaptive decisions and actions together with long-term transformative visions. A shift towards active management and governance rooted in multistakeholder collaboration, such as resilience-experimentalist or decision-theoretic approaches, offers a potential solution.[88]

Here, the main challenge lies in the research-implementation gap we mentioned at the outset, with around two-thirds of environmental assessments published in the research literature failing to translate into actions, primarily due to a lack of planning for implementation besides power dynamics, conflicts of interest and other practical limitations.[89] Until recently (e.g., IPBES 2022),[90] empirical research lacunae persisted, particularly in understanding the link between human-nature relationships and ecosystem management strategies and in exploring how these relationships can drive action.[91] Bridging this knowing-doing gap with eco-augmentation requires translating scientific knowledge into practice by engaging local practitioners to match ecological priorities with social opportunities through knowledge co-production and co-learning.[92]

To do so, what Leopold termed the "anomaly of modern ecology" nearly a century ago already must be finally overcome:[93] Alongside recent trends in sustainability studies, eco-augmentation sciences must evolve towards interdisciplinarity, integrating ecological and social approaches via mutual translations, if they are to influence the global trajectory of the Anthropocene. Drawing on a combination of scientific pluralism and standpoint epistemology to strive toward global inclusive diversity will help us navigate, in turn, the heterogeneous belief systems subsequently at stake and whose interactions involve asymmetric power relationships between epistemic actors.[94]

Global Inclusive Diversity

Global inclusive diversity means reconciling Indigenous, local, traditional and scientific ecological knowledge systems (Box 4) across their cultural, ontological and linguistic variations — rather than merely aggregating them. A key challenge is then transforming that global inclusive diversity into effective environmental governance, planning and management toward better futures. Predating the Nature's Contribution to People model (IPBES 2019), frameworks for equitable and empowering knowledge-sharing environments, such as the “multiple evidence base” approach, will also help foster epistemic cross-fertilisation, typically under three main forms: namely, one-way integration of knowledge, parallel synergies across knowledge systems and co-production of knowledge based on mutual generation processes throughout.[95]

BOX 4. Indigenous, local and traditional ecological knowledge (ILTEK)
Indigenous, local and traditional ecological knowledge systems are commonly defined as cumulative bodies of practice and belief, evolving through adaptive processes and transmitted culturally across generations, about the relationships between living beings and their environment.[96] Anchored in direct historical experiences of disturbances, they provide resilience-driven ecosystem management that complements scientific adaptive management, contrasting with the technocratic alteration of social-ecological feedback loops in Anthropocenic societies.[97]

While the appropriateness of each cross-fertilisation strategy depends on the specific context, issue at hand, scale and history of interactions between knowledge systems, adjudicating between them requires negotiating the joint assessment of convergence and divergence across various forms of knowledge despite profound differences and partial incommensurabilities.[98] Translations between knowledge systems involving stakeholders in different positions of power to enforce their culture, ontology and language mark a key opportunity for technoscientific diplomacy to represent those epistemically disempowered.[99] What will be expected as a result is complementary valid and usable knowledge endowed with three core features: legitimacy, as proceeding from a respectful epistemic diversity; credibility, as evidence-based and truthful; and saliency, as relevant to the users’ needs.[100]

Once crystallised into legitimate, credible and salient knowledge, global inclusive diversity will be pivotal in fortifying the science-society-policy interfaces necessary for effective environmental governance, management and planning toward better futures. By highlighting blind spots and preconceptions, reinterpreting existing data and generating new evidence, this diversity of knowledge systems, cultures, ontologies and languages will enhance the adaptability and transformative capacity we need in eco-augmentation for more resilient and sustainable social-ecological systems.

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