Building a Global Ecosystem Research Infrastructure to address global grand challenges for macrosystem ecology

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Abstract

The development of several large-, 'continental'-scale ecosystem research infrastructures over recent decades has provided a unique opportunity in the history of ecological science. The Global Ecosystem Research Infrastructure (GERI) is an integrated network of analogous, but independent, site-based ecosystem research infrastructures (ERI) dedicated to better understand the function and change of indicator ecosystems across global biomes. Bringing together these ERIs, harmonizing their respective data and reducing uncertainties enables broader cross-continental ecological research. It will also enhances the research community capabilities to anticipate and address future global scale ecological challenges to the planet. Moreover, increasing the international capabilities of these ERIs goes beyond their original design intent, and is an unexpected added value of these large national investments. Here, we identify specific global grand challenge areas and research trends to advance the ecological frontiers across continents that can be addressed through the federation of these cross-continental-scale ERIs.

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Abstract. The development of several large-, 'continental'-scale ecosystem research infrastructures over recent decades has provided a unique opportunity in the history of ecological science. The Global Ecosystem Research Infrastructure (GERI) is an integrated network of analogous, but independent, site-based ecosystem research infrastructures (ERI) dedicated to better understand the function and change of indicator ecosystems across global biomes. Bringing together these ERIs, harmonizing their respective data and reducing uncertainties enables broader cross-continental ecological research. It will also enhances the research community capabilities to anticipate and address future global scale ecological challenges to the planet. Moreover, increasing the international capabilities of these ERIs goes beyond their original design intent, and is an unexpected added value of these large national investments. Here, we identify specific global grand challenge areas and research trends to advance the ecological frontiers across continents that can be addressed through the federation of these cross-continental-scale ERIs.

Introduction. Governments, decision-makers, researchers and the public have all recognized that our global economies, quality of life, and the environment are intrinsically intertwined (USGEO 2019, USGCRP 2018). The ecosystem services that our environment provides include food, air and water quality, biogeochemical cycling, biodiversity, soil fertility, and energy, all of which are under threat from the growing needs of a global society (IPBES 2019; Díaz et al. 2018). These threats are the unintended result of increasing energy demand, water and food demand, land use change, species loss, invasive species and other anthropogenic activities (Ehrlich 1997, IPCC 2021) and have the potential to change the fundamental trajectory of society (Newman 2019, Waters *et al.* 2016, Turner 2010). This creates unique challenges never faced before by society or science—how best to provide a sustainable economic future while understanding and managing the changing environment and human health upon which it relies.

Globalization creates an increasingly interconnected world with greater potential to change the flow and distribution of energy, materials and species across the planet—humans are increasingly changing the biophysical, biogeochemical and biotic environment at the global scale. To understand and manage an intertwined world that is subject to rapid large-scale changes, globally distributed data that are long-term and interoperable are needed. Such data are necessary for forecasting and understanding the context of future ecological conditions (Dietze *et al.* 2014) and the societal challenges they may pose (Loescher *et al.*

2017). Contemporary examples of such challenges are the genesis and transmission vectors for new zoonotic diseases (HIV, Ebola, and SARS-CoV-2 viruses) and the transport of other insect and animal vector diseases (Hanta and West Nile viruses). Hence, we are entering an era of large-scale, interdisciplinary science fueled by global data sets that will be analyzed by current and future generations of scientists. Increasing streams of information from remote sensing platforms, process-based models, and research infrastructures have proven scientifically important (De Rosnay 2014). Such importance has increased awareness of these data by ecologists, hydrologists, meteorologists, modelers and other scientific disciplines, but not yet established the case to advance the ecological frontiers that span both larger spatial areas (continents), and longer time periods (decades), and across multiple disciplines.

To collect such big data and to further advance our collective understanding of ecological processes at the levels of local to continental scales, several Ecosystem Research Infrastructures (ERIs) have emerged over the past decade; these provide an historically unique opportunity. The coevolution of both continental-scale ERIs (approach) and ecological sciences (theory) has birthed a new science discipline: macrosystem ecology (Heffernan *et al.* 2014). Each ERI has its own historical foundation and has developed its own scientific strategies and conceptual approaches towards large-scale ecological observing (Loescher *et al.* 2017). This is the product of extensive bottom-up community input and top-down programmatic input that uniquely addresses their respective socio-scientific challenges, *e.g.*, Villarreal *et al*. 2018, 2019, ESFRI 2018, EC 2006, NRC 2001, 2003, 2004, AIBS and IBRCS 2003, 2004a-f). As a result, a comparison of the continental-scale ERIs reveals some substantial differences, especially in design, which make it difficult to link research objectives and data closely. The global context of changes in our environment and the growing demands on the provision and use of data across continental boundaries, however, require further development of ERIs, which in turn necessitates closer strategic coordination and stronger interoperability of data.

For the first time in history, scientists have at their disposal a collective ERI capability across most of Earth's continents to tackle new, societally, and scientifically relevant questions. Now it is time for these ERIs to federate their capabilities to tackle the programmatic work and meet the grand challenges at the global macro scale (Table 1). Here we describe this foundational science rationale for a global ERI infrastructure: the Global Ecosystem Research Infrastructure (GERI). Even though the GERI is currently terrestrial-based, broader inclusion is encouraged to bring together other ERIs and networks in support of this endeavor, and more broadly integrate atmospheric, terrestrial, coastal and ocean observations within their social-ecological context.

The Global Ecosystem Research Infrastructure (GERI). This GERI is an integrated network of six analogous, but independent, site-based research infrastructures (Table 1) dedicated to better understand the function and change of indicator ecosystems across global biomes. GERI supports excellent science that informs political and managerial decision-making addressing grand societal challenges. We envision that this GERI will deliver harmonized data, international partnerships and enable new understandings of global ecological processes—stretching across continents, decades, and ecological disciplines—in ways that were not previously possible.

At the first G7 Science Ministers' meeting in 2008, the Group of Senior Officials on global research infrastructures (GSO) was established (GSO 2017). GSO´s mandate includes identifying research infrastructures of global interest (GRIs), and new areas of possible cooperation. At the GSO 14th meeting in Shanghai (December 2019), GERI was endorsed as an official GSO case study (see 17 framework criteria in GSO 2017). This decision underpins the strong commitment to GERI of its six founding countries and organizations. As recommended, GERI follows the GSO Best practice Framework of GRIs, ensuring all GERI stakeholders benefit from the successful implementation of the globally accepted standards defined in the Framework.

All of the member GERI observatories are equally important in the ecosystem monitoring of our planet, and its governance has been designed to reflect this notion. GERI's system of governance utilizes sociocracy principles (*i.e*., dynamic governance) (Buck *et al*., 2017), which is built upon the trust and 'group understanding' established over several years' of catalytic workshops, and which does not infringe upon the fiduciary relationship with their respective sponsors and shareholders. This is a necessary requirement for international partnerships with different sponsors. Nor does any individual organization act as a lead. Instead, a Governance Board Chair rotates among the organizations and with established working groups help advance and harmonize our common science questions, protocols, parameters, and data systems are other ways in which GERI actively balances the needs among its members (*e.g.,* Huber *et al.* 2021).

The Concept of Global Ecological Grand Challenges. Several community efforts have identified global ecological grand challenges (NRC 2011) and questions (Munsche *et al.* 2019, Sutherland *et al.* 2013), along with grand challenges for specific sub-disciplines such as functional plant ecology (Korner 2011), sustainable development (Crow 2010), soil science (Lavelle 2000), and marine ecosystem ecology (Borja 2014). From these syntheses, we recognize two key attributes to address '*grand challenges'*.

First, ecological grand challenges are meant to be aspirational and identify salient gaps in our ecological understanding. They also articulate large scientific and societal needs identified from the culmination of planning efforts, and as such, each challenge is crafted at a specific point in time. But the complex issues that led to a grand challenge are relevant for an entire era, and therefore inform iterative efforts that have spanned decades, as in the case of advocating for, designing, and operating ERIs. We recognize, however, that an ERI should be periodically re-assessed and adapted to fit the changing rubric of the complex socio-ecological system in which it is embedded (Kulmala 2018, Schimel and Keller 2015).

Second, ecological grand challenges transcend geopolitical and continental barriers. The conceptualization of the Earth System as a complex and coupled natural-human system includes interconnected biotic and abiotic processes at the global scale (NASA 1986). This Earth System concept underscores our current limited ability to understand local ecological processes that are dependent on other processes or drivers unfolding elsewhere. While this notion also harkens back to Odum (1953), only now are we beginning to realize the capability to systematically observe these patterns across continents and decades, including the human causes and effects of ecological change (Angelstam *et al.* 2019, Chapin *et al.* 2009, Smith *et al.* 2009). Despite the global ubiquity of a grand challenge, its intensiveness and emphasis vary with geography and with the capacity of various countries or regions to address the challenges. For example, the impacts of sea-level rise are more immediate and visible for coastal communities and small island nations than for others. The contributing factors to sea-level rise, however, may impact those other communities through coupled atmospheric processes, as well as any services that the coastal communities may provide to these inland communities (*e.g.,* food, transportation). Hence, we need an integrated socio-ecological approach to understand the feedbacks among ecological, economic, cultural and social dimensions when tackling grand challenges.

Grand Challenge Questions for the ERIs. The science rationale to build GERI is to address global grand challenges that cannot be achieved by any single ERI. In all cases, the overarching scientific philosophy and mandate of each individual member ERI is the product of extensive community (bottom-up) and top-down input and also reflects the respective geopolitical characteristics. Comprehensive datasets from each ERI are focused on ecosystem science, population and community ecology, and biodiversity. All ERIs are charged with enabling their research and educational communities to broadly advance ecological understanding. Taken together, there are common inherent approaches that all ERIs embrace: (i) estimate and provide essential ecological observations; (ii) adopt the cause-and-effect paradigm; (iii) broaden our understanding in spatial and temporal variability in the ecological drivers and processes; (iv) provide a scaling strategy; and (v) estimate observational uncertainty. A first step towards integrating (federating) the ability of these ERIs to address global grand challenges is to align individual scientific mandates among continents and RIs (Table 2). In this way, the value-added benefits of global activities can easily be justified within their own program and funding constraints, *i.e*., no new mandates are required. The value-added activities gained by bringing together the capabilities from each ERI directly address the call for new approaches to new challenges (Suresh 2012, Uriate *et al*. 2007). That is, in addition to applying the scientific mandate of each ERI globally (Table 2), new grand challenges can be specifically addressed as part of their global federation. We describe several of these in the sections that follow.

Ecological Teleconnections. There are new emergent ecological properties becoming apparent, particularly at continental and cross-continental scales that require a broader global ecological understanding, *e.g*., Schmitz *et al.* 2018, Higgins and Vellinga 2004. Teleconnections, *i.e*., ecological 'information' or 'services' being related to each other over large distances, are evident beyond regional climate and ecological processes, often considered in conjunction with global trade and use natural resources, *e.g.,* land use, deforestation, water use, nutrient transport, nitrogen deposition, and especially greenhouse gas emissions by human producers. A common example is how El Niño oscillations influence climate patterns across large regions of the earth, and in turn, affect ecological processes. Furthermore, exogenous drivers outside our regional-to-continental boundaries may also affect the ecological processes therein. Such patterns have shown a synchrony in the spatial and temporal connectivity of one ecological event that contributes to other ecological processes. For example, extra-tropical land use change affects the genesis and magnitude of the South-Pacific climate dipole, which in turn, affects the masting of North America Boreal Pines and the bird species that feed off them (Strong *et al.* 2015). Similarly, ecological connections between global and regional phenomenon may not always be apparent. For example, to mitigate global increases in atmospheric CO_2 concentrations, reforestation is strongly encouraged in some regions though in others, afforestation is an advocated approach (Bond *et al.* 2019). We argue that in an increasingly connected global world, the horizons of ecology need to look across and between traditional scientific disciplines to examine causal processes, particularly considering changing synoptic climate, new migrations, and human mediated changes in mass and energy flows. Much ecological research has historically focused on the ecosystem and regional scale; only now, with enabling infrastructure and new macrosystem constructs are we able to more fully able to analyze and understand the complex ecological interactions across our planet.

Integration of humans and ecology in the Anthropocene. It is impossible to refute that humans are both part of and reliant on the natural world (Lewis and Maslin 2015, Pickett *et al.* 2011, Crutzen 2006). There is an increasing global importance and awareness of human behavior being a key driver of ecological change, which has led to recognition of the Anthropocene (Robin and Steffen, 2007). This recognition of human influence on the Earth has merged with core ecological concepts to better understand complex climate-eco-sociological systems. For example, the concepts of resilience (capacity of a system to experience perturbations while retaining essentially the same function and structure, Holling 1973), adaptability (capacity of the actors within a system to manage resilience, Berkes *et al.* 2003), and transformability (capacity to create fundamentally new system states when the existing system cannot maintain itself, Chapin *et al.* 2009) have advanced our thinking of how to integrate the social and ecological dimensions. Our current understanding, however, is often based on single use cases, specific disciplines, and/or constrained time/space domains, and is thus rarely applicable or scalable to other systems. Moreover, much of these activities is based on correlative statistics from populations and/or demographics, which do not provide a robust predictive capability (Bourgeron *et al.* 2018). Thus, here too, a broader theoretical and practical integration between the social and ecological dimensions is needed to reflect the human dimension of ecosystems and the socio-ecological feedbacks that will ultimately affect societal wellbeing and development (Fisher *et al*. 2015). For example, how resilient, adaptable, and transformable are small coastal communities that are tied to tourist and local fisheries, to saltwater intrusion that affects local ecosystem and estuarine processes? Integrating the social dimension with ecological studies and developing testable socio-ecological theory is a challenging and active area of research (Muelbert *et al.* 2019, Lang *et al*. 2012, Bettencourt and Kaur 2011, Kates *et al*. 2001,) that will be proactively enabled by the GERI.

Near-term Ecological Forecasting. Currently 'ecological forecasting' is done at 25 to >100 years' time scales and provides the context for long term predictions of climate change for reports concerning ecological impacts and intergovernmental multi-decadal planning, *e.g*., IPCC 2021. This approach, while useful, is also difficult to interpret for near-term time scales (*e.g.,* days to the next 1-2 years) and arguably fosters a culture that does not embrace responsibilities for impacts that will not be apparent for much longer timespans. Moreover, >25-year forecasts do not provide a useful decision-space for natural resource managers who have to make more immediate informed decisions. Therefore, a basic scientific question arises: how will climate and ecosystem processes interact in the next season, next year, and in the next 2 years? If we embrace such a question, we may also need to ask: if there are revolutionary advances in near-term climatic predictability, particularly at regional scales, what knowledge, infrastructure (both observational and computational), and local-to-global collaboration is needed to forecast the ecological consequences and optimize human decisions?

A goal for near-term ecological forecasting should be that it is used to provide '*actionable'* data (information that can be acted upon) for decision-making and education for the public, government, business, and science. For example, phenological forecasting for 1-10 years is strongly needed for natural resource managers to optimize their practices, *e.g.*, in relation to the changing in timing of leaf out, leaf senescence, water usage by ecosystems, or onset of summer drought, in response to the changing climate. We do not advocate that near-term forecasting is a panacea that will provide known futures. Rather, '*actionable'* encompasses the cultural paradigm required of researchers to ensure terms (*e.g.*, means, trends, decision-space) and associated uncertainties of forecasts are communicated in such a way that is understood and usable by managers. Only then will managers develop the means to translate '*actionable*' science into well-informed risk mitigation strategies, and decisional trade-space.

Although there have been strong efforts to work towards ecological forecasting (Loescher *et al.* 2017, Dietze *et al.* 2014), it is evident that there is still a missing consensus for an approach to near-term ecological prognosis. Moreover, signal-to-noise ratios of many ecological processes are typically large in both time and space, taking ≥10-y to determine a trend (Sierra *et al*. 2009). Such trends may wrongly assume that signal-to-noise ratios do not decrease further with future anthropogenic change (Keenan *et al.* 2011, Odum 1953). This untested assumption is a challenge to predict ecological processes at smaller time and space scales. For example, how can we downscale large spatial scale (global) processes to the near-term (<10-y) and to local and regional scales? Much of current ecological forecasting efforts rely on generalized linear models (*e.g.,* generalized additive model, Paniw *et al*. 2019) and combinations of data assimilation approaches (*e.g.,* Kalman filters, Luo *et al.* 2011) that need further development to achieve a clear understanding of the changes that underlie ecological processes to have accurate prognostic capabilities. As a related challenge, machine learning approaches and process-based models used for forecasting have difficulty estimating the effects of extreme events/values. This is often due to their inability to represent values that are outside the variance structure (*i.e*., data space) to which they have been parameterized or trained. Therefore, if extreme events/values become a new normal (*i.e*., shift in parameter space), then current models cannot predict these future values or even expected simple, near-term (*i.e*., within the next 1-2 years) extreme events. In other words, we currently lack both the theoretic process understanding, the statistical data volumes, and process-based representation in models to currently achieve accurate near-term ecological forecasting, clearly making this a grand challenge for ERIs.

Cross-ERI Interoperability of Observations. Each ERI is designed to address specific questions, and the experimental design, observational methods, and data infrastructure are mostly unique to these (Figure 2). Until recently, ERIs were built without the challenging requirement for their observations to be interoperable (or even intercomparable). Thus, the ERIs today comprise a patchwork of research infrastructure and data collection that fares poorly when judged against the rubric of effectively leveraging and harmonizing investments to advance science and to serve society across disciplines or across scales.

Many global research planning efforts call for multiple integrated approaches to better understand our environment (*e.g*., DIICCSRTE 2013, EC 2012, Schimel *et al.* 2011), and they call for accessible long-term interoperable data sets to forecast global environmental change (Kulmala 2018, Suresh 2012, Heinz 2006). According to one such planning effort, current [US] environmental monitoring programs, are "distributed [across agencies] to an extent that reduces their potential effectiveness" (PCAST 2011). We maintain that this likely holds true globally as well. As per above, this is likely because data from existing earth observation programs were specific for a diversity of questions and purposes. This challenge is critical and has yet to be solved (Holdren *et al.* 2014).

Many directives call for interoperable data (rf. USGEO 2019, Kulmala 2018) but fail to define what is meant by 'interoperable' or define a unifying structure that can tackle these larger issues associated with generating new environmental knowledge. Incorporating information science or computer science to make ERIs interoperable is challenging (*e.g*., FAIR Principles, Garcia-Silva *et al.* 2017, Wilkinson *et al.* 2016), but making ontologies or metrology for true science interoperability is also challenging (note: that we also recognize technical, cultural, organizational barriers towards building 'full' interoperability, Vargas *et al*. 2012). Some data scientists address 'scientific utility' through activities such as shared and reproducible notebooks (*e.g*., Jupyter), and/or through other structures such as machine-readable metadata (*e.g.,* the International Standards Organization standard 19115). These practical cyberinfrastructures implement interoperability, but also have to be effective at global scales, across federated ERIs, and with great respect for the underlying ontological and metrological challenges (Ruddell *et al*. 2014, Horsburgh *et al.* 2011). Ideally, scientific interoperability should be designed-in *a priori*, but pragmatism requires it to be instead built organically and flexibly upon existing ERIs, structures, and technologies that span both boundaries and eras.

Currently, there are serious efforts at community-based forums that bring together top-down and bottom-up approaches at the forefront of data science and management, *e.g.,* the National Science Foundation's DataOne, EarthCube, European Open Science Cloud, and the Federation of Earth Science Information Partners, the Research Data Alliance, the Open Geospatial Consortium. It is in these forums that another unifying strategic [process] framework has emerged to describe what information is needed by the research community to make the data more scientifically useful, and to foster scientific interoperability of environmental data for research, management, and policy purposes. As a grand challenge, the international collaborative engagement in GERI is an ideal forum to bring together 'big data', AI and machine learning, scientific and societal imperatives, leadership, and a platform to implement (and learn from) *scientific* interoperability in partnership with these community-based forums.

Conclusion. We know that natural, managed, and socioeconomic systems are subject to complex interacting environmental stressors (*e.g.,* some rapid and visible taking days to years, like extreme precipitation, droughts, heat waves, and wildfires, while others are subtle and develop over decades or longer, like changes in concentrations of atmospheric constituents that alter climate and ocean acidification). The resultant feedback of these stressors on ecosystem processes play out over extended periods of time and space (NRC 2007) which erode the world's environmental capital (PCAST 2011, Rockström *et al.* 2009) and disrupt many ecosystem services, such as fisheries and agricultural production. We argue that the success for building global ecological understanding will be measured by the ability of scientists to address global environmental challenges by linking observations from a range of sources and spheres of influence, *e.g.,* observatories, networks, integrated experiments, and investigator-driven, hypothesis-based research, rf. Peters *et al.* 2008, 2014. Such optimization of the data will accelerate and deepen our scientific insights into complex socio-ecological and Earth systems, and better inform a societal understanding of natural and anthropogenic change in a time of need for adaptation and mitigation.

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Author contributions

HWL and RV contributed the 'original concept and wrote the main manuscript text'; MM, RV, CW and PP contributed towards the 'original concept'; PM, BR, and RV provided final review and editing; MG produced Figure 1; All authors intellectually contributed towards 'the main manuscript text' and have reviewed and approved the manuscript.

Competing interests

All the authors declare there is no conflict of interest.

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Table 1. Current Participating Environmental Research Infrastructure (ERIs) in this Global Ecological Research Infrastructure (GERI) Project. All GERI data is registered in the Dynamic Ecological Information Management System – a Site and dataset registry (DEIMS, https://deims.org/).

Environmental Research Infrastructures	webpage	Host country/continent
National Ecological Observatory Network (NEON)	neonscience.org	USA / North America
European Long Term Ecosystem, critical zone and socio-ecological systems Research Network (eLTER)	lter-europe.net	Germany / Europe
Integrated Carbon Observing System (ICOS)	icos-ri.eu	Finland / Europe
Terrestrial Ecosystem Research Network (TERN)	tern.org.au	Australia / Australia
Chinese Ecosystem Research Network (CERN)	cern.ac.cn	China / Asia
South Africa Ecological Observatory Network (SAEON)	saeon.ac.za	South Africa / Africa

Table 2. The current governing science principles or grand challenge questions from each of the Participating GERI observatories.

Terrestrial Ecosystem Research Network (TERN)
How are our ecosystems responding to environmental pressures, and how might positive trends be enhanced, and negative consequences managed?
How is our environment likely to alter in the future, for example in relation to a changing climate?
How are significant environmental assets –soils, carbon stocks, water, vegetation and biodiversity – responding to such changes and to their management? and
How resilient are the ecosystem services upon which our society and many of our industries depend, such as soil health, nutrient cycling, fire mitigation, provision of clean water, crop pollination and carbon sequestration?
Chinese Ecosystem Research Network (CERN)
How to evaluate on the responses and adaption of the structure and functions of the main ecosystems to global change?

How to diagnose and assess the quality of different ecosystems under the influences of climatic change and human disturbance?

How to built the theory and provide practical approaches to restore the degraded ecosystems?, and

How to provide the scientific & technical support for both the management of eco-environment and the high-efficient agricultural development to secure both ecological safety and food safety?

National Ecological Observatory Network (NEON)

How will ecosystems [among continents] and their components respond to changes in natural- and human-induced forcings such as climate, land use, and invasive species across a range of spatial and temporal scales? And, what is the pace and pattern of the responses? and

How do the internal responses and feedbacks of biogeochemistry, biodiversity, hydroecology and biotic structure and function interact with changes in climate, land use, and invasive species? And, how do these feedbacks vary with ecological context and spatial and temporal scales?

South Africa Ecological Observatory Network (SAEON)

To develop and sustain a dynamic South African observation and research network that provides the understanding needed to address environmental issues, to encompass;

- ecosystem functioning that benefit society; including biodiversity, hydrology, biogeochemical cycling and production, soils and sediments and disturbance regimes, and
- to distinguish natural variability of ecosystem functioning (including extreme events) from responses to anthropogenic impact that result from global change, such as; global change drivers that encompass; CO_2 loading, climate change, changing marine geophysical patterns, sea-level rise, ocean acidification, land and sea use and management, harvesting, nutrient loading, acid deposition, hydrological functioning, sedimentation, alien organisms, diseases, pests, and pollution.

European Long Term Ecosystem, critical zone and socio-ecological systems Research Network (eLTER)

To track and understand the effects of global, regional and local changes on socio-ecological systems and their feedbacks to the environment and society,

To identify drivers of ecosystem change across European environmental and economic gradients, To explore the relationships among these drivers, responses and developmental challenges under the framework of a common research agenda,

To provide recommendations and support for solving current and future environmental problems and targeted at supporting knowledge-based decision-making concerning ecosystem services and biodiversity.

Integrated Carbon Observing System (ICOS)

To provide long-term, continuous observations of concentrations and fluxes of the greenhouse gases (GHGs) that include carbon dioxide, methane, nitrous oxide, and water vapor.

To facilitate research on biogenic and anthropogenic greenhouse gas fluxes, climate-carbon feedbacks, and adaptation to climate change impact.

To provide data that can permit evaluating GHGs emissions and their regional dynamics, and thus the efficiency of the mitigation activities against climate change.

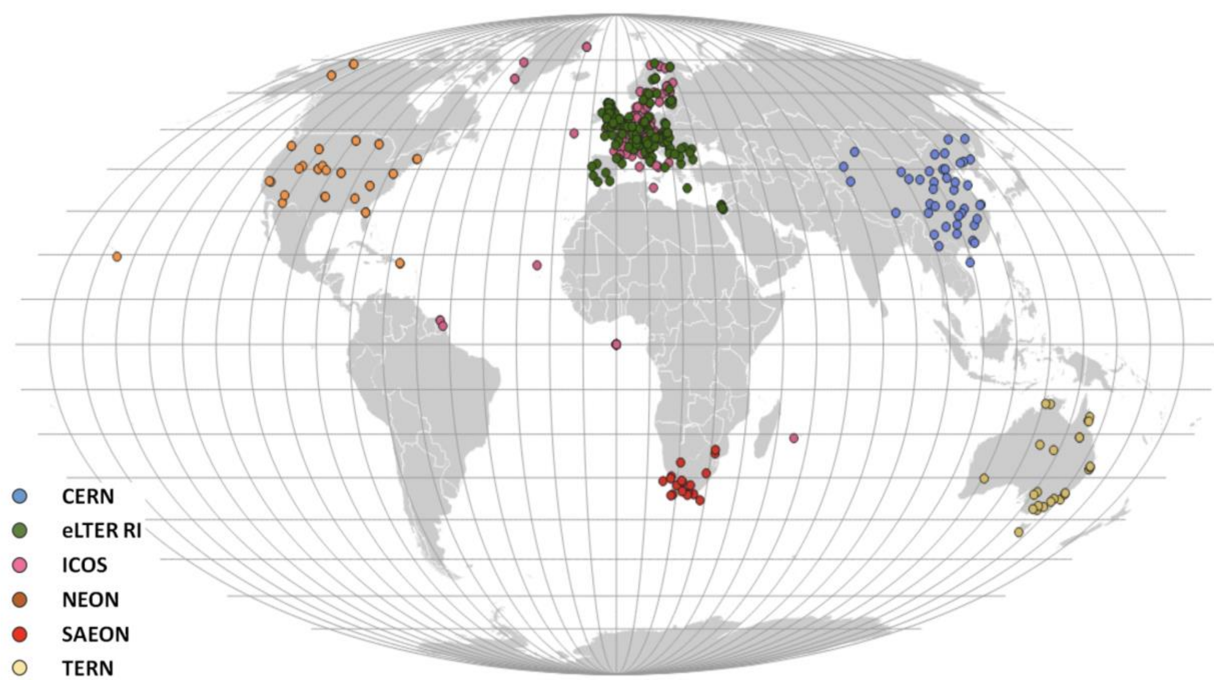

Figure 1. Global distribution of GERI sites

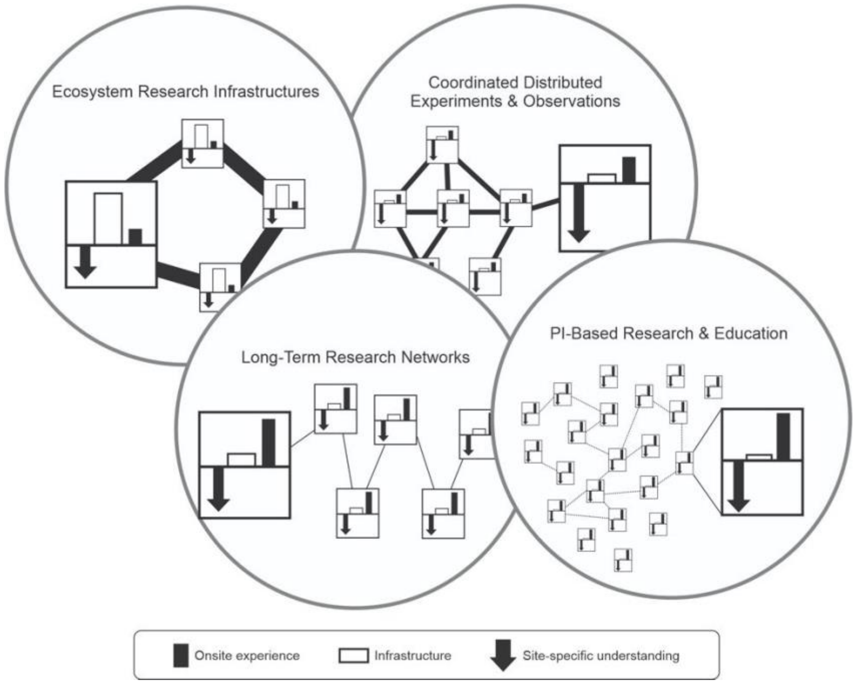

Figure 2. Research data are generated from different sources and types of organizations. Each type of organization is motivated by different research questions, has different level of strength onsite experience, site-specific understanding, and infrastructure (*e.g.,* consistency and long-term operations). Large-scale ERIs can take advantage of collaborative relationships and strong interoperability frameworks (depicted by the large interconnecting bars). GERI connects these ERIs and can be leveraged to address global-scale grand challenges.