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Social Ecological Systems in Flux

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Abstract

A world in flux confronts the present generation, raising fears of systems gone awry. Whether it is the prospect of runaway climate change or the dangers of unbridled artificial intelligence, these dilemmas suggest that scientific and technological remedies have not been matched by progress in harnessing social and political capacities for collective action. Part of this impasse stems from a gap between the multidimensional nature of contemporary global crises and unidimensional modes of understanding and managing them. In this article, we describe an integrative approach rooted in the paradigm of social ecology that might enable us to tackle these challenges more comprehensively. We discuss, for example, how a social ecological perspective focuses attention not only on the carbon footprint of society but also on the social footprint of carbon. We review the tenets of social ecology and reflect on its promise for spurring new modes of collaborative research and collective action, including more effective strategies for planetary governance.

INTRODUCTION

One powerful, though grim, way of chronicling human history is by describing it as a sequence of crises: the fall of the Roman Empire, the Great Plague, World Wars I and II, the oil crisis of the 1970s, famine in Ethiopia in the 1980s, the Asian financial crisis in the 1990s, terrorism and the great recession of the 2000s, and the recurring cycle of violence in the Middle East. Each of these crises, while massive in scope, might be retold by historians as a singular event with a dramatic focal point (war, famine, recession)—a story with a coherent plot. But accounts of these events have been distilled by time and authorship into clear narrative form, and we no longer see the complexity of each of these times.

The present times see the world again in crisis, but the reality we experience feels like one with many and diverse focal points, or possibly a diffused amorphous one. The world and each of our lives are affected by sweeping changes on many, perhaps all, fronts—economic, environmental, financial, ideological, and cultural. It is not a simple narrative that we can tell about the present age, but a complex one (or possibly multiple complex ones) as ongoing change continuously affects each aspect of our lives. The reality of the times (and, in fact, each one of the tumultuous periods earlier mentioned) is wrought by complexity and not akin to any simple rendering.

Gunderson & Holling (2002) coined the term "panarchy" to describe the dynamics of sweeping change that affect systems at all scales, from the micro- to the macroscopic levels. In so doing, they described complex systems where multiple nested subsystems mutually influence each other over extended periods and across different environmental and societal levels. These reciprocal influences between multiscalar systems and their subsystems can lead to greater resilience, reflected in the ability of systems either to return to normal (quasi-equilibrium) cycles in the face of abrupt shocks or, alternatively, to transform into newly functioning systems altogether.

The notion of multiple interlinked systems is highly pertinent to the kinds of systemic changes the world is undergoing today. The components of contemporary socioenvironmental problems often operate on different ontological planes (the material or physical; the financial, political, and symbolic planes) and interact in emergent, unpredictable ways. Material systems, for example, are ultimately linked thermodynamically, but what of the coupling between, say, hydrocarbons and culture, or of climate and identity? Instead of seeming manageable through adaptive feedback loops that bring systems into normal functioning, the systemic changes being experienced in this age threaten to become runaway processes that may become more, not less, extreme over time. A number of examples illustrate this point, which leads to a discussion of scholarly orientations that might better suit this newfound complexity.

Climate Transformation

The scientific consensus has coalesced around the role of greenhouse gas emissions in the unparalleled upward trajectory of mean global temperatures over time. The scholarly community has acknowledged, for some decades now, that complex socioeconomic-cultural systems have contributed substantially to the generation of such carbon emissions, and that solutions will require systemic responses from all these systems (e.g., Rayner & Malone 1997). But society's responses seem inadequate, and even maladaptive, vis-à-vis the multisystem complexities we now face during the early twenty-first century. In order to limit climate change to no more than 1.5°C over the next 50 years, comprehensive responses are need within and across every nation, and yet, there is insufficient coordinated action (Tollefson 2021).

Rather, we see conflicted responses and policy impasse within countries, sometimes driven by deep ideological conflict, such as in the United States, where inertia around climate action is deepened by a politically and culturally divided society with administrations shifting between liberal and conservative. And, internationally, geopolitical divisions threaten every global initiative.

Rather than deviation-suppressing feedback mechanisms, some of these ideological and geopolitical rifts may in fact be deviation-amplifying (Maruyama 1963). What may result, as some scientists have predicted, is runaway climate change (e.g., Steffen et al. 2018). And as we are witnessing a record retreat in Antarctic sea ice (Liu et al. 2023), scientists wonder if climate change may be approaching a tipping point (Lenton et al. 2019). If the changes the world is now seeing continue to accelerate rather than recede, then this generation (and certainly the next) may experience changes in their environment that are cataclysmic. For scholars, one intellectual challenge stems from the need to understand interactions across different ontological planes, i.e., the natural (climate) and the symbolic (ideology).

Efforts at decarbonization themselves are fraught with conflict. The task of decarbonization will impose differential burdens on societies and different groups within them. Though significant research has been conducted on the threat of climate change to society, the socioeconomic impacts of responses to climate change (i.e., mitigation and adaptation), especially to the most vulnerable, are relatively underappreciated (Lejano & Kan 2022).

The Cybercene

The dawning of the digital age brought increasing awareness of how the Internet, wireless communications, and other digital technologies are transforming the global economy and enhancing everyday life. However, concerns have arisen over the past decade that the encroachment of the digital world into our day-to-day routines and global systems of financial and cultural exchange may be ungoverned and unpredictable. Only now are educators and social workers seeing the massive effect of the digital world on child development, as more and more children are turning away from the physical world outside toward online encounters with environments and other people, leading to adverse health impacts, juvenile mental health problems, and other harms (see Hollis et al. 2020). For example, the alarming increase in teenage suicide rates may be, at least in part, attributed to the effect of social media, e.g., through cyber-bullying and heightened feelings of social isolation (Massing-Schaffer & Nesi 2020). Artificial intelligence, increasing in strength and scope, is threatening to displace human reasoning and decision-making, leading to fears of cyberwarfare, digitally triggered financial meltdowns, mass disinformation, or autonomous weapons and military escalation (see Ford 2015, Singer & Friedman 2014). Seen in this light, the cybersphere can be viewed as, potentially, another unpredictable runaway system in flux (see Nardi et al. 2018). Some scholars suggest that the age of the Anthropocene (Crutzen & Stoermer 2000), when humanity dominates nature, is giving way to the Cybercene, when the networked digital universe begins to dominate humans' lives and their impact on the planet (Schuler 2023, Sommer 2019).

These crises would seem to fit the description of wicked problems (Rittel & Webber 1973), for which no solely technical solution would suffice, which no one disciplinary expertise can handle, which bode irreversible change and thus are not amenable to trial and error approaches, and for which there is no consensus on what a solution or set of solutions should look like. At the root of these wicked problems are a number of defining conditions:

1. The problem is rooted complex interactions across multiple, ontologically different planes (e.g., material, financial, cultural).
2. In contrast to the emergent, ungoverned interactions across different planes, societal responses call for coordinated action within and across all scales of human activity—at individual, institutional, and national levels.
3. The changes are potentially irreversible and existential.
4. Very little time remains for implementing effective solutions, a feature that some scholars suggest makes these dilemmas "superwicked" (Levin et al. 2012).

These systems in flux exhibit a multidimensionality that exceeds any disciplinary orientation (see Berkes et al. 2003, DeFries & Nagendra 2017, Rosenbloom 2020). In contrast, the response from academics mostly reflects the disciplinary orientation of the natural sciences, which highlights the great divide between the physical-scientific study of nature versus the social-humanist study of culture. As Berkes (2023, p. 176) writes, "sustainability requires multilevel, integrative, and interdisciplinary research and action, with attention to both the ecological and the social subsystems." The scholarly community must respond to these challenges more effectively.

Thesis

The interdisciplinary field of social ecology emerged as a paradigm and scholarly lens that focuses on transactions across subsystems, such as cross-scale interactions within and among physical and sociocultural systems. This focus on multiscalar transactions across different ontological planes (e.g., psychology and nature) offers a promising response to the emergent problems of systems in flux.

The social ecological orientation sensitizes researchers toward interactions across different subsystems or dimensions of the global community. New questions for investigation result from this conceptual orientation. Carbon is not simply modeled as an input-output relation but as an institution, supported in practice and discourse in each society. Inasmuch as scientific investigations of climate change emphasize the carbon footprint of society, there is much less attention paid to the "social footprint of carbon"—i.e., institutionalized social patterns around carbon and the potentially profound societal and cultural changes that can result from decarbonization or carbon trading. Whatever solutions society constructs to confront the climate crises, these cannot be understood as simple technical fixes.

In relation to the cyberworld, a social ecological orientation primes researchers to study complex interactions across the natural, built, sociocultural, and cyber spheres of human communities. It is, in part, the inherent tendency to study these different spheres as separate systems that make it more difficult to understand the encroachment of one onto the other. In social ecology, the notion of place necessarily integrates all these spheres of human experience—e.g., for children growing up today, natural and built environments are increasingly being supplanted by virtual ones. And what of the way these trends are themselves intertwined with each other, perhaps synergistically?

Integration across disciplines is needed to more fully comprehend the roots of these crises and their impacts on society. Moreover, such integration is demanded if effective solutions are to be sought and achieved—the complex nature of these phenomena demands it. Social ecology offers a transdisciplinary framework that might better support scholarly interventions needed to respond to these crises. In the succeeding sections, we describe the roots and philosophical orientation of social ecology and then discuss how the above issues might be more deeply understood through the lens of social ecology.

SOCIAL ECOLOGY AS A BASIS FOR MODELING AND MANAGING SYSTEMS IN FLUX

The preceding section highlights some of the most daunting dilemmas facing humanity during the early twenty-first century. These crises are highly complex in that they are each driven by multiple causes, manifested at multiple environmental levels, and highly synergistic—i.e., they reinforce and exacerbate each other through positive feedbacks that are often difficult to discern, let alone mitigate. A core premise of our analysis is that social ecology provides conceptual principles and research methods that are useful for understanding and managing the turbulent changes and existential threats that have arisen during the early Anthropocene.

In this section, we consider three different facets of social ecology that can help shed light on the rapid and pervasive changes humans are confronting in today's world. One characterization of social ecology is as an interdisciplinary field of study (rather than a separate discipline per se) that seeks to understand the structure and functioning of people–environment relationships. The research literature in social ecology includes empirical findings about participants' activities and experiences observed across a variety of environmental contexts, as well as ecologically oriented theories of crime, human development, urban planning, public health, and other phenomena (e.g., Bronfenbrenner 1979, Cohen & Felson 1979, Stokols 1996).

A second facet of social ecology are the socioenvironmental systems situated in specific regions of space and time that provide the structured contexts in which people's everyday activities are organized. A growing portion of people–environment systems now also have a presence in cyberspace, apart from or in addition to their physical and temporal coordinates. Scholars of social ecology have studied a wide array of social ecological systems, from the individual behavior settings (e.g., homes, classrooms, workplaces) that comprise a person's routine activity system (Barker 1968, Bronfenbrenner 1979, Chapin 1974, Michelson 1985) to cities and exurban regions, the Earth system as a whole, and the global cybersphere (Barker & Schoggen 1973, Haberl et al. 2016, Park et al. 1925, Steffen et al. 2015, Stokols 2018). The cumulative findings from these multiscale studies constitute the empirical data base of the social ecology field.

A third characterization of social ecology is as a scientific paradigm, or set of core concepts and methods that can be used to model and manage the complex dynamics within and between existing socioenvironmental systems. These general paradigmatic assumptions are central to the more specific, ecologically grounded theories and research programs developed by scholars working in different fields such as psychology, sociology, criminology, urban planning, and public health. The social ecological paradigm is valuable, above and beyond the empirically grounded literature of social ecology, in providing a broad-gauged analytic framework to identify key contextual factors that impact people's transactions with their surroundings, and to inform the design of future environmental and societal improvement strategies (Stokols 2018, Stokols et al. 2013).

Social Ecology as an Interdisciplinary Field of Study

The field of social ecology stems from the work of evolutionary biologists during the nineteenth century, who carried out naturalistic field studies of plant and animal habitats (see Darwin 1859, Haeckel & Lankaster 1876). They defined ecology as the study of organism–environment relationships and documented the adaptative processes by which plant and animal groups accommodate to each other and to the nonliving features of their habitat (e.g., its climatic and geological conditions). These early biological studies of the relations between organisms and their environment were later extended to the study of human populations living in large urban regions by Park et al. (1925) and other scholars at the University of Chicago during the 1920s and later. Their research on the relationships between people and urban environments came to be known as human ecology, which highlighted biological and economic processes of people's adaptation to their urban surroundings. An important finding from this work was spatial gradients in the distribution of health and behavioral problems across different geographic zones of urban areas (e.g., extending from poverty-ridden districts in the inner city to more affluent suburbs located outside the urban core).

A shortcoming of the Chicago School's concentric zone theory of urban environments and spatial distribution of behavioral disorder was its emphasis on biological and economic facets of human ecosystems, but relative neglect of sociopolitical, legal, and ethical considerations (e.g., environmental justice concerns), as well as the influential role of environmental symbols in human behavior and well-being. Firey (1945), for example, argued that the physical features of human ecosystems convey symbolic as well as material meanings that sometimes contradict each other. Homeowners may resist selling their dwelling for substantial profit because of their psychological attachment to and sense of community in their neighborhood. Alihan (1938) offered a critique of the Chicago School and called for a broader interdisciplinary approach to the study of human communities, integrating the concerns of bioecology and economics with the perspectives of other fields such as sociology, psychology, anthropology, law, ethics, and urban planning. Like Alihan, other scholars including Emery & Trist (1972), Binder (1972), Bookchin (2005), and Moos (1976) referred to this more encompassing, cross-disciplinary view of human–environment relations as social ecology. Building on these earlier scholarly efforts, the term social ecology is now widely used to denote a transdisciplinary approach to the study of people–environment relations that brings together the theories and methods of diverse academic fields and the nonacademic perspectives of societal sectors like government and industry (Haberl et al. 2016, Stokols 2018).

Social Ecological Systems Situated in Physical, Temporal, and/or Cyber Regions

The focal units of study within various programs of social ecological research are the physical or virtual people–environment systems that exist from micro (local) and meso (regional) to macro (societal and global) scales. Miller (1978), in his comprehensive treatise *Living Systems*, defined a system as "a set of interacting units with relationships among them" (p. 16). He distinguished between physical or concrete systems with specified spatial and temporal boundaries and conceptual systems organized around a set of internally consistent propositions and corollaries about some facet or facets of reality (e.g., Euclidean geometry, the periodic table). A conceptual system can also be an abstract representation of the main components, and flows of energy and information, as they occur within an actual physical system [e.g., Von Bertalanffy's (1950) analysis of the energy and informational flows in open versus closed systems, the latter characterized by relatively impermeable boundaries with their environmental surroundings]. Within the category of concrete physical systems, Miller further differentiated between living systems (e.g., plants and animals residing in a particular biome), on the one hand, and nonliving or abiotic systems, on the other (e.g., the electrical grid of a city, or nowadays, the digital technologies that comprise the Internet of things).

Building on earlier conceptions of human–environment systems, Berkes et al. (2003) distinguished between simple systems, which can be adequately represented using a single perspective, as in the case of Newtonian mechanics, and complex systems that have several attributes not observed in simple systems, such as nonlinearity, uncertainty, emergent and multiscalar properties, and self-organization—for instance, biological, social, and environmental systems. They defined social ecological systems as a category of complex systems characterized by the coupling of particular social systems—for example, organizational and corporate entities or state and national governance structures (see Folke et al. 2019, Katz & Kahn 1966)—and ecological systems "comprised of self-regulating communities of organisms interacting with one another and their environment" (Berkes et al. 2003, p. 3). Berkes et al. observed that a social ecological system typically subsumes many subsystems, hierarchically arrayed in a nested structure that spans local to more distal scales. Both social and ecological systems are themselves complex in their own right, as Berkes et al. noted. However, when the connections and interactions between these two kinds of systems are explicitly considered, new complexities become apparent, above and beyond the complex features of social and ecological systems viewed separately.

A notable source of complexity in social ecological systems is that "phenomena at each level of scale tend to have their own emergent properties and different levels may be coupled through feedback relationships" (Berkes et al. 2003, p. 6). Accordingly, social ecological systems must be analyzed and managed simultaneously at different scales. Berkes et al.'s analysis of social ecological systems draws directly on Gunderson & Holling's (2002) panarchy model of multiscalar, human–environment systems and the mix of internal and external forces that account for periods of quasi-stasis as well as substantial transformations in complex adaptive systems.

Our analysis of social ecology as an overarching conceptual framework (or scientific paradigm) for understanding and managing high levels of flux in contemporary social ecological systems, outlined in the next section, builds squarely on the foundational ideas contributed by Miller, Katz & Kahn, Berkes et al., Gunderson & Holling, and other systems theorists.

Social Ecology as a Scientific Paradigm—Core Tenets

Several types of social ecological systems have been studied from multiple disciplinary perspectives, yielding a wide array of theoretical insights and empirical findings—especially vis-à-vis human behavioral, developmental, health, societal, and global sustainability outcomes, which can be understood as by-products of system dynamics, resources, and constraints. In this section, we delineate a general set of conceptual and methodological tenets that constitute the social ecological paradigm and are reflected in more specific, ecologically oriented theories and empirical analyses of people–environment relationships. Viewed as a scientific paradigm (Kuhn 1970), social ecology provides an overarching, meta-analytic perspective—a conceptual mapping system or problem-framing device—for modeling and managing societal problems in relation to alternative spatial, temporal, sociocultural, and virtual (cyber-mediated) contexts. These broad principles of social ecology offer analytic guidelines that can be used in combination with each other to gain a broader understanding of human–environment transactions at local, regional, and global scales. At least four tenets of the social ecological paradigm were noted above and are briefly summarized in the following subsections.

Multidimensional components of human environments. All branches of ecology assume that the environmental milieu of social ecological systems includes multiple, interdependent features. Biological ecologists study the relationships between living and nonliving components of plant and animal biomes. The home territory of a plant or animal, for example, includes members of its own species as well as other life forms and the abiotic features of its environment. Human ecologists studying urban environments highlight geographic and economic influences on population health outcomes. Also, the communities that social ecologists study encompass symbolic as well as material features, physical and sociocultural components, natural and built (designed) elements, and place-based as well as virtual domains. As shown in **Figure 1**, these distinct facets of our surroundings constitute four major spheres of environmental influence, namely, the natural, built, sociocultural, and virtual (or cyber) domains of modern-day human communities (Stokols 2018).[1] All four domains are thoroughly intertwined and interdependent with each other and, together, exert a combined impact on personal and collective behavior and well-being. Though the four domains are inherently fused together in human communities, the axonometric diagram shown in **Figure 1** graphically separates them to highlight the different foci or distinct phenomena that are unique to each one. Also, the four domains emphasize different

[1]The natural environment consists of the plant and animal species living in a particular area, abiotic features including geologic and climatic conditions, and various resources produced through nature-based rather than human-initiated processes. The built environment includes physical resources created by people, such as their buildings, vehicles, and tools used to produce other products. The sociocultural environment subsumes organizational and institutional entities, political and economic structures, social norms, legal codes, and the social activities that people perform as members of groups and communities. The virtual environment encompasses computing and mobile communications equipment, the World Wide Web, the Internet of things, social media, virtual reality, and other digital technologies.

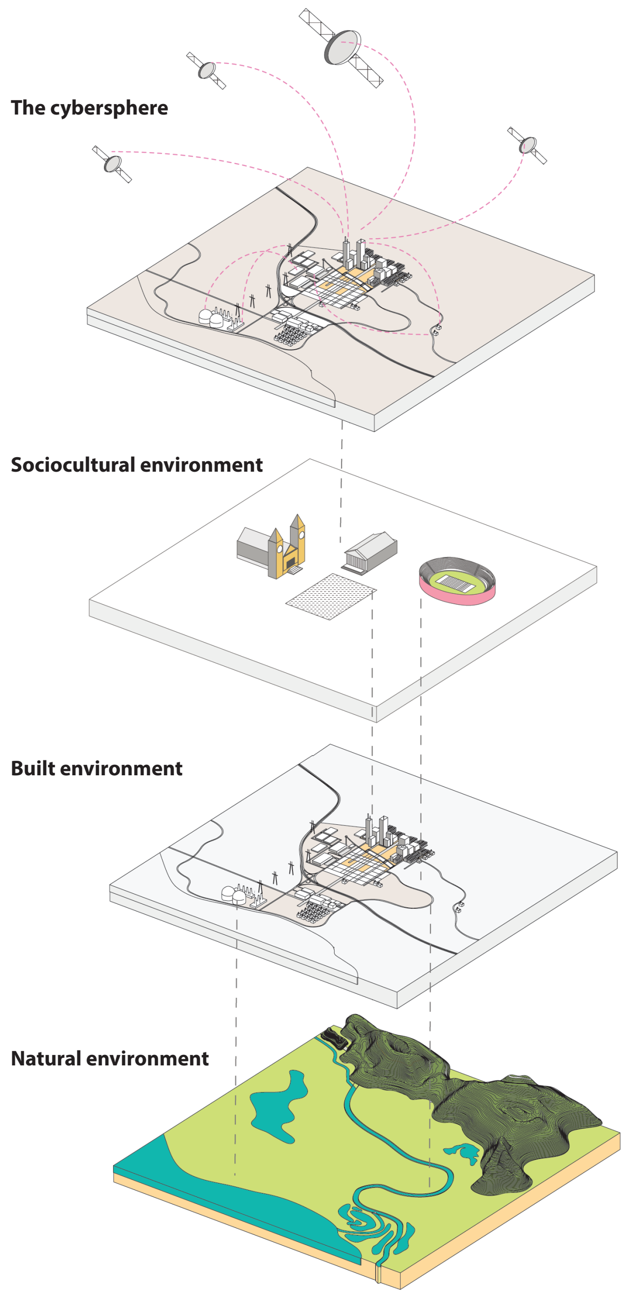

Figure 1

Interconnections between four environmental spheres in human communities. The four spheres are inherently interdependent and intertwined, but they are graphically separated here to highlight the distinctive phenomena that are unique to each sector. Also, the four spheres emphasize different ontologies for understanding human communities—for instance, the material or physical features of natural and built environments, and the cyber and semiotic phenomena subsumed by the virtual and sociocultural spheres. Adapted with permission of the publisher from Stokols (2018).

ontologies for understanding human environments—for instance, the material or physical properties of natural and built environments, and the cyber and semiotic phenomena encompassed by the virtual and sociocultural domains. For purposes of representation, the four spheres are teased apart and shown as distinct layers in **Figure 1**, but the reader should note that they are ontologically different and incommensurate with each other, and therefore cannot be combined into a composite mapping (or some multiattribute valuation scheme).

Multiscalar and nested structure of social ecological systems. Social ecological systems are arrayed across multiple geographic, social, and temporal scales (Levin 1992)[2]. Each system (e.g., home, neighborhood, community, nation, global biosphere) situated at one or more environmental levels is part of a nested structure, where local situations and settings are embedded in larger, more remote regions (e.g., homes within neighborhoods within cities and regions). Participants in social ecological systems vary in the complexity of their social structure, ranging from individuals, groups, and organizations to larger communities, societies, and international entities. Moreover, people's encounters with their surroundings can be studied over short or long periods (e.g., assessments of near-term versus longer-term health outcomes among victims living in war-torn regions).

Centrality of systems theory in social ecological analyses. As previously noted, social ecology is rooted in the concepts and assumptions of systems theory and seeks to explain how environmental structures and people's reactions to their surroundings change over time (Berkes et al. 2003, Bronfenbrenner 1992, Gunderson & Holling 2002, Miller 1978, Von Bertalanffy 1950). The organization and functioning of human environments continually evolve in response to biospheric and behavioral forces (e.g., geologic and climatic shifts; humans' consumption of fossil fuels; development of new technologies, buildings, and transit systems). Environments and their inhabitants are dynamic systems where individuals and groups respond to changes in their surroundings and, in turn, proactively modify the environment to better suit their needs. When the fit between people and their environment is lower than desired, they may experience physical strain, emotional stress, and other kinds of negative feedback (Selye 1956). In some cases, individuals fail to achieve a state of balance with their surroundings. Instead, the negative impacts of environmental demands become more severe through a process of deviation amplification (Maruyama 1963). Chronic exposure to environmental threats in those situations can lead to exhaustion and ultimately death.

Transdisciplinary and translational orientation of social ecology. Because social ecological inquiry subsumes so many categories and levels of environmental influence, it is inherently transdisciplinary in its approach to understanding people's encounters with their surroundings. In addition to drawing on concepts and theories from multiple fields, ecological studies also use multiple methods and metrics to study the environment, human behavior, and well-being. Many

[2]Levin's analysis of pattern and scale in ecological systems posits that systemic patterns observed at higher levels of scale (e.g., cumulative global increases in atmospheric carbon emissions evidenced by rising of CO_2 concentrations in parts per million each year; see Scripps Inst. Oceanogr. 2023) are driven by changes occurring at more micro (nested) system levels [e.g., the failure of corporations or national governments to curtail corporate or national emissions levels in accord with Intergovernmental Panel on Climate Change (IPCC) and Paris Climate Accord recommendations]. The patterns observed at each system scale are a product of system changes occurring within nested levels of the larger system. Levin's research suggests that shifts in the social footprint of carbon at a global level are driven by cumulative changes in cultural values, driven by corporate and governmental policies related to carbon emissions that are situated at lower (e.g., corporate and national) subscales of the global system.

of these investigations are aligned with the transformative goals of social ecology noted earlier, in that they are intended to improve society as well as to promote scientific discovery. Translating scientific knowledge into solutions for complex problems (e.g., organizational and public policies designed to reduce carbon emissions and promote greater use of renewable energy sources) requires collaboration between scholars and community members representing diverse disciplinary, professional, and citizen perspectives. Social ecology emphasizes a transdisciplinary action research (Stokols 2006) approach where academic and nonacademic perspectives are brought together to better understand and manage environmental challenges.

THE SOCIAL FOOTPRINT OF CARBON—A SOCIAL ECOLOGICAL PERSPECTIVE

In this section, we illustrate the potential value of the social ecological paradigm for the analysis of complex issues, such as those mentioned in the beginning of this article, and for interventions intended to enhance biospheric sustainability and the relationships between humans and their surroundings. Our analysis is grounded in social ecological assumptions about the complexity of multiscalar, socioenvironmental systems and the interdependent linkages among natural, built, sociocultural, and cyber facets of human communities.

Figure 1 provides a convenient pedagogic guide that can structure how we might use a social ecological lens to deepen collaborative, interdisciplinary research for ameliorating twenty-first-century global dilemmas. It depicts how social ecologists understand place or society as an intertwining of various spheres of the world that humans (and nonhumans) experience. This depiction sensitizes researchers to focus their attention, first, on phenomena that occur within each sphere, but also on the interactions between them.

In his seminars on reflexive sociology, Pierre Bourdieu suggested that scholars should focus not just on the primary, traditional objects of their study but also on the relations between them (Bourdieu & Wacquant 1992). An example of this orientation is his own work on imagining multiple forms of capital, e.g., social and economic, and their action within the entire space of relations (Bourdieu 1986). This attention to relationality, as opposed to substantialism, informs the social ecological endeavor. It is also, as these authors suggest, a guide to interdisciplinary research.

The value of focusing explicitly on the interrelationships among different societal spheres becomes evident when analyzing the complex sources and manifestations of global climate change. Consider, for example, the scientific reports of the IPCC, the most recent of these being the *Sixth Assessment Report* (AR-6) (IPCC 2023). The assessment is primarily a summary of extant scientific knowledge on the carbon footprint of society, i.e., the sources and flows of carbon from human activity and its impacts on climate. The primary focus is on the modeling of these flows of carbon and climatic changes resulting from them. There has been some criticism of previous assessment reports for the relative neglect of social dimensions of the problem and predominant focus on natural scientific aspects, and as a result, AR-6 includes more discussion of social scientific considerations. But it is still mostly focused on physical-scientific modeling.

This is not to say that the assessment is a technical simplification of the phenomenon—indeed, the science of carbon and climate, at least as discussed in AR-6, is of such complexity that its many authors deserve credit for their efforts to make it legible to those outside these scientific disciplines, including policy makers (IPCC 2022). However, as we have discussed, the strongly physicalistic orientation of the reports necessarily creates a fundamental reductionism to such work, and it is here that a social ecological framework can provide guidance.

The predominant orientation of the IPCC assessments is toward a natural science understanding of the Earth system, though there is input from social scientists in gauging the impacts of climate change on society. The primary focus, nonetheless, remains that of viewing the world in

Table 1 Comparative features of the carbon footprint of society (CFS) and social footprint of carbon (SFC) perspectives

Key theme	CFS framework	SFC framework
Meaning of carbon	Carbon as a material substance	Carbon as an institution
Systems framework	Carbon as an autopoeitic system	Inter-relationships among different spheres (**Figure 1**)
Analysis of carbon	Patterns of carbon usage and emission	Social-cultural origins and impacts of carbon usage
Focus of intervention	Technologies for decarbonization	Institutions for decarbonization
Equity concerns	Distributive allocation of carbon reductions	Social-cultural and economic impacts of carbon reduction

thermodynamic terms, and so framed, society is discussed in terms of carbon throughputs—as an input-output machine with carbon as its primary unit of exchange. From the perspective of social ecology, a critical assessment requires that gaps in such framing are explored. For example, inasmuch as the focus is placed on the carbon footprint of society, what of the social footprint of carbon (e.g., Lejano & Kan 2022)? A social ecological framework, as illustrated in **Figure 1**, suggests that researchers address the inherent interdependencies among multiple societal sectors—specifically, reciprocal interactions between the natural, built, cybernetic, and sociocultural spheres. This reorientation can help identify several new avenues for collaborative research.

As an example, consider prior research on so-called ecological footprints, beginning with the foundational work by Wackernagel & Rees (1996). Their research established a framework for accounting the ecological costs of modern-day lifestyles and compared different nations according to nonmonetary metrics (see, e.g., the Global Footprint Network, **https://www.footprintnetwork.org/**). This approach has led to much subsequent work focusing specifically on the carbon footprint of society, using carbon (expressed in units such as metric tons per year of greenhouse gas emissions, normalized to carbon) as the unit of measure (e.g., Moran et al. 2018). The model underlying this useful accounting exercise focuses on carbon inputs and outputs, directing the greatest attention to the chemical mass balance. The danger, however, is that such an accounting framework might neglect the role of the sociocultural sphere in this dynamic, e.g., how carbon usage is rooted in social and organizational practices, family lifestyles, and cultural values.

Social conventions and meanings associated with carbon can strongly influence how individuals, organizations, communities, and nations use carbon; one obvious example is Southern California's car culture (Lutz 2000). A social ecological perspective shines a light on the ways that the sociocultural sphere interacts with the material and semiotic dimensions of natural, built, and cyber systems in flux. **Table 1** provides a dialectic table that juxtaposes defining features of the conventional carbon footprint of society approach and a social ecological social footprint of carbon perspective.

Take, for example, the note in **Table 1** that compares the idea of understanding carbon solely as a material substance and that of understanding it as an institution. In other words, carbon is not just a chemical element that cycles through society; it is itself wrapped up in the social and institutional life of a place. Sociocultural values and practices moderate various uses of carbon in society (e.g., how people get to work, how they prepare their food, how they dress, etc.). Patterns of work and commerce are wrapped around carbon use. For these reasons, we should focus more attention on how changes in carbon usage might impact, and in turn be influenced by, the local lifestyles and institutions of a place. As suggested in **Table 1**, it is not enough to understand carbon within a self-contained or autopoietic system (Luhmann 2008) such as the focus on its material cycling within society. Rather, the material sphere interacts with the other dimensions (e.g., the sociocultural) of life in a place. Analysis would involve tracking not just carbon's sources and sinks but its sociocultural generators and impacts, as well.[3]

The focus of environmentally supportive interventions, then, would revolve around not solely the technological challenges of decarbonization but also the institutional dimensions of it. Going back to the example of the automobile, one can look at a city like Huntington Park in Southern California. Huntington Park is home to a concentration of backyard industries featuring engine repair and overhaul, auto-body repair and painting, chrome-plating, and lowrider servicing. In short, the city has a local economy that is wrapped around the internal combustion engine (Lejano 2023). What happens to its ways of life and local economy as society transitions away from the gasoline/diesel engine (and away from the automobile altogether)? Looking more globally, what happens in developing nations, still in the early stages of carbon-based industrialization, for whom the promise of large-scale transfers of green technology from the first world has not (as yet) occurred?

There has been, in recent years, a call for more concerted attention focused on the sociocultural dimensions of decarbonization. Beckfield & Evrard (2023, pp. 168–89) write, "to date, natural scientists, technology experts, economists, and policy makers have embarked upon transition-related research in earnest, but sociologists have kept their distance. As a result, energy transitions are often abstracted away from the social relations that will ultimately determine success or failure."

Viewing society primarily in terms of carbon throughput, researchers have focused mainly on reducing the carbon footprint of society. This leads to much valuable work on mitigation and technological retooling to reduce greenhouse gas emissions. This analytic approach also leads to other proposals, such as carbon trading, aimed at increasing efficiencies in how the world manages carbon-emitting activities. But a social ecological view requires examining linkages between carbon emissions and the sociocultural sphere. Carbon itself is institutionalized into the fabric of society, woven into it both in the macroscalar level (e.g., the industrial landscape of a region) and in the microscalar level (e.g., individuals' lifestyles and the practices and policies of their communities, such as the use of renewable or nonrenewable fuels for cooking and transit). Carbon sequestration or trading carbon between regions changes the fabric of relations within communities, and researchers should begin focusing explicitly on the social sources and impacts of carbon production and mitigation. To the extent that carbon becomes a universal denominator (e.g., under carbon pricing schemes that potentially can affect every carbon input into society), so might the impacts of decarbonization reach into the microscale practices of everyday life, such as a family's transition toward plant- versus animal-based diets or the purchase of electric versus petroleum fueled vehicles.

On a global scale, it may well be that the carbon transition described by the IPCC places the greatest burdens on developing countries and vulnerable communities within them. The increased vulnerability (as opposed to resilience) in these communities means that transitions, such as decarbonization and retooling of energy use patterns, will be most difficult for the already marginalized. This leads to important research questions around the effects of transitions on employment patterns, changes in everyday life among the marginalized, and even the fit between new institutions/practices and local cultures and economies. How will densely populated cities adjust, given the substantial changes that climate change mitigation and adaptation directives require in both built form and patterns of movement? And in proposing such sweeping changes to regional

[3]We use the term "social" as a placeholder for the world of living beings. As others have stated (e.g., Dietz et al. 2020), our analyses must encompass the experience of nonhuman beings, as well, whose welfare must occupy a central place in our investigations.

economics and lifestyles, is the first world, speaking through the IPCC, imposing yet another heavy burden on developing economies (Lenzi et al. 2021)?

Just as changes in carbon throughput can impact the sociocultural patterns of a place, so too can sociocultural phenomena impact carbon footprints. Multidirectional relationships among societal sectors (such as between sociocultural and natural environment spheres) require collaborative investigation. For example, researchers should pay closer attention to impacts of ideological movements and cultural divides on carbon emissions. The ever-shifting pendulum of US politics, swinging from conservative to liberal administrations, and its impact on climate action is but one example. Consider, for example, the effect of the Trump administration's withdrawal from the Paris Climate Accord in terms of stalling progress on decarbonization (Collins 2020). Changes in the realm of ideology and meaning express themselves through changes in the carbon footprint of a community or a nation. A social ecological perspective requires that scholars inquire into the impacts on climate of trends, such as ideological division, increasing nativism and neo-fascism, and more globally, the role of geopolitical tensions that fuel intense cross-national competition for scarce natural resources and the environmentally destructive impacts of unmitigated warfare. Some of this work already has begun on a more limited scope (e.g., Dietz et al. 2015, Jahn 2021), but it is evident that these phenomena will require more concerted collaborative investigation bridging multiple disciplines.

Another important aspect of the social footprint of carbon model is that it examines how sociocultural factors influence what occurs in other societal spheres, such as the cybersphere and the built and natural environments. Rather than viewing each of the four spheres in **Figure 1** as relatively autonomous systems, the social footprint of carbon model emphasizes the interpenetration of sociocultural forces with the other three sectors, particularly as the social world impinges directly on nature and the climate system, but also impacts the natural world through its influence on what occurs in the cybersphere and the built environment. For instance, one could view the Internet of things or artificial intelligence systems as relatively autonomous, self-perpetuating systems in their own right, independent of any sociocultural controls or constraints (as purely technical versus sociotechnical systems). Yet the climate-related impacts of the cybersphere and the built environment depend greatly on how governments, corporations, and the regulatory and public sectors deploy new digital technologies and/or new transit and building construction technologies. So, what occurs in the built, natural, and cyber spheres and their impacts on the climate system are not independent from each other, but rather are woven together through a complex fabric of sociocultural understandings and practices (e.g., governance and regulatory strategies).

Such analyses would have to examine cross-scale linkages in a deeper way, tracing relationships between phenomena on the micro scale to changes on the macro scale (Levin 1992). For example, might children's daily activity patterns in the world's major cities be shifting indoors, with more time spent in both play and learning online, and what might be the impact of the increasing role of the cybersphere on the overall carbon footprint of cities? And, conversely, how might a changing climate contribute to a shift in the balance between indoor and outdoor activity?

Several interesting research questions arise surrounding interactions between the cybernetic and natural spheres. As the world community is speedily reorienting life around the cybersphere, how sustainable is this sweeping change? Some scholars are already calling for more studies of the large energy requirements (and associated greenhouse gas emissions) of the cybersphere and its requisite large-scale server farms (Nardi et al. 2018). And, what of the role of the cybersphere in propagating misinformation about the global climate crisis and exacerbating internecine ideological warfare and geopolitical instability (Ford 2015)? On the other hand, might new digital connectivities based on empathy or other prosocial incentives help foster collective action around climate change (Lejano 2023)? Furthermore, in what ways might climate change mitigation and adaptation be mobilized to create a more sustainable, benign, and socially supportive cybersphere?

These types of relational (as Bourdieu might put it) research agendas require new initiatives for organizing and managing teams of multidisciplinary researchers and, invariably, intellectual reorientation to better appreciate the power of transdisciplinary scholarship and community practice (Hirsch Hadorn et al. 2008, Rosenfield 1992). It is not surprising that some of the earlier work around studying the science of team science originated from within the social ecology community (e.g., Stokols et al. 2003, 2008). Part of the social ecological agenda may be to foster closer scientific teamwork through critical inquiry, which involves tracing gaps in the research of a monodisciplinary orientation and assessing the value added through cross-disciplinary collaboration. Furthermore, the roots of the cross-disciplinary collaborations can be traced to the multifaceted roots of the problem phenomena, themselves, which derive from the reciprocal interdependencies among multiple societal spheres.

Real-world intervention demands multipronged action, which, in turn, requires multiple disciplines acting in concert. Much can be learned from the world's recent experience with COVID-19, in that understanding the problem required seeing it as much more than just a microbiological problem. It also involved understanding issues of ideological division, misinformation, and organizational inefficiency. It involved understanding socioeconomic issues, such as the uneven burdens borne by different countries and the most vulnerable communities within them. Moreover, it involved understanding the impacts of COVID-19 on the local and global economies. Such complex phenomena require transdisciplinary research collaboratives to fully understand them. In other words, the research community needs to match the complexity of the object of study with a nuanced and diversified spectrum of analytics—"to the things themselves," as the phenomenologist Husserl (see Husserl & Moran 2012) suggested.

Figure 1 can be used as in a mixed scanning approach (Etzioni 1986), where research teams first take stock of the larger picture and decide which issue areas are most critical (and which areas of intervention most promising) and then focus on designing research and intervention initiatives addressing these key areas. How does such a social ecological perspective improve upon conventional multidisciplinary research being conducted today? First, there is an effort to focus on boundary phenomena spanning the natural, built, sociocultural, and cyber spheres, where one domain of influence interacts with another—i.e., relational inquiry that examines interactions between diverse fields of research and community practice. Second, researchers do not simply divide up the project, allowing each to work within their individually circumscribed disciplinary margins—rather, it requires active translation across disciplinary boundaries toward the goal of achieving broad-gauged, transdisciplinary understandings of multisystem interactions (Pohl et al. 2021). This may require boundary actors, specifically, professionals trained in engaging multiple disciplinary researchers and community partners in thinking through complex issues together (Goodrich et al. 2020, Klein 2021).

DEVELOPING SOCIAL ECOLOGICAL STRATEGIES FOR IMPROVED PLANETARY GOVERNANCE

Thus far, the discussion has revolved around fostering inter- and transdisciplinary scholarship. The proposed multidimensional, relational focus rooted in the social ecological paradigm can provide guidance in matters of governance as well. One can imagine **Figure 1**, depicting links between the cyber, sociocultural, built, and natural environments, as an overarching monitoring and interventional reconnaissance system that tracks events and changes in the four sectors, perhaps scaled to monitor regional, national, and global events.

All of the sectors are interwoven and highly interdependent, and each sector can be seen as having both direct or indirect effects on particular target outcomes (e.g., regional or global greenhouse gas emissions rates) and also receiving influences from the other three sectors. Within our analysis, the sociocultural sector encompasses a wide range of sociopolitical phenomena (see also footnote 1), including corporate and governmental policies pertinent to environmental protection and other urgent societal challenges (e.g., disease pandemics, nuclear arms proliferation, cybercrime and online dissemination of misinformation). Given the overlapping, interdependent nature of the cyber, sociocultural, built, and natural environment sectors, one goal of the proposed reconnaissance system (perhaps administered by an IPCC-like research and global governance structure, e.g., an Intergovernmental Panel for Planetary Survival) would be to track and, at times, intervene to ameliorate a wide range of global dilemmas (e.g., climate change, pandemics, sources and victims of violence/war, cyber-driven chaos) at regional, national, and/or global levels.

For instance, the sociocultural sector can have direct adverse effects on the natural environment through a government decision to burn down large portions of the Amazon rainforest (Turrentine 2019) or corporate practices that prioritize fossil fuel consumption over the use of renewable energy sources (Ekwurzel et al. 2017, Heede 2014, Wang et al. 2023). Given the disproportionately negative impact of some government and corporate entities and their leaders on carbon emissions, a potentially high-leverage strategy for curbing environmentally destructive government and corporate practices might entail the tightening of international regulations and sanctions against the crime of ecocide (Ferris 2021, Promise Inst. 2023, Stokols 2020). At the same time, the sociocultural sector's impact on the natural environment (e.g., via carbon emissions) can be less direct and more mediated through other sectors, such as the built environment and cybersphere [e.g., government decisions to increase LEED (Leadership in Energy and Environmental Design) certification of buildings (US Green Build. Counc. 2011); adoption of zero-carbon cement production technologies (Xi et al. 2016); or through a state or criminal organization's efforts to spread disinformation about the climate crisis via the Internet, social media, or the dark Web (Grabosky 2016)].

Among the major global governance challenges confronting humanity are to identify the highest-leverage intervention points across various societal sectors and to implement ameliorative actions in the most opportune and impactful ways both within and between them. Our collective capacity to understand and manage the social footprint of carbon, thus, would be enhanced by tracking and modifying the above kinds of inter-sector linkages and using the monitoring/governance system to decide where and when to intervene in particular sectors (and whether at regional, national, and/or international levels). The key is to imagine a governance structure that has the capacity and commitment to coordinate across diverse societal sectors. This may involve an umbrella organization that bridges multiple agencies or a steering committee that governs a network of institutional actors (Provan & Kenis 2008).

Another key to achieving more effective organizational design would be to incorporate governance mechanisms, such as those described by Ostrom (2017), that achieve coordination across nested/polycentric institutions that parallel the nested structure of impacts spanning multiple environmental scales. Ideally, such a governance structure would have the capacity to evaluate interventions, using a systems approach to monitor feedback mechanisms and interactions across sectors. Mixed-scanning strategies are directly relevant to governance, wherein the multisectoral body examines the entire field to assess how the system is changing (e.g., whether aspects of the system in flux are changing in runaway fashion) and can coordinate specific actions that focus on subissues embedded in the system.

Social ecology offers a paradigm for structuring governance arrangements in ways that parallel multidisciplinary research teams. Ideally, these governance strategies can extend the scope and impact of the research endeavor itself. Governance requires a participatory design, wherein multiple publics are engaged in the task of setting and implementing policies. This requires translation of information across disciplinary and sectoral lines, especially in coordination with the public and other actors in the field.

IN CONCLUSION

When the state of the world seems so much in flux, most of us share the sense of being caught in a system that is incomprehensibly out of control. But it is only when we are able to step back and reflect on the whole that we might see things in clearer light. Russell Schweickart was an astronaut on Apollo 9, the first crewed lunar module. Reflecting on the experience of looking down on the Earth from outer space, he recounts:

> When you go around the Earth in an hour and a half, you begin to recognize that your identity is with that whole thing. That makes a change. You look down and you can't imagine how many borders and boundaries you cross. That wake-up scene the year before, there you are, hundreds of people killing each other over some imaginary line that you are not even aware of, you can't even see it. From where you are the planet is a whole and it's so beautiful and you wish you could take each individual by the hand and say, "Look at it from this perspective. Look at what's important." (Schweickart 1985, p. 73)

One can imagine a related sentiment from the many scientists and activists working on the climate crisis. They must wonder, Why don't people understand that we must all work together collaboratively to reduce carbon emissions and planetary warming? Given the great store of scientific information that tells us it is time to act (IPCC 2023), how is it possible for humanity not to act to save this one world that we share?

As we have discussed, when we view the issue from the sole perspective of the material (i.e., the natural sciences), we fail to see the invisible lines that divide, setting group against group, individual against individual, and impeding collective action. What we suggest is that an integrative pursuit, rooted in a social ecological orientation, offers us a way forward. Many of the dilemmas that originate in the sociocultural realm, such as ideological polarization or recurring conflict at regional and international levels, are not new issues for sociologists and other social scientists. But what the social ecological orientation offers is a basis for collaboration among hitherto compartmentalized disciplines, so essential for tackling the existential dilemmas facing us in the early twenty-first century. In this review, we have outlined some of the potential of the social ecological paradigm as an analytic and action-oriented framework for comprehending and managing these dauntingly complex problems. We recognize, for example, that carbon is more than a material construct and in fact is a social institution in itself. As such, efforts to stem global carbon emissions must not only consider technological remedies of climate change (e.g., geoengineering, carbon sequestration strategies) but also address the social and cultural underpinnings of excessive carbon consumption.

Working in concert, the scholarly community can more deeply understand not only why the peoples of the Earth do not naturally band together, but also how we might arrive at new ways to build collective action. Sherif (1958) conducted a social psychological experiment at a summer camp for boys, wherein he observed the behavior of two opposing teams that competed for various resources. Their initially benign competition quickly devolved into intense hostility between the opposing groups of campers. But when Sherif introduced a shared crisis (a breakdown of the camp's water supply system) that threatened the well-being of both groups, he was able to foster shared, superordinate goals and problem solutions that could be achieved only by both teams working together. The creation of superordinate goals, in effect, served to deescalate prior conflict between the two groups, and their relationships became more harmonious as they worked together to resolve a common threat. Clearly, the breakdown of a summer camp water system is by no

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means commensurate with the complexities of larger-scale socioenvironmental systems currently in flux in today's world. However, Sherif's concept of superordinate goals has relevance, in our view, for imagining more effective governance strategies to reverse or at least slow climate change (and other global dilemmas). Specifically, world leaders, researchers, and citizens around the globe must devote more of their effort toward building environmentally protective initiatives organized around superordinate aspirations (bridging local, national, and international interests) to alleviate sociocultural constraints against the enactment of collaborative climate solutions.

Research by Steffen and colleagues (2015, 2018) revealed that the Earth system already has exceeded certain planetary boundaries related to biodiversity loss and biochemical flows (e.g., phosphorous and nitrogen accumulation in land, freshwater, and marine resources). Furthermore, the planet is dangerously close to exceeding other boundaries linked to land use and climate change. Humanity may continue to achieve technological inroads toward curbing the excessive perturbations we are seeing in physical properties of the Earth system. Yet, to effectively curtail societal sources and adverse impacts of these planetary changes (e.g., exacerbated by our current systems of industrial agriculture and urbanization, and the burgeoning electrical power demands of modern digital technologies), we must allocate substantially more research and mitigative effort to better understand and manage the sociocultural origins and consequences of a destabilized Earth system—a set of issues we have referred to in this article as the social footprint of carbon.

Karl Mannheim (1935) observed just prior to the outbreak of World War II that humans' technological capacities seem to have outpaced their abilities to cooperate and solve problems collaboratively in the sociocultural realm. This means, for example, that work addressing the social bases of national and global problems must keep apace of physical and natural science research aimed at rebalancing the Earth system (e.g., through various geoengineering solutions). Only in this way can we aspire to what Mannheim described as a more nuanced and contextually attuned "substantive rationality" to counter humans' myopic reliance on mechanistic, means–end problem-solving strategies. The latter approach Mannheim labeled "functional rationality," which tends to be morally neutral, decontextualized, and often emerges from monodisciplinary approaches. Whereas functional rationality gives rise to more narrowly framed analyses of environmental crises, substantive rationality is better suited to developing comprehensive, social ecological understandings of the intersystem, multiscalar sources of societal and planetary turbulence—and fostering the kinds of superordinate, cross-national goals that can help empower more effective strategies of planetary governance in future years.

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