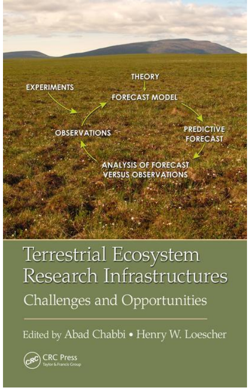

Terrestrial Ecosystem Research Infrastructures Challenges and Opportunities

Abad Chabbi, Henry W. Loescher

Integrated Experimental Research Infrastructures

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Abad Chabbi, Henry W. Loescher, Mari R. Tye, David Hudnut

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Integrated Experimental Research Infrastructures: A Paradigm Shift to Face an Uncertain World and Innovate for Societal Benefit

Abad Chabbi, Henry W. Loescher, Mari R. Tye, and David Hudnut

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1.1 Introduction

The sustainability of our managed and natural environments is critical for the future of humankind and to ensure long-term quality of life. We also recognize that the environment and our economics are intrinsically linked (PCAST 2011, Holdren et al. 2014). The services provided by these ecosystems (e.g., food and fiber, fuel, biodiversity, biogeochemistry, water and energy, air quality) (MEA 2005, Heinz 2006, FAO 2011, FAO et al. 2012), however, are under threat due to dramatic changes in climate, chemical climate, land use and management, invasive species and species loss, and other human activities (Vitousek et al. 1997, NRC 2001, 2007). Understanding the responses of the biosphere to the anthropogenic drivers of environmental change is both an intellectual grand challenge and a practical necessity. Enhancements or disruptions of these services by human-caused environmental change could alter the fundamental trajectory of society over large parts of the world.

A wide range of biotic and physical processes link the biosphere to the geosphere, hydrosphere, and atmosphere. Despite this link, our understanding of the biosphere does not match our increasingly sophisticated understanding of Earth's physical and biogeochemical dynamics at the regional, continental, and global scales. Because many of these responses and feedbacks are large-scale processes, they need to be studied in an integrated way with standardized, coherent measurements for long periods of time (Doney and Schimel 2007). To date, the existing monitoring programs that collect data to meet regulatory, monitoring, and natural resource management objectives are not designed to address climate change and other new, complex, environmental challenges, that is, "Existing monitoring networks, while useful for many purposes, are not optimized for detecting the impacts of climate change on ecosystems" (Backlun et al. 2008) and "Fragmented federal investment in monitoring ecological change weakens national priorities" (PCAST 2011). While this fragmentation has been recognized, it is partially manifested by the need to maintain agencies and government directives and how resources (funding support) are managed (Vargas et al. 2016). But also, the societal and scientific imperatives to have a more integrated, synergistic, and cross-network approach have fostered the programmatic challenge of how best bring these networks and funding directives closer together.

It is important to note that there are different programmatic structures and rationales/missions for environmental research infrastructures (RIs). Some are principle investigator, bottom-up organizations with minimal governance, others that are more top-down with large institutional and organizational structures, and many in between (see Loescher et al., Chapter 2 for more discussion). RIs can also be characterized by their organizational structure and function: Ecological Observatory Networks (EONs) (centrally organized, primarily top-down institutions), Long Term Research Networks (LTRNs) (primarily Principle Investigator driven), and Coordinated and Distributed Experiments and Observations Networks (CDEOs) (see Peters et al. 2014 for more discussion). It is on this latter classification that we focus the discussion in the chapter. While we adopt the RI classification schema outlined in Peters et al. (2014), we also recognize that new RIs are emerging globally and this is an open area of discussion. Furthermore, each have their own nuances on how they meet their goals and mission, how they interact among RIs and stakeholders, and their funding and operational timelines.

Generally, RIs typically observe either the cause (e.g., climate, air pollution, or land cover change) or the ecological processes that are affected by the drivers, their feedbacks, and interactions (e.g., phenology of plants, changes in plant and animal population dynamics and distribution ranges, changes in biogeochemical cycles, feedbacks to the soil–plant–atmosphere water continuum), that is, one aspect or the other in the cause and effect paradigm. Prior to this decade, environmental RIs rarely provided long-term, consistent integrated observations that include the causes (drivers of change), affected processes (response variables), and their interactions. Only in the recent decade have we seen the advent of continental-scale RIs that embody the cause and effect paradigm in a planned and consistent manner. Examples include The National Ecological Observatory Network (NEON, www.neonscience.org, Chapter 2) and the Terrestrial Ecosystem Network (TERN, www.tern.org.au, Chapters 13 and 16) that embodies EON and CDEO functions in their organizational structures.

Broadly speaking, environmental sciences (ecology, ecosystem, remote sensing, regulatory, etc.) and CDEOs can be classified into two different and complementary experimental approaches:

1. *A noninvasive comparative design*, which may consist of observations and monitoring of different ecosystem types across an expected environmental gradient (cause) or range of responses (process-level information). This experimental approach may also adopt a substitution of time for space in classical chronosequence design (Cowles 1899, Warming 1985). This approach provides a powerful understanding of a range of conditions and their behavior in present time and provides important baseline understanding (e.g., what is the range of conditions today).
2. *An experimental manipulation design*, which may consist of the alteration of relevant forcing or process-level variables within or among ecosystem types. The range of manipulation is often chosen to represent future conditions, because the nature of disturbance is changing from more discrete, stochastic natural forms (e.g., storms, insect outbreaks, fire, flooding) to more chronic forms (e.g., increasing temperature and nitrogen deposition, CO_2 fertilization, population growth, changes in long-term precipitation patterns, changes in plant traits). This approach is particularly illustrative because we expect ecosystem processes will behave differently with chronic, long-term disturbance (Smith et al. 2009). Hence, this approach can provide important data on the unexpected nonlinearities in ecosystem behavior with chronic disturbance, for example, tipping points, process-level sensitivity, species migration, and community changes.

These two approaches are both necessary to advance our understanding of future world and if coordinated can provide unique insights into the causes, effects, and system feedbacks of anthropogenic change.

Used in combination, these two types of experimental design can provide inferences that can span large time and space scales, and is the core rationale for many experimental RIs. Also, when used in tandem, data from these two approaches can inform mechanistic, statistical, and predictive modeling frameworks to further be applied in natural resource management, societal planning, food security, and the like. Both approaches provide rich context to inform our gaps in knowledge, identify which new observations and models are needed, and to challenge theory (cf. Chapters 2 and 7).

There are good examples of both these experimental approaches in environmental RIs. The gradient approach (#1) has been used effectively to assess species richness, turnover and biodiversity (Soininen 2010), and edaphic controls on phosphorus and nitrogen in novel soils (Vitousek and Fields 2001, Vitousek 2004). Likewise, networks focused on large-scale manipulations have also advanced our understanding, for example, manipulating precipitation as a forcing variable on ecosystem responses (PRECIPNET, Weltzin et al. 2003); tree species' interactions with nitrogen deposition (NitroEurope, Sutton et al. 2007); and examining ecosystem-level carbon-use and water-use efficiencies and other biogeochemical interactions with forced Free-Air Carbon Dioxide Enrichment (FACE, Ainsworth and Long 2005). Due to the state of the science at the time of these studies and the pragmatism of funding requirements, many of these experimental studies were reductionist in their approach. Moreover, these studies have been typically restricted geographically (primarily to the United States or Europe), and their experimental designs or data collection methods across sites were not consistent. The associated biases in this restricted/reductionist approach were also apparent in global meta-analyses and did not reflect important patterns within specific biomes (Fraser et al., 2012). Indeed, Ehrlich (1997) also noted the limited capability of this type of reductionist study and called for a broader, more integrated approach among time and space scales and among ecosystems to provide new ecological insights on how these systems behave.

Only since the last decade has there been a widespread recognition of the need to integrate experiments with observations, models, theory, and across ecosystem, biomes and continents (Marshall et al. 2008, Peters et al. 2008, Robertson 2008, Schimel and Keller 2015). Moreover, such an integrated approach can also foster better predictive capabilities by iteratively challenging theory, observations, experiments, and models (and associated analytics) to advance scientific discovery and provide actionable results for societal benefit (see Section 1.2, and also discussed in Jiang et al. 2016, Loescher et al. 2016, Chapters 2 and 6) (Figure 1.1).

Implementing this integrated and novel approach adopts

- The cause and effect paradigm
- The ability to scale results in time and space and across taxa (from genes to biomes)

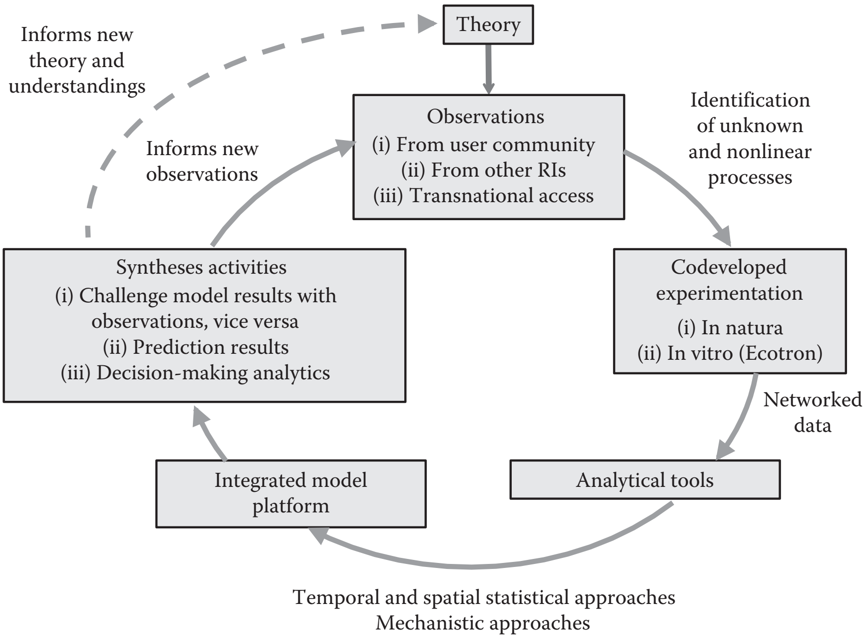

FIGURE 1.1
Conceptual diagram depicting the *overarching philosophy of this project* (and how the spiral management approach will be applied to the science), where (i) theory informs the types of hypotheses and questions to apply, and in turn the observations made, (ii) from observations, unknown and nonlinear behaviors are identified which need to be elucidated by (iii) the codevelopment/execution of experiments, from there, (iv) analytical and statistical data tools are used to reduce the amount of data into a synthetic understanding and further inform (v) the model platform, and (vi) synthesis activities, which, in turn, inform new theory, new observations, and new understandings.

- Specific anthropogenic causes (drivers) of change: changing climate, species loss, invasive species, and land-use change
- Specific ecological processes, feedbacks, and interactions of biodiversity, biogeochemistry, ecohydrology (water), infectious disease, and the transfer of mass and energy (environmental physics)
- A philosophical framework to enhance ecological predictive skill (Section 1.2)
- Ecosystem concepts of stability, resilience, adaptability, and transformability (Table 2.2)

The impact and understandings derived from this integrated approach has yet to be fully realized. With new emergent environmental RIs, we are only beginning to ask ecological and societal relevant questions that span across different continents (Vargas et al. 2016). A common example is how

El Niño, Northern Pacific, and other atmospheric–oceanic oscillations telecommunicate across large regions of the earth and control climate and, in turn, affect ecological processes. Cross-continental spatial and temporal scale synchrony in one ecological process can cascade/feedback to other processes and economies. For example, earlier and/or false spring leaf-out across continents (i.e., the United States) has implications for water usage, earlier midsummer droughts, (migratory) animal habitats, and agronomic economies (Allstadt et al. 2015). In another example, we know the genesis of synoptic drought conditions differs in Australia, China, Southwestern United States, and Europe, but the controls on this genesis are not well understood. This ability to ask questions across different continents is particularly salient given that ecological and societal imperatives transcend geopolitical barriers.

1.2 Predictive Ecology as a Core Premise for an Integrated Distributed Experimental Infrastructure

In order to build a sustainable future society, we must better understand the drivers of environmental change, the ecosystem processes they affect, and their interactions and feedbacks. We do this both for basic research (i.e., scientific discovery) and also to build a twenty-first-century bioeconomy (i.e., applied understanding and actionable results).

Key to this effort is developing our ability to forecast ecology or to develop the prognostic decision space (in engineering terms) that, in turn, provides the information to better preserve, conserve, improve, adapt, and mitigate our ecosystem services, for example, securing our food and water supply. Put another way, we need to understand and forecast how ecosystems will respond to current and future changes, including the ability to inform new management approaches and determine (potential) environmental tipping points, that is, management targets.

Without sufficient understanding of the drivers and mechanisms underlying these sensitive interdependencies and nonlinear behavior between ecosystems and the anthropogenic environment, scientists will be unable to assess the impacts, control the risks, provide decision-making tools, or potentially reap the benefits of anticipated large changes in ecosystem structure and function. Key benefits will include improved protection and management of biodiversity, increased production and sustainability of human-exploited ecosystems, greenhouse gas mitigation, and climate adaptation.

The goal is not to advocate an experimental RI for the sole purpose of experimentation alone. Rather, the core philosophy of experimentation is to elucidate as yet unknown processes and nonlinear behavior in ecosystem functions (e.g., tipping points, stochastic behavior, reorganization of species and ecosystem functions). This cannot be done in isolation from other scientific endeavors. We need key types of data and approaches that require theory, core observations, experiments, analytical capabilities, and modeling framework (Figure 1.1). To enhance predictive skill, we must start with theory that informs the type and signal:noise needed for new observation needs. This, in turn, informs the type of experiments needed to elucidate unknown (but suspected) behavior that, in turn, informs the analytical tools and modeling activities before recommencing the cycle to inform new understandings, theory, and potentially what new observations and experiments need to be performed (Figure 1.1). This cycle is revisited over and over again for specific questions, each time gaining new insights and forecast precision. This integrative philosophy is used very successfully to enhance the predictive skill in weather forecasting and epidemiology (Loescher et al. 2016; Chapter 2), and we advocate the same ecological forecasting philosophy toward building an environmental experiment RI. While this approach is still novel in ecology, it is becoming more broadly accepted worldwide, and other RIs are adopting the same approach (i.e., AnaEE, NEON, TERN).

1.3 Prototyping Integration of Experimental Platforms

Experimentation is by its very nature at the forefront of our knowledge, constantly testing the bounds of our understanding. Establishing infrastructure is typically executed for facilities, both physical and information (see Section 1.4), that are considered "baseline" or considered as a community standard so that the widest possible group of stakeholders can utilize its function—and not constantly be changing to accommodate the latest thinking. Here, the underlying problem is establishing an infrastructure that can be used for ecosystem/ecological experimentation where it has to (1) provide physical and information facilities that have to be standardized in approach and (2) provide dynamic capability to support the current frontier of ecological thought. At the same time, it cannot be everything to everyone.

There are many different kinds of experimentation, and the previous text assists in constraining the scientific scope to estimating nonlinear behavior of ecosystem processes due to (mostly) anthropogenic causes. But still, there have been in situ long-term experimentation on grassland diversity and productivity as those found at Cedar Creek, MN, United States (e.g., Tilman et al. 2001, 2006), and the use of large animal enclosures to challenge theories governing plant biodiversity (Carson et al. 2014, Carson and Schnitzer 2003)—to ex situ short-term experimentation with the monolith extract of whole ecosystems to manipulate drought conditions (Arnone et al. 2008, Malone et al. 2013), and everything in between. The challenge remains: how to best provide both the physical and information facilities for an environmental RI that meet the broadest possible scientific and societal needs? Put another way, experimental infrastructure, instrumentation, ecosystems studied, timescale of experiments, and research focus broadly vary. This large heterogeneity in approach brings great opportunities for advancing knowledge, but is also a large programmatic challenge in constraining scientific scope, optimizing construction and operational budgets, flow of information to respond/utilize the experimental results, and in engagement of stakeholder communities.

There are environmental RIs that provide a single experiment across continents, such as NutNet (ecosystem nutrient addition across the globe, www.nutnet.umn.edu/) and Drought Net (precipitation manipulation, wp.natsci.colostate.edu/droughtnet/). On the European Strategic Forum on Research Infrastructures (ESFRI) roadmap is the Analysis and Experimentation on Ecosystems (AnaEE, www.AnaEE.com): a European-wide effort to develop an integrated open-access experimental user facility—and is faced with the challenge of providing the broadest possible scientific scope while constraining construction and operational budgets. It is a classic and difficult cost–benefit activity pertaining to system engineering.

In addition to the challenge of balancing scope and budget, the ESFRI approach requires buy-in from EU member countries, which provides political and funding challenges. This approach of knitting EU country interests together is part of the strategy, so that only part of the RI construction costs comes from the European Commission in the form of structural funds. The societal needs from partner countries provide the rationale to support the remaining resources needed to fully construct and operate an ESFRI RI, that is, AnaEE. This approach also justifies the in-country support of existing in-country facilities and can contribute to the overall experimental RI. The scope of these in-country contributing facilities has to be overlaid and meshed with the overall scope of the RI, providing additional challenges to define and refine overall scope.

In the case of AnaEE, small-scale end-to-end prototype efforts (from physical infrastructure to information that can be used) are called for to better (1) inform overall scope; (2) inform the needed construction activities to inform and optimize operational needs; (3) develop a dynamic framework for the ongoing integration and optimization of experimental, analytical, and modeling platforms through community-driven processes; (4) inform a sustainable business model (operational model) that can innovatively bring together researchers, academicians, private sector, and planners and decision-makers; and (5) build trust and understanding among stakeholder communities.

FIGURE 1.2
The need for robust lessons learned from prototypes is not a linear process, rather a cyclic workflow that is an ongoing dynamic process, and each aspect is revisited often to assure innovation, cross talk among participants occur, and to optimize efficiencies. This cyclic workflow is a high-level management criteria and maps to all aspects of prototype development.

These prototype efforts also adopt a spiral workflow (Figure 1.2), in that it is management's responsibility to continually iterate design and implementation choices based on lessons learned. In this way, our ability to truly (1) implement a philosophy that integrates theory, observations, experiments, models, and analytics as a truly innovative, transformative, and novel approach and (2) inform the programmatic and technical constraints, schedule and budget, and risks needed to operate key physical experimental infrastructure and improve its scientific capability to tackle grand challenge questions across a range of environmental conditions and ensure the efficiency of data flow. The lessons-learned approach sharpens and defines scope and informs business plans (operational plan). Spiral workflows have been used successfully in many corporate workplaces, but is novel when building RIs and in the environmental sciences.

For example, in the AnaEE, Preparatory Phase has identified in situ (i.e., *in natura*) and ex situ (i.e., in vitro or Ecotron) experimental platforms among several partner countries. Prototype workflows facilitate the links among scientific requirements, experimental design, and experimental data from these platforms to modeling solutions that can run near- real-time simulations that can manage the means to control the experimental protocols and validate flow of information from site(s) to the final product. These prototype efforts also assist in understanding the management and resources needed to integrate such experimental platforms at larger scales, but the challenge still remains in understanding which platforms provide the greatest scientific impact, which platforms will be supported by in-country resources, and how they will be knitted together to address science and societal questions at continental scale. Science and societal questions, in this case, could be considered two sides of the same entity. Their mutual integration in this work drives and is driven by the spiral workflow concept.

1.4 Integrated e-Infrastructure for Efficient Data-Centric Knowledge

Everyone recognizes the need to model our understanding of the system behavior that is elucidated by experiments (Figure 1.1). This activity is key in developing skill in our prognostic capability and providing decision-making tools. Researchers and decision-makers require actionable knowledge, for example, Dilling and Lemos (2011) and Briley et al. (2015). But getting raw data into information and actionable knowledge is not easy and is an inherent design of the RI (also see Stocker 2016; Chapter 15).

1.4.1 Acquisition and Dataflow

A distributed model to collect experimental data from the field or ex situ chambers across countries to be used centrally is a difficult proposition. If such a design is to be constructed from scratch with the same acquisition systems, the data structures, formats, and metadata formats, they can be more easily managed, but the challenge still remains on how to collect the data from the field to a centralized location for QA/QC and further processing. Typically, sending data from the field requires a number of strategies, in part based on the size of the data, and includes some combination of fiber communications, Internet, sneakernet, and satellite phone. Each method has its own nuances and costs to manage. If, as in the case with AnaEE, each distributed experimental location has its own data acquisition system (e.g., datalogging and on-site storage system), then additional complexity arises to develop data and metadata standards that facilitate the transport, storage, analytics, use, and accessibility of the data. There is no simple solution, and this is an active area of research.

Now that we have embraced the era of "Big Data" and given that the experimental data resides at a central repository, researchers will likely ask questions beyond the scope of the experimental data alone. In other words, being able to merge experimental data with other spatially explicit data, economic data, and other drivers of change, modeling environments, other analytical approaches, etc., to increase its sphere of inference. In order to do so, other data will have to be ingested by the researchers from other sources. The challenge then lies in keeping track of the myriads of large data sets and associated software and processing configurations that are used and in making them reproducible—a core premise of the scientific method. The usage of software packages to do this is not necessarily new to computing scientists but is very new to environmental science, and their use is becoming more widespread. Such software packages are Kepler (kepler-project.org), Taverna (www.taverna.org.uk/), BioVal (www.bioval.com), and other workflows, and more advanced functionalities are being developed and tailored specifically for these environmental science purposes. As with Section 1.2, these workflows are being prototyped, applied, and tested across a suite of RIs, and we expect their widespread application to become more routine in the coming years.

1.4.2 Informatics

Many lump much into the discussion about informatics. But there are a few key questions that informatics address for environmental data: (1) What is needed to use and reuse data? (2) How is data archived? (3) How is attribution, providence, and persistence of the data managed? In addition to informatics, there are other data-related functions that are needed by RIs that are best suited for computer scientists, that is, computing and archival systems architecture that facilitates the ease in accessing and moving data from one repository to another, and maintaining data integrity (when using compression software). There are very few standards for informatics, for example, spatial reference standard held by Open Geospatial Consortium (www.opengeospatial.org). Currently, there are numerous, cross-pollinated community forums where these standards and best community approaches are being derived, for example, EarthCube (earthcube.org), Research Data Alliance (rd-alliance.org), Earth Science Information Partnerships (www.esipfed.org), EUdat (https://www.eudat.eu), and CoopEUS (www.neonscience.org/content/coopeus) to name a few. These community forums are advancing informatics in earth and environmental sciences but with no critical mass in a single organization.

There are two notable areas of discussion about informatics. First, when making data from one source interoperable with data from other sources (Table 1.1), the data nomenclature (controlled vocabularies) and the systematic logic that links the nomenclature systematically (semantic ontologies) are still developing. There are some controlled vocabularies and ontologies that are currently being used (e.g., Darwin Core, Ecological Metadata language), but by necessity researchers are quickly moving past these structures and the refresh rate of structures like Darwin Core is slow to catch-up. Hence, new systems are being developed and fostered by the research community. Another reason they are developing is that at the frontier of RI science, new types of data are being generated which are difficult to classify. For example, what to call and classify a sample of ground-up mosquitoes used to generically determine the presence or absence of zika virus?

Second, the collection, quality control, and curation of data are a scholarly activity that is an integral part of advancing our science and deserves to be recognized, that is, attribution. Authorship of data and its provenance (including where it came from and what it means, i.e., metadata) and documenting it as a citable reference can be done digitally via Persistent Object Identifiers (POIs), with Digital Object Identifiers (DOIs) being the most common form. DOIs are managed by International DOI Foundation (www.dio.org), and can be costly to maintain. Moreover, when an end user

TABLE 1.1

Rapid Pace of Large-Scale Environmental Global Changes Underscores the Value of Accessible Long-Term Data Sets

Interoperability Framework	
1. Aligning science questions and hypotheses, requirements, mission statements	• Mapping questions to "what must be done" • Defines joint science scope/knowledge gaps • Define interfaces among respective infrastructures
2. Traceability of measurements	• Use of recognized standards • Traceability to recognized standards, or first principles • Known and managed signal:noise • Managing QA/QC • Uncertainty budgets
3. Algorithms/procedures	• What is the algorithm or procedural process to create a data product? • Provides "consistent and compatible" data • Managed through intercomparisons • What are their relative uncertainties?
4. Informatics	• Standards—Data/metadata formats • Persistent identifiers/open-source • Discovery tools/portals • Ontologies, semantics, and controlled vocabularies

Note: The degree to which research infrastructures are truly interoperable is the degree to which these four elements are adopted by collaborative facilities; This table highlights the interoperability framework to make scientific data useful across research platforms (interoperability may look different for other research areas, for example, education and outreach). Real tasks can be applied to each of these focus areas. This is an active area of research. Signal:noise and uncertainty estimates must be part of this framework, because uncertainties need to be known a priori for data to be used in any Bayesian or data assimilation approach, that is, prognostic capability and ecological forecasting.

downloads a time series, it is a discrete block of time, but the original time series is more often than not being amended and the time series continues in the data repository. POIs also identify a discrete time series that can be reproduced. So the challenge becomes when to apply a POI?, for the entire, continually augmented time series, or an individual POI for each discrete time series that is downloaded. The latter option can become quite costly if an RI expects a lot of use from their data. As such, many environmental RIs are adopting a hybrid approach of developing an in-house POI system for a time series data set that is being continually augmented and a unique identifier (subset) for each download that assures the reproducibility of the data set.

1.4.3 Data Transformation, Analytics, and Modeling

Clearly, the knowledge and new understanding (Stocker 2016; Chapter 15) are derived from transforming raw data into higher-order data products, whether they be statistical analyses, mechanistic models, or used in Bayesian data assimilation for ecological forecasting (Jiang et al. 2016; Chapter 6). Basic transformations of conversion of raw units to calibrated quantities, statistical averaging, and spatial interpolations are commonplace in environmental RI data toolboxes. But based on funding pragmatism alone, Environmental RIs cannot provide all the analytic tools required (or expected) by all researchers. On the other hand, there are many researcher-initiated analytical tools that are being made freely available via the web, for example, R packages, Java and Python codes, and Github development. In parallel, there are also newly developed software(s) that can "wrap" research-level code to make them operate more robustly in the context of larger cyber-infrastructure architectures and make them more available to a broader user base, for example, D4Science. It is this frontier that seems to hold promise of "Big" RI data having more utility while also balancing fiscal constraints.

Models that explain our current understanding come and go with time and new understandings. Many models and model intercomparisons have been made and have provided new understandings, for example, Huntzinger et al. (2016). However, advancing ecological understanding is often hampered by the fragmentation of modeling resources in terms of scope, data requirements, architectures, and modeling approaches. Excellent and well-tested models are available, but these use diverse data formats and software platforms, often conflating data definitions, I/O procedures, and algorithms. RI software architecture requires up-to-date documentation, run-time testing such as tests of pre- and post-conditions, and unit tests; but these methods have rarely been applied when developing ecosystem models. Ecosystem science must therefore facilitate the development of efficient, parsimonious solutions based on articulation of tested modules. Many of these modeling solutions are closed systems, difficult to maintain even by their developers, that is, extend current modeling solutions by attempting to control and centralize development leads slow progress of modeling capabilities and little responsiveness to upcoming societal demands. An alternative is to develop frameworks, which capitalize on existing process modules, build new modeling solutions, and provide functionalities to perform simulations. Environmental RIs are also faced with what/which models to support. There are several initiatives are under development, and there is a strong case to make them interoperable in order to increase their respective capacities. Part of these initiatives are the development of (1) a common model architecture such that submodel routines or modules can be easily altered for a better comparative understanding the contribution of specific model components toward our overall understanding of system behavior.

Similar to the "wrappers" mentioned earlier, "adaptors" are built to allow individual model components or modules to be added or removed from the overall model within the workflow software, (2) standard to report model uncertainty is still nascent, and (3) a community model (or community configured model) that acts as a baseline with which other model behavior can be compared and contrasted to.

1.5 Innovation Capacity, New Market Opportunities, and Strengthen Competitiveness through Distributed Experimental Infrastructure

Generally, environmental RIs represent an untapped resource for innovation worldwide. The need to better integrate large-scale "Big Data" science into the private sector is articulated as a "must do" by stakeholders, governments, and the public (Pulwarty and Maia 2015). Yet opportunities to do so are limited and successes even less common. Often, success occurs by happenstance (see Figure 1.3a) rather than targeted consideration of the joint interests of public and private entities. Here, we change the current (low-success) paradigm of scientist-centric and initiated innovation by developing stakeholder-based needs first, then engaging scientist skillsets (Figure 1.3b). This model has been used for other public/private enterprises and knowledge transfer (e.g., medical industry, cancer research, agrochemical), but has not yet been applied for environmental/ecosystem science. Yet to advance the state of the science, more research is needed to ensure codevelopment of such integration, including lessons learned from previously successful and unsuccessful public/private collaborations; scalability in size, scope, and diversity of partners; how to plan for the extensibility of public/private integrations; how to overcome legal, political, cultural, and institutional barriers; and codevelopment of dynamic business models that can accommodate change.

The innovative merits of experimentation RI are as deep as they are broad. But the utility of integrating environmental RI with the private sector has yet to be fully realized. Academicians, modelers, data scientists, etc., recognize the importance of "exporting" their science to private industries but lack a venue to do so that is fair, equitable, and objective. Further, the opportunities to advertise advances in the science and engage the attention of private industries are limited. That is, it is not clear to either party *how* experimental environmental RI can be used to benefit and meet the needs of the private sector. To date, the need for this integrative imperative has been acknowledged, but the vision and opportunity to integrate science, academia, and the private sector have not occurred within the experimental environmental realm. Such integration could benefit traditional sectors such

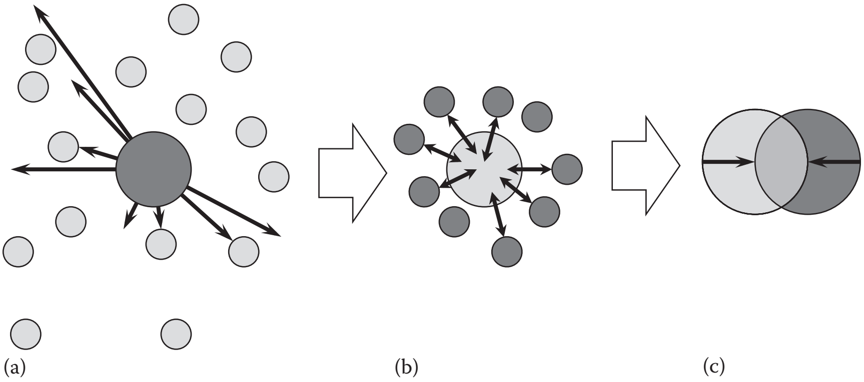

FIGURE 1.3
Conceptual diagram of how the dynamic to engage public/private partnerships will change from the current paradigm. Academicians and researchers already often work closely (shown in dark gray), while the private sector (e.g., planners, government agencies, small-to-medium-size enterprises, and decision-makers) does not have formal established interactions (in light gray). (a) Depicts the current paradigm where much of the interaction stems from academia outward to engage private interests (represented by arrows). Efforts vary in scale and focus, with correspondence to private interest often unplanned and serendipitous. (b) Are current efforts to shift the current paradigm by researching and codeveloping the strategic dynamic that emanates from the private sector, bringing academic partners closer, and specifically targeting core functions and products desired by the private sector and deliverable by academia. We note that (c) represents a desirable sustainable model from longer-term public/private partnerships, which includes formalized interconnectivity, and joint collaborations occur within an overlapping and trusted structure.

as the agronomic economy, rural and urban planners, high-impact weather mitigation natural resource managers, environment regulation, and supporting innovative technologies. In a time of limited public funding, the factors contributing to managing these sectors are just a subset of the plethora of competing needs being weighed by planners who need to prioritize the use of scarce resources (funding and otherwise). While decision-makers may be aware of environmental/ecosystem science advances and likely benefits of inclusion in their policies or projects, they often lack the information to be able to quantify those benefits and make informed choices.

Emergent economies, for example, risk and resilience management, federated data services ("Big Data," Future Earth), and food security, also provide novel areas for innovative research and collaboration. For instance, traditional flood-risk mitigation policies tend to favor solutions that require lower capital investments. While this approach is more affordable initially, the resultant solutions—for example, resistive barriers, such as levees—often prove to be not only unsustainable but also exacerbate the consequences to society and ecosystems when failure does occur (Adger et al. 2012, Tye et al. 2015). Enhancing decision-makers' access to integrated knowledge of changing hazards, exposure, and vulnerability as well as the benefits of ecosystem services to regional biodiversity, improved habitat protection and conservation, and potential mental and physical health benefits is an obvious step toward enhanced resilience. We define resilience as systems that recover to a stable state after a disruptive event that led to systematic failure (Tye 2015). Thus, a resilient system balances ecological, economic, and societal factors and facilitates a "graceful failure" and subsequent recovery.

There are countless position papers that call for the integration of public/private innovation partnerships for policy and decision-making (e.g., Dilling and Lemos 2011, The Royal Society 2014, Tye et al. 2015). And while this is an imperative, we choose to take smaller, more intentional steps toward building this new economy. As such, we have identified there are a few early adopters who seem to be natural partners in the initiation and propagation of these types of public/private partnerships.

Insurance and reinsurance companies are increasingly exposed to economic impacts from weather and climate extremes (Munich Re 2015). There are a variety of reasons for these increases, including societal changes and climate variability and change. Increasingly urbanized societies in vulnerable locations and an associated loss of resiliency have contributed substantially to the trends (Donner and Rodríguez 2008, Flood and Cahoon 2011, Sweet and Marra 2014), and this will continue. Population increases also bring stresses on food and water supplies, which are more likely to collapse under climate extremes such as droughts (Vörösmarty et al. 2000, Rosegrant and Cline 2003), and the built nature of cities amplifies climate variations such as heat waves and intense rain events (Coutts et al. 2007, Rosenzweig et al. 2011).

To date, the analyses used by re/insurance companies to evaluate their exposure rely on the integration of theory–model–observations to advance prognostic capability and evaluation of exposure. Underlying assumptions are based on recent observations, current climate, and other known drivers of changes in ecological processes. These assumptions are not expected to hold true for future conditions given chronic and long-term changes in the environment (e.g., nitrogen deposition, increases in population, temperature, and CO_2) and increases in the frequency and severity of weather and climatic events. The only way to glean insight into the impacts from, and likely future evolution of, these changes is through Experimental RI and integration of results with climate model output. In addition, changing the status quo from one of *risk response* to *risk mitigation* requires an integrated approach that balances the expertise of financial, social, environmental, and academic partners. Hence, codesigned and codeveloped experimental data are of benefit to re/insurance institutions to reduce portfolio exposure and advance socio-ecological–socioeconomic resilience through integrated land-use planning.

1. *Agronomy and Agro-Business*: Food security is becoming more paramount with each passing day (Whitacre et al. 2010, FAO 2011, FAO et al. 2012, Chavez et al. 2015). Traditional agronomic experimental

designs to test crop yield, water-use efficiency, genetics, and management techniques are a natural fit with the experimental approaches found within the RI. Traditional process–based models to manage natural resources, for example, crops, land erosion, and water use, also rely on theoretical and observation-based models to generate estimates of risk. However, the assumptions guiding these models do not always match reality and have limited opportunity to evaluate feedbacks between the agronomic and simulated output. With a focus on a different factor, the need for integrated planning to manage evolving responses to anthropogenic changes is similar to that of the re/insurance industry.

2. *Sensor/instrumentation companies* have a history of working with academicians to advance innovation, and hence are natural partners. There is an identified and immediate need to automate the linkage between observations and data flow activities (e.g., flow of data from sensor to quality assurance and quality control algorithms) to an ensemble of high-level data products and modeling activities. This integrated workflow for environmental RIs (novel sensor design, sensor-to-final data product) is a frontier and a large opportunity for industry partnerships. But there is also a longer-term vision of likely new discoveries and future types of sensing technologies required to manage and balance natural resources, societal well-being, and science. Partnerships with Experimental RI potentially offer explicit climate change scenarios, introduction of (invasive) species, broader comparative capability, diverse modeling platforms, effect data flow, common standards, informatics, and the like, to enhance the production of results and competitive advantage.

We have also identified legal barriers to developing public/private partnerships. For instance, intellectual property rights (IPRs) and data sovereignty issues arise when working across geopolitical borders. Legal frameworks have been developed separately by the public and private communities, respectively, to manage some of these issues. There are active community forums where these discussions and frameworks are developed, for example, RDA, DataOne, OGC, Earth System Integration Partnership, and others. However, there are only a few examples where these frameworks have been codeveloped, for example, National Center for Atmospheric Research's Engineering for Extreme Climate Partnerships (ECEP, Tye et al. 2015) and some relevant University Technical and Innovation parks. The novelty lies with public/private partnerships where competitive advantage and periods of data propriety become negotiable. On one hand, public funding mandates open access to the data. On the other hand, private enterprises wish to maintain a competitive advantage, which implies data propriety. A proven compromise entails "value-added" analytics applied to the openly available data. But the community using the research infrastructures determine the shared goals, culture, and common vision for the multidisciplinary data integration. But the advantage is really only competitive for a few years at a time, for example, 2–3 years, after which the analytics can also become public. This approach has been adopted within ECEP, whereby collaborative research is carried out between academia and the private entity and a moratorium placed on data sharing until after journal articles have been published. The result is a net win for both research and industry, facilitating scientific advances and short-term competitive advantage, and demonstrating that the private entity is at the forefront of technology. Hence, to maintain the corporate advantage and to maintain at the competitive forefront, development of new analytics becomes a long-term, sustainable partnership. This becomes a manageable task where research activities can be codeveloped and roadmapped a priori and also implies the need for new business models for both public and private enterprises to take advantage of such partnerships (Figure 1.4).

This is not to say that there are not both institutional and cultural barriers that still exist. Public/private partnerships are still nascent in the environmental sciences and require a cultural shift for implementation. Building

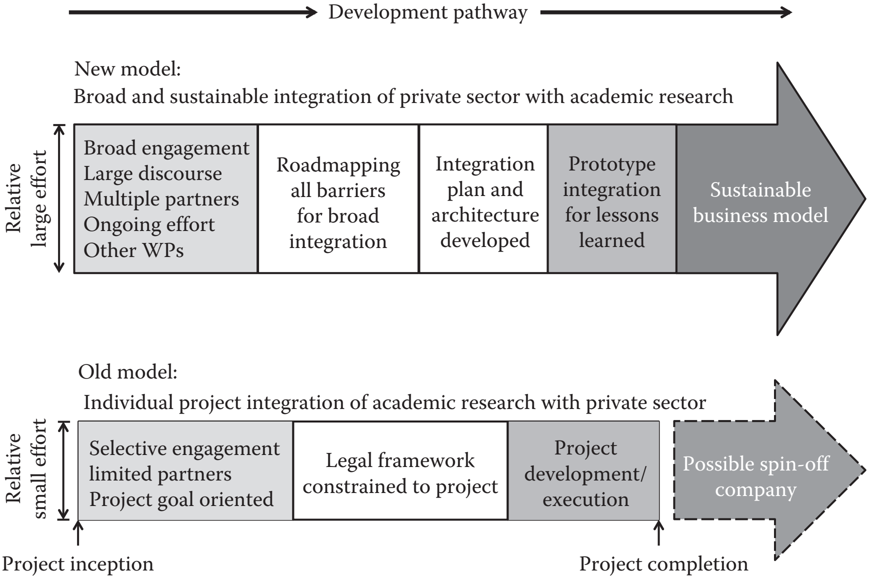

FIGURE 1.4
Here, we change the current (low-success) paradigm of scientist-centric and initiated innovation by developing stakeholder-based needs first, then engaging scientist skillsets (i.e., Figure 1.3). Moreover, we identify barriers to implementation, required architecture, and prototype integration into a sustainable development pathway. This model has been used for other public/private enterprises and knowledge transfer (e.g., medical industry, cancer research, agrochemical), but has not yet been applied for environmental/ecosystem science.

cultural capital determines and disseminates the shared goals and common vision for the multidisciplinary data integration. It is about changing discipline cultures and working toward community building, which generates trust, sharing and providing data, and constructing bridges between experts in different fields. Multidisciplinary community building is a long-term effort as cultures, languages, and approaches are quite different among public and private enterprises, as well as across disciplines. Developing a shared culture does not happen overnight and requires the codevelopment of joint long-term goals and the activities to foster a cultural change, for example, trainings, joint strategic planned efforts, and building new cohorts of stakeholders and early career users. However, the end goal is one of a collaborative community that can work independently, yet balance the needs and expertise of other sectors.

1.6 Future Directions in Working Internationally

Each country designs its stimulus (research) infrastructure to address the needs of its own citizens and better societal benefit. Yet the increasing interconnectedness of the ecology of the planet and our economies loudly calls for better integration of our ecological understanding and the overarching fabric of our global society. We, the environmental RIs, need to demonstrate the need for global integration and not just meet national priorities. The societal discourse and awareness of this global interconnectedness is building, for example, 2015 Paris Climate Talks (www.green-alliance.org.uk/paris2015.php). We are not only in the age of "Big Data," but also how are we going to use "Big Data" to better a global society.

Data from environmental RI play a role in advancing this imperative. The voluntary organization, Group on Earth Observation (GEO, www.earthobservations.org) calls for governmental and "a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations and information" consists of government and other nongovernment organizations. Top-down efforts like GEO help bring "Big Data" together to address this imperative. It may also seem like environmental RIs are top-down efforts, which is partially true in how they are constructed and funded. Their success, however, will be based on how well their data are used by—and their facilities can adapt to—the changing needs of the stakeholder and user communities. Their success will not solely be judged on how well they meet large-scale government agreements.

Grassroots efforts of environmental RI managers and global thought-leaders recognize the yet untapped scientific potential of virtually linking these infrastructures (Tim Clancy, personal communication). Coordination among international RIs provides added value to the previously made investments worldwide (e.g., physical designs, instrumentation, and human resources, lessons learned) and also leverages the shared scientific and intellectual capital that has already gone into the several RIs, namely, AnaEE, NEON, TERN, Integrated Carbon Observing System (www.icos-ri.eu), LTER (www.lternet.edu), Chinese Ecosystem Research Network (www.cern.ac.cn/0index/index.asp), International LTER (www.ilternet.edu), and many other key in-country national environmental facilities. The bottom-up coordination among these organizations currently revolves around adopting the integrated philosophy of ecological forecasting (Figure 1.1), the interoperability framework (Table 1.1), and building the stakeholder communities to use these environmental RIs as "new instruments."

Each of the environmental RIs is in a different stage of their own development and culture. Working together brings about much more of each of their individual strengths rather than shortcomings. Each RI is unique, with their own unique set of programmatic problems to solve. Lessons learned from one RI is often applicable to another. Some solutions transfer to other RIs, others in part, and others not at all. That said, there are also many countries that cannot afford large-scale environmental RIs, but their inclusion in the global dialog and participation is also paramount to success. Again, efforts at the RI level need to be inclusive and engage less fortunate researchers and countries to broaden participation and our global understanding of the drivers and processes of environmental change. Lastly, the open and collegial international communications and collaborations need more than ever to be reinforced, which will allow us to have ongoing lessons learned. The point is that building RIs is a frontier science, and we are already learning from each other of the potential pitfalls, risk management, and how to best accelerate development and user engagement.

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