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Perspective

Opportunities to foreground human embeddedness in the Anthropocene biosphere

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SUMMARY

Dominant traditions in Western science have traditionally separated humans from nature, a division that is reproduced in the distinction between natural and social sciences. This rift has persistently hampered the ability of sustainability science to comprehensively understand and address the profound challenges of the Anthropocene. In this perspective, we aim to challenge entrenched separations between humans and nature by emphasizing the embeddedness of humans in the biosphere. We conceptualize embeddedness from a systems perspective and illustrate it using case studies on human microbiomes and freshwater availability. We discuss how a focus on embeddedness can increasingly be adopted in sustainability research through developments in sensing, modeling, and commoning practices. By highlighting these conceptual and practical opportunities for studying embeddedness in the biosphere, we seek to support transdisciplinary dialogues and practices toward sustainable futures.

INTRODUCTION

Life coevolves. All living beings—microorganisms, fungi, plants, and animals—are embedded within a single biosphere, continuously coevolving with the living conditions on Earth.[1–5] The biosphere encompasses all living beings and their relations, including their interactions with the lithosphere, cryosphere, hydrosphere, and atmosphere.[6] Phenomena, such as nutrient cycling, climate regulation, and animal migration patterns, emerge from interactions and co-evolutionary dynamics in the living biosphere.[7–10]

Situating and understanding phenomena as embedded in the biosphere is critical for addressing sustainability challenges. The planetary climate emergency, geopolitical conflicts, increasing inequality, and rapid ecosystem degradation require efforts and strategies that prioritize care for living systems and foster beneficial outcomes for all organisms.[11–13] Relational values—those reflecting the qualities of relationships between humans and other parts of nature—have been proposed as leverage points for policy interventions.[14,15] Disconnection from and domination over nature and people are seen as root causes of persistent challenges and barriers to transformative change in addressing biodiversity loss according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).[16] For example, characterizing lands as "natural," "intact," and "wild" obscures humans' historical roles in profoundly shaping landscapes and ecosystem functions. Environmental archaeological and palaeoecological research on human niche construction reveals that historical practices, including burning, hunting, species propagation, domestication, and cultivation, have left long-term legacies across the terrestrial biosphere.[17–19] Treating humans as part of landscape histories can thus foster regenerative and restorative practices, and help define communities' relations in ecosystem management or restoration practices.[18]

Solution-oriented work increasingly examines the linkages between the natural world and human societies to identify leverage points for sustainability transformations.[20–24] Approaches that view humanity and its cultures as inextricably intertwined with more-than-human life, rather than merely linked, are also gaining increasing attention in sustainability science.[25–28] Aimed to generate actionable knowledge for addressing sustainability challenges, social-ecological systems perspectives highlight how humans, their cultures, and social structures are part of and dependent on the biosphere.[29–31] Research, policy, and practice concerning social-ecological systems have long strived to develop analytical and theoretical frameworks that adequately integrate ecological dynamics alongside social and institutional ones—particularly for addressing nonlinear interactions, cascading effects, and cross-scale feedbacks.[32] Such approaches can still differentiate entities within the biosphere, without implying a dichotomy. Berkes and Folke[33] already pointed out in their early work that in the social-ecological systems perspective, "the delineation between social and natural systems is artificial and arbitrary."

Providing alternatives to human-nature dualism and anthropocentric modes of inquiry, however, remains challenging. Research fields often conceptualize hierarchies and dissimilarities between humans and nature.[34] Dominant positions in Western science continue to conceptualize human agency as an external driver or factor of non-human ecology and evolution.[18,35] It is not mainstream in policy-relevant fields to study biosphere dynamics as an integrated interplay of relationships and processes, and to go beyond conceptualizing humans and nature as separate, albeit interdependent, entities. For example, earth system models (ESMs) are used to study human impacts on climate and the complex interdependencies among various biological, chemical, and physical processes, without explicitly representing humans and their social, cultural, and economic responses to the environment.[36] Integrated assessment models (IAMs) have been coupled externally to ESMs to study feedbacks mediated primarily by greenhouse gas emissions. Yet, there is scant physical representation of the distribution of human societies over the surface as an interactive component of the biosphere.[37–39] The complex interplay between the dynamics of the biosphere and social, cultural, and economic processes is therefore not captured.[36] Hence, there is an urgent need to foster approaches that situate humans not only as interdependent but also embedded in the biosphere.

By foregrounding embeddedness in the biosphere, the focus shifts to how phenomena—whether processes, events, or patterns—emerge from and are influenced by the dynamic interactions among living organisms and their surrounding ecological, geological, and atmospheric systems. Recognizing the embeddedness of humans in the biosphere should be adopted more deeply and broadly within sustainability science to go beyond human-nature dualism. With this perspective, we aim to encourage dialogue on the ways to study embeddedness in the biosphere by highlighting key conceptual and practical aspects. We offer a brief review of conceptualizations centered on intertwinedness and situatedness within the biosphere and explore the meaning of embeddedness through a system perspective. Lastly, we identify opportunities for studying embeddedness that arise from recent advances in sensemaking strategies. In doing so, we hope this perspective will serve as an invitation to foreground embeddedness in the biosphere further.

TOWARD CONCEPTUALIZING EMBEDDEDNESS IN THE BIOSPHERE

Providing alternatives for "human-nature dualism" and anthropocentric modes of inquiry requires transforming scientific practices dominated by dualistic thought.[25,26,40] The roots of the conceptual separation between society (the realm of human activities, social structures, culture, and technology) and nature (the physical and environmental backdrop to that realm, including all non-human life forms) have been ascribed to the Enlightenment era and Western-dominated sciences.[41,42] Intersecting processes of colonialism and industrial capitalism have been generally described to further "sever relations between mind, body, and land," contributing to biodiversity loss, social and environmental injustice, climate change, poverty, and pollution.[43] In this section, we discuss alternative conceptualizations to dualistic notions and how they emphasize compositions, relations, and evolutionary dynamics within the biosphere (Figure 1).

Carefully involving multiple ways of knowing can weave together ways of thinking, feeling, and doing that allow for understanding of situatedness and relationships in the biosphere.[45,46] West et al.[40] argue that relational perspectives can be fruitfully brought into contact with other knowledge systems. Nurturing reciprocity between academics and Indigenous peoples and local communities has been argued as a way to identify pathways for fostering living in harmony with nature.[35] Embracing difference, "walking" and "thinking with" multiple ways of knowing can be productive to advance fair and symmetrical dialogue.[45,47] Indigenous theoretical approaches, and the feminist and decolonial research that have emphasized them, "challenge fundamental anthropocentric, rationalist division between the social and the natural and provide tools to notice interdependence and reciprocal care."[48]

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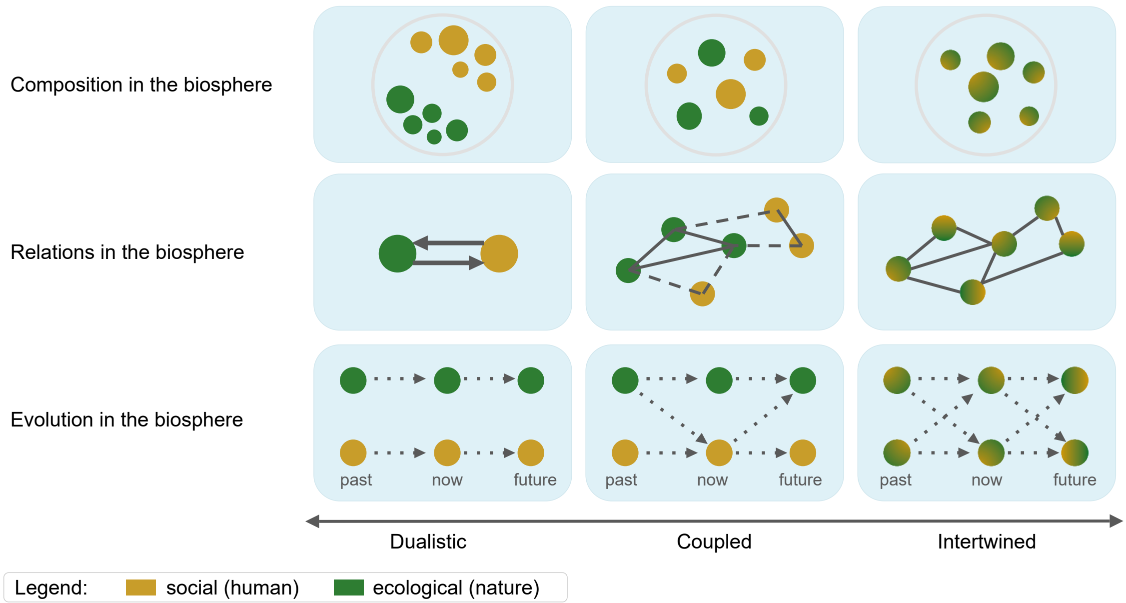

Figure 1. Perspectives on the separation of humans and nature

Inspired by Mace[44] and Reyers and Bennett,[28] this figure represents a simplified spectrum of conceptualizing separation between the social and ecological realms along three themes: composition of the biosphere, relations in the biosphere, and evolution of the biosphere.

Place-based notions of "becoming family," "making kin," and "co-becoming" represent ways to define "society" in ways that include more-than-human beings.[49] Examples of localized perspectives on situatedness within the living world are the notions of "domūs" and "dwelling." Cassino et al.[47] employ the concept of domūs (derived from the Latin term for "house") to discuss more-than-human Native Amazonian conceptions of the world as a mosaic of domains (or domūs) that are cared for, managed, and cultivated by different beings. In this way, their conceptual model presents the forest as fully domesticated by the action of a multiplicity of beings, who possess symmetrical agencies and are constantly interacting socially. The notion of dwelling directs the focus on how human beings actively participate in the ongoing multi-species creation of the environment and shape their lived experiences through tangible experiences within it.[50,51] It highlights that knowing and acting are co-constituted.[51] These perspectives, therefore, emphasize the composition of actors and their relations in an intertwined way (see Figure 1).

The Gaia hypothesis presents a global perspective on embeddedness. Lovelock and Margulis proposed the notion of Gaia in the 1970s to conceptualize the planet as perpetually self-regulating, cooperative, and evolving.[52] It highlights relations and evolutionary dynamics as it focuses on how life shapes its living conditions through different relationships and throughout the entire history of the Earth.[53] For example, life has created and maintains the imbalances that make the atmosphere breathable. Gaia does not represent a given and static habitable container with living beings as its components, but rather something that continuously emerges from life itself.[53] The notion of Gaia thus attributes the task of forming the conditions for lasting over time and expanding in space to lifeforms themselves.[54] The concept enables studies of biotic processes that blur the lines between the "individual" and the "environment" by considering the environment as an extension of heterogeneous living beings.[53] The concept also directs studies to encompass spatial scales and geological evolution since deep time.

To stimulate dialogue and experimentation among different ways of understanding actors, relations, and evolutionary dynamics within the biosphere, we see a systems lens as a promising perspective to unpack how embeddedness could be studied. Social-ecological systems research is rooted in complex system science, relating to concepts such as resilience and adaptive capacities.[30,33] Systems thinking in sustainability science has evolved to understand the biosphere as a set of interacting components where each influences and is influenced by the other.[55,56] In simple terms, "systems" in sustainability science refer to integrated wholes that are larger than the sum of their parts.[55] A system's boundaries are defined by the researcher and understood as porous and changeable.[57–59] Boundaries are therefore considered to be nested within, or themselves nesting in, other systems—presupposing the importance of taking into account cross-scale interactions.[5,60,61] A complex adaptive systems lens forces a recognition that all system components shape each other continuously across various spatial and temporal scales. As such, it emphasizes composition, relations, and evolution within the biosphere. We therefore view it as a promising perspective for unpacking how embeddedness can be studied.

UNPACKING EMBEDDEDNESS THROUGH SYSTEMS THINKING

In the following section, we use systems thinking to offer three key aspects for conceptualizing embeddedness in the biosphere. We employ the terminology of system elements, relations, and their

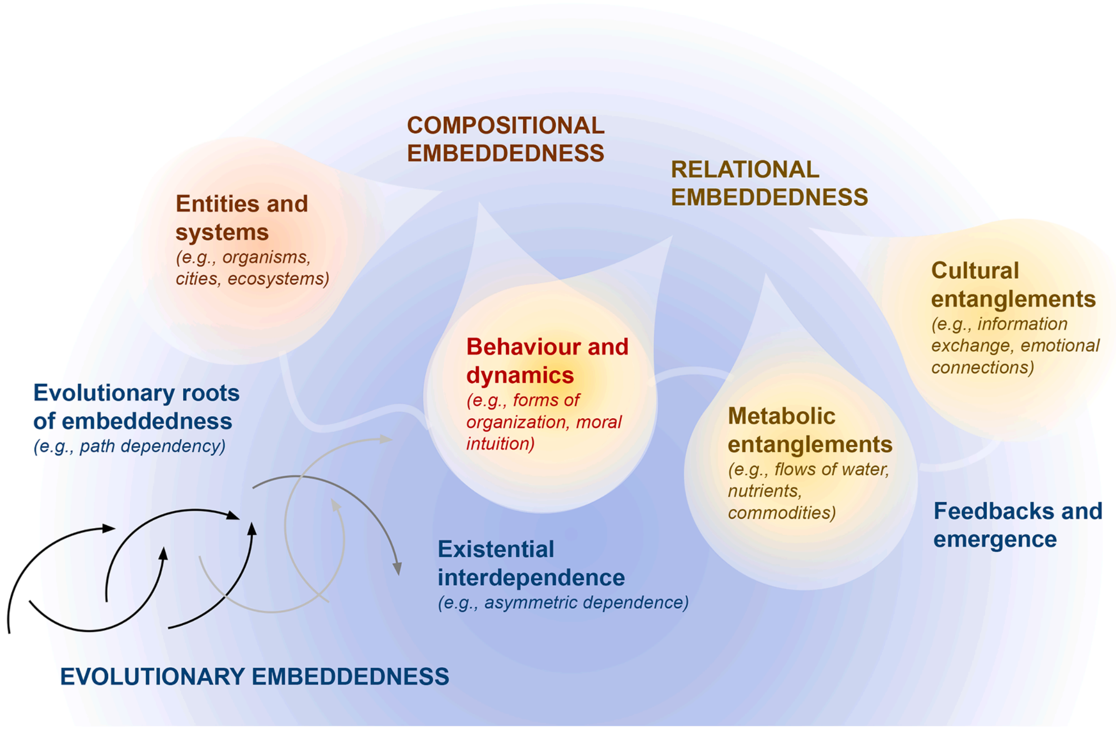

Figure 2. Three dimensions of embeddedness: compositional, relational, and evolutionary
Making sense of embeddedness in the biosphere requires considering these three dimensions together.

dynamics to discuss embeddedness in terms of "compositional," "relational," and "evolutionary" embeddedness (see Figure 2). In short, we use compositional embeddedness to study how a phenomenon in the biosphere is composed of, and a part of, elements or events related to life processes. Relational embeddedness refers to the idea that phenomena emerge through processes and interactions concerning living organisms. Evolutionary embeddedness refers to how phenomena are constituted by as well as co-evolving with the evolutionary dynamics of the biosphere across multiple temporal scales. These three dimensions are applied to the topics of "human health and microbiomes" and "freshwater availability" in Boxes 1 and 2.

Compositional embeddedness refers to the idea that phenomena consist of interconnected elements related to life. The human body, for example, is composed of organic materials and contains or even constitutes a whole system of living microorganisms (see Box 1). With this dimension, the embeddedness of a phenomenon in the biosphere can be studied in terms of its composition or how it is part of larger systems. These heterogeneous elements can constitute material building blocks, but can also be "events," i.e., temporary nodes produced through the dynamic intersection of multiple processes. For example, life processes such as photosynthesis play a role in supplying moisture to the atmosphere and shaping rainfall patterns (see Box 2). To unpack how a phenomenon is embedded in the biosphere, one can thus look at the heterogeneous elements, events, or processes that constitute it. In other words, considering compositional embeddedness means answering the question "*what* is embedded in what"?

Relational embeddedness refers to the idea that the biosphere and its constituents come into being through relationships. By considering relational embeddedness, research practices thus turn to flows, connections, interactions, and intra-actions,[84] such as those through trade flows (metabolism), social processes of organization (behavior), or information exchanges (culture). We propose that analyses of relational embeddedness can be studied by considering either external relations (i.e., interactions) or internal relations (i.e., intra-acting). This means that one can look at the flows, connections, and interactions between predefined entities. For example, virtual water trade establishes dependencies on water resource availability in other regions of the world (see Box 2). One can draw from process-relational perspectives, perceiving, for example, the human body as emerging from processes and relations within broader biosphere dynamics (see Box 1).[64,85] The dimension of relational embeddedness shifts the focus to "*how* a phenomenon is embedded." It therefore allows us to consider dependencies and the co-constituting nature of events in the biosphere.

Evolutionary embeddedness refers to the idea that phenomena emerge and continue to change through a series of events and processes that unfold over time. With this dimension, we aim to direct attention to the temporal contingency or path dependency of how phenomena come into being and to the open-endedness of future change. Evolutionary embeddedness can be studied as historical explanations, potential future coexistence (the existential interdependence of multiple lifeforms), coevolving feedback, and the emergence of complex adaptive dynamics and higher-order structures from embedded, but simpler building

Box 1. Human health and microbiomes

The human body coevolves with multiple organisms, both living within and outside it. Human bodies are the product of relationships with their environment, including flows of water, air, nutrients, information, and cultural imaginaries.

COMPOSITIONAL EMBEDDEDNESS

The human body is composed of organs, including the gut, skin, lungs, and brain, that act in concert with human microbiomes. Moreover, it is a part of its environment that intricately influences the functioning of these organs. The diversity of the microbiomes of the human gut, lung, and skin arises from exposure to healthy microbiomes such as those in soils. Conversely, some herbicides inhibit microbial metabolism in soils and the diversity of microbiota within humans. Research studying humans as holobionts—an assemblage of host and multiple other species—has explored how this symbiosis between the human body and gut microbiota dynamically shapes physical and mental health, moving beyond dichotomies of human and nature, and mind and body.[62] Similarly, studies highlight the complex interactions between geographies, diet, the microbiome in the human gut, and malaria severity.[63]

RELATIONAL EMBEDDEDNESS

Vegetation growth provides humans with oxygen, organic matter, shelter, food, fuel, and a place for recreation and regeneration of well-being. The relationships between, and human activities engaging with, land and other species—such as the cultivation of vegetables or implementation of biodiversity policy—can transform the land and the soil microbiome, which in turn affects human bodies. The chemical elements essential for human health are transformed and transported throughout the biosphere by both micro- and macrobiology.[8,10] The embeddedness of processes such as biologically mediated transport of nutrients, trade, modes of agricultural production, and the predation, grazing, and movement of animals affects the human body's chemical composition. Moreover, studies on human-nature connectedness have shown that physical connection with and seeing oneself as part of nature improve an individual's health, well-being, and sense of place across geographies.[64,65]

EVOLUTIONARY EMBEDDEDNESS

The intensification of agriculture through high-chemical input and heavy machinery usage both reduces microbial diversity in soils and adversely impacts soil fertility over time.[66,67] These impacts can lead to yet higher levels of production intensification and chemical input application. In turn, this cycle leads to the production of less nutrient-dense crops and impoverished nutritional intakes that impact human well-being and the quality of decision-making. Microbiome networks in the soil affect the availability of nutrients for plants and, thereby, the food harvested by humans. Regenerative agriculture with attention to plant and soil health leads to deceleration of this degradation and well-being, as well as more nutrient-dense plant-based foods for humans and animals.

blocks.[61,86] Evolutionary dynamics shape the structure and interactions of compositions and relations. The evolutionary perspective allows for explaining and complementing contemporary compositional and relational dimensions (e.g., the current microbial content of human bodies explained by evolutionary theory, see Box 1), as well as for identifying asymmetrical interdependencies (e.g., that humans depend existentially on the water cycle, whereas the existence of the water cycle is relatively unaffected by human existence, see Box 2). Beyond biological evolution, evolutionary embeddedness can also be used to explore the embeddedness of cultural evolution in human societies and how cultural change influences, and coevolves with, genetic and environmental factors.[87,88] For example, the domestication of plants and animals by early human societies during the Neolithic Revolution not only shaped human culture and social organization but also drove lasting genetic adaptation, environmental change, and complex feedback processes. Pastoral populations experienced the genetic evolution of lactase persistence, whereas the increase of amylase gene copy numbers has been shown in agrarian societies that consumed large quantities of starch.[89,90] Dietary and wider cultural shifts also altered environmental conditions through tillage, deforestation, wetland cultivation, and grazing practices.[19] Shifting environmental conditions, alongside the more densely populated social centers, have been linked to new selective pressures that have increased populations of pathogens.[91,92] Increases in malaria-transmitting mosquitoes, for example, eventually led to genetic adaptations such as sickle cell mutations in human populations, enhancing resistance to the disease.[93,94]

Evolutionary embeddedness, therefore, helps explain "*why* a phenomenon has emerged in the biosphere," including human societies and their cultures, languages, and technologies. This question helps understand systemic transformations. It allows us to explore processes that bring new system properties into existence, what system parameters enable continuous regeneration, or what structures and entities allow the system to self-organize for resilience and new emergent properties, thereby coping better with shocks and disturbances. Evolutionary embeddedness facilitates investigations into how multiple dynamics combine to affect the biosphere.

OPPORTUNITIES FOR STUDYING EMBEDDEDNESS

The three dimensions of embeddedness, presented in the previous section, provide key aspects for understanding the embeddedness in the biosphere. We offer these dimensions to foster space for genuine dialogue and exchange among multiple research approaches and ways of knowing, addressing critical

Box 2. Freshwater availability

Freshwater emerges through inextricably connected living Earth system processes and thus is embedded in the biosphere.

COMPOSITIONAL EMBEDDEDNESS

Water is a part of all ecosystems. Animal bodies, vegetation, soil, and the atmosphere are largely composed of water. Moreover, the composition of the quality and quantity of freshwater available is influenced by interactions in the biosphere. Eutrophication is, for example, the process in which a high nutrient concentration in water bodies (e.g., by fertilizer runoff) causes a proliferation of the growth of organisms that may deplete the oxygen in the water, which can lead to critical regime shifts from biodiverse and complex-life-friendly to more simplified states.[68]

RELATIONAL EMBEDDEDNESS

Freshwater moves around in the Earth system and is shaped through processes related to life. Globally, around 40% of terrestrial rainfall originates in evaporation from land.[69] These evaporation patterns are known to be influenced by human water and land use. Irrigation has been found to increase precipitation downwind, whereas deforestation decreases it.[70–77] Anthropogenic climate change intensifies the water cycle, increasing the risks of extreme events such as pluvial flooding and droughts.[78] Many regions worldwide heavily depend on the import of agricultural commodities and the associated embodied water use, as they are affected by chronic water scarcity relative to their populations.[79]

EVOLUTIONARY EMBEDDEDNESS

Freshwater availability depends on events over time. Growing population sizes and economic activity lead to increased water requirements for drinking water, irrigation, and energy production. One third of all freshwater withdrawals are from groundwater sources, supplying domestic, agricultural, and industrial water use.[80] Groundwater also plays a role in many environments by sustaining baseflow in rivers, lakes, and wetlands during periods of low or no rainfall.[81] With the increased risks of floods and droughts arising from anthropogenic climate change, groundwater storage becomes strategically important.[81] It has been found that basins with existing freshwater stress continue to lose stored water faster than non-stressed basins worldwide.[82] Groundwater system response times are often orders of magnitude slower than pumping rates. "Fossil groundwater" refers to the groundwater that was recharged during the wetter and cooler climates of the Late Pleistocene and Early Holocene.[83] Current and future freshwater withdrawals and stress, therefore, link to recharge processes across decades and millennia.

blind spots and working productively with potential tensions.[25,95] Recognizing, reimagining, and empirically studying phenomena embedded in the biosphere requires experimentation with multiple research designs and spaces for ontological and methodological pluralism. This means embracing a coexistence of different understandings of "what exists" (ontology), "what can be known about the world" (epistemology), "how this knowledge should be gathered" (methodology), and "why knowledge should be gathered/what should be done with the knowledge" (axiology).[96,97] It also includes reflexivity on the situatedness of research practices. In this section, we provide a set of opportunities across three sensemaking strategies to illustrate how a focus on embeddedness can be increasingly operationalized within a wide range of sustainability science practices (Table 1).

Studying embeddedness through sensing practices

Sensing and being attentive to life in the biosphere can be used to better understand the dimensions of embeddedness and to inform practices of care, control, stewardship, and governance.[98,99] Sensing is often associated with technological devices (sensors) which register phenomena either *in situ* or remotely, and has also focused on human senses (hearing, sight, taste, smell, and touch). However, sensing is not the sole reserve of humans and their technologies; other organisms are continually sensing, responding to, and signaling changes in their wider ecologies. Their perceptual worlds, or Umwelten, range beyond the human(-made) senses, including, for example, the electric fields that sharks and platypuses detect and the magnetic fields that robins and sea turtles feel, and the polarization of light as seen by honey bees and other insects.[100] Collective sensing—sensing and communication loops beyond individuals—is common across the biosphere (e.g., among ants[101] and bacteria[102]).

There are a myriad of opportunities for cultivating new ways of understanding embeddedness by "re-searching"[95] what can be sensed and opening up science to various ways of knowing. This is especially the case for traditional or tacit knowledge systems, since they can foster learning about different ways to attune to the living world. Exploration of idioms and words from multiple languages can help with this, as they are often rooted in specific and located relations, and express multiple ways of (inter)being in the world. Terms such as "sentipensar la tierra,"[103] for example, illustrate how thought cannot be seen as separate but arises from "thinking and feeling with the Earth." Since it may not always be possible or desirable to translate them into a toolkit of scientific research, these practices of learning and researching, informing what it is that can be sensed, should be performed in conversation with multiple actors, to avoid the co-opting and appropriation of Indigenous knowledge and scholarship.[104]

The development and spread of technological applications also generate ways of further understanding embeddedness through sensing practices. For example, through innovation in earth observation and the widespread use of smartphones, drones, and other low-cost sensing technologies, people can become "citizen sensors." Increasingly, scientists and practitioners are tapping into

Table 1. Summary of opportunities for adopting embeddedness in the biosphere through sensing, modeling, and commoning practices

Opportunities for adopting embeddedness in research			
Sensemaking strategy	Research focus	Tools and approaches	Ethical reflections
Sensing (*becoming aware of how life coevolves*)	opening up science to various ontologies, knowledge systems, and languages	technological advancements in smartphones, satellites, and other sensors, enabling citizen science and participatory sensing for environmental governance	misuse of tracking data, research-related emissions, sentient beings reduced to data points, the role of "expert-knowledge," and top-down governance
Modeling (conceptualizing, visualizing, processing data, simulating, and formulating recommendations)	representing an integrated interplay between elements, avoiding perceiving social dynamics as external influences on natural dynamics and vice versa	developments in mathematics for representing evolving systems,collective modeling practices through participatory and situated modeling approaches	on the situatedness of modeling practices within the context of production and use, equity concerns, the plurality of values, and worldviews
Commoning (shaping material and immaterial commons)	emphasizing processes, practices, and collaborations that bring about shared (im)material commons, more-than-human commoning	tools and innovation in law-making, government, and democracy	enclosure and exclusion

unique biosensing capacities, working with life forms as varied as lichens, mussels, seabirds, and human beings to understand our shared worlds.[105–109] Researchers are also exploring the possibilities for "biological Earth observation" using networks of animal-borne environmental sensors, or an "Internet of Animals."[110,111] These initiatives build on global tracking networks, such as the MoveBank and the Ocean Tracking Network.[112–114]

Doing so at increasingly ambitious scales, scientists extend long-standing human practices of sensing the environment together with other organisms. These practices open new ways of perceiving environments and shaping biosphere relations.[115] For example, there has been a rise in interest in integrating empirical data into modeling for governance, e.g., in the form of digital twins for the ocean.[116] Sensors integrated into the urban environment can provide city planners and other stakeholders with crucial data on urban biodiversity, the influences of light and sound pollution, and where to prioritize conservation interventions. Citizen and community science allow anyone with a mobile phone to collect environmental data, presenting opportunities beyond just participatory sensing of the environment to more meaningful engagement in co-production of evidence for policy.[117]

However, sensing infrastructures incur material and carbon costs, and data quality and access inequities can widen action gaps across contexts unless addressed. Sensing practices—making new maps and foregrounding the agency of some phenomena—are also embedded in the biosphere.[118] In addition to those outlined below, ethical considerations will be case-specific. For example, many methodological developments relevant to sensing and modeling are associated with non-trivial carbon footprints and social risks such as access inequality and data sovereignty.[119–121] It requires a critical awareness of power dynamics, dominant paradigms, and impacts. What is not being sensed, and why? Which, and whose perspectives are missing? Novel sensing practices emerge from particular political and economic contexts, which shape their implications for both knowledge production and governance. Thus, while they open up possibilities for making sense of and acting within the biosphere in novel ways, they also raise a series of concerns.

For instance, ecologists have noted the potential for new forms of tracking and biologging technology to be misused or hacked to cause harm to or kill tagged animals.[122] New conservation surveillance technologies are being used for top-down monitoring and policing of people within protected areas, beyond their intended purposes for monitoring wildlife.[123] New forms of digital, data-intensive governance privilege particular forms of expertise over others and heighten the issues associated with a "digital divide."[124,125] We, therefore, caution against an uncritical celebration of these new forms of sensing, including the rapidly increasing use of artificial intelligence to process and make sense of data, even as we recognize their potential for more sustainable and just ways of relating to and living in the biosphere.[126,127] Advances in sensing methodologies, therefore, need to go hand in hand with critical reflection on the relationship between the researchers, the agency of the elements being sensed, and their environment.

Studying embeddedness through modeling practices

A complementary strategy to understand the different dimensions of embeddedness is modeling. Examples are simple conceptual diagrams to unravel the composition of a system, integrated assessments to highlight relations, and simulation models to understand evolutionary dynamics. Modeling approaches aim to capture an integrated interplay between elements in the biosphere, attempting to avoid perceiving social dynamics as external influences on natural dynamics and vice versa.[26,39] One such example is agent-based modeling. The agents in these models can be individuals (e.g., humans, fishers, and fish) or collective actors (households, organizations, and fish populations), which dynamically interact with each other and their environments.[128] Other examples are World-Earth and Human-Earth system models that aim to capture the coevolving dynamics between "the social (the world of human societies) and the natural (the biogeophysical Earth) sphere,"[129] emphasizing the closing of social-ecological feedback loops on up to planetary scales, representation of multi-level social-ecological network entanglements, and different kinds of agency across scales.[130] Attempts to develop co-evolutionary frameworks and build co-evolutionary models have also been made for various systems, such as for capturing catchment evolution.[131]

Emerging process-relational approaches to modeling social-ecological systems shift the focus toward the changing interactions and relations between entities of interest.[132] Relational approaches, however, require models to be able to represent evolutionary features (e.g., mutations) and repurposing of current states into new areas of state space. For example, when fish evolved to live on land, the organs to breathe underwater were no longer needed. Over evolutionary time, they mutated and were repurposed, enabling terrestrial creatures to hear. Standard mathematical approaches struggle to capture shifting relationships.[133] Another modeling challenge when developing models of the phenomena in the biosphere is the need to model processes at different time scales. There is some work on that front, but most models today only deal with one or two characteristic time scales.[134]

The role of modeling in shaping knowledge, forecasts, and policy requires rethinking the full iterative chain of the model's role in sustainability science/policy making, including the creation of conceptual diagrams, simulations, calibrations, validations, and recommendations for policy and practice.[135,136] Generating insights on embeddedness in the biosphere requires iterative exchange between empirical research and computational developments to simulate processes. Empirical research is not only relevant for data gathering, but also for identifying research questions, potential explanations, and in-depth knowledge of the context of social-ecological interdependencies.[132] Moreover, acknowledging that modeling practices coevolve with socio-political structures and lived experiences can open up space to assess underlying assumptions, values, and interests.[137] To systematically interrogate these entanglements—inspired by both the concept of situated knowledge and by process-relational philosophies—Klein et al.[138] call for "situated modeling" to stimulate reflection on the situatedness of practices in the construction and use of models, and to welcome heterogeneous perspectives in modeling practices, for example, through participatory approaches.[84,139,140] With these directions for modeling practices, we hope that advancements in understanding can be made for collaborative acts of care, without generating the impression that techno-managerial solutions will bring "socio-environmental justice"[141] or that they allow full control over coevolution within the biosphere.[142]

Studying embeddedness through commoning practices

Sensemaking in the biosphere is also an ongoing, collaborative activity. Commoning practices play a role in producing our worlds and in our capacities to make sense of them.[143] The notion of "commoning" is popularized by the historian Peter Linebaugh to "describe the social practices used by commoners in managing shared resources and reclaiming the commons."[144,145] Building on research on common pool resources, or the commons, commoning has been brought forward to open up possibilities for responding to current socio-environmental challenges.[48,146–148] Commoning as conceived by Donna Haraway, emphasizes active participation, care, and responsibility in the production and maintenance of shared worlds. It is tied to the notion of making kin—forming relationships across species, ecosystems, and communities—and imagining a future where people are deeply connected to one another and to the more-than-human world.[149] It can be defined as "the imaginative act of casting your experience forward along ways that join with others in carrying on a life together."[95] The notion of commoning draws attention to the continuous creation of commons, including subjectivities, relations, and imaginaries.[48] It is therefore an active process that highlights the three dimensions of embeddedness by expressing the compositions of actors, relationships, and historical contingency.

Recent advances in the conceptualization of the commons and commoning create opportunities to study how futures are collectively shaped by all living beings and how property relations are reworked.[143,150] Scholars have brought forward the notion of "more-than-human commoning" to conceive of commoning in less anthropocentric ways and to account for non-human agency and affordances.[48] The notion of the commons has also been broadened to apply not only to resources but also to biophysical systems that regulate Earth system resilience (e.g., planetary commons[151]), institutions binding them, and the associated management processes.[152] It has, for example, been applied to study the justice challenges and negotiations of communities.[48] There have been calls to develop tools for collective organization in sustainable development, governance, law, politics, finance, and education.[95] For example, innovation in deliberative democracy (e.g., citizen assemblies[153]) and eco jurisprudence (e.g., as rights of nature[154]). Some political theorists have called for the inclusion of non-humans in democratic processes, rethinking the idea of a political *demos* to enable the full inclusion and representation not just of non-humans but of ecosystems and the biosphere as a whole.[155,156] An example of practical, yet tentative, applications of such ideas includes the representation of "nature" on corporate boards.[157]

While highlighting these shifts and opportunities for shaping collective futures, it is important to note that the commons are not inherently just or equitable.[48] Noting that commons are continuously shaped and built by commoning practices highlights the idea that they are not static or fixed, but are inclusive to all subjectivities and are susceptible to enclosure and violence. Conceptualizations of what collectively shapes change range from local grazing lands to global commons, such as the high seas and deep seabed minerals.[158] Commoning practices can foreclose some entities, practices, and ways of being.[159] This includes addressing issues of asymmetrical relations of difference and power.[143]

CONCLUSION

Human societies do not exist in parallel beside the biosphere but rather are embedded within the continuum of its living fabric.

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There is a need for dominant research, policy, and market-mediated practices to direct attention to life-supporting relations within the biosphere and to direct action toward carefully living in concert with organisms in the web of life.[51] Dualistic approaches that disassociate humans from nature have been widely recognized as barriers to addressing sustainability challenges and understanding biosphere dynamics.[6,20,22,26,160] But despite a myriad of research practices focusing on the interdependencies of humanity and the rest of the biosphere, or applying relational perspectives, human-nature dualism still permeates the mainstream in many policy-relevant fields. Sustainability challenges, therefore, require a concerted push to embrace frameworks, methods, and insights for profoundly recognizing humanity's situatedness in the biosphere.

To stimulate such investigations and analysis, this perspective presents key conceptual and practical opportunities of studying embeddedness in the biosphere. Taking systems thinking as a starting point, we argue that three dimensions are essential for understanding embeddedness: compositional, relational, and evolutionary embeddedness. Moreover, we discuss opportunities for foregrounding embeddedness in research, drawing on recent developments in sensing, modeling, and commoning practices. These opportunities include shifts in (1) research questions that do not separate "natural" versus "social" categories, (2) tools and approaches that can increasingly capture embeddedness within the biosphere and therefore collectively with all elements in the biosphere, and (3) ethical reflections toward embedding research in the dynamics of power relations and physical impacts. This perspective thus aims to facilitate a diversity of ways to make sense of human embeddedness in the biosphere and to support the living world.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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