Understanding large-scale, complex, human–environmental processes: a framework for social–ecological observatories

Patrick Bourgeron[1,2], Andrew Kliskey[2]*, Lilian Alessa[2,3], Henry Loescher[4], Kinga Krauze[5], Arika Virapongse[2], and David L Griffith[2,6]

There is a growing consensus that transdisciplinary environmental networks are required to generate knowledge of the dynamics of coupled human–natural systems (CHANs) and to assess societal and policy consequences of complex environmental issues. Few of the existing large environmental observatory networks collect much, if any, data on the CHANs coupling mechanisms, reaffirming the need to develop observing approaches and structures that address the interoperability of the diverse data being obtained from these systems. We review the characteristics of existing environmental observatories and similar initiatives used to monitor CHANs, and identify opportunities for interoperability among them. From a synthesis of the characteristics of environmental networks representing a wide spectrum of research approaches and applications, a conceptual framework of a typical Social–Ecological Observatory (SEO) is presented to support long-term, multi-scaled CHANs observations through a common set of principles for organizing the observatories. Finally, we identify three areas of emphasis where progress is needed to support the use and application of SEOs.

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An array of scientific, policy, and management agendas and programs have been launched in recent decades in response to the global scale of critical social–ecological issues (Palmer *et al*. 2004; Young *et al*. 2006; Van der Leeuw *et al*. 2011; Díaz *et al*. 2015). Despite considerable investment in infrastructure, monitoring, and research, there is currently little compatibility among programs. They differ vastly in funding, mandate, and scope; in the various emphases on research (eg US Long Term Ecological Research; LTER), policy (eg Intergovernmental Platform on Biodiversity and Ecosystem Services; IPBES), and management (eg Programme on Ecosystem Change and Society; PECS); and in approaches ranging from top-down monitoring (eg National Ecological Observatory Network; NEON) to bottom-up research networks (eg LTER). The diverse sets of principles, quality criteria, and success factors of these programs can hinder comparison and integration of results (eg Binder *et al*. 2013; Hinkel *et al*. 2015).

In a nutshell:

- Social–ecological observatories (SEOs) are organized to carry out long-term, large-scale, integrated social and ecological observations
- Existing Earth-system observatories can be characterized by their management and organization; the scales of observation; emphases on research, applications, and policy; and approaches to analysis
- Organizational models for SEOs include Long Term Research Networks, Coordinated Distributed Experiments and Observations Networks, Observatory Networks, and Integrated Observatory Networks
- Clear data standards and methods for bringing diverse data types together within and across disciplines are crucial for SEOs
- The science-to-knowledge-to-action process is critical for successful SEOs

In particular, there are global efforts to develop interoperable and organized networks, infrastructures, and observatories to generate a baseline of standardized long-term, large-scale datasets about human and natural dimensions of the Earth system (Heffernan *et al*. 2014; Peters *et al*. 2014a). There is scant information on the synthesis of guidelines (Lang *et al*. 2012) and/or on the aggregation of the different approaches within a common framework for specific purposes (Imperial *et al*. 2016a,b; Scarlett and McKinney 2016) toward better use of existing resources and operational contexts. Because it is typically unrealistic to create new networks as the need arises, it is imperative to review the evidence for guidelines from existing environmental observational networks and the establishment of partnerships among multiple existing programs

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[1] *Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, Boulder, CO;* [2] *Center for Resilient Communities, University of Idaho, Moscow, ID* *(akliskey@uidaho.edu); [3] *US Department of Homeland Security, Washington, DC;* [4] *Battelle–National Ecological Observatory Network, INSTAAR, University of Colorado, Boulder, CO;* [5] *European Regional Center for Ecohydrology, Uniwersytet Lodzki, Lodz, Poland;* [6] *Intelligence Community Postdoctoral Research Fellowship Program, University of Idaho, Moscow, ID*

and networks. Many studies with emphases on different disciplinary, spatial, and research domains, and with different desired outcomes have addressed the establishment of these guidelines and programs, which makes it difficult for researchers and practitioners to design and implement environmental observing systems that incorporate the human and natural dimensions.

By its reductive nature, disciplinary research can offer only a limited means of understanding coupled human–natural systems (CHANS; Alessa *et al.* 2009; Lang *et al.* 2012; Seager *et al.* 2012). CHANS science has emerged as a framework to guide relationships between different human and biophysical components, including technology and stakeholders that are not typically involved in such projects, by viewing them as coupled through complex feedbacks and dependencies (Binder *et al.* 2013; Goring *et al.* 2014). The CHANS concept is synonymous with social–ecological observatories (SEOs) and is an operational term used by the community of scientists working in this field of study. Without effective integration of observations across multiple scales and across different domains (Tress *et al.* 2005; Lang *et al.* 2012), the ability of science to meet current societal needs will continue to be slow, imprecise, and in the worst cases, ineffective (Knight *et al.* 2008; Esler *et al.* 2010; Walsh *et al.* 2014).

Beyond data issues, an integrative and holistic approach is necessary to develop effective sustainability science that synthesizes different sources of knowledge, including local and traditional knowledge; relevant disciplines in the natural, social, political sciences, as well as in the humanities; and multi-sectoral alliances (Lang *et al.* 2012; Berbés-Blázquez *et al.* 2014). The broad diversity of organizational structures (Peters *et al.* 2014a) and the disparate scope and scale of existing observational networks (Cumming *et al.* 2013) make it difficult to link social and ecological observational networks together (Robertson 2008). Most insights on transdisciplinary team and network building focus on single entities, such as: (1) a large team or network (Stokols *et al.* 2008; Lang *et al.* 2012; Cooke and Hilton 2015); and/or (2) network governance of specific management applications at landscape/regional scales (Imperial *et al.* 2016a; Scarlett and McKinney 2016). We provide a compilation of design principles for SEOs that draws from the large and diverse array of literature on environmental network-building approaches and on practical experience. The number of CHANS studies being published has greatly increased in the past 20 years and has contributed to the emergence of SEOs.

The purpose of this paper is threefold. First, we provide an overview of representative environmental observatories, their defining characteristics, and a set of design principles. We illustrate the use of these design principles for each of the observatories selected. We explicitly identify characteristics as close as possible to the actual attributes that promote or hinder the processes behind SEO development and implementation. In particular, we emphasize assessing the complementarity of existing networks in light of these attributes, including their differences and similarities, the most effective linkages among players, and knowledge/data gaps. Second, we formulate a framework to guide future SEO development and outline the challenges, processes, and milestones to meet those challenges, taking into consideration the context in which SEOs are created. Consequently, we explore the expanding role of environmental observatories, the constraints imposed by observatories' design on the usability of results, and a possible remedy, namely the development of SEOs from partnerships between distinct but coordinated observatories. Finally, we explore the challenges in complying with the design principles for SEOs using case studies of three emerging SEOs. The article concludes with three areas of emphasis needed to further enhance SEO development.

Expanded scope of observatories

Changing factors that affect CHANS have given rise to a number of issues in sustainability science (Kohler *et al.* 2014). These factors include interacting physical, biological, and social drivers (Dietz *et al.* 2007; Kliskey *et al.* 2016); education, public health, and social cohesion problems (Durante *et al.* 2013; Milanovic 2013); extreme climatic and weather events (Carnicer *et al.* 2011; Soares-Filho *et al.* 2012); and ecosystem services (Daily *et al.* 2009). When seen through the lens of CHANS (Bazilian *et al.* 2011), specific issues of sustainability have been characterized as "wicked problems" (Rittel and Webber 1973; Shindler and Cramer 1999). Issues become more intractable when the dynamic processes and interactions among the spatial scales and the social and ecological domains of CHANS create uncertainty about future environmental conditions and differences in social values. Some of these differences make it virtually impossible to define an optimal condition at all spatial scales and in all social–ecological domains. Wicked problems are defined by their technological character, social contexts, and high degree of divergent perspectives on the problem (Chapin *et al.* 2008; Farrell and Hooker 2010). Addressing such complex problems requires data at multiple spatial scales, resolutions, and knowledge domains. Several efforts have been undertaken to shift from disciplinary/multidisciplinary environmental networks that involve members from different disciplines working in parallel or sequentially, with separate goals for each discipline (Choi and Pak 2006), to transdisciplinary networks that develop a systems-level holistic approach informed by methods and theory from several disciplines requiring synthetic methods or theory (Choi and Pak 2006), in order to explicitly investigate CHANS. Examples include the US-LTER (Collins *et al.* 2007) and the International Long Term Ecological Research network

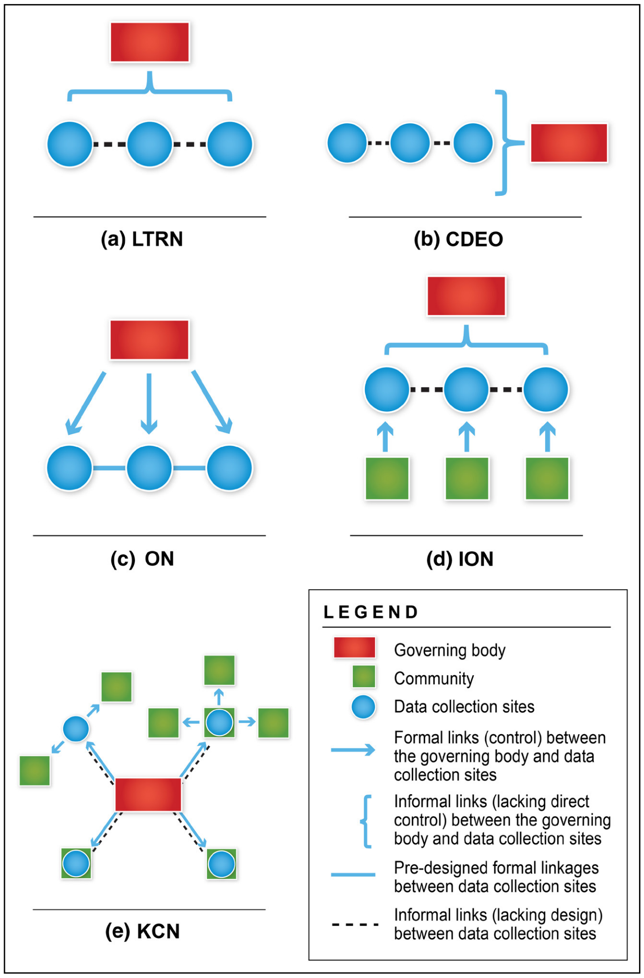


Figure 1. *The governance structures for different organizational models of potential social–ecological observatories (LTRN – Long Term Research Network; CDEO – Coordinated Distributed Experiments and Observations Network; ON – Observatory Network; ION – Integrated Observatory Network; and KCN – Knowledge Coordination Network).*

(ILTER; Bourgeron *et al.* 2001a; Ohl *et al.* 2007), as well as broader calls for such networks (Vajhala *et al.* 2007). Discussion of these and other networks are found in the following sections. Nonetheless, no existing observatory fully provides comprehensive and integrated CHANS data.

This can only be addressed by creating observatories optimizing partnerships among existing ones, and developing open and inclusive platforms for observing and monitoring the status, trends, and thresholds of the planet at different scales, including tracking of changing processes and systems (Carpenter *et al.* 2012). The big data generated by large infrastructures, expected to advance science (Peters and Okin 2017) and address social benefits (NSTC 2014), will not by itself offer solutions acceptable to the majority of stakeholders (Seager *et al.* 2012). A pragmatic, theoretical, and operational framework – one that integrates multi-scale ecological and social observations, as well as other sources of knowledge (eg local, traditional, non-scientific, etc), and engages partners in a multi-stakeholder and mutual learning platform to address complex large-scale environmental issues – has yet to emerge.

Characteristics of existing Earth-system observatories

Existing observatories differ in four key characteristics: governance structures; the scale of observations, integration, and synthesis; emphases on research, applications, and policy; and types of research strategies conducted. These differences must be considered when formulating guidelines for establishing future SEOs and partnerships.

Governance

Governance structures for environmental observatories refer to items such as an advisory board, the establishment of rules and regulations, the mechanisms defining the relationship between observing units required to balance the powers among them, and the process by which research questions and hypotheses are developed. The observatory governance structure (Imperial *et al.* 2016a) has a bearing on how social or biophysical dimensions can be integrated within and between observatories, as well as their sustainability, adaptability, and interoperability potential. On the basis of our compilation of existing evidence, we identified five organizational models for environmental observatories (Figure 1, Table 1): Long Term Research Networks (LTRNs), Coordinated Distributed Experiments and Observations Networks (CDEOs), Observatory Networks (ONs), Integrated Observatory Networks (IONs), and Knowledge Coordination Networks (KCNs).

LTRNs are networks of research sites that are programmatically designed and primarily structured for site-based fundamental research. Network-level research questions are formulated to leverage site-level research, and LTRN coordination is mandated by the funding agency. CDEOs are networks of independently funded research sites. Site coordination is a function of the investigators agreeing to share research questions, creating joint research programs and projects capitalizing on site-based work, and working toward partial harmonization and standardization of data, sampling strategies, and experimental design. Governance of CDEOs is lateral because the agreements are made between independent investigators and their collaborators. Unlike LTRNs, coordination among CDEO members is not mandated by the funding agencies, a characteristic that provides flexibility, yet may hinder research and data sharing beyond the original agreement. ONs are characterized by a high level of research infrastructure and a structured, top-down governance framework; community input for ONs is very prescribed

Table 1. A comparison of the different types of observing systems, including key characteristics, benefits, and limitations of each

Organizational model	*Characteristics*	*Benefits/limitations*
Long Term Research Networks (LTRNs)	• Collection of domestic research sites • Initiated and supported through a single agency • Each research site typically led and governed by independent investigators • Moderate level of coordination for core datasets	*Benefits*: optimizes scientific creativity *Limitations*: data sharing between sites ad hoc; data collection methods vary by site; limited spatial coverage; high signal-to-noise ratio
Coordinated Distributed Experiments and Observations Networks (CDEOs)	• Collection of principal investigator research sites that are initially funded by different source • Sites join together when investigators agree to share research questions, and use similar sampling strategies and experimental design • Lateral governance based on voluntary agreements between independent investigators	*Benefits*: coordinated hypothesis-driven experiments; large spatial coverage; standardized research design; low-cost implementation; community-driven *Limitations*: Variable length of records for sites and investigator participation; high signal-to-noise ratio
Observatory Networks (ONs)	• High level of research infrastructure, with the most structured, top-down driven governance framework • Community input is highly prescribed • Research questions and approaches determined before implementation • Financially supported by a single funding agency	*Benefits*: highly controlled and standardized; high statistical power *Limitations*: high cost; limited scope for innovation, flexibility, and integration of legacy data; culturally foreign for many scientists
Integrated Observatory Networks (IONs)	• Merging of on-the-ground participation from local-level investigators • Well-established scientific approaches that address research questions at multiple scales; local investigators and large-scale science initiatives interact to develop scientific and management questions, data collection techniques, and data products	*Benefits*: efficient use of time, funding, and human resources; high spatial range; community-driven; high potential for supporting local-level sustainable environmental management *Limitations*: Monitoring target often focused on small-scale issues; protocols are simple and static; high potential for variation among observations; human observers may require regular training; culturally foreign to most scientists
Knowledge Coordination Networks (KCNs)	• To advance a field or create new directions in research or education by supporting groups of investigators to communicate and coordinate their research, training, and educational activities • Crosses disciplinary, organizational, geographic, and international boundaries	*Benefits*: opportunities for new collaborations, including international partnerships, and address interdisciplinary topics; encourages the development of innovative ideas for novel networking strategies, collaborative technologies, and development of community standards for data and metadata *Limitations*: does not support primary research or monitoring

(Schimel and Keller 2015). ONs set standardized research questions and approaches that are determined before any research infrastructure is identified and constructed. Linkages between research sites of LTRNs, CDEOs, and ONs may occur through bottom-up community discourse among researchers. In general, larger infrastructure investment is associated with a more formalized, top-down governance structure, because there are often direct management requirements by funding institutions.

IONs and KCNs are the most recent organizational models. IONs represent a merging of on-the ground, local-scale investigations to address research questions at larger (and multiple) scales. IONs utilize a push–pull communication strategy in which local investigators interact to develop larger-scale science initiatives. Research sites of IONs are depicted as informally linked (Figure 1), since site structure and research are often driven by local-scale community input. IONs emerge through the process of formalization of research design and planning among cooperating sites. Suited to transdisciplinary approaches (Tress *et al.* 2005), IONs are used to increase diversity of perspectives, observation scope, buy-in from regional stakeholders, and more efficient alignment in research, land management, and policy decisions. KCNs bring together interdisciplinary teams of researchers, educators, managers, policy makers, and other stakeholders to conduct collaborative research. KCNs aim to facilitate networks of individually funded researchers and stakeholders to be able to integrate a variety of disciplines, sectors, and backgrounds in ways that create new perspectives. KCNs provide opportunities for new research and networking strategies but do not support primary research or monitoring.

Scale

The scale at which observatories function is another way to characterize existing efforts. It is common for observatories to change the scale at which they function over time: this is due to existing observatories that transition from smaller- to larger-scale studies, or when another (sometimes overlapping) subset of existing observatories has branched out from the study of well-defined disciplinary systems (eg ecological systems, land-use systems, social systems) to the study of CHANS, their interactions, and their drivers. Sites, however defined, usually determine the scale at which intensive data collection is intended to be representative of the different ecological and social systems found in the geographic unit of interest. The conceptual spatiotemporal relationships of the sites to the domain of the observatories must be established for meaningful interoperability across platforms (Peters *et al.* 2014a) and to avoid scale mismatches (Cummings *et al.* 2006, 2013). This is also critical in avoiding leadership issues (Imperial *et al.* 2016a), which can be a function of observatory development (Imperial *et al.* 2016b).

Research goals

The diversity of emphases in existing observatories along a gradient of approaches to research, applications, and policy is another way to characterize existing projects. The variety of goals and management of different observatories constrains the level of possible standardization and integration of activities from design to data collection and interpretation.

Analytic strategy

The final way to characterize observatories is based on a fundamental issue in data integration for performing analysis within and between observatories: the constraints imposed by a choice of analytic strategy used to collect observations in different domains. Four analytic strategies (inductive–deductive, generative–verificative, constructive–enumerative, subjective–objective) of research design have been identified and conceptualized as a set of continua (Table 2). Most individual studies can be placed in locations between the extremes on the continua (Goetz and LeCompte 1981), each with specific characteristics that fit different disciplines (Table 2). A particular study may combine both constructive and enumerative units of analysis, and certain complex studies, like LTRN cross-site comparisons, may begin by generating propositions that are subsequently verified. Furthermore, any combination of the four strategies may be used in transdisciplinary programs, as different disciplines and sectors have favored one or more of the above strategies. In this context, research – and in particular comparative, cross-site, cross-network research – is best considered as a problem in data reduction and control of variation (Goetz and LeCompte 1981; Bollen *et al.* 1993). Therefore, it is imperative

Table 2. A review of the characteristics of the four analytic strategies

Types of analytic strategies	*Characteristics*
Inductive–deductive	• The place of theory in a research study • Inductive begins with collection of data, then builds theoretical categories and propositions from relationships discovered among the data • Deductive begins with a theoretical system, develops operational definitions of the propositions and concepts of the theory, and matches them empirically to some body of data
Generative–verificative	• The position of evidence within a study • The generalizability attempted in the study • Verificative strategy tests propositions developed elsewhere and also commonly attempts to generalize • Goal of verificative is to establish the extent to which a proposition is “true”, and the broader context to which it applies • Generative seeks to discover constructs and propositions using one or more databases • Generative is often inductive, while verificative is frequently deductive • Generative may be informed by theory just as verificative may have no theoretical framework
Constructive–enumerative	• Reference to the ways in which the units of analysis of a study are formulated and delineated • Constructive seeks to derive analytic categories by a process of abstraction in which units of analysis are developed or discovered • Enumeration relies on previously derived or defined units of analysis that are then subjected to systematic counting procedures
Subjective–objective	• Subjective patterns are viewed from the perspective of the object, entity, or group under investigation and then the appropriate strategies are those that elicit and analyze subjective data to reveal how the research subject conceptualizes their own experiences and worldview • Objective patterns are viewed from the perspective of conceptual categories and explanatory relationships

to clearly identify the units of analysis and analytical techniques to avoid the production of incompatible data (Goetz and LeCompte 1981).

Observatory frameworks

It is against this background of multiple types of governance, study scales, research goals, and analytic strategies that Earth-systems observatory science is becoming increasingly complex. Little is typically done upfront to identify the characteristics of each observatory, thereby hindering broad integration across observatories. Results from the characterization of major and representative existing observatories are shown in WebTable 1. The selected observatories follow different organizational models and vary in primary focus, scales, and research strategies, thereby constraining the capacity of each program to establish partnerships.

Biophysical, social, and transdisciplinary observatories use all types of organizational models, although some are more comfortable for scientists than others. For example, LTRNs and CDEOs have the best cultural fit for many academic, disciplinary scientists because principal investigators manage each research site independently. In contrast, ONs often require cultural adaptation from academic scientists because they are highly structured and controlled by top-down management.

There are fewer examples of coordinated large-scale, long-term, and standardized observation frameworks among the social sciences than in the biophysical sciences (WebTable 1). High complexity and variability in discrete social science datasets limit opportunities for interoperability and synthesis of large-scale observation of social phenomena. The modern census, which records information about entire human populations on decadal scales (Baffour *et al.* 2013), may be the most widely implemented social science ON that exists worldwide. However, these datasets have limited capability to capture the complexity of human social structures and cultures, which are represented by the diverse approaches and methods of numerous social science disciplines, such as sociologists, political scientists, and anthropologists. To help fill this gap, IONs can be used as distributed frameworks to understand social processes and dynamics evident in human communities (Moran *et al.* 2014).

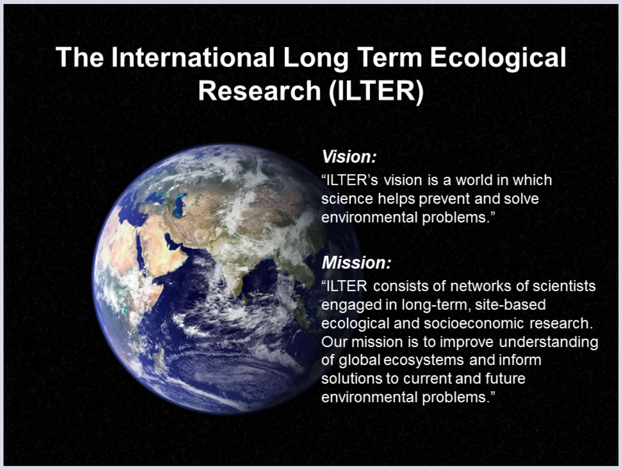
Most recent initiatives seeking to forecast ecosystem change recognize the importance of investigating CHANS dynamics, but long-term monitoring of human activities over a broad temporal scale coupled to ecological changes is a relatively new objective (Redman *et al.* 2004; Peters *et al.* 2014a). To date, some integrated human–environmental observatories (WebTable 1) have been tested as CDEOs (eg Human–Environment Regional Observatory, MacEachren *et al.* 2006) or as LTRNs (eg US-LTER, Redman *et al.* 2004; Robertson 2008). US-LTER, for instance, has investigated human perception of ecosystem services, the effect of these perceptions on human behavior, and how these perceptions and behaviors affect ecosystem structure and services over the long term (Collins *et al.* 2011).

As an example of a human–environmental ION, the Community-based Observation Network for Adaptation and Security (CONAS; Alessa *et al.* 2015) uses sensors and human observers (local environmental experts) to collect data on social behavior and environmental change by using a community-based observing network (CBON) methodology. CONAS is co-developed, operated, and governed by a team of community representatives, indigenous non-governmental organization members, and university researchers.

The importance of identifying the attributes of the different observatories and assessing how they affect performance is illustrated by the following examples. The incorporation of CHANS studies within the US-LTER started in the late 1990s, with the stated goal of expanding the approach from two urban sites to the entire network (Grimm *et al.* 2000). This effort led to an ambitious call for a truly network-based CHANS approach (US-LTER 2007) through the implementation of the Integrative Science for Society and the Environment Initiative (ISSE) (Collins *et al.* 2007). Despite clear network-level successes (Gosz *et al.* 2010; Robertson *et al.* 2012), the initiative stayed largely grounded at the level of the site or a limited number of sites (Groffman *et al.* 2017) rather than at the network level, due to competition among research priorities and perspectives within the funding agency (the US National Science Foundation [NSF]). This is a consequence of the US-LTER being established as an LTRN with single agency support (Table 1).

Despite this failure to achieve a network-level change in approach, there are several positive unintended consequences to the ISSE stemming from the creation of international SEO prototypes. They include: the shift of the ILTER KCN (Panel 1) from a biophysical environmental network (Gosz 1996) to a CHANS SEO (Maass and Equihua 2015) via the implementation of a strategic plan patterned after the ISSE (Bourgeron *et al.* 2014; the creation in Europe of "A Long-Term Biodiversity, Ecosystem and Awareness Research Network" KCN (Ohl *et al.* 2007; ALTER Net, http://alter-net.info) that launched the LTER-Europe network LTERN (www.lter-europe.net) comprising two categories of networks: one of biophysical sites (LTER-Europe) and the other a Long-Term Socio-Ecological Research network (LTSER, www.lter-europe.net/lter-europe/infrastructure/sites-platforms/categories) (Panel 2); and the funding of sustainability focused, regionally based KCNs such as the Mountain Social Ecological Observatory Network (MtnSEON) (Panel 3). These examples indicate that multi-funded, membership-driven KCNs provide a solid basis for the emergence of future networks of networks and related initiatives.

Panel 1. The International Long Term Ecological Research Network (ILTER)



The International Long Term Ecological Research (ILTER)

Vision:
"ILTER's vision is a world in which science helps prevent and solve environmental problems."

Mission:
"ILTER consists of networks of scientists engaged in long-term, site-based ecological and socioeconomic research. Our mission is to improve understanding of global ecosystems and inform solutions to current and future environmental problems."

P Bourgeron

Figure 2. *Vision and mission of the International Long Term Ecological Research Network.*

The ILTER (www.ilternet.edu) is a KCN comprising an international network of 44 national-level networks of scientists engaged in long-term and site-based ecological and socioeconomic research and monitoring, with a strong interest in capacity building. Patterned after the US-LTER, the ILTER was created in 1993 as an informal network of like-minded, long-term ecological networks performing biophysical, ecosystem-based, site-level research (Gosz 1996) without core funding, formal governance structure, or charter. As it matured, the ILTER adopted a formal, bottom-up governance structure and a set of rules after its first strategic plan was adopted in 2006 (Hamburg and Bourgeron 2006; Kaufman *et al.* 2006; Figure 2). The ILTER transitioned from its previous status to a fully autonomous, self-sufficient international organization with the capacity to contribute to global research (eg Shibata and Bourgeron 2011). Following a series of workshops, the ILTER adopted the ISSE CHANS approach that was explicitly formulated in the strategic plan. The ILTER is now a LTSER (Shibata and Bourgeron 2011; Singh *et al.* 2013; Maass and Equihua 2015; Mirtl *et al.* 2018). The ILTER has generated several new international networks that are either more restricted in scope and/or regional in scale (eg see Panel 2).

ILTER members have expertise in the collection, management, and analysis of long-term environmental data and, together, they are responsible for creating and maintaining a large number of unique long-term datasets (Vanderbilt *et al.* 2015). ILTER has been a partner for many global environmental initiatives (eg PECS, Global Land Programme, DataONE) and many ILTER scientists participate in international programs. The network is well positioned to inform policy and management decisions by addressing temporal (long-term) and spatial (international network) scales seldom accounted for in scientific research (Vaughan *et al.* 2007; Parr 2013). For instance, an international symposium to assess the contribution of long-term CHANS studies to planning and management for sustainability of water resources in Europe and elsewhere was convened in cooperation with the European Long-Term Ecosystem Research Network and the ILTER. There were 210 attendees (including researchers, planners, and decision makers from 31 countries), 95 talks, and 50 posters. The results were disseminated as reports, recommendations, and peer-reviewed articles (Moss *et al.* 2014).

The strength, flexibility, and adaptability of the ILTER KCN lie in its bottom-up governance style that provides a framework for connecting researchers who can self-organize around research topics on a voluntary basis. ILTER collaboration is usually conducted through workshop series. Examples of such work include: analysis of ecosystem services (eg Shibata and Bourgeron 2011; Vihervaara *et al.* 2013; Maass *et al.* 2016); nitrogen cycles (eg Shibata *et al.* 2015); and data sharing (eg Vanderbilt *et al.* 2015, 2017). The main weakness of the network is the lack of core funding and the voluntary basis of membership dues. Consequently, the ILTER can be vulnerable to changes in the priorities of its members.

■ Design principles for SEOs

SEOs as engagement systems

We frame the design of SEOs as observatories that engage diverse researchers, policy makers, and community members in science (Figure 5) in order to: coordinate diverse existing or new observatories and data streams, including non-scientific sources; define new initiatives; gather a variety of knowledge types and viewpoints for innovation and development in science, policy, management, and business; establish partnerships; allow for information planning and policy; develop new curricula; guide new opportunities for generating large environmental datasets; and enable efficient use of existing funding and seek new opportunities. SEOs of this type differ from existing observatories by offering an explicit framework to collect heterogeneous data and derive interconnections among different components, including the activities/events that mediate between social and biophysical components of a system, related processes (Redman *et al.* 2004), and external context (eg political and environmental contexts; Ashley and Carney 1999; Hinkel *et al.* 2015) that drive and are driven by such interconnections.

Beyond the existing observatories, this approach to SEOs as engagement systems expands upon many dimensions of integrated assessments that emerged in the 1980s, as scientists and policy makers struggled to tackle complex issues by integrating economic, land management, and climate-change data to guide decision making from local, regional, and national scales (Tol and Vellinga 1998; Lessard *et al.* 1999; Jensen *et al.* 2001; Bourgeron *et al.* 2009). It enhances past methodologies in two ways. First, SEOs are intended to build upon the experience and value of existing observatories that operate at different scales and in different domains, thus providing a broader knowledge base beyond each observatory's scope. Second, SEOs would provide a lasting structure to integrate newly acquired information and knowledge into

Panel 2. Moving from the regional Knowledge Coordination Network (ALTER-Net) toward Coordinated Distributed Experiments and Observations Networks (LTSER of LTER-Europe)

In 2004, the European Commission funded a network of excellence, the ALTER-Net (A Long-Term Biodiversity, Ecosystem and Awareness Research Network), as a step toward a pan-European, distributed institute studying human–nature interactions. ALTER-Net (www.alter-net.info) brought together 24 research centers and researchers from 17 countries, with the intention of: creating a network for European long-term terrestrial and freshwater biodiversity and ecosystem research, based on existing facilities; developing approaches to assess and forecast changes in biodiversity, and the structure, functions, and dynamics of ecosystems and their services; and considering the socioeconomic implications of and public attitudes toward biodiversity loss. The specific challenge was to create a mechanism for enabling long-term research by establishing methodological standards, a data-exchange platform, instigating interdisciplinary and trans-sectoral collaboration (particularly in the realm of science policy), and fostering a transition from ecological to socioecological research in order to support the DPSIR (driving forces, pressures, states, impacts, responses) causal model. The DPSIR model was adopted by the European Environment Agency, demonstrating that it can serve as a unifying framework for describing the interactions between society and the environment.

As a KCN, ALTER-Net succeeded in two ways. First, as a network of excellence, it moved from funded to non-funded as a voluntary but durable consortium of institutions focused on biodiversity, ecosystem services, environmental management, and policy. It has continued to contribute to the lasting integration of Europe's research capacity on biodiversity through a summer school, multi-site experiments, science-policy conferences, and horizon scanning for High Impact Action demand. Second, collaborative efforts led to cultural changes within and among KCN institutions, which allowed the merging of national LTER networks located on two sides of the former Iron Curtain into a unified European LTER network (2007, www.lter-europe.net), being in fact an example of a Coordinated Distributed Experiments and Observations Network (CDEO). That triggered processes of network extension to new countries and sites, better representing economic, social, and environmental gradients across Europe. CDEO strengthened the in-situ components of the network, both observational and experimental, and imposed a need for a fully operational data management system synchronized with European initiatives (eg Shared Environmental Information System; SEIS). It simultaneously raised interest in the European Commission for funding and supporting such systems. On the other hand, the combination of a KCN knowledge base and site-based research of CDEO created a push for LTSER platforms to concentrate on CHANS LTSER is operationally part of the LTER-Europe infrastructure; however, it is strongly linked to multi-stakeholder platforms and biophysical and administrative contexts. LTSER facilitates knowledge, co-production, and co-design of research outputs involving citizen science, social survey, cognitive mapping, Bayesian network, and Agent Based Modeling methodologies in all European landscapes (Figure 3). During the past 5 years, LTSER has been conceptualized and translated into a set of obligatory features and information/parameter sets. It has also built up the capacity of the network to acquire and implement projects integrating social, economic, and ecological domains (eg Openess, Life+ EnvEurope, Infraia EXPEER, Infra eLTER), but also business, resource management, education, and science, that fit current European and global policies and targets. The LTSER initiative of LTER-Europe has become a step toward initiating a larger process within the ILTER network.


K Krauze

Figure 3. *Cultural landscape of the West Polesie LTSER (Poland) primarily established for analyzing historical, social, and economic drivers of biodiversity changes, and participatory development of long-term management plans.*

existing knowledge bases. Elements of this approach include assessing the interoperability and representativeness of the data. Integration of diverse sources of information across domains has long been recognized as a priority for regional ecosystem management (Slocombe 2001). The need for addressing scalability at landscape, regional, and continental scales (Peters *et al.* 2014a) and for integrated, iterative approaches to data modeling with learning (Peters *et al.* 2014b) has more recently been discussed. In an international context, challenges to data sharing include unequal distribution among networks of information management expertise, user-friendly tools, and resources (Vanderbilt *et al.* 2015). Language and translation have also been issues (Vanderbilt *et al.* 2017). All approaches must assess knowledge gaps, data gaps, and data representativeness, but should also determine the feasibility and need for a new network.

As pragmatic engagement systems, SEOs would offer an integrated system for environmental regulation that includes strategic planning, objective setting, performance standards, monitoring, and review of the overall process. They would inform decisions with CHANS knowledge, advance innovative and anticipatory research, and stimulate cultural synthesis and innovation. They could therefore inform triple-loop learning (learning how to learn) that redefines the norms and protocols of human behavior, individual and collective learning, and processes that contribute to the formulation of social–ecolog-

Panel 3. MtnSEON as a regional Knowledge Coordination Network

The Mountain Social Ecological Observatory Network (MtnSEON) coordinates a loosely connected suite of 12 CHANS-focused projects concerned with integrated approaches to examining and resolving CHANS issues specific to mountain landscapes and communities of the American West. Individual observing and monitoring projects with this KCN include the following areas of focus: rangeland management and conservation, invasive species, lake and river systems, social consequences of fire dynamics in the wildland–urban interface (WUI), CHANS training for a wide variety of stakeholders, and development of community-based observing networks (CBONS). The KCN provides a venue for sharing inter- and transdisciplinary frameworks, experiences, and challenges, and has also been able to support synergistic activities that address some of these items. For example, MtnSEON has developed a current practices archive for CHANS research and practice (the SES-CPA, available on request from the authors). A variety of other efforts have been made to foster cross-disciplinary sharing. For instance, workshops have explored the development and application of CBONS methodologies in rangeland management. Assessments of vulnerability and resilience in the WUI have been conducted. A rapidly expanding CHANS led to the formulation of several ideas that were further developed in another workshop (with the participation of several MtnSEON participants. A curriculum was designed to support training in SES concepts and practice (Virapongse *et al.* 2016) for middle management officers in federal land management agencies. The curriculum developed by MtnSEON was offered to an initial cohort of management professionals as the Social–Ecological Systems Training and Education Program at the University of Idaho from October 2016 to April 2017.


J Finnell/The Nature Conservancy

Figure 4. *Rangeland landscape of Rock Creek Ranch, Central Idaho, part of the community-based observing network Working Group for the MtnSEON Knowledge Coordination Network.*

A key part of this KCN is enhancing communication across the network and facilitating cross-fertilization projects. For example, through MtnSEON annual meetings and smaller workshops, the CBONS methodology has been adapted from its origins as an observing technique in Arctic maritime domains to an implementation for rangelands management by the Blue Mountains Working Group (Griffith *et al.* 2018; Figure 4). Additionally, several general issues addressed by MtnSEON on CHANS dynamics in the WUI were directly addressed by a NSF-funded CHANS grant (to PB, CNH Colorado Front Range Wildland/Urban Interface) in the Colorado Front Range and further incorporated in an international study of ecosystem services (Panel 1).

ical solutions (sensu Palmer *et al.* 2004) for sustainability of the biosphere. Such SEOs would promote collaborative enterprises and communication of knowledge beyond the research communities. Additionally, this collaboration would create opportunities for young professionals to interact, to recruit people who engage a broad range of stakeholders in ways that address wicked problems, and to create transformative knowledge (that is, knowledge that drives social change and generates sustainable futures). For example, in response to changes in the US Forest Service (USFS) Forest Planning rules that incorporate ecosystem management principles to provide desirable ecosystem services, the USFS Northern Region developed an SEO prototype under various scenarios involving uncertainty and change. This prototype includes many of the guidelines presented here for its regional Integrated Restoration and Protection Strategy. The resulting framework allows for the explicit evaluation and exposition of realistic strategies that can increase the likelihood of socially beneficial outcomes, while reducing the risk of negative outcomes (Panel 4).

A roadmap for SEOs: processes and challenges

In order to act as effective engagement systems, SEOs must be flexible and adaptable while maintaining structure and the capacity to self-organize in response to challenges, new opportunities, and the needs of stakeholders. As used in this paper, SEOs are networks of networks: collections of different but coordinated organizational models that measure human–environmental relationships within a shared scientific context.

When designing SEOs, it is important to focus on the added value of network-to-network linkages, rather than simple linkages among individual sites (Figure 7). The network approach implies that projects within the SEO are connected and that activities take place at different organizational levels. To define possible linkages between networks, the different dimensions of network complementarity (similarities and differences in governance, focus, scales, and analytic strategies) must be clearly identified. Such inter-network linkages take place at two of the three levels of activities conducted in Earth observatories (Figure 7): cross-site research (eg spatial and temporal variability, regionalization, and biodiversity) and at the highest levels of network activities (eg technical committees, lessons learned, and links to global initiatives).

The specific governance of an SEO may be structured as any of the five organizational models previously discussed (LTRNs, CDEOs, ONs, IONs, and KCNs). However, the SEO-specific goals, funding, and desired outcomes will constrain the choice of model. KCNs provide the most flexible and cost-effective SEO structure. However, its main limitation is that it only supports coordination, but not new research. Two examples of KCNs acting as the governance structure of SEOs are the ILTER and MtnSEON. The ILTER (Panel 1, WebTable 1) has a very flexible structure: it is self-funded (via membership dues); it does not prescribe activities to its member networks; and site participation in coordination activities is voluntary. It is very adaptable and can respond quickly to new needs as they arise, but its shortcomings include a lack of external funding to drive large-scale initiatives and create specific products. MtnSEON (Panel 3, WebTable 1) is an NSF-funded Research Coordination Network (RCN) that connects independent projects across the western mountains of the US to develop capacity among all projects to more efficiently answer research questions. While more structured than the ILTER, MtnSEON provides both funding and a flexible structure for participants to join different projects together under specific, shared coordination themes.

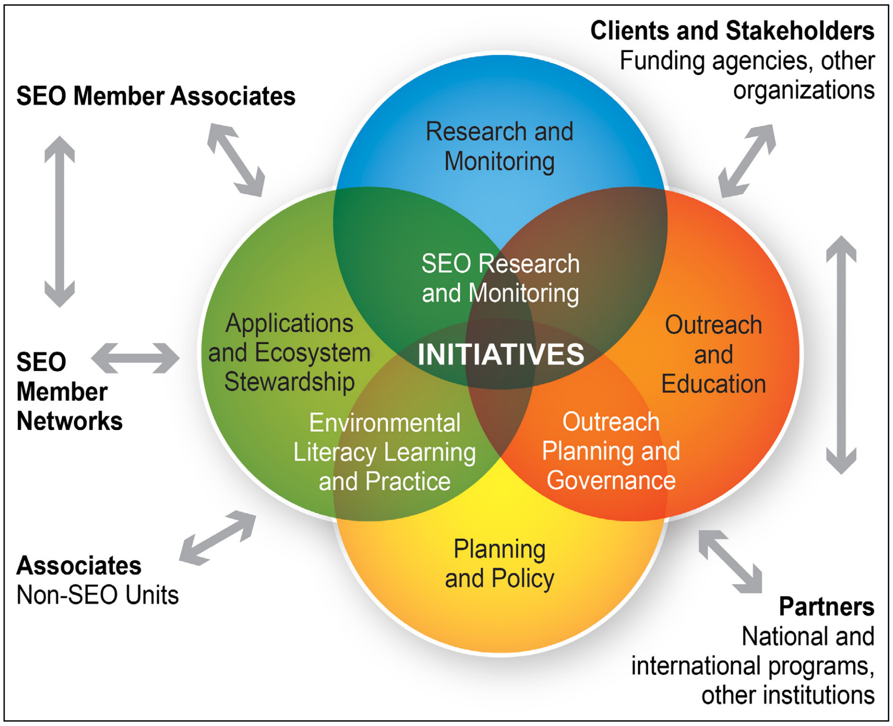


Figure 5. *Social–ecological observatories as an engagement system showing members, associates, stakeholders, and partners.*

Thus, one of the challenges in designing SEOs is being able to identify:

(1) the differences and similarities in the internal and external actors to optimize effectiveness;
(2) the most effective linkages between the actors; and
(3) the kinds of processes that can best promote effective collaboration among actors at appropriate scales.

To address this challenge, we formulated a set of specific criteria to meet and questions to answer in three broad categories, drawing upon a combination of experience and published studies (WebTables 2–4). These categories include:

(1) vision and strategy (WebTable 2): clear outcomes, strategy for partnerships, type of ILTER research involved, etc;
(2) leadership and organization (WebTable 3): mapping the structure of the leadership team and identifying contextual factors influencing transdisciplinary collaboration and partnerships; and
(3) group expertise, support, and infrastructure (WebTable 4): experience level of the core group, amount of funding, information management, technological infrastructure, rewards, etc.

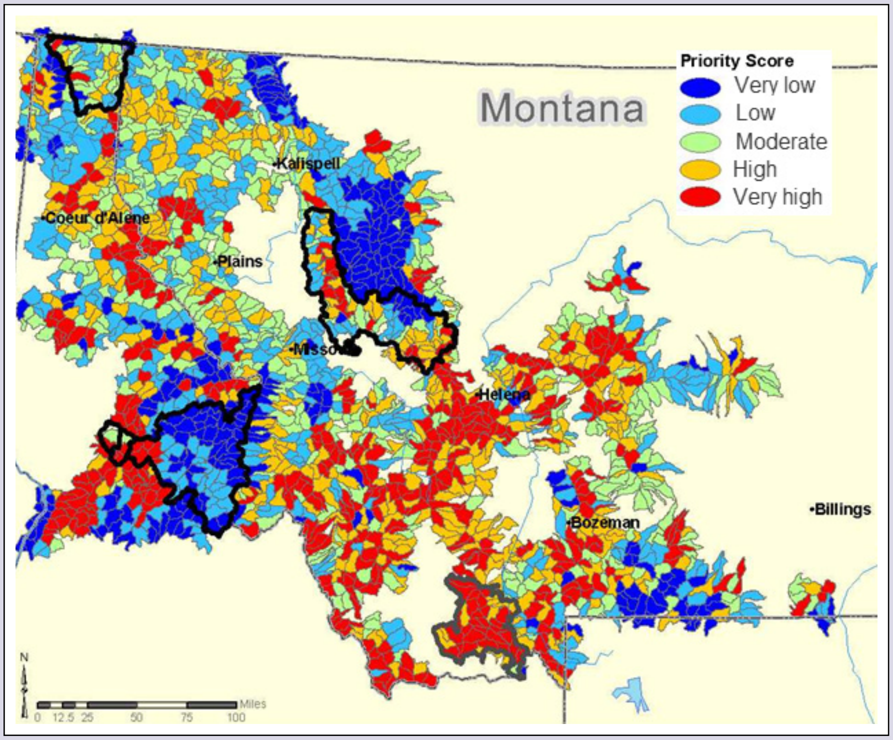
Together, these tables provide a template to assess current observatories and to inform and guide the formulation of new SEOs and partnerships. The criteria provide a means to assess whether the new SEO is needed and adequately equipped to complete its task.

■ Conclusion: the way forward

As research and academic institutions are called upon to address increasingly complex environmental issues, new tools must be added to the existing toolbox. By proposing SEOs as engagement systems to frame and generate the new datasets needed to understand large-scale, complex, human–environmental processes, we highlight three areas where progress is needed. The first is the most obvious and familiar to many scientists: data standardization, interoperability, and synthesis within and between disciplines and within and between initiatives are crucial. A variety of mechanisms to help support interoperability already exist and need to be strengthened. Nearly all large-scale science initiatives include support for data acquisition, processing, and archiving. In addition, platforms must be developed for the uptake and application of information tools and/or support, and for the maintenance of web portals that include transdisciplinary data (Lewis *et al.* 2017). Partner observatories of SEOs must formalize agreements to share concepts, strategies, and practices, so that their activities can become more ingrained and sustainable.

Panel 4. The US Forest Service Northern Region Integrated Restoration and Protection Strategy as a prototype SEO

Since the USFS adopted the philosophy of ecosystem management (Overbay 1992; Jensen and Bourgeron 2001), integrated ecological assessments were developed and implemented to provide a structured process from formulation of issues to assessment to implementation for sustainability (Bourgeron *et al.* 2009). Sustainability is here defined as meeting current needs without compromising the ability to meet future needs. In this context, the USFS Northern Region recently updated its Integrated Restoration and Protection Strategy (IRPS) (www.fs.usda.gov/goto/r1/irps; Bourgeron *et al.* 2014) to provide information in identifying and prioritizing potential watersheds for achieving forest and grassland plan goals and objectives. Planning processes such as IRPS are inherently complex because of the need to integrate multiple datasets, build partnerships, and incorporate economic and social values. Consequently, they require the participation of numerous actors, involve decisions within and across spatiotemporal scales and administrative boundaries, and are subject to rapid potential changes in short-term objectives.



USFS

Figure 6. *Map integrating results for all the themes of the Northern Region IRPS, illustrating potential locations for addressing multiple management objectives for restoration or protection in a subregional area. The priority score in the figure was calculated, considering the contributions of the priorities of the six themes. In the current version of the DSS, the priority score for a theme was simply calculated as the average priority score over all scenario components of the theme (ie all scenario priorities in a theme were equally weighted and therefore contributed equally to the priority score for the theme).*

As a prototype of the kind of SEOs implementing the ideas developed in this article, the Northern Region IRPS used the framework of a spatially explicit decision support system (Ecosystem Management Decision Support System; Reynolds *et al.* 2014). By setting the context for partnerships among existing observatories and for collaboration among all stakeholders, they were able to integrate datasets from different disciplinary and spatial domains. This provided a consistent, transparent, and reproducible approach to identifying and prioritizing restoration opportunities. The IRPS assessed several key planning questions and identified opportunities and potential priorities for 19 key single resource values of six themes that may be at risk to current or projected disturbance and other agents of change, resulting in priority scores for land units (Figure 6; Bourgeron *et al.* 2014). Notably, a wide array of stakeholders participated in the process to confirm that these were, in fact, the important issues to address.

One of the key findings of the exercise was that the potential opportunity areas not only provided a useful starting point for discussions, but also afforded a useful context for developing feasible community-based project-opportunity areas. When locally determined feasibility factors are combined with a consistent identification of value and risk factors to include systems conditions, social context, and human values, actual project opportunities in the context of regional landscape conditions can be identified very effectively. In addition to the 19 regional-scale resource assessments, others may be added at the local level to better address questions such as "why here?" and "why now?" The effectiveness of any assessment depends equally on the scientific methodology and the participation of key actors. The overall approach presented here offers the opportunity to integrate other assessments related to major national initiatives at regional and finer scales.

Secondly, even if technological efforts become established, SEOs should be within the context of transdisciplinary integration of natural, social, and engineering sciences. However, forcing such cooperation among scientists simply does not work. Not all members of existing observatories need be involved in the integration effort, but those genuinely interested in the process should be supported and encouraged by the individual networks. SEO frameworks rely on the cooperation and goodwill of a growing community of social and natural scientists that have united to take a more holistic and transdisciplinary approach to science, with special attention to social–ecological systems (Schoon and Van der Leeuw 2015).

The third area of emphasis is the process of advancing from science to knowledge to action (Kerkhof and Lebel 2006), and this process is the backbone of the science, policy, and planning interface. The value of knowledge brokering to support the development and implementation of policy must be recognized, so that articulated steps can be taken in SEOs toward such need-oriented goals (Hering 2015). SEOs must address the fact that decisions made are often inconsistent with biophysical, social, and technological realities, and such oversight can lead to disastrous consequences (Knight *et al.* 2008). SEOs can efficiently link research-based knowledge and action if they are designed as arenas of shared responsibility (Kerkhof and Lebel 2006), embedded within larger systems of power and knowledge that evolve over time. Future SEOs can provide the sustainable framework needed to address global environmental change, while facilitating decision making regarding local and regional issues.

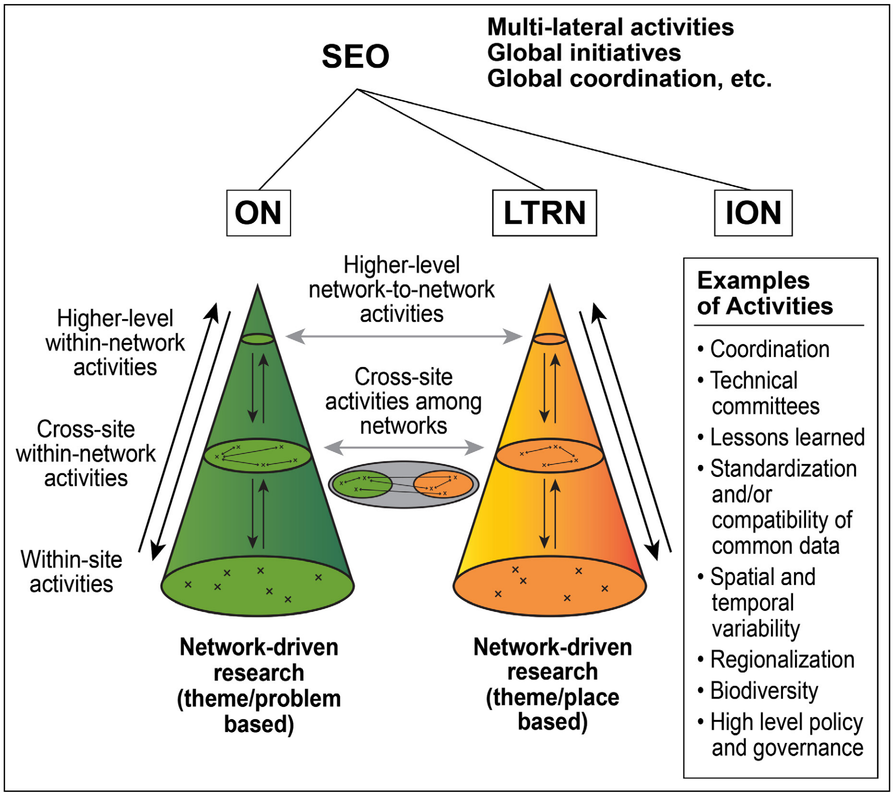


Figure 7. *Social–ecological observing systems as a network of networks.*

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