challenges

Perspective

The Lack of Alignment among Environmental Research Infrastructures May Impede Scientific Opportunities

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Received: 5 June 2017; Accepted: 13 July 2017; Published: 18 July 2017

Abstract: Faced with growing stakeholder attention to climate change-related societal impacts, Environmental Research Infrastructures (ERIs) find it difficult to engage beyond their initial user base, which calls for an overarching governance scheme and transnational synergies. Forced by the enormity of tackling climate change, ERIs are indeed broaching collaborative venues, based on the assumption that no given institution can carry out this agenda alone. While strategic, this requires that ERIs address the complexities and barriers towards aligning multiple organizations, national resources and programmatic cultures, including science.

Keywords: Environmental Research Infrastructures; climate change; fragmentation; ESFRI; governance; societal challenges

1. Introduction

There is a societal and scientific imperative in understanding how anthropogenic change affects ecosystems, the economies they sustain and the services they provide. However, an excessive economic exploitation of ecosystem services now threatens food security, natural and managed ecosystems and biodiversity across Europe and around the world [1]. Environmental Research Infrastructures (ERIs, Table 1) focus on quantifying the change in natural and managed ecosystem processes (e.g., biodiversity, plant ecophysiology and agronomic techniques, nutrient cycles and soil physics, atmospheric chemistry, water resources) and the drivers of these processes (invasive species, land use, climate and chemical climate changes) [2,3]. While ERIs fulfill a global demand for scientific data products, their vision can only be realized through the political will of funding agencies and ministries. In doing so, they are essential in addressing the corresponding societal challenges, ERIs remain a largely untapped scientific resource worldwide [4,5], in part because the management of the data, data products and services they provide lacks the coordination among stakeholder groups, i.e., specific data and products for specific stakeholders.

On one hand, this creates inefficiencies in data collection, funding and management. And on the other hand, this becomes a strategic opportunity to harmonize ERI services and facilities, and to optimize their respective resources to deliver their data, data products, and value-added services to the broadest possible group of end-users. In this paper, we describe (i) the development pathways and science culture that has led to current fragmentation of the European research landscape and the underlying difficulty to integrate ERIs, and (ii) conclude with recommendations to foster greater benefit from these novel ERIs.

Table 1. Examples of Environmental Research Infrastructures (ERIs) that are designed to address societal challenges across large temporal and spatial scales, e.g., [6]. This demonstrates the global distribution and scientific diversity of ERIs.

Name	Description	Location
Aerosols, Clouds and Trace gases Research InfraStructure network (ACTRIS); www.actris.net/	Aerosols, Clouds and Trace gases	Europe
Advanced Modular Incoherent Scatter Radar (AMISR); isr.sri.com/iono/amisr/	Space weather	North America Polar
Analysis and Experimentation on Ecosystems (AnaEE); www.anaee.com/	Ecosystem manipulations	Europe
Chinese Environmental Research Network (CERN); www.cern.ac.cn/0index/index.asp	Terrestrial Systems	China
Earthscope; www.earthscope.org/about/observatories	Seismology and geodesy	US
European Incoherent Scatter Scientific Association (EISCAT); www.eiscat.se/about/	Space weather	European Polar
European Multidisciplinary Seafloor Observatory (EMSO); www.emso-eu.org/	Oceans	Europe
European Ocean Observatory Network (EuroSites); eurosites.info/	Oceans	Europe
European Plate Observing System (EPOS); www.epos-ip.org/	Seismology and geodesy	Europe
Global Earth Observation Systems of Systems (GEOSS); www.earthobservations.org/	Environmental	Global
Integrated Carbon Observation System (ICOS); www.icos-infrastructure.eu/	Terrestrial and oceanic systems. Greenhouse gases	Europe
Lifewatch; www.lifewatch.eu/	Biodiversity	Europe
National Ecological Observatory Network (NEON); www.neonscience.org/	Terrestrial and freshwater ecosystems	United States
OOI (Ocean Observatories Initiative); www.oceanobservations.org/	Oceans	Western hemi-sphere
South African Ecological Observatory Network (SAEON); www.saeon.ac.za/	Terrestrial systems	South Africa
Terrestrial Ecosystem Research Network (TERN); www.tern.org.au/	Terrestrial systems	Australia

2. Exploring the Roots of Europe's Fragmented Research Landscape

When the European Strategy Forum on Research Infrastructures (ESFRI) was established in 2002, 32 countries adopted its goals [7], thereby committing to pan-European ERIs. Since then, only 22 countries formalized participation; nine of which have not updated their commitments in recent years [8], (Figure 1). The combination of political pragmatism, tensions and uneven national funding instruments has hindered the development of European ERIs, adding to their inherent difficulty in securing funding commitments from national partners, even though ERIs are prioritized in national roadmaps (e.g., Nederland for the EU's LifeWatch, United Kingdom for the EU's Integrated Carbon Observing System, and several in the US, NSF [9,10]. These national roadmaps link their in-country priorities to pan-European ERI endeavors and in doing so, highlight their respective needs and expectations in terms of research, the economy or science-based decision-making support. While European countries fund ERI development, they appear to lack the political will to earmark specific resources to further plan, build and operate ERIs. Even though, the very basis of an ERI nevertheless provides both a planning horizon for governmental officials and encourages stakeholders worldwide to provide active support to its development and operational lifecycle.

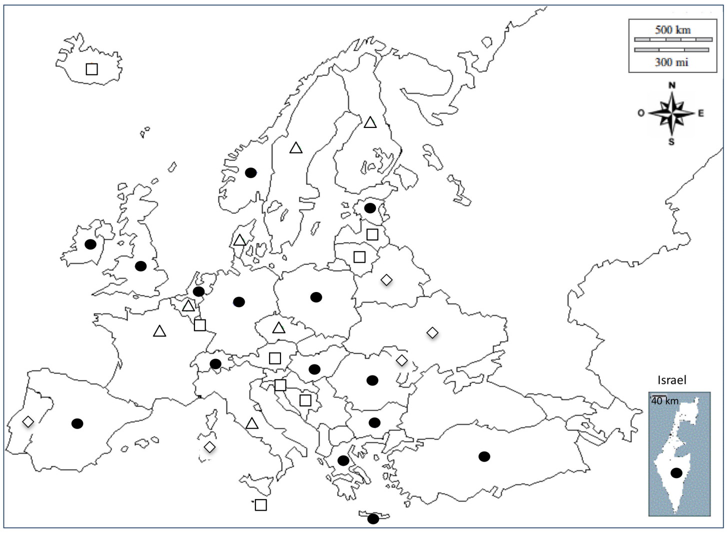

Figure 1. We highlight the, (i) commitments to formalized ERIs in National roadmaps (open triangle), (ii) presence of a National roadmap indicating commitment to one of more ERI (filled circle), (iii) absence of a National roadmap and/or piecemeal involvement in ERI (open square), and (iv) none of the above (open rhombus). This is a result of all 22 national roadmaps (www.esfri.eu/national-roadmaps).

The design, planning, construction and operational phases of ERI follow formal development pathways [5], which are nevertheless new to the environmental field. Stakeholders (scientists, funders, policy-makers, etc.) therefore often lack the social context and culture to advance these projects [11]. Contrary to publicly-funded Preparatory Phases (which consist in bringing the project to the required level of legal and financial maturity), the effective implementation of a European ERI depends on voluntary participation and national membership fees [12]. This generates a misalignment between the funding amounts required for the ERI and the in-country funding cycles, which renders the development of an ERI all the more complex and further contributes to the fragmentation of the research landscape [13]. The example is not only germane to the EU. It is also a common problem in Australia's TERN (Table 1), for example.

3. Solutions for ERI Governance and Management

Each ERI follows a unique development pathway. Much in the same way that corporate startups are thought to be "agents of change" in the market for research and development. ERIs aim to re-invent the current inefficient means of managing research [9,10,14]. Given that ERIs are funded through public grants rather than competing in the global economy, researchers tend to focus on delivering data and knowledge, rather than demonstrating the added economic value of their approach. It remains that ERIs are at the frontier of the research community, and as such, this necessitate the need to have active scientific input in its management and governance [5]. Only through bringing together scientific output and management will the profile of ERIs be raised in terms of visibility and intelligibility to stakeholders other than the scientific community. For now, few ERIs emphasize scientific input and stakeholder needs into project management [5,7,14–18]. In defense of project management, the constraints in schedule, lack of scope definition, and miss-aligned funding cycles often necessitates the lack of stakeholder involvement for short-term gains, rather than long-term, more sustainable operations. However, ERIs can draw inspiration from entrepreneurs in the open market for innovation, where ERIs can strengthen their managerial approach and broker a keen appreciation of the issues at stake, thereby creating new value-added opportunities for science and societal benefit. Scientists are seldom trained in management at this scale and complexity, though ERIs would benefit if such formal training were made available. Because there is no one-size-fits-all governance model for European ERIs, their current piecemeal management approach all too often favors 'self-serving, short-sighted strategies with harmful consequences' [14]. The ESFRI [15] itself recognizes ERI consistently lack coherent management structures.

The key to an ERI's success thus lies in robust scientific input as well as stakeholder engagement and 'ownership' [4]. The project manager's role is to pragmatically balance the pressures of schedule, budget, human resources, risk management, and client relations to execute the construction and operation of an ERI [10,15]. Instrumental to ERI success is an organizational structure designed to maintain a certain degree of creative tension among researchers, user communities, and engineering and management interests [5]. Ultimately, those that are legally responsible for the sponsor (funding agency or ministry) must be entrusted with legal responsibility of ERI and must also have the diplomatic skills to generate enough trust to broker often difficult and contentious design decisions (which in turn have implications on science scope, budget, schedule, etc.). In order to avoid disenfranchising stakeholder communities, however, any management decisions that have science impact should be brokered with its science leadership, following a clear rationale that is transparently communicated to the stakeholder communities. This is a particularly salient issue given that the scientific culture is very open-ended, e.g., scientists 'eyes are always bigger than their (our) bellies' as opposed to project management, which focuses on constraining a problem with just enough efficiency to 'move the ship forward'. If designed correctly, governance and management structures can balance top-down directives (i.e., project management, science) with bottom-up efforts (i.e., user and stakeholder engagement) with the aid of system engineering [5]. This approach is often difficult to implement from inception, where all ERIs have to integrate additional governance and management functions and/or structures as they develop, in order to address new complexities or pressures along the way. External evaluations of ERIs (required by sponsors), should explicitly review science scope, management and governance competencies, strategic planning and stakeholder involvement on a regular basis [6,7,14,19].

One—if not the most important feature of an ERI- is the deep scientific vision and creativity that is brought to bear [5]. This should never be staunched. Science, at its core, sets out to explore and discover new frontiers, which challenges the need to programmatically deliver and operate a scope-constrained ERI. ERIs thus need to incorporate structures to guarantee an interface with new ideas, scope and ultimately tackle new scientific frontiers. Funding to incorporate these new ideas and scope are, however, typically allotted on a case-by-case basis. Another challenge lies in best constraining the scientific scope in order to meet the budget, schedule and risks. In this regard, system engineering tools are helpful. While system engineering tools are used in physics, oceanography, astronomy, geodesy and seismology infrastructures, they remain novel for the environmental and ecological sciences. The US National Science Foundation (NSF) requires formal system engineering from all their infrastructures [20], while the EU developed the ESFRI reference model [7,21], which can lead to more detailed system engineering approaches. System engineering tools include system architecture, work breakdown structures, requirements (scope) capture, roles and responsibility definition, interfaces, resource-loaded schedule, critical path analyses, ongoing reporting matrices, controlled library and decision-making processes [22]. Because of the numerous management pressures on an ERI, their development pathway is always non-linear. System engineering tools provide a means to 'linearize' the problems that face project management, and they also provide a robust approach that has yet to be fully realized by the stakeholder communities, i.e., how to precisely harmonize data, networks, and understanding that has been available to other research disciplines. Because each ERI is different, we would not necessarily advocate using all these system-engineering tools to their highest potential. Each ERI should rather be encouraged to determine which tools make sense in managing science scope and how that translates into project management. For instance, the NSF model for environmental sciences still needs refinement, as system-engineering efforts within the National Ecological Network Observatory was not a balanced effort. Likewise, the ESFRI Reference Model requires a great deal more fidelity.

New governance and managerial challenges arise after construction when justifying ongoing operations (e.g., in EU parlance: a "business model"). Having a functional governance and management structure assists in tackling new challenges as they emerge. In a time of declining research budgets [23], the typically large operational expenditure of ERI encourages them to further justify their mission statements [24]. Additional ERI rationale should include regional (or country-wide) added economic and policy value relevant decision-making [3]—even if it goes beyond the ERI's original intent to deliver basic science [12]. In other words, basic science is good, but how can an ERI benefit society in innovative ways? During operations, additional challenges manifest and require ERIs to (i) accelerate new and transnational collaborations [7], (ii) diversify their resource portfolio, (iii) develop new services outside their original scope [12] and (iv) avoid duplicating efforts and optimize their approach across ERIs and other networks [13,25–27]. Robust governance and management structures must also have the capacity to address these challenges by establishing the structures and functions within their organization as well as empowering stakeholder involvement. In doing so, ERIs further develop their capacity to meet external societal and economic needs (Figure 2).

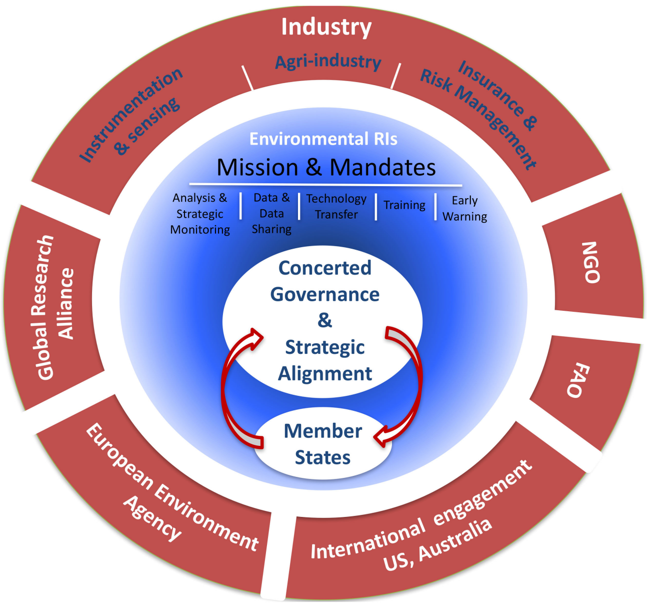

Figure 2. A conceptual diagram that outlines the need to internally align the governance and the directives of sponsors (in this case, the member states) to further optimize and add value to other external needs and economies, e.g., industry, non-governmental organizations, the United Nations Food and Agriculture Organization, and the like. This example highlights the external agronomic needs and economies.

4. Advancing the Capabilities of Future ERIs

Each ERI is unique in terms of its scope and its development 'environment' upon its inception. Yet, all have common development pathways and barriers to overcome. Because each ERI is novel and unique (and perceives itself as such), they all either lack the programmatic foresight to recognize some of these common pathways and barriers, or their most immediate programmatic needs take precedence. Learning from each other would be a first step in minimizing the impacts from these barriers and establishing better tools to integrate the scope, data, operations and services among existing ERIs. These real and common barriers in ERI development are:

a. All ERIs are first challenged by integrating science into a constrained project scope. Merging science and project management is as much a clash of cultures as it is a pragmatic necessity. Merging these cultures is less of an issue for the sciences where their research can only be accomplished by the infrastructure itself, e.g., high-energy physics, astronomy.

b. Establishing formal project management is foreign to ERIs, the lack of which can be a source of failure. The need to manage cohesively the scope, budget, schedule and risks is particularly important, in light of distributed infrastructures supported by equally distributed funding sources.
c. External optimization of design and deliverables, which can or cannot occur in the context of 'nearest neighbors'. Successful ERI rely on being used and a sense of ownership from their stakeholder communities, thus enabling innovation [11]. ERIs capable of optimizing their design and deliverables in partnership with universities, networks, infrastructures and the like, effectively demonstrate fiscal and social responsibly, all the while increasing stakeholder involvement. The key challenge is to implement this approach within the ERI's original scope.
d. The ERIs need to justify their *raison d'être* in terms of providing services and decision-making tools at a local and regional level increases as they become more operational. Additional services may not have been included within an ERI's original design, but as ERIs approach an operational stage, they all find themselves navigating a changing funding landscape that requires them to be creative and innovative to further advance their operations and economic relevancy. For example, a focused ERI on biodiversity or ecosystem functions may likely embrace the societal needs to inform food security, water management, public health or other economic relevance to further justify their operations, and
e. Internal diversification and optimization of resources. Resource diversification and optimization strategies require ERI to challenge existing funding paradigms and develop diversified and sustainable funding models. In Europe, for instance, ERIs secure core funding from Member States (MS), Associated Countries (AC) and the relevant ministries—which all operate according to different funding mandates and cycles. Such mandates and requirements for economic relevancy will change during operations, as anticipated in the corresponding business models. Securing sufficient investment from MS and AC to support ERI management activities is essential, and misalignment of funding cycles may cause delays in their development.

Upon inception, the short-term necessity to pull together all the design elements and set an ERI on a development pathway (within the associated funding horizons) is a daunting task. Each ERI is faced with its own suite of pre-conditions, but all have to contend with different scientific and project management cultures. Bringing these cultures together is instrumental to its success.

Many governments have mandates and policies that ERI data can contribute towards. For example, in the EU, the Sustainable Development Goals (SDGs) are not legally binding, but member states are expected to take the lead and set up national frameworks including ESFRI RIs to achieve the respective 17 SDGs. Countries have primary responsibility for monitoring and reviewing progress in this area, which will require the timely collection of quality and easily accessible data that can be done only through a coordinated and integrated ERIs. Data from ERIs are designed to directly contribute to regional monitoring of ecosystem sustainability in order to meet the SDGs. With respect to European environmental policies, climate change is already having an impact on public health, food security, security of water supply, migration, peace and security [28,29]. ERIs are contributing significantly to meeting these political visions and policies. This also leads to more cost-efficient use of the support provided by the Member States' and Associated States' to the ERIs.

For the first time in the history of environmental science, we have the opportunity to ask societally relevant questions at spatial and temporal scales that have been previously unattainable. Moreover, we are now able to advance new scientific philosophies capable for making a substantial contribution to global societies that are adapting to a changing environment [11,30], and all the while bringing about more sustainable economies [4]. A more systemic sharing of 'lessons learned' from successful ERIs and intentional planning and planning forums are likely to help ERIs to overcome these identified barriers. We could then expect more transformative science yielding more products, deeper understandings, correspondingly better capability to address societal needs. Overcoming these barriers will also bring about the integration of ERIs with other research infrastructures to even further optimize resources and foster new understandings. Demonstrating societal relevance and optimizing the resources for ERIs will make the use of ERIs to more common place in advancing science and helping society (Figure 2). In turn, this may bring down current barriers to Big Science investments [31,32], for multilateral knowledge exchanges to push technological frontiers and ultimately serve innovation [33,34].

Acknowledgments: This work was supported by the European Commission through the FP7 project Analysis and Experimentation in Ecosystems Grant Agreement (AnaEE) http://www.anaee.com/. Number 312690 and, the H2020 ENVRIplus Grant Agreement number 654182 http://www.envri.eu/. Henry W. Loescher acknowledges the National Science Foundation (NSF) for ongoing support. NEON is a project sponsored by the NSF and managed under cooperative support agreement (EF-1029808) to Battelle. The authors also acknowledge the collective contributions from numerous community-lead discussions and workshops over the past 5 years. Finally we thank Adriana Voicu and Margaux Dillon for their technical support and two anonymous reviewers for their constructive criticisms and insightful suggestions.

Author Contributions: Abad Chabbi conceived the idea for the manuscript, initiated the writing of the paper and led the work; Henry W. Loescher contributed with the overall concept, ideas, and writing of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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