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Genesis, goals and achievements of Long-Term Ecological Research at the global scale: A critical review of ILTER and future directions

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HIGHLIGHTS

- ILTER supports collaborative ecosystem, critical zone and socio-ecological research.
- ILTER balances requirements of a research community and external user groups.
- ILTER has increased its coverage and recognition by major partners like GEO.
- ILTER fosters the alignment and harmonization of ecosystem research networks.
- ILTER provides knowledge required for sustainable development in global collaborations.

GRAPHICAL ABSTRACT

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ABSTRACT

Since its founding in 1993 the International Long-term Ecological Research Network (ILTER) has gone through pronounced development phases. The current network comprises 44 active member LTER networks representing 700 LTER Sites and ~80 LTSER Platforms across all continents, active in the fields of ecosystem, critical zone and socio-ecological research. The critical challenges and most important achievements of the initial phase have now become state-of-the-art in networking for excellent science. At the same time increasing integration, accelerating technology, networking of resources and a strong pull for more socially relevant scientific information have been modifying the mission and goals of ILTER. This article provides a critical review of ILTER's

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mission, goals, development and impacts. Major characteristics, tools, services, partnerships and selected examples of relative strengths relevant for advancing ILTER are presented. We elaborate on the tradeoffs between the needs of the scientific community and stakeholder expectations. The embedding of ILTER in an increasingly collaborative landscape of global environmental observation and ecological research networks and infrastructures is also reflected by developments of pioneering regional and national LTER networks such as SAEON in South Africa, CERN/CEOBEX in China, TERN in Australia or eLTER RI in Europe. The primary role of ILTER is currently seen as a mechanism to investigate ecosystem structure, function, and services in response to a wide range of environmental forcings using long-term, place-based research. We suggest four main fields of activities and advancements for the next decade through development/delivery of a: (1) Global multi-disciplinary community of researchers and research institutes; (2) Strategic global framework and strong partnerships in ecosystem observation and research; (3) Global Research Infrastructure (GRI); and (4) a scientific knowledge factory for societally relevant information on sustainable use of natural resources.

1. Motivation and conceptual background

1.1. Overall motivation and role

Societal wellbeing and the human use of natural resources depend on continuously available ecosystem services. Ecosystem structures and functions providing these services interact in extremely complex spatial patterns from local to global scales. The time scale of interactions ranges from microseconds up to phenomena driven by variations in Earth's orbit (e.g. ice ages and the Milankovitch cycles). Ecosystem and biodiversity research are challenged to disentangle processes and their drivers across the appropriate temporal and spatial scales in order to understand the planet or "Earth System" in search of answers to the grand challenges facing humanity like climate change, loss of biodiversity, eutrophication and pollution. Key questions in this respect are:

- How are ecosystems/biodiversity changing or adapting to global change?
- What are determinants of ecosystem resilience?
- What are the critical combinations and extent of drivers that will manifest as tipping points beyond which ecosystems may be altered irreversibly?
- How can societies respond locally, nationally and at international levels to sustain resilient ecosystems, their services and biodiversity?

The amount of data that is needed to analyze environmental change and to develop appropriate mitigation measures is far beyond that which a single ecologist and even a single research site can collect, process and synthesize. Recent scientific publications and position papers of key strategic bodies have pointed out that a collective effort within the research community and the users of environmental data in science, policy and business is needed to create the environmental research infrastructure for answering the above questions and dealing with the practical problems of living in a world of rapid social, economic and environmental change (Allen et al., 2014; Asmi, 2014; Balvanera et al., 2013; Fraser et al., 2013; ICSU, 2010, 2014; IPCC, 2013; Peters et al., 2008, 2014). Embracing the era of "big ecology" and its associated "big data" thus requires the establishment of a "network of networks" consisting of existing research infrastructures with the capability to integrate environmental and socio-economic data, information and expertise from many sites distributed widely around the globe. (See Fig. 1.)

Contributing to this collective effort, the overall purpose of the International Long-Term Ecological Research Network (ILTER, https://www.

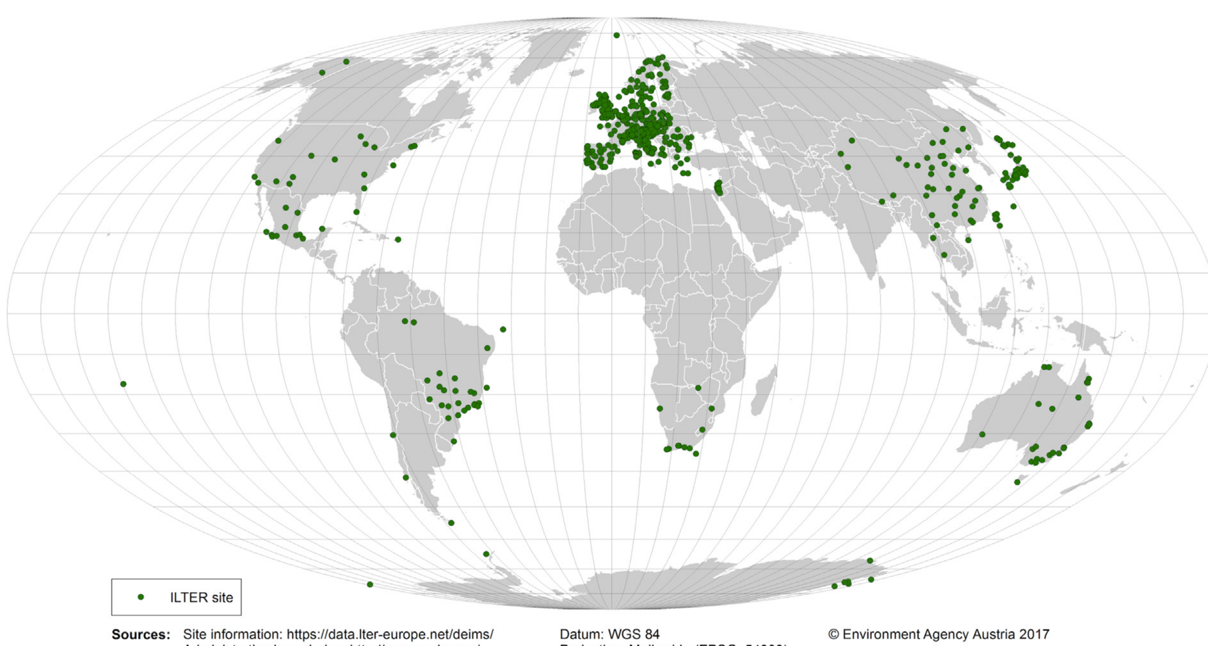

Fig. 1. Global distribution of ILTER in-situ facilities (sites, platforms). Dots in the ocean are either marine sites or sites on small islands. Based on DEIMS status as of 20th July 2017; all facilities with a documentation status of above 80% and formally acknowledged by their respective member network coordination are included.

ilternet.edu/) is to provide a globally distributed network and infrastructure of long-term research sites for multiple uses in the fields of ecosystem, biodiversity, critical zone and socio-ecological research, and to secure the highest quality interoperable services in close interaction with related regional and global research infrastructures and networks. ILTER is characterized by the following components and activities:

- A Global Research Infrastructure, comprising
  - o ~700 long-term ecological research (LTER) sites
  - o ~80 long-term socio-ecological research (LTSER) platforms
  - o a large data legacy gathered for more than a century
  - o increasingly standardized metadata on data and sites
- A network of 44 national networks and several (continental) regional groups with robust governance structures
- A partner within a network of related environmental research and observation networks, collaborating at all levels of organization (sites, countries, regions, global)
- A network of ~200 institutions
- A network of several thousand scientists (community)
- A network of multiple research disciplines
- A network of research teams working over decades at focal field sites
- A scientific knowledge factory reflected by tens of thousands of papers published on findings generated at LTER facilities and by LTER teams
- A strategic and structuring process
- A range of public good outputs including science education, outreach and environmental policy contributions

The high spatial and temporal resolution of ecosystem monitoring carried out at LTER Sites enables the detection of both slow, but significant, and extreme changes in ecosystem functioning responding to the presence, absence, mix and intensity of pressures/drivers. The ILTER whole-system approach helps understanding the influences and interactions of multiple and complex ecosystem variables including socio-economic factors (see PPD and DPSIR framework in Chapter 1.2). ILTER helps to overcome the short-term variability of the heterogeneous and distributed ecosystem research landscape by generating hot spots for interdisciplinary ecosystem research at well-equipped and geographically dispersed sites, operated in the long term by experienced research teams. The long-term engagement of such expert teams supports proper archiving and documentation of the ILTER data through an ever increasing number of data sets and assessments in different interdisciplinary contexts. Therefore, ILTER data represent an essential and irreplaceable legacy for documenting long-term trends in environmental conditions for science and policy, locally, regionally and globally.

In a nutshell, ILTER is unique among ostensibly similar research networks in that it features 1) a global network of ecosystem research sites in a wide range of biomes; 2) a focus on long-term, in-situ observation-based research; and 3) a coordinating structure working towards convergent research infrastructure development and strategies that integrate “bottom-up” and “top-down” approaches.

1.2. Conceptual background and uniqueness

The unifying approach for the elements and organization of ILTER inter alia as a Global Research Infrastructure (GRI) is based on four conceptual pillars (Fig. 2):

- **Long-term**: dedicated to the provisioning, documenting, continuous collection and use of long-term data on ecosystems with a time horizon of decades to centuries.
- **In-situ**: site-based data generation at different spatial scales across ecosystem compartments of individual *in-natura* sites, environmental zones and socio-ecological regions.
- **Process orientation**: identifying, quantifying and studying the interactions of ecosystem processes affected by internal and external drivers. As for socio-ecological systems ‘process orientation’ applies to both processes related to ecosystem services and to social processes (e.g. stakeholder engagement, multi-directional knowledge transfer, and collaborative decision-making; Haberl et al., 2006) required to facilitate transdisciplinary research and policy making.
- **Systems approach**: LTER enables the long-term investigation of ecosystems, Earth systems, environmental systems, socio-ecological systems, hydro-geo-ecosystems etc., in the long-term. The common denominators are „systems “(the Earth's biosphere system receiving solar energy as opposed to the deep Earth system), where abiotic and biotic components interact at different scales, and the human use of such systems and their services takes place. All these meanings of „system “are covered by the term „ecosystem “as used in the ILTER concept.

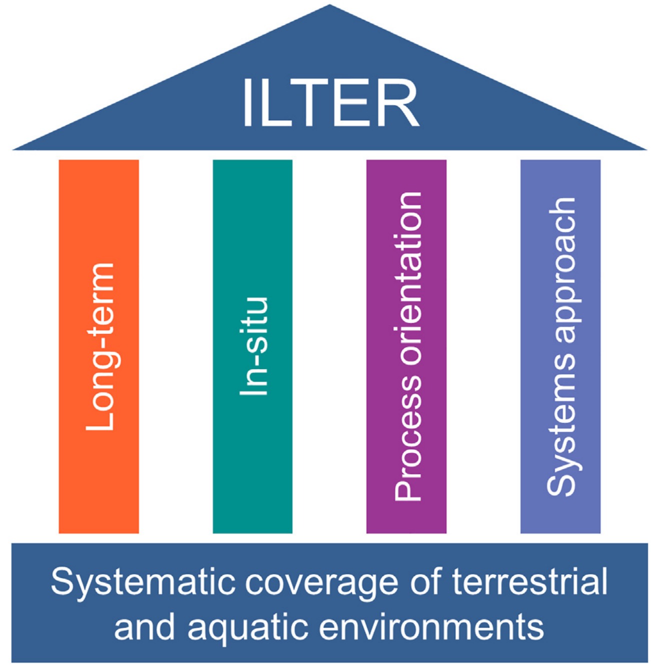

Fig. 2. The ILTER conceptual pillars.

ILTER's distributed network of several hundred sites implies wide-scale systematic coverage of major terrestrial and aquatic environments for multiple uses, enabling multi-scale approaches across broad socio-ecological transects (Fig. 2).

In practice, this means that all ILTER facilities have adopted an “ecosystem” or “whole-systems” approach in which key components of the system (e.g. drivers, pressures, states, impacts, responses (DPSIR) on ecosystem services and societal benefits and societal responses) are either appropriately observed over time or, if possible, subjected to manipulation and experimentation to support, e.g. predictive modeling. Further, ILTER's vision adopts an approach to socio-ecology as a transdisciplinary field integrating a broad array of social and natural sciences and humanities (including knowledge derived from non-academic stakeholders). ILTER activities therefore form an important component of holistic earth observation.

ILTER's common conceptual approach enables data and information from subsets of sites to be selected to address multiple environmental and social issues related to the effects of key drivers of global change. ILTER's global network of sites, therefore, provides a unique and adaptable platform supporting the foundational research needed to address large scale societal challenges in a way that cannot be provided by local, national or regional facilities acting alone. The uniqueness of ILTER - as a combination of the five conceptual pillars - in comparison with other networks was analyzed for the ILTER Strategic Plan 2006 (ILTER, 2006). More comprehensive studies have been carried out by the COOPEUS and RISCAPE projects (http://cordis.europa.eu/project/rcn/104476_de.html, http://cordis.europa.eu/project/rcn/206418_de.html). ILTER has been interrogated, analyzed and categorized in comparison with the major global elements of the landscape. The RISCAPE report will provide an objective evidence of ILTER's role in the global context.

This approach is in line with the Macro-Systems Ecology (MSE) conceptual scheme, which provides a unifying framework for the holistic study of ecosystems at broad spatial and temporal scales (Heffernan et al., 2014). This framework integrates biological, geophysical, and social concepts and treats the components of regions to continents as a set of hierarchically interacting parts of an ecosystem.

Integrating ILTER's various components, wide scope and research activities from national to global networks requires a unifying conceptual model that represents our current understanding of the Earth system, and applies across scales at which biodiversity and ecosystem research infrastructures are developed. The Press Pulse Dynamics model (PPD, Collins et al., 2011; Fig. 3) has been broadly used in ILTER for this purpose.

The PPD conceptual model is suitable for ILTER because it is dynamic (iterative and including feedbacks), holistic (including both the social systems and biophysical systems including the critical zone), and considers multiple spatial and temporal scales. It can be used to focus on long-term ecosystem, biodiversity, critical zone and social-ecological research agendas through the identification of, and connections among, six strategic research questions (H):

1. How do long-term press disturbances and short-term pulse disturbances interact to alter ecosystem structure and function (**H1**)?
2. How can ecosystem structures be both a cause and consequence of ecological fluxes of energy and matter (**H2**)?
3. How do altered ecosystem dynamics affect ecosystem services (**H3**)?
4. How do changes in vital ecosystem services alter human outcomes (**H4**)?
5. How do human behaviors and institutions respond to changes in the provision of ecosystem services (**H5**)?
6. Which human actions influence the frequency, magnitude, or form of press and pulse disturbance regimes across ecosystems and what determines these actions (**H6**)?

2. A short history

2.1. Incubation by NSF and US LTER

Although long-term ecosystem studies and monitoring programs have been established since the mid-1800's, and often addressed critical questions regarding natural resources management and policy (Bennett & Kruger, 2015), it was the National Science Foundation (NSF) of the United States of America (USA) that first coined the term “Long-Term Ecological Research” (LTER) and officially launched a competitive program of academic research grants in 1980 to:

1) initiate the collection of comparative data at a network of sites representing major biotic regions of North America, and
2) evaluate the scientific, technical and managerial problems associated with such long-term comparative research (US LTER Network Office, 1998)

Insights gained from the first thirteen years of the US LTER (Vanderbilt & Gaiser, 2017) resulted in a desire to establish LTER as an international network. Thus, the NSF initiated the inaugural meeting of the ILTER in 1993, attended by 39 scientists and administrators from 16 countries. The Network was launched with three members

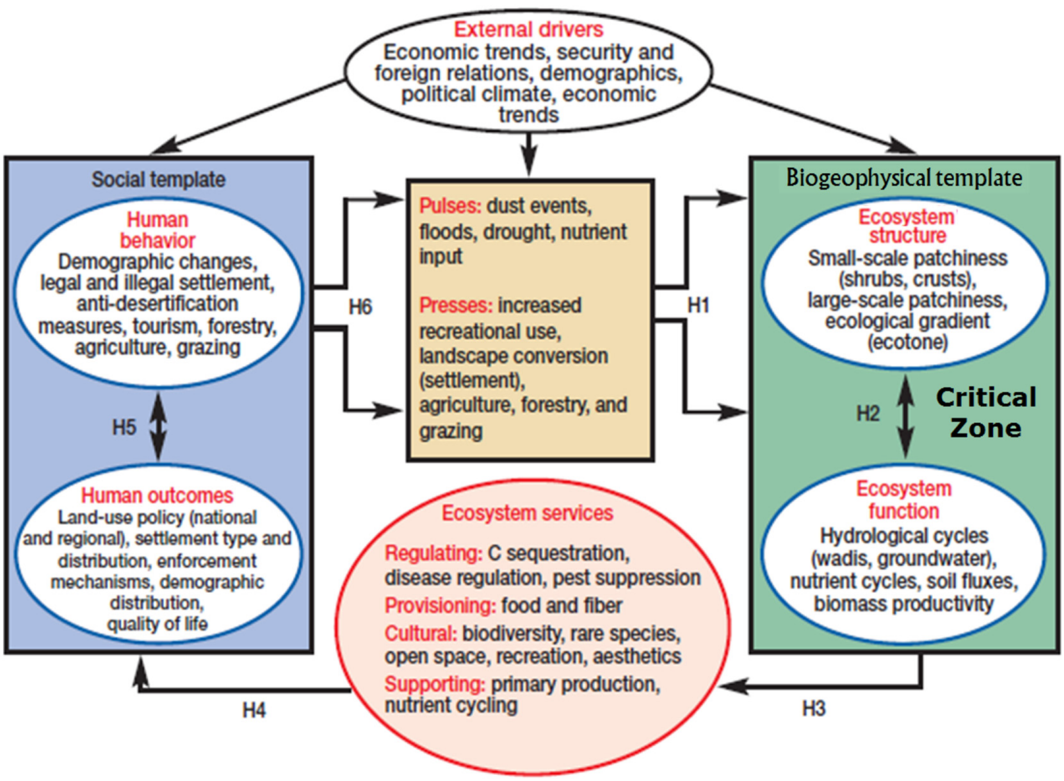

Fig. 3. Press Pulse Dynamics Framework as a basis for long-term, integrated, social–ecological research, including components of ILTER and Critical Zone. The right-hand side represents the domain of traditional ecosystems and critical zone research; the left-hand side represents traditional social research associated with environmental change; the two are linked by pulse and press events influenced or caused by human behavior and by ecosystem services, top and bottom, respectively, Collins et al., 2011, modified). Individual items shown in the diagram are illustrative and not exhaustive. H1 to H6 are explained below.

and the membership grew rapidly to 15 in 1998 (US LTER Network Office, 1998) with Jim Gosz (USA) as chairman. The NSF continued to support ILTER through the US LTER Network Office (ILTER, 2006). This *status quo* endured until the 2003 business meeting at which the NSF announced their intention to gradually withdraw their direct support for ILTER and their expectations that ILTER would become a self-reliant and truly international network.

2.2. ILTER taking flight

The ILTER responded positively to this challenge by electing non-USA chairs alternating between continents to reflect the globally shared responsibility (Hen-Biau King from Taiwan until 2006, Terry Parr from UK 2006–2011, Manuel Maass from Mexico 2011–2015, Michael Mirtl from Austria since 2015) and by selecting an executive committee consisting of six regional representatives. By 2006 the ILTER had 34 members and had developed and ratified a formal 10-year strategic plan including a policy statement and bylaws for operations (ILTER Strategic Plan, 2006). This strategic plan marked a formal transition of ILTER to a broader disciplinary approach than traditional LTER by calling on the expertise of researchers (biophysical and social-ecological), practitioners and other stakeholders (ILTER, 2006). In order to provide more depth to its operational structure while maintaining its “bottom-up” character, a new governance structure was designed (Chapter 3.3). Thus, over the three-year period from 2003 to 2006, ILTER broke new ground and turned into a truly self-organized global network with a unifying strategy, documentation and operational goals and by-laws.

Since 2006 till the present day, ILTER has made steady progress concerning fund-raising, proving its global value through fostering cross-site science, refining its organizational structure and procedures, and growing its coverage to 44 active member networks. Further, ILTER strengthened its networks' credibility through publishing standardized site information on DEIMS-SDR (Dynamic Ecological Information Management System Site and Dataset Registry). ILTER also created collaborative linkages with other global scientific organizations and established itself on the international conference circuit by successfully initiating an authentic tri-annual ILTER Open Science Meeting accessible to all like-minded scientists irrespective of membership status. The energy and leadership for this flowed from wholly voluntary, sustained and creative contributions by individuals and their respective organizations, despite the obvious challenges of cultural and language diversity, geography, international politics, and personal, financial and time constraints.

3. Network characteristics and major achievements

3.1. Network structure and categories of ILTER in-situ facilities

ILTER features a hierarchical organizational structure (Fig. 4). Member networks (in most cases countries) consist of LTER Sites and LTSER Platforms and usually contribute to related continental or Regional Groups. The four Regional Groups are: Europe (LTER Europe) and East-Asia-Pacific (EAP), and the informal Regional Groups “Africa” and “Americas”. Chapters 4.2 and 4.3 expand on the Regional Groups' role and achievements.

Shaping the in-situ facilities´ composition of ILTER has focused on (1) the fine tuning of a modular design that is globally applicable, (2) construction by drawing from extensive resources in 44 member networks, and (3) the identification of geographic and topical gaps, where appropriate existing sites need to be identified or new sites have to be established (e.g. Metzger et al. 2010, Mollenhauer et al., 2018). Also at the site level, ILTER features a hierarchical design (Fig. 5) with an increasing number of facilities and decreasing complexity and instrumentation towards the bottom of the hierarchy:

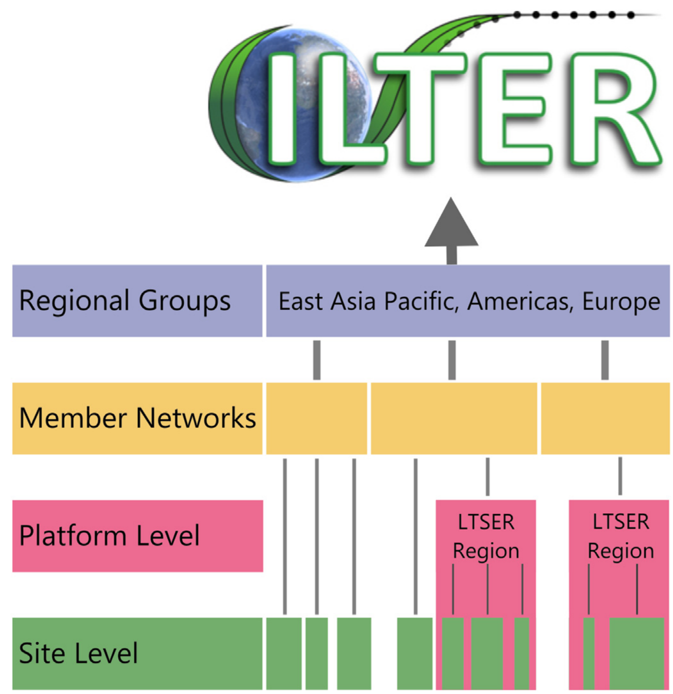

Fig. 4. Hierarchical organizational structure of ILTER. From bottom to top: LTER Sites and LTSER Platforms constitute Member Networks such as LTER China (CERN), US-LTER or LTER Germany. Member Networks organize in Regional Groups like LTER-Europe, often for reasons related to regional scientific foci, technical and funding aspects.

(1) Regional multi-scale and interdisciplinary case study areas (**LTSER Platforms**), comprising multiple smaller scale elements in a spatially nested design (Dick et al., 2018).
(2) Smaller scale ecosystem research sites (**LTER Sites**): for details see the supplementary material (Chapter 2).

a. Fully instrumented **LTER Master Sites** as hot spots for instrument-intensive research, ideally suited for co-location with more specific RIs, e.g. small scale experiments or specialized monitoring programs
b. **LTER Regular Sites** covering major ecosystem processes to allow analyses and assessments of overall ecosystem functioning (with a lower level of instrumentation and cost-efficiently customized according to the specific ecological profile of the site)
c. Well-connected **LTER Satellite Sites** for specific purposes (might be less equipped or extensive, but serving special purposes such as increasing coverage, monitoring larger scale processes to enable upscaling or monitoring species with regional relevance only)

(3) Design-link with large scale, representative environmental monitoring schemes (e.g. co-location with regular national air or water quality monitoring, e.g., EU Water Framework Directive)

The aspiration of ILTER is to create a global network of LTSER platforms with coverage across socio-ecological zones (Metzger et al., 2010). There has been great progress in this regard, with approximately 80 platforms currently established (Dick et al., 2018), albeit progress has been uneven over time and across geographic space (e.g. Metzger et al. 2010, Mollenhauer et al. 2018). These platforms serve as regional, inter-

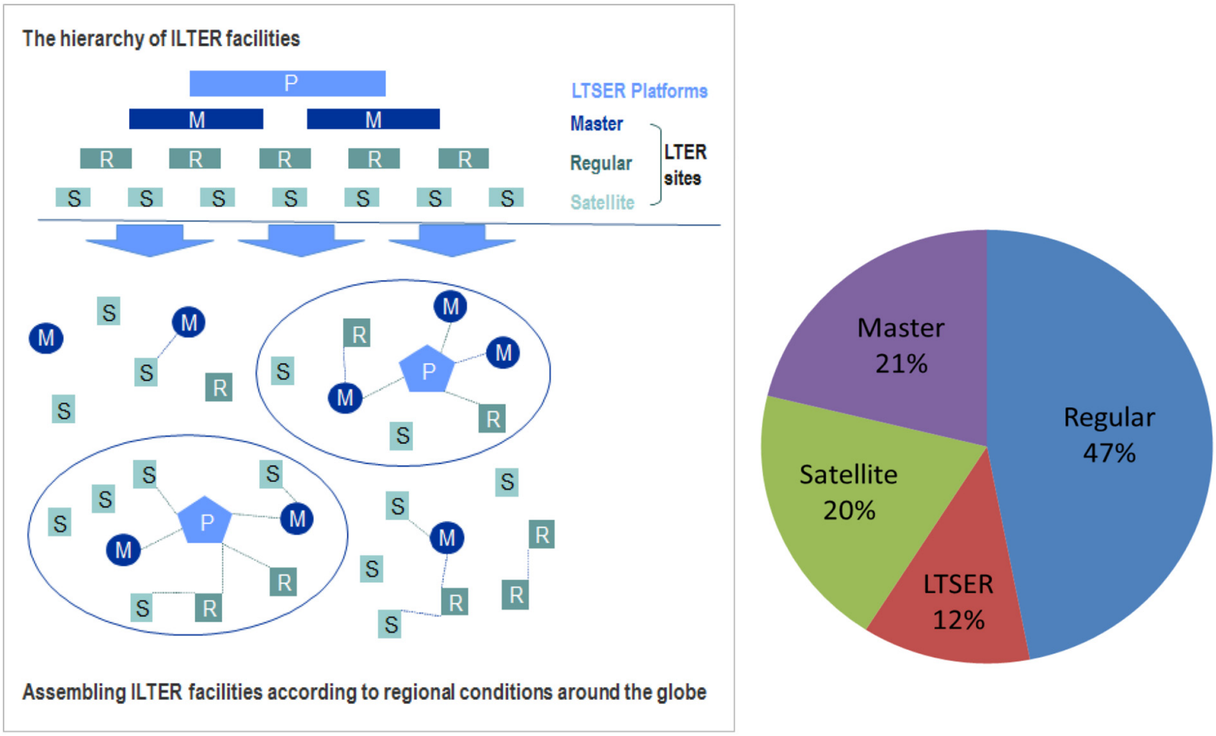

Fig. 5. Left: The hierarchy and spatial construction of ILTER facilities: LTSER Platforms, LTER Sites (Satellite, Regular, Master). Usually LTSER Platforms comprise LTER Sites of different categories, but LTER Sites can occur outside the LTSER Platform context; Right: Distribution of ILTER in-situ facilities across categories ($n = 688$).

and transdisciplinary case study areas for addressing the grand societal challenges of the 21st century within a reflexive, iterative and inclusive research framework (e.g. Dietz et al., 2003; Haberl et al., 2006; Jourdan et al., 2018; Ostrom, 2009; Singh et al., 2013). Indeed, cross-disciplinary work has become increasingly relevant for LTER Sites also at smaller spatial scales.

Fully instrumented Master Sites are integrated nodes between related research infrastructures (e.g., functional interfaces and co-location with C-flux monitoring and experimental networks), linking them up with the long-term data legacy of LTER. The in-situ LTER network is in many cases already complementary to e-infrastructures (e.g. LifeWatch and EUDAT in Europe; DataOne globally).

3.2. Network development and status

ILTER has been continuously growing since its foundation with up to three membership applications per year, reaching a total of 44 member networks (mostly countries). Member networks can be formally inactive with respect to participation in international activities. New member networks that wish to become formally acknowledged by ILTER are usually supported by LTER representatives of neighbor countries or the respective ILTER Regional Group and are required to provide (1) an Expression of Support of a related national authority, (2) a physical network of in-situ facilities, (3) a data policy and (4) a formal application presentation to the ILTER Coordinating Committee. As an interim status, sites in countries that do not yet have a formal member network can become affiliated sites. Details about the Member Networks are presented in the supplementary material, Chapter 1.

ILTER has invested substantial effort since 2015 to achieve a globally comparable documentation and categorization of LTER facilities by the end of 2017. This endeavor comprised the specification and adoption of ILTER facility categories (Chapter 3.1), the establishment of 36 mandatory attributes describing these facilities (sites, platforms; see supplementary material, Chapter 5), a globally distributed registration, documentation and acknowledgement process, as well as the development of supporting IT services in the DEIMS Site and Dataset Registry (DEIMS-SDR, Chapter 3.4). In this respect ILTER Accredited Sites are defined as long-term facilities belonging to an ILTER member network reaching the accreditation criteria that include a clear conceptual design and sufficient documentation of the site in DEIMS-SDR and datasets. ILTER Affiliated Sites: If a country lacks an ILTER related network, but one or several individual sites or platforms are interested in collaborating within ILTER, they may become affiliated as a nucleus for a possible future ILTER Member Network.

From October 2017 onwards, only ILTER facilities with full documentation in DEIMS-SDR and accreditation by the related member network will be formally acknowledged by ILTER. The established services provide a reliable network status for various stakeholders, ranging from researchers in search of data and suitable sites for emerging research projects to funding shareholders requiring an overview of available RIs.

The following figures (Figs. 6–9) provide an overview of the ILTER physical site network and the distribution of selected site characteristics.

3.3. Governance

ILTER has established a solid and professional governance structure that comprises the following elements (Fig. 10):

ILTER Members are in most cases national LTER networks, consisting of scientists collectively engaged to conduct scientific research according to the ILTER mission, vision and goals. The ILTER Coordinating Committee (ILTER CC) is the main body of designated representatives of the ILTER Member Networks (see below)

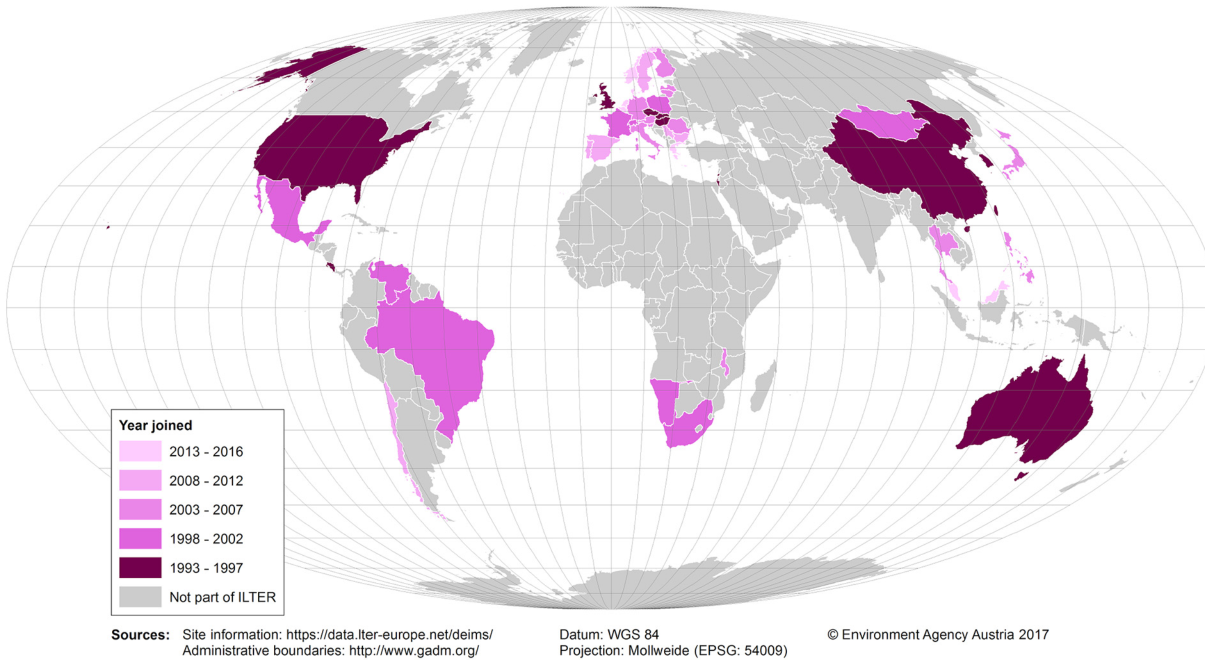

Fig. 6. ILTER member networks and year of accession to ILTER. Founding members (dark magenta) and highly dynamic regions such as Europe are clearly visible.

and it is ILTER's primary decision-making body, whereby each ILTER member has one vote. The ILTER CC convenes annually and holds telecons during the year. The ILTER Executive Committee (ILTER EC) is responsible for day-to-day organizational aspects of ILTER between the ILTER CC meetings. It is responsible for putting decisions taken by the ILTER CC into action. The ILTER EC interacts virtually through monthly teleconferences. The members of the ILTER EC are the ILTER Chair and Co-Chair, the chairs of the ILTER Regional Groups, the chairs of selected ILTER Committees (e.g. Science Committee and Information Management Committee) and the ILTER Secretary.

In 2007, the ILTER Association was founded in Costa Rica, so that ILTER became a legal entity on its own and its Member Networks formally joined this association. The obligations and rights of these structural elements, their interaction and functioning is defined in the ILTER bylaws (https://www.ilter.network/?q=content/governance). For the ILTER communication strategy see supplementary material, Chapter 7.

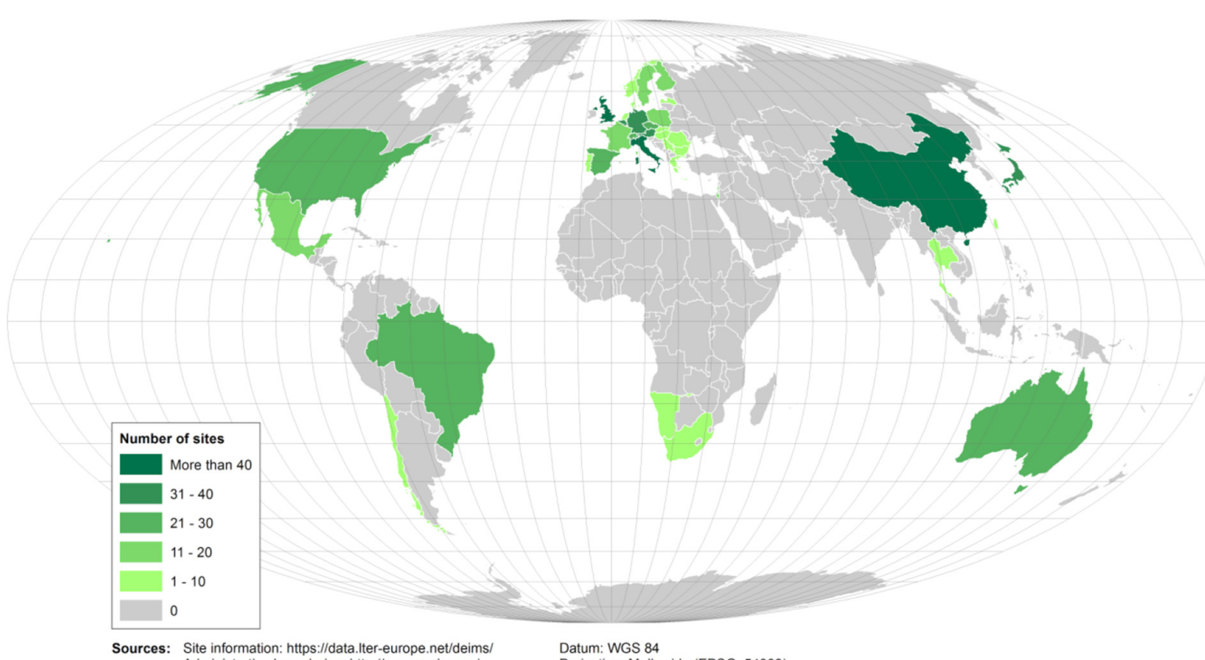

Fig. 7. Number of in-situ facilities (sites, platforms) per member network. Based on DEIMS status as of 20th July 2017; all facilities with a documentation status of above 80% and formally acknowledged by their respective member network coordination are considered in the figures.

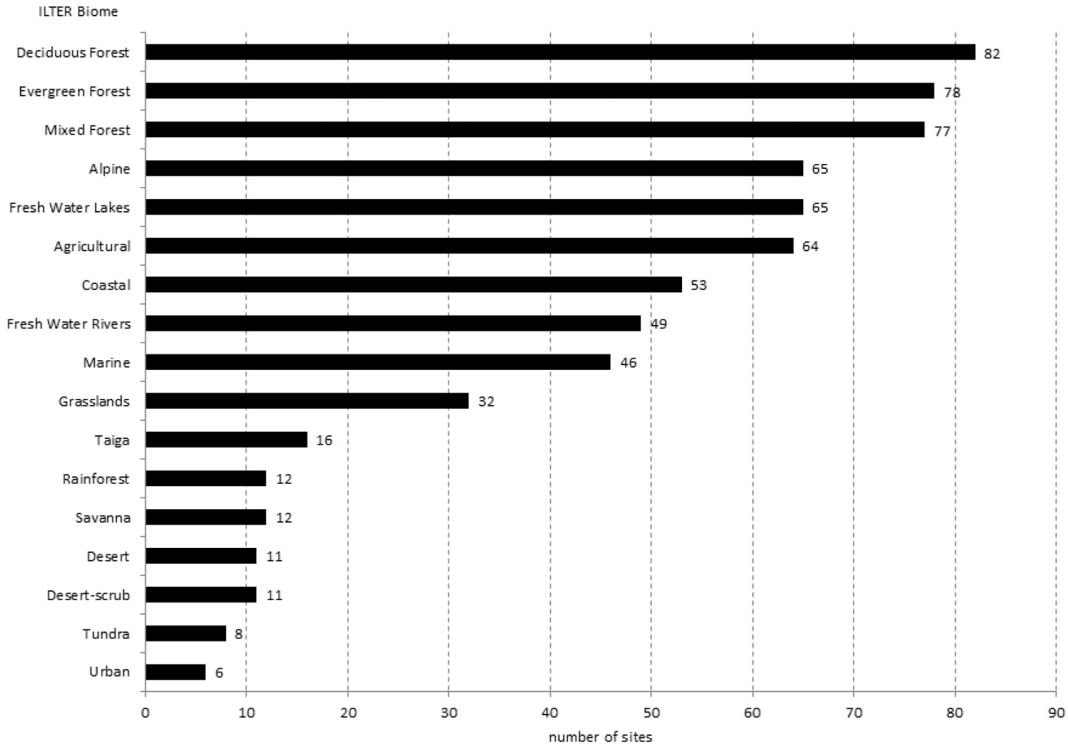

Fig. 8. Distribution of in-situ facilities across ILTER biomes (WWF 2017; $n = 690$).

3.4. Network level data management services and standards

One of the goals of ILTER is to improve the comparability of long-term ecological data and site metadata around the world, and facilitate exchange and preservation of these data. ILTER member networks are committed to free and open data sharing (Vanderbilt et al., 2010) to support science on all levels. The ILTER data infrastructure is based on existing data infrastructures provided by different member networks or regional nodes (Vanderbilt et al., 2015), most prominently US-LTER, LTER South Africa (SAEON), LTER-Australia (TERN/LTERN), LTER-Europe (eLTER, eLTER RI), LTER-Taiwan (TERN), LTER-China (CERN/CEOBEX) and LTER UK (ECN). Many other member networks are not so advanced and have limited resources to develop their own systems. Therefore, the ILTER Information Management Committee is working on different projects that aim to enhance the discoverability and reusability of long-term research data on a global scale. This includes activities on (a) common metadata schemas and semantics, (b) common documentation of research sites, (c) common documentation of

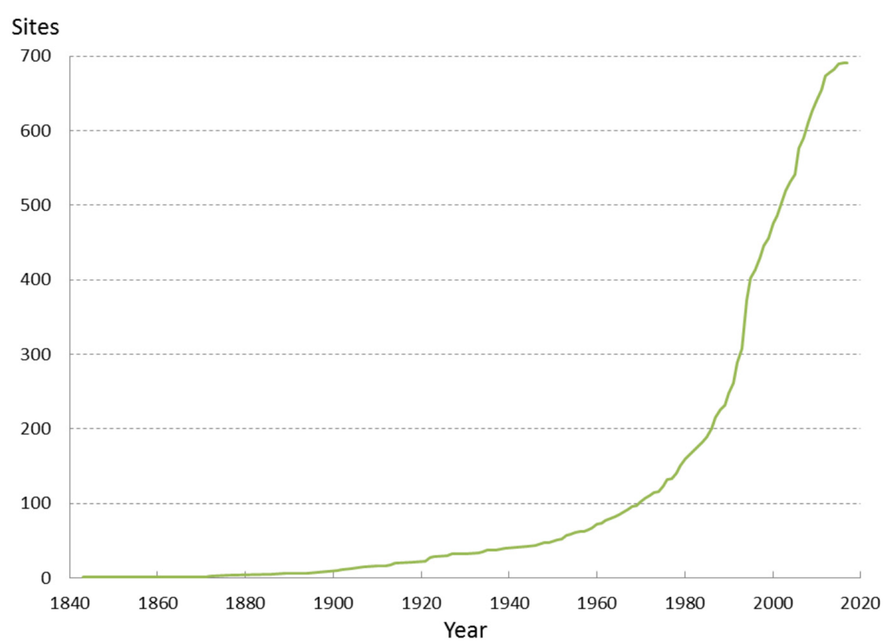

Fig. 9. Year of establishment of ILTER in-situ facilities, showing continuous growth with highest growth rates in the early 1990s ($n = 691$). [Source: ILTER].

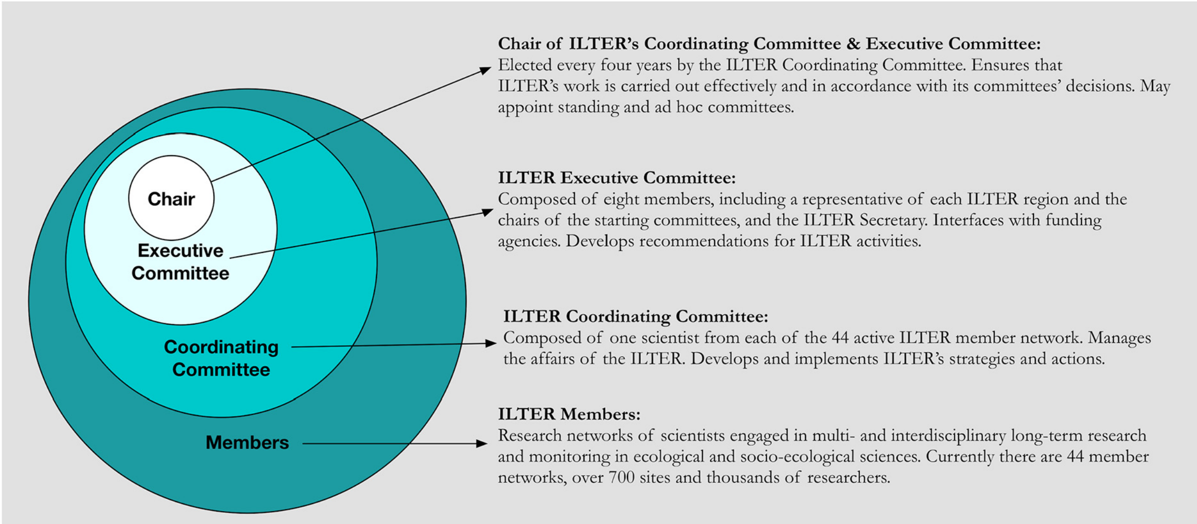

Fig. 10. ILTER membership and governance structure (https://www.ilter.network/?q=content/governance).

datasets, (d) a catalogue of datasets across the different data resources, and (e) a common sharing policy.

3.4.1. Common metadata standards

ILTER adopted the Ecological Metadata Language (EML, Michener et al., 1997) as a common metadata language (Vanderbilt et al., 2010). For European sites the additional use of the INSPIRE metadata specification (European Commission, 2008, 2014), which is based on ISO19115/19139, is recommended (Kliment & Oggioni, 2011).

3.4.2. Common semantics

The Environmental Thesaurus (EnvThes, http://vocabs.ceh.ac.uk/evn/tbl/envthes.evn, Schentz et al., 2013) was developed to provide a common and stable semantic backbone for documenting research sites, data products and datasets. EnvThes extends the US LTER Controlled Vocabulary (Porter, 2010) with links to other controlled vocabularies. It is open, based on current semantic web standards (SKOS and SPARQL) and supports multilingualism.

3.4.3. Common site catalogue

The *Dynamic Ecological Information Management System, DEIMS-SDR* (http://data.lter-europe.net/deims/) provides a common and standardized catalogue for the distinct identification of observation facilities (e.g. sites, stations, sensors, datasets, persons) used by ILTER (https://data.lter-europe.net/deims/tutorial/ilter-fields). The DEIMS-SDR is based on Drupal 7 and an extension of the current version of DEIMS (Version 2) was developed by US LTER (Gries et al., 2010). For each research site, a landing page is provided featuring information on the site itself, as well as additional, related information (e.g. datasets and data products). An exchange format for site information, based on INSPIRE Environmental Monitoring Facility application schema, (http://inspire.ec.europa.eu/documents/Data_Specifications/INSPIRE_DataSpecification_EF_v3.0rc3.pdf) was developed.

3.4.4. Common metadata registry

DEIMS-SDR also provides a web-based service to document and share scientific datasets if a local or national repository is missing, implements the ILTER community profile (Kliment & Oggioni, 2011) and allows the export to different XML formats (e.g. EML 2.1.1, BDP, ISO19115, INSPIRE). In addition, the DEIMS-SDR includes a direct link to upload datasets e.g. on the open eScience data sharing platform B2SHARE (Ardestani et al., 2015).

3.4.5. Common discovery catalogue

The ILTER information management community identified DataONE, a distributed network of data centers (Michener et al., 2011, 2012), as a facility to share and distribute ILTER data. In order to be ingested by DataONE, the metadata must conform to the Ecological Metadata Language (EML) (Vanderbilt & Gaiser, 2017). ILTER also shares data through the GEOSS (Group on Earth Observation System of Systems, http://www.geoportal.org/) Data Portal. Here either EML, ISO19115/19139 or the INSPIRE metadata profile could be used as common standards.

3.4.6. Common sharing policy

Along with advances in the technical integration of data, the cultural and social aspects of data sharing are thoroughly addressed by ILTER (Vanderbilt et al., 2015; Vanderbilt & Gaiser, 2017). When using data on a global scale, data integration supported by 'machine-to-machine' interaction must be ensured, which is often difficult due to varying provenance and data ownership. While agreeing on open data in principle at the global scale, putting the common data sharing principles into practice is still an issue in many of the member networks and at the local level. Providing practical experiences at various organizational levels and across working cultures around the globe, ILTER contributes to the identification of technical, legal and policy bottlenecks (Kissling et al., 2015). Accordingly, one of the key tasks of the ILTER Information Management Committee will be the definition of common standardized licenses which can be applied to the data shared within the ILTER community.

3.5. Multiple user communities and multiple usages of the ILTER facilities

As outlined above, the ILTER network covers a wide range of ecosystems (terrestrial, freshwater, transitional waters), disciplines and research foci (from basic ecosystem research to applied and sustainability research). Accordingly, LTER Sites and their long-term data are used by multiple scientific disciplines and user communities:

3.5.1. Researchers, authorities, citizen science

LTER Sites have long-term experience in securing basic infrastructure (power supply, towers, data transmission) and operation (baseline ecosystem monitoring of standard parameters, maintenance, data nodes), and adapting to the needs of various user communities (flexible site designs). Scientific users, authorities (e.g. to fulfill legislation like the EU Habitat directive) and citizen scientists can focus on different system components and therefore use different subsets of the basic ILTER infrastructure (installations, long-term data). The ILTER infrastructure also provides an ideal foundation for short-term experiments. Moreover, projects or even specialized research infrastructures might cost-efficiently integrate more specific installations at LTER facilities and thereby contribute to unique knowledge and data hot spots. The transdisciplinary structure of LTSER Platforms allows for the integration of a broad base of stakeholders (policy makers, economic interests, local residents, community activists, etc.) into the scientific process. Periodic meetings, social research and an open conduit for communication are built into the research design to assure two-way learning between scientists and stakeholders, participation of stakeholders in every phase of the scientific process, social relevance of the research, and maximum potential for policy uptake (Haberl et al., 2006; Singh et al., 2013).

3.5.2. Critical Zone (CZ) science

A flagship example of multiple usage of LTER site infrastructure is the interaction with Critical Zone research (see Supplementary material, Chapter 3). The CZ Observatories (CZO) approach has much in common with the whole-system approach (often watersheds) used by ecosystem ecologists (incl. ILTER) to quantify nutrient cycling and energy flow through a landscape. For both disciplines, there is a strong congruence in size of watershed (typically from a single ha to hundreds of km^2); a focus on quantifying water and nutrient inputs, outputs and storage/transformations; and a disciplinary focus on the biotic-abiotic linkages that govern energy flow and movement of solids and solutes through a landscape. A harmonization of ILTER and CZ research would provide large benefits to both communities. This would require several steps, including 1) development of a shared vision for Critical Zone science using an observatory approach (internal harmonization), and 2) development of better cross-disciplinary understanding of the LTER and CZ research approaches (cross-network harmonization). Such a harmonization would be enhanced by co-location of sites, which has already been formalized in China, Australia and Europe. In Europe specifically, harmonization is further facilitated by eLTER RI which is being constructed as a generic infrastructure for joint usage.

3.5.3. Socio-Ecological Systems or Human-Environment Systems research (SES, HES)

Increasing the spatio-temporal scale of ecosystem research and its field sites from small plots or small catchments to cultural landscapes and regions systematically expands the scope of ecosystem research to include socio-ecological systems. The related infrastructures of LTSER platforms form an integral part of the eLTER Infrastructure in Europe (Mirtl et al., 2013). These areas consist of clusters of sites plus the required soft infrastructure for inter- and transdisciplinary regional studies (communication platforms, stakeholder interactions, cross-domain data integration). Such studies integrate qualitative and quantitative methods at multiple scales, natural and human/social science competence, as well as stakeholder collaboration, and thus support the development of regionally adapted approaches, e.g. in spatial planning (Dick et al., 2018).

In conclusion, with its well-documented sites across all continents, the ILTER network is well poised to further advance the concept of site usage by various user communities and serve as a generic backbone infrastructure for ecosystem ecology, critical zone and socio-ecological research. The power of the ILTER site documentation is such, that proper candidate sites can be easily chosen for individual research projects and joint campaigns. Developing an understanding of the connections between different ecosystem compartments, and between past and present, will pay large dividends in protecting and enhancing the ecosystem services that support human societies.

3.6. Science initiatives

3.6.1. Overview

Within ILTER several science initiatives have been organized and implemented to foster international research collaborations (Table 1). These mainly bottom up initiatives usually receive a seed grant from ILTER and cover various research disciplines and topics such as community ecology, biodiversity, biogeochemistry, ecosystem service, socio-ecology, water and material cycles, sustainability and resilience (Wall et al. 2008; Vihervaara et al. 2013; Shibata et al. 2015; Rozzi et al. 2015; Tang et al. 2016; Maass et al. 2016, Müller et al. 2016). New findings and scientific outcomes of these initiatives were presented at ILTER's 1st Open Science Meeting (OSM) in Kruger National Park, South Africa in October 2016. Overall >160 oral presentations, >70 posters and >10 keynote talks were presented at the OSM providing an excellent overview on current scientific achievements of the ILTER network, emerging research questions, individual case-studies and international collaborative studies (e.g. GEO, IPBES, INI and others, Chapter 4.1).

In the recent years, ILTER members initiated research programs to utilize the innate advantages of the ILTER network (Table 1). Below, we expand upon two of these, and focus on their value as a “proof-of-concept” regarding the scientific benefits offered by the network.

3.6.2. Litter decomposition initiative – TeaComposition

Litter decomposition represents one of the largest fluxes in the global terrestrial carbon cycle and diverse, large-scale decomposition experiments have already been focusing on this fundamental soil process. However, these are most often conducted using site-specific litters and methodologies, which makes comparison of data across different experiments and sites challenging due to the lack of common protocols and standard matrices. To overcome these constraints, the ILTER TeaComposition initiative uses a standardized TeaComposition method and has applied this method at 450 (mainly ILTER) sites across the globe (Djukic et al., in press; Fig. 11) involving two types of tea: Rooibos tea (slow decomposition rate) and Green tea (faster decomposition rate). The teas are incubated at a standardized soil layer and at a specific time in year for the period of 3 years (with several sampling points during the incubation). The overarching goal of the TeaComposition initiative is to study temporal litter decomposition and its key drivers for the present and predicted climate scenarios worldwide, which in turn should provide a “common metric” for decomposition comparison across the sites, ecosystems and biomes.

3.6.3. Nitrogen initiative

Nitrogen (N) is an essential element for life, and most living organisms can only make use of reactive nitrogen, which includes inorganic forms of nitrogen like ammonium, nitrate, and organic N compounds like urea, proteins, and nucleic acids. Too much nitrogen in the environment results in various threats to ecosystems and society (Sutton et al.

Table 1
Example of the on-going active ILTER science initiatives (as of 2017).

Themes (names) of ILTER research initiative	Principal investigator
Nitrogen	Hideaki Shibata
Litter decomposition: “TeaComposition”	Ika Djukic
Diversity - stability hypothesis	Elli Groner
Herb layer biodiversity: ForestREplot	Kris Verheyen
Stewardship of social–ecological systems: PECS	Manuel Maass
Socio-ecohydrology	Kinga Krauze
Lichens as indicators for atmospheric nitrogen pollution and climate change[a]	Pedro Pinho
TRAIL - Long-term ecological research for citizens[a]	Caterina Bergami
Data integration across continents[a]	Michael Liddell

[a] Recent initiatives based on a broadly ILTER call from 2016 for new bottom-up initiatives.

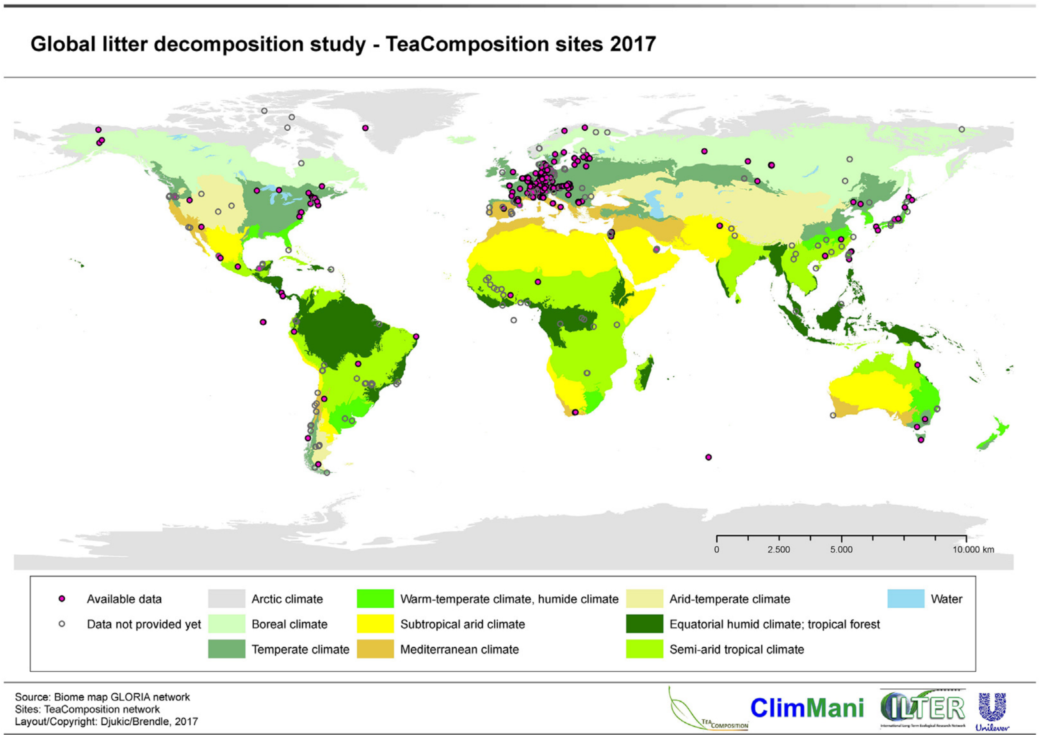

Fig. 11. Distribution of LTER Sites and sites of other networks involved in the ILTER TeaComposition initiative across the nine zonobiomes (Djukic et al., in press).

2013). The ILTER-Nitrogen initiative was launched at the ILTER annual meeting in Sapporo, Japan in 2011 and is driven by the overarching question: "What are the ecosystem responses to reactive nitrogen changes across global ecosystems?" with three focal topics (i) the use of lichens for bio-monitoring of nitrogen pollution, (ii) global analysis of the factors driving N_2O emission from soils, and (iii) understanding the long-term legacy impact (i.e. previous environmental changes and various human perturbations) on current nitrogen cycles and budgets locally, regionally, and globally. Cross-site comparisons and meta-analysis using long-term site-based data from multiple LTER Sites have been conducted (Shibata et al. 2015). Also, an international training program (including lectures and field demonstrations) was organized to expose young researchers to state-of-the-art analysis of nitrogen cycling in ecosystems with a focus on key ecosystem processes and implications for environmental pollution (e.g., in Japan 2016; http://shibahideaki.wixsite.com/ilter-n2016 and Portugal 2017).

3.7. Key indicators of scientific output

In 2013, ILTER compiled a bibliography of all LTER research outputs (Li et al. 2015). Research outputs included scholarly articles, book chapters, theses and dissertations, popular news articles, edited volumes, commissioned reports, patents, data and metadata descriptions of data, poster and presentation abstracts, meeting and workshop proceedings, compendia, and other materials compiled by regional, national, and local ILTER networks and sites. In total, over 30,000 research outputs and over 30,000 (meta) data outputs were collected from most of the 40 ILTER networks, spanning approximately 40 years of research (Li et al. 2015).

In a new Google Scholar search for the terms "LTER" OR "ILTER" OR "long-term-ecological-research" OR "long-term-ecosystem-research" OR "Long-Term-Ecological-Research-Network" OR "Terrestrial-Ecosystem-Research-Network" OR "Chinese-Ecosystem-Research-Network" OR "South-African-Environmental-Observation-Network" OR "Environmental-change-network", 141,930 research outputs from 1993 to 2016 resulted (Fig. 12). The same search conducted in the Web of Science (thus restricted to ISI publications) yields 951 hits (Fig. 12). Both search results, however, show a clear increase in research output of the ILTER network over time as well as an increase in publications per LTER Site (Fig. 12).

The quite low number of ISI publications retrieved from the Web of Science search might be explained by two different issues: First, a search in the Web of Science is restricted to title, keywords and the abstract and second, several ISI publications may not mention any of our search terms even in the entire manuscript even though the publication is a product of ILTER activities. Although we cannot clearly distinguish between these two potential effects we compared publication lists provided by national networks with our search results from the Web of Science (Fig. 13) and estimated that a more reasonable number of ISI publications is four to five times higher.

In conclusion, as shown by Li et al. (2015) and our basic search outlined above, there is an impressive and still increasing research output by the ILTER network. To ensure a more accurate report in future, LTER Site data users should also be encouraged to consistently refer to ILTER by including the term `ILTER´ at least in the list of keywords.

Beside these literature surveys, ILTER scientists and national networks recently published special issues in different ISI journals. In 2016, the German LTER network published a special issue in Ecological Indicators (Haase et al. 2016) compiling 13 research articles from German LTER Sites and two LTER Sites from Finland and Japan. The UK LTER network (Environmental Change Network; ECN) also published a special issue in 2016 in Ecological Indicators covering in total 15 articles (Sier & Monteith 2016). Over the past two decades, the topic of ecosystem services (ES) has attracted significant attention and progress has been made in improving our understanding of ecosystems functions and how humans benefit from them. Consequently, two further special issues covering topics such as linking biodiversity indicators and ES, quantifying trade-offs among multiple ES, predicting ES changes under varying scenarios (climate, land use, deposition), and developing modeling environments have also been published (Fu et al., 2013, Fu and Forsius 2015).

During the 1st ILTER Open Science Meeting in South Africa, two further ILTER special issues were initiated. While the special issue in

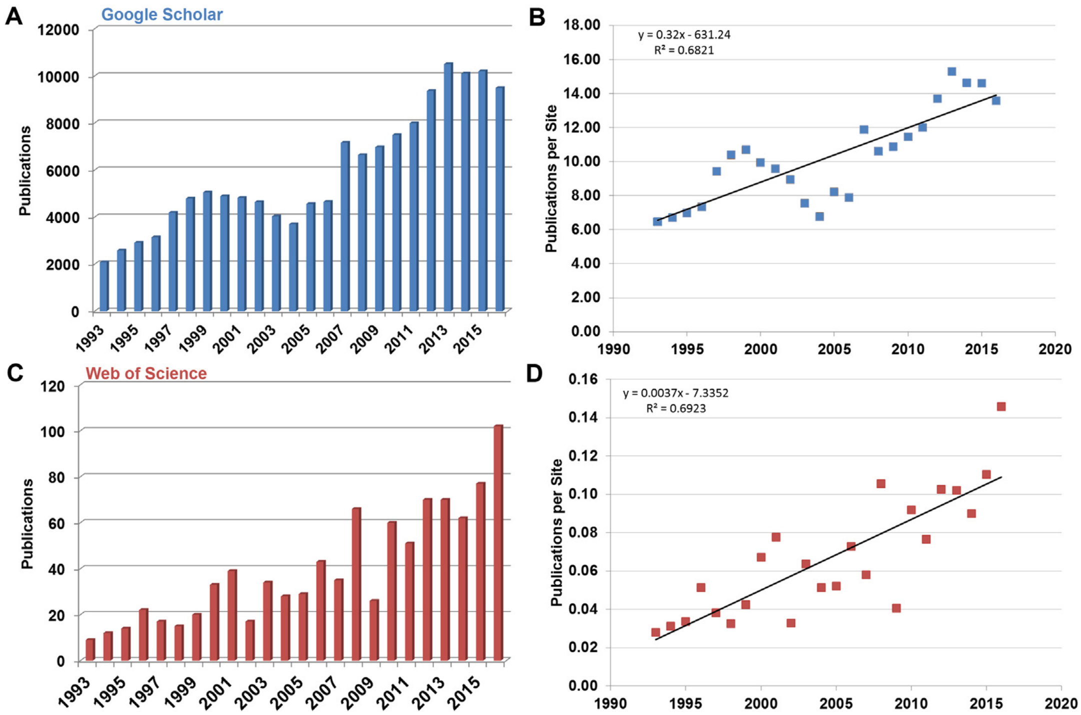

Fig. 12. Publications per year based on a Google Scholar (A) and a Web of Science (C) search, and publications per site reflecting the increase of LTER sites over time (Google Scholar (B) and a Web of Science (D) search).

Science of the Total Environment (Haase et al., in progress) focuses on large-scale and cross site comparisons, the second special issue in Regional Environmental Change (Dirnböck et al., in progress) compiled examples from a broad variety of LTER Sites across the globe. In addition, various review articles covering different topics were published (e.g. on LTSER, Dick et al., 2018).

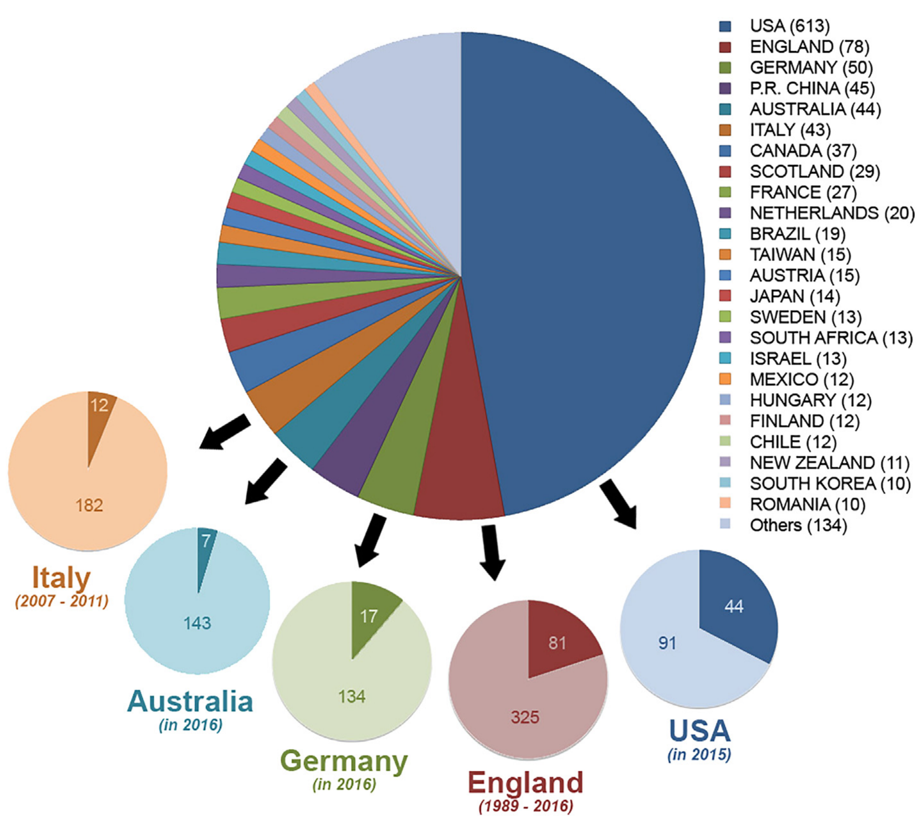

Fig. 13. Publications by country found by a Web of Science search. Absolute numbers are given in the legend. For selected countries we verified our findings from the Web of Science search with information received from the respective country. The numbers in the lower charts indicate the percentage of actual publications that we found in the Web of Science. Based on availability of data, we considered different time series here (given in brackets).

4. Global embedding, pioneering regional LTER developments and large scale policy implications

4.1. Global embedding and partnerships

ILTER collaborates with partners in different roles or combination of roles in the following areas: (1) in-situ observation and research, e.g. GEOBON, GTOS, UNESCO WNBR, PECS; (2) services, tools and data provisioning, e.g. GLP, GEO-DAB, FutureEarth; (3) science-policy interactions framework, e.g. INI, IPBES. These examples (indicated by acronyms) are briefly described as follows:

Since November 2016, ILTER is a Participating Organization of **GEO (Group on Earth Observations)** and ILTER representatives contribute to the GEO In-Situ Observation Resources Foundational Task. ILTER's DEIMS-SDR is currently brokered into the GEOSS (Global Earth Observation System of Systems) Common Infrastructure (GCI) and was adopted as a prototype for a global observation site registry across networks. The many LTER Sites provide a wealth of high quality surface data, which makes them suitable as a global calibration, validation and verification facility for Remote Sensing (RS) data providers. In turn, ILTER already uses RS based data products (e.g. in the Asia-Pacific Biodiversity Observation Network AP BON). Recently, ILTER and GEO BON scientists suggested a core set of environmental variables to be measured at monitoring sites (Haase et al., 2018). ILTER's experiences, component networks and databases represent a major asset for re-establishing the Global Terrestrial Observation System GTOS. In the GEO Carbon and GHG (Greenhouse Gas) flagship initiative, ILTER may have a role to provide data and information on underlying ecological processes and filling observation gaps in the terrestrial domain for regional and global carbon and GHG budget analysis.

The Global Land Program (GLP) is an interdisciplinary community of science and practice fostering the study of land systems and the co-design of solutions for global sustainability (https://glp.earth/). Collaboration examples include the usage of LTER Site metadata in GLP representatives analyses and joint training activities, e.g. on land-related sciences with socio-ecological topics for PhD students (Shibata and Bourgeron 2011).

The **Program on Ecosystem Change and Society (PECS)** aims to integrate research on the stewardship of socio–ecological systems, the services they generate, and the relationships among natural capital, human wellbeing, livelihoods, inequality and poverty (http://www.pecs-science.org/). PECS was launched by the International Council for Science (ICSU) and (UNESCO), and became a core project of FutureEarth (see below) in 2014. A team of ILTER researchers (Maass et al. 2016) contributed to a special PECS Feature: “Knowledge for Sustainable Stewardship of Social-ecological Systems”.

Interactions with the **Intergovernmental Panels on Biodiversity and Ecosystem Services (IPBES) and Climate Change (IPCC)** consist of the provisioning of status and trend data at different scales, as well as resulting publications. IPBES provides policymakers with scientific assessments about the state of knowledge regarding the planet's biodiversity, ecosystems and the benefits they provide to people, as well as the tools and methods to protect and sustainably use these vital natural assets (www.ipbes.net). ILTER encourages all members to participate in the ongoing IPBES review process at several levels by providing alerts regarding relevant findings. Mutually, IPBES and IPCC reports and strategic papers contribute to identifying knowledge gaps and key LTER research questions.

Critical Zone Observatories (CZO) were introduced earlier and linkages to ILTER were shown in Chapter 3.5 and Supplementary material, Chapter 3. In 2017, a joint survey of the geo-hydrological models used at LTER Sites and CZOs was undertaken (Baatz et al., in review). Next collaboration steps are workshops on integration options (2017) and future integrated modeling efforts across observatory networks (2018).

The **US National Ecological Observatory Network (NEON)** will provide data from sensor arrays (aquatic and terrestrial) as well as physical grab samples for biogeochemical fluxes, community structure, and net energy and water balance. Data are collected from over 100 US sites. Partnerships with many US LTER sites are developing, in which LTER provides long-term context and ancillary measurements with which to evaluate the high-intensity data produced by NEON. NEON has been used as a reference for standard environmental observation design in several ILTER component networks (e.g. TERN, a Memorandum of Understanding signed in May 2013). At the global level an ILTER-NEON Memorandum of Cooperation was adopted in 2017.

Composed of 669 biosphere reserves in 120 countries **the World Network of UNESCO Biosphere Reserves (UNESCO WNBR)** promotes North-South and South-South collaboration and represents a unique tool for international co-operation through sharing knowledge, exchanging experiences, building capacity and promoting best practices. Given the focus on biodiversity and ecosystem services, there are intrinsic linkages between Biosphere Reserves, specifically those with a strong research component, and LTSER Platforms. Cooperation at sites that are both ILTER facilities and Biosphere Reserves will be strengthened. A special emphasis will be on developing countries and on ways to improve the capacities in performing standard measurements on ecosystem change and its drivers in accordance with GEO/GEOBON concepts. WNBR recommends Biosphere Reserves with a strong research focus to register and document their sites in DEIMS.

FutureEarth (FE) is a 10-year initiative to advance Global Sustainability Science, build capacity in this rapidly expanding area of research and provide an international research agenda to guide natural and social scientists working around the world (www.futureearth.org). Main potential fields of interaction relate to (1) global e-infrastructures for environmental change research and ILTER's related web service DEIMS, and (2) using the knowledge-interaction network of FE as part of ILTER's science-policy framework.

The **International Nitrogen Initiative (INI)** is a global research program with the overall goal to optimize nitrogen's beneficial role in sustainable food production and minimize nitrogen's negative effects on human health and the environment resulting from food and energy production (www.initrogen.org/). ILTER has a strong linkage to INI, especially through the recently launched INI program “Towards INMS” (International Nitrogen Management System; http://www.inms.international/), which aims to improve the understanding of the global and regional N cycles and investigate and test practices and management policies at the regional, national and local levels with a view to reduce negative impacts of reactive nitrogen on the ecosystems. Various data and research findings from LTER Sites across the globe are expected to contribute to the global N assessment in the Towards INMS projects in the coming years. (www.initrogen.org/.)

4.2. ILTER's pioneering regional and national network developments

ILTER has, ever since its beginnings, benefitted from the triggering effect of strong member networks and regions. ILTER has continuously capitalized on member networks setting the pace in different fields, ranging from scientific initiatives (e.g., N-initiative/ Japan) to IT-developments (e.g., DEIMS by US LTER & LTER-Europe), new research trends (LTSER in Austria, Chile, Romania and France) and – last but not least – the re-design of entire national ecosystem research infrastructures (e.g., in South Africa). These triggering roles shift across Member Networks and regions mainly according to the timing of respective national or regional scientific and RI strategies, — and related investments. Recent examples of very active countries and networks leading innovation in given fields are presented in the following subchapters.

4.2.1. LTER East Asia Pacific Regional Group (EAP)

Ecological studies in the East Asia Pacific region are focusing on spatial patterns of biodiversity in forests (Chang et al., 2013; Ishihara et al., 2011) and coastal and marine ecosystems (Alcala and Russ, 2006), carbon cycles in forest ecosystems (Muraoka et al., 2015; Kondo et al., 2017), nitrogen cycles (Fang et al., 2015; Shibata et al., 2015) and ecohydrology (Trisurat et al., 2016). Some of the terrestrial ecosystem sites are operating carbon and water flux observations and overlap with the AsiaFlux network (including JapanFlux, OzFlux, ChinaFlux). A strength of this regional network is its international collaborative research addressing ecological questions along the climatic gradient, and climate and human impacts on biodiversity and ecosystem services. Further research topics include investigations of differences in climate change trends expected in East and Southeast Asia as compared to other regions (e.g., IPCC, 2013; Pfahl et al., 2017) and studying the possible influence of global warming on ecosystems by conducting open-field warming experiments (Nakamura et al., 2010; Chung et al., 2013; Noh et al., 2016).

Biodiversity observations in various ecosystems are conducted in collaboration with the Biodiversity Observation Network in Asia-Pacific region (APBON; Nakano et al., 2012). Several ILTER Master Sites are facilitating to bridge in-situ and satellite observations for studying biodiversity and ecosystems under climate change (Muraoka and Koizumi, 2009; Muraoka et al., 2012; Ishii et al., 2014, Karan et al., 2016). JaLTER has a good partnership with the "Phenological Eyes Network (PEN)" in bridging in-situ and satellite observations of terrestrial vegetation canopy phenology and photosynthesis by sharing forest sites for their automated monitoring of canopy phenology and spectral reflectance (Nasahara and Nagai 2015).

4.2.2. LTER Australia: TERN/LTERN

The Australian Terrestrial Ecosystem Research Network TERN has been an exemplary model of an integrated ecosystem observatory network, as promoted by ILTER. TERN was established in 2009 by joining the forces of several ecosystem research communities in Australia, building upon existing capabilities in remote sensing, flux, and plot-based monitoring, as well as creating new capabilities to fill gaps notably in data integration and delivery, plot-based ecological surveillance monitoring, synthesis, and modeling. By building upon and integrating existing capabilities, TERN was able to rapidly deliver a national research infrastructure for ecosystem monitoring on the Australian continent, which took a comprehensive approach operating at multiple temporal and spatial scales. The TERN research infrastructure covers different ecological compartments (soil, water, biodiversity, atmosphere; see Fig. 14). So, similar to the situation in Europe, the Australian terrestrial ecosystem research infrastructure built on past and current data collection activities across all levels of government, research organizations, universities, private companies and non-government organizations, and is supported by all levels of government.

In spite of its trend-setting role, increasingly tight fiscal constraints since 2014 have forced TERN to restrict its capabilities. This has resulted in the decommissioning of the dedicated synthesis facility and biodiversity focused LTERN facility, the migration of the soils capability to other national research organizations, and has severely limited operations across all other capabilities. In response to Australian Government priorities, TERN has restructured its operations in 2017 to enhance integration across all parts of its ecosystem observatory, and to ensure it can achieve as much as possible with its limited funding. This new structure focuses on three levels of ecosystem monitoring: (1) process-based monitoring encompassing plot-based flux and ecological monitoring (compliant with the ILTER Master Site category); (2) ecosystem surveillance monitoring using standardized methods at hundreds of plots across the continent (akin to ILTER satellite sites); and (3) remote sensing and spatially modeled data across the continent. This ecosystem observatory continues to be supported by central data services that provide discoverable data and data storage, as well as central coordination and governance. This restructure means some registered LTER Sites, including the 'LTERN' group of 12 sites, will no longer form a core component of the TERN research infrastructure. The full effect of this controversiall change for the research groups associated with these sites has yet to be seen (Lindenmayer, 2017). TERN has reaffirmed the importance of long-term research and its commitment to ILTER, and as part of its next work program, it will be working to strengthen and support the LTER community in Australia (encompassing both TERN and non-TERN sites).

4.2.3. LTER South Africa: SAEON/EFTEON/SMCRI

LTER in South Africa is organized by the South African Environmental Observation Network (SAEON). SAEON is an institutional network supported by and reporting to the government and its original design

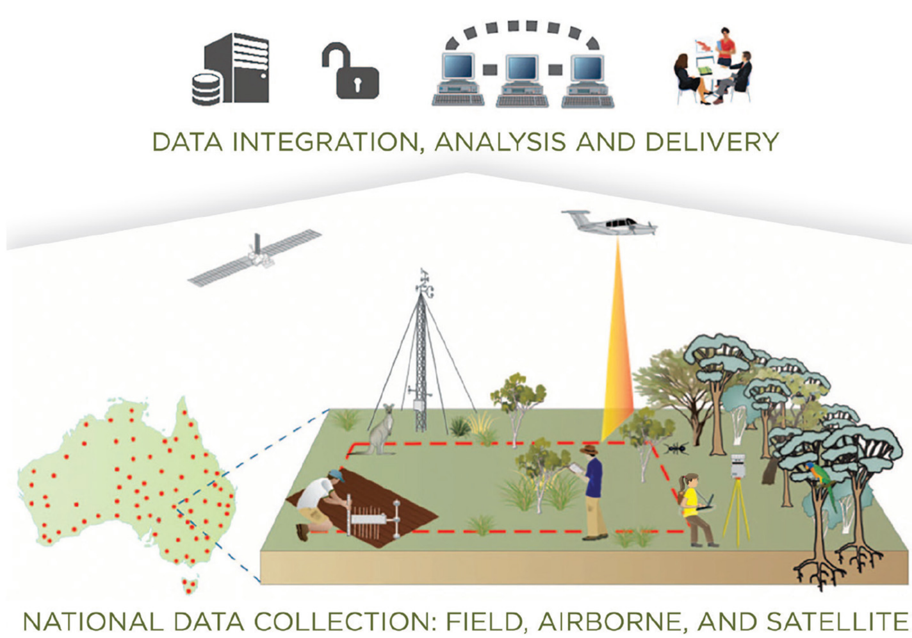

Fig. 14. Overview of the Australian Terrestrial Ecosystem Research Network (TERN); (http://www.tern.org.au/rs/7/sites/998/user_uploads/File/Facility%20Brochures/TERN%20flyer_20161114.pdf).

provided for six nodes or field stations. These nodes are located to cover four of South Africa's main terrestrial biomes, the coastal region and the offshore marine systems bordering South Africa. Each node has established a constellation of observation sites aligned to the broad objectives of ILTER. Coastal and offshore systems are largely studied by a combination of relatively expensive moored instruments for in-situ physical oceanography, associated observations of biota, remote sensing, experimentation (e.g. Marine Protected Areas, fishing trawler exclosures) and modeling. Terrestrial and freshwater systems have largely been studied by a combination of low-cost in-situ observations of biota (occurrence, abundance, productivity), atmospheric conditions, stream flow, groundwater, soil moisture, experiments (e.g. altitudinal and land-use gradients, fire treatments, grazing exclosures, rehabilitation), natural resource use (e.g. food production and harvesting, fuelwood gathering, conservation, industrial impacts) and the effects of large infrequent events (e.g. droughts, floods, fire storms, harmful algal blooms, locust outbreaks).

Recently, the South African Department of Science and Technology has commissioned proposals for several national-scale research infrastructures (Department of Science and Technology, 2016). Given the importance of Global Change to South Africa as a developing economy, these RI's included two that are currently being implemented and integrated by SAEON, and will also be made accessible to international scientists. The first RI is called the Expanded Freshwater and Terrestrial Observation Network (EFTEON). The design of EFTEON provides for an additional six nodes, each centered on a flux tower. These nodes will study strategically important landscapes rather than be site-bound. A range of in-situ observations will be performed and integrated with remote sensing and social-ecological monitoring to offer unique research platforms to the global research community in the fashion of LTSER platforms. The second RI is called the Shallow Marine and Coastal Research Infrastructure (SMCRI). This RI will add seven coastal sites with standard moored physical oceanography instruments to SAEON's portfolio and add new specialized facilities to be shared among the sites including a water quality laboratory, a decompression chamber for deep sea diving, acoustic telemetry equipment, stereo baited remote underwater video systems and a light aircraft for airborne surveys. Jointly, the two RI's increase the government's investment in SAEON by 180%, and are aimed at progressively expanding SAEON's data management, scientific and administrative capacity.

Ultimately, the South African Government is using the expansion of SAEON as a mechanism to capitalize on South Africa's globally important geographic location by the increased opportunities to train and employ scientists and to collaborate internationally through ILTER and other global programs.

4.2.4. LTER in Europe: towards an integrated long-term ecosystem, critical zone and socio-ecological research infrastructure (eLTER RI)

The development of LTER in Europe provides a living example of the initiating, structuring and streamlining impact of ILTER. Between 1993 and 2001, ILTER officials in collaboration with the US State Department stimulated the establishment of 6 Member Networks. Catalyzed by a major European Network of Excellence funded by the EC, (ALTER-Net) the number rose to 16. Major conceptual components were developed, and LTER-Europe was formally founded in 2007. Currently, LTER-Europe comprises around 400 ecosystem research sites and 35 Long-Term Socio-Ecological Research (LTSER) platforms. They are operated by approximately 100 institutions in 26 Member Networks. Given the long history of ecological research in Europe and related physical infrastructures, the major challenge was to reduce the intrinsic fragmentation of the field through a concerted process across and within 26 countries and their specific national structures and funding schemes.

Decisive ingredients to this process were (1) the integrative approach based on jointly developed and commonly accepted standards (e.g. site categories) and jointly used tools (e.g. site registry), (2) the involvement of a wide range of disciplines and research groups, (3) governance structures which allowed concerted actions of LTER-Europe across various scientific and technical service oriented flagship projects at the European scale, and (4) the continuous embedding in the European Research Infrastructures and environmental monitoring landscape (e.g. UNECE Working Group on Effects) which stimulated an ever increasing level of formalization of LTER. Driven by the high relevance of human-environment interactions in the complex European cultural landscapes which have, for millenniums, influenced environmental history, LTER-Europe took a leading role in developing and implementing the Long-Term Socio-Ecological Research approach (Singh et al., 2013).

The complex LTER process in Europe currently comprises three major layers:

- LTER-Europe, the Regional Group of ILTER, representing the big pool of sites and institutions in 26 countries, on which the other layers capitalize.
- LTER Flagship projects at the European scale (currently: eLTER H2020 project), where nationally coordinating and other key LTER institutions from the 26 countries collaborate in consortia to further advance LTER in Europe both technically (services, tools) and strategically, and jointly conduct multi-site based research.
- The eLTER ESFRI process, aiming at establishing a formalized eLTER Research Infrastructure (eLTER RI) through the Roadmap process of the European Strategy Forum on Research Infrastructures (ESFRI), which is in charge of strategically shaping RIs in the European Research Area (ERA).

The LTER flagship project eLTER H2020 (European Commission funded, 2015–2019) identifies scientific user requirements and develops services alongside 4 scientific use cases, which represent a gradient of complexity and rely on long-term data from 162 sites from 21 countries. It strives to produce services and tools of global usability, both for ILTER and other partners like GEO. The most prominent example at this stage is DEIMS-SDR (see Chapters 3.2 and 4.1).

The eLTER ESFRI process, launched in 2015, aims at formally anchoring LTER in the European environmental RI landscape. Unlike several existing thematic environmental RIs focusing on single elements of environmental change, eLTER RI will holistically and in the long term embrace the combined impacts of stressors on a wide variety of European ecosystems. It will hence occupy a vital, yet unfilled, niche in the European RI landscape, and have integrative effects through close collaborations and co-location with sister infrastructures like ICOS (carbon observation system), AnaEE (experimental terrestrial ecosystem research) and LifeWatch (biodiversity e-infrastructure). A major achievement of the eLTER ESFRI process was joining forces with the European Critical Zone research by building one generic backbone infrastructure for multiple use, comprising standard observation across system components of concern for various scientific communities (Fig. 15). eLTER RI is politically supported by 17 countries and promoted by 160 Research Performing Organizations from 27 European countries.

4.2.5. LTER China: CERN/CEOBEX

The Chinese Ecosystem Research Network (CERN) is fundamentally designed in a similar hierarchical way as the basic ILTER hierarchy of site categories. Currently the CERN network consists of 44 sites (16 croplands, 12 forests, 7 grasslands & deserts, 8 wetlands, 1 urban), and is closely linked with ChinaFlux (70 flux towers), Atmospheric Network (5 stations in 53 sites), Tibet Plateau Network (20 stations), Coast and Bay Network (11 stations and 15 buoys), and Phenological Network (30 sites). The oldest CERN sites have operated from 1955. The main unifying service in CERN is the in-situ observation data accumulation and sharing system (see Fig. 16), which provides data for GEO ground verification with 1 km resolution. The CERN facilities also include forecasting, experimentation and supporting services (e.g. operation, testing, data and modeling), and are supported by the Chinese Academy of Sciences (CAS). In 2016 another re-design process was launched,

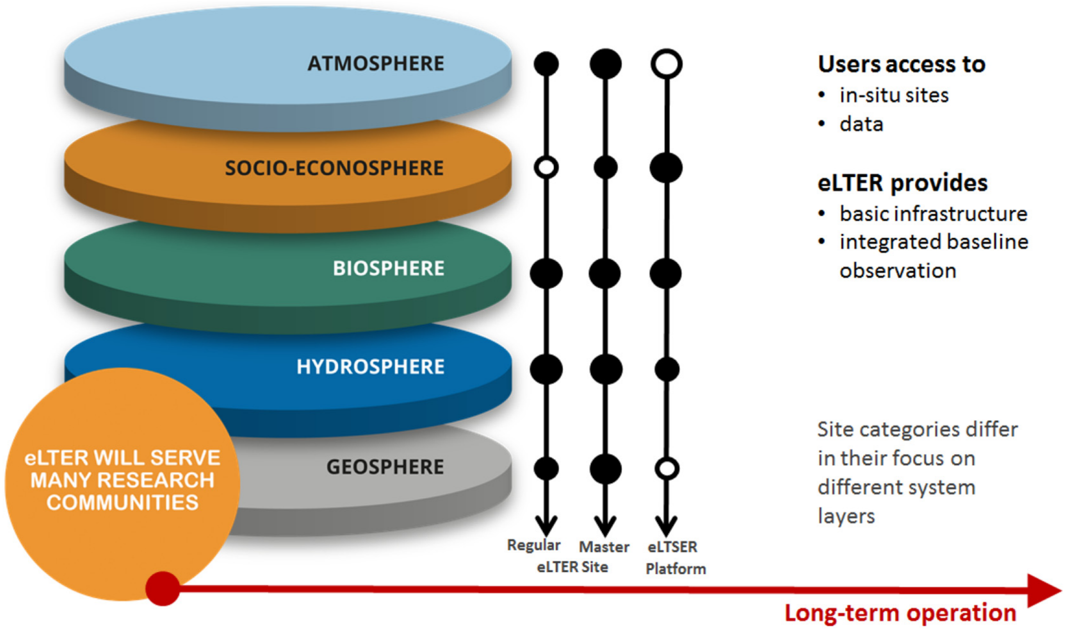

Fig. 15. eLTER RI's approach for serving various scientific disciplines with a generic ecosystem Research Infrastructure. The vertical lines represent different categories of LTER facilities (sites, platforms) and the black spheres indicate the relevance of given system layers in the respective site design.

aiming at an even better integration of the observational and experimental elements under the name "Chinese Terrestrial Ecosystem Observation and Experiment Network" (CEOBEX).

The main goals are:

- Acquire observational and experimental data on ecosystem functions and relevant environmental factors based on a precise, real-time and continuous measurements
- Fully understand the processes and mechanisms underlying changes in ecosystem carbon nitrogen-water cycles in the context of global change
- Predict the changes in terrestrial ecosystem services, and become a service center for the prediction and early-warning of ecological safety in China.
- Develop forward-looking collaborative research

4.3. Large scale policy examples

Policies are often based on scant information and non-scientific sources and therefore case studies of policies that are largely and directly based on LTER science are scarce. We nevertheless present here three illustrative cases, one at the national level in South Africa one at the continental level in Europe (but of global relevance) and the final one from Australia that uses an ecosystem level assessment to develop international policy guidelines.

4.3.1. Rehabilitation (South Africa)

South Africa's current research and policies on hydrology and forestry have evolved from a 60 years long-term Forest-Hydrology

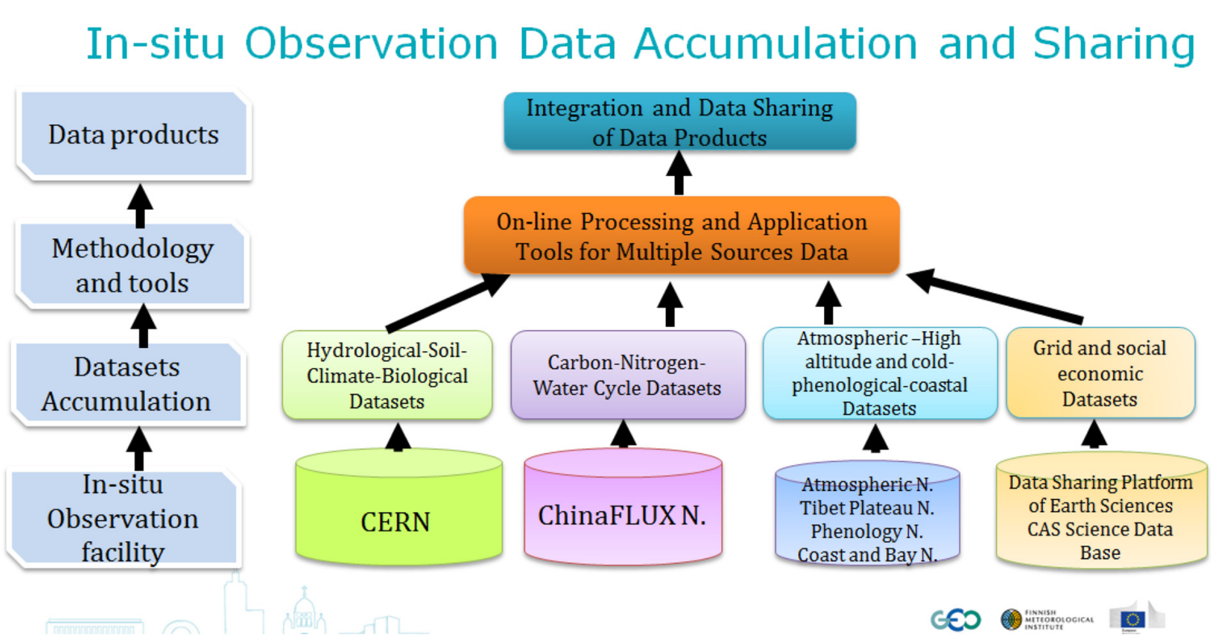

Fig. 16. In-situ observation data accumulation and sharing system in CERN.

Experiment (Bennett & Kruger, 2015). The experiment was designed and launched in the late 1930's to compare the water use of indigenous forests with plantations of exotic trees. Plantations were found to significantly reduce stream flow. This result directly shaped policies on national forestry management, invasive species control and fire management policies. Importantly, a large-scale enviro-social labor-intensive public program called 'Working for Water' also followed from the research. The program continues to provide jobs for unskilled laborers who are employed to clear alien invasive vegetation from riparian zones and which results in improved stream flow. Given that South Africa is largely semi-arid, water-scarce, and with a high unemployment rate, this program addresses all-important environmental and social objectives. Two of the experimental sites have recently been revived by SAEON after they were interrupted for nearly 20 years. Historical datasets were rescued from being lost and monitoring was expanded to actively contribute to understanding an emerging crisis, the current drought (http://www.saeon.ac.za/enewsletter/archives/2017/october2017/doc01). One is an 80-year old stream flow research infrastructure at Jonkershoek which is currently being equipped to address a new research focus on climate change and its eco-hydrological impacts. The site is located in the metropolitan area of Cape Town which is in the 3rd year of a continuous extreme drought and both the historical and recent data SAEON obtained from Jonkershoek have been used to inform local decision makers about the frequency and severity of comparable past events. The Jonkershoek site therefore continues to influence national and local policy-making in South Africa.

4.3.2. N-impact on biodiversity where N-thresholds are exceeded

In many European countries (and worldwide) airborne nitrogen coming from fossil fuel burning and agriculture exceeds critical thresholds and threatens the functioning of terrestrial and aquatic ecosystems. One effect is that high levels of nitrogen stimulate the growth of certain plant species only which then outcompete other, often rare, species. As a consequence biodiversity declines. Dirnböck et al. (2014) studied long-term monitoring data from 28 forest sites with a total of 1335 permanent forest floor vegetation plots from northern Fennoscandia to southern Italy to analyze temporal trends in vascular plant species cover and diversity. At sites where nitrogen deposition exceeded the critical load, the cover of forest plant species preferring nutrient-poor soils (oligotrophic species) significantly decreased whereas plant species preferring nutrient-rich soils (eutrophic species) showed - though weak - an opposite trend. These results showed that airborne nitrogen has changed the structure and composition of forest floor vegetation in Europe. Plant species diversity did not decrease significantly within the observed period but the majority of newly established species was found to be eutrophic. Hence it was hypothesized that without reducing nitrogen deposition below the critical load, forest biodiversity will decline in the future. It was also shown that the habitat-specific empirical critical load values, which are empirically well based and politically agreed thresholds from the context of the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP), are useful indicators for the sensitivity of forest floor vegetation to N deposition. These and many other scientific findings of negative impacts of N emission on ecosystems and human health have led to new European emission thresholds, which were negotiated during the revision of the CLRTAP Gothenburg protocol and the National Emission Ceilings Directive (NEC-D) of the EU. The main guideline for policy makers, summarizing the current knowledge, was the assessment report of the CLRTAP (https://www.unece.org/index.php?id=42861).

4.3.3. Ecosystem assessment – LTER Australia

In Australia, the Victorian Tall Eucalypt Forest Plot Network, an ILTER Site, has proven instrumental in informing two significant global policy frameworks: (1) the International Union for the Conservation of Nature's Red List of Ecosystems (Burns et al., 2015), and (2) the international statistical standard System of Environmental-Economic Accounting (Keith et al., in press). Key to the enablement of these policy frameworks was the availability of long-term data, and a depth and breadth of knowledge from decades of sustained ecosystem research. The results of these two investigations, considered together, provide a compelling story of the impacts of native timber harvesting on ecosystem dynamics and other natural assets and industries reliant on ecosystem services provided by the forest ecosystems. To date, findings have led to a change in threat status (from Endangered to Critically Endangered) of an Australian marsupial, Leadbeater's possum (*Gymnobelideus leadbeateri*), and establishment of an Industry Taskforce and a State government committee of inquiry. Ultimately, the Critically Endangered status is a result of the rapidly declining abundance of large old hollow-bearing trees and the limited current area of old growth forest in the ecosystem. This lack of resource is due primarily to historically unsustainable native timber logging practices, in combination with stochastic wildfires.

The economic benefits from native forest logging are small compared to other industries in the region. However, as highlighted by the ecosystem assessment (Keith et al., in press), the ecological impacts are highly significant. Disturbances to ecosystem dynamics are so extensive that ecosystem collapse is probable before 2067. In 2018, the Regional Forest Agreement, a 20-year plan for natural resource use within Australian forests, is due for re-negotiation, with opposing interests calling for the maintenance of the existing native timber harvesting on one hand, and additions to the national park network on the other. Research enabled by this LTER Site will be critical to providing an evidence base for negotiations.

5. Synthesis & outlook

5.1. Towards ILTER mission and goals 2020–2030

When ILTER was founded in 1993, neither the speed of global change nor many of the recent technological and organizational developments in environmental research existed or could be anticipated; both of these now set the pace for global research and observation networks. For example, the concepts of "Research Infrastructures" (RI) or even "Global Research Infrastructures" (GRIs) were not established and used in their current meaning. An unprecedented technological push in several fields of high relevance for ILTER, ranging from site instrumentation, molecular techniques, to data transmission, processing, access, integrated analyses and assessment, mobility and communication, has allowed for an exponential growth of concerted ILTER activities across sites and overall interoperability. Moreover and strongly linked to these advancements, ILTER's current science-policy framework emerged. This framework fosters regional-, continental- and global-level integration, including a push for publication of open data – e.g. Open Government Initiative in the US (https://obamawhitehouse.archives.gov/open). However, these emerging opportunities have so far been only partly exploited for a range of reasons. The level of formalization, governance and permanent management required to maximize the utility of the data collected have yet to be established, and the protracted global harmonization processes to align fragmented national and regional building blocks is ongoing. More generally, there is also a lack of suitable global level funding schemes, working cultures and new high level positions that are required to run GRIs, as well as proper incentives for experts in a traditionally h-index focused academic career environment to choose such careers.

While ILTER has achieved some of its long-term goals, global politics and policies have resulted in new challenges and opportunities for both ILTER and its individual component elements (member networks, sites, etc.). Among other responses, national and regional/continental science policies have led to a range of high-level research infrastructure road map developments (e.g., Department of Science and Technology, 2016; ESFRI Roadmap 2016, http://www.esfri.eu/esfri_roadmap2016/roadmap-2016.php). The call for improvements to ecosystems science has even resonated with a global religious leader who stated that: "Greater investment needs to be made in research aimed at understanding more fully the functioning of ecosystems and adequately analyzing the different variables associated with any significant modification of the environment." (Francis, 2015). In the face of global change, the core challenge of the global ILTER network consists of blending its achievements and long-term role with present requirements and foreseeable future demands. In doing so, two angles have to be equally considered: (1) External requirements from different user groups ranging from actual research and environmental policies to funding shareholders; and (2) internal requirements like technical, managerial and LTER research community focused demands.

In 2016, ILTER launched an in-depth review of its mission and goals. In retrospect, and concerning the 10-year strategic goals (ILTER, 2006):

> ILTER was highly successful in fostering collaboration and coordination among ecosystem and socio-ecological researchers and research networks at local, regional and global scales, as evidenced by the constant development of powerful LTER networks and the scientific output of LTER site teams. The level of cross-site activities is still far below its potential, but it has been stimulated by, for example, ILTER science and bottom-up initiatives.

> Recent efforts have improved the comparability of data from LTER sites around the world, and facilitated exchange and preservation of these data, while concentrating on standardized documentation of the global LTER site networks and elaborating the services required for large scale data set uploads and their documentation.

> In delivering scientific information to scientists, policymakers, and the public to meet the needs of decision-makers at multiple levels, the dominant impact was not achieved by ILTER as a global network, but rather in a distributed fashion at the level of member networks, sites and platforms, via distributed scientific publishing and reporting of observed data in multiple national and regional contexts.

> Similarly, the education of the next generation of LTER scientists represents an intrinsic element of LTER Site and LTSER Platform development and operation. ILTER scientists engage at "their" sites in the long-term, securing transfer of very specific ecosystem knowledge and data over decades and generations. ILTER facilities form part of the national and regional site networks and infrastructure backbone with long-lasting relations to respective local and national education and other stakeholders.

Analyzing impacts and achievements is a first step in the endeavor to perform more effectively in an increasingly competitive landscape of global research networks and infrastructures. In this process one has to carefully distinguish between the role and mandate of (1) the actual ILTER network and (2) its component elements (member networks, sites etc.), which are largely self-organized and self-maintained according to regional and national framework conditions and funding schemes. Guiding core questions include: What can ILTER do and achieve as a self-reliant organization based on the predictable funding and binding members´ in-kind contributions? What are cost-efficient high-impact activities? What distributed impact can it provide by exploiting the strategic LTER framework in fields beyond the actual global network mandate? Which are the most promising fields for such multi-level leverage? What goals shall specific ILTER activities address, and which shall be achieved via strategic alliances with partners like GEO or FutureEarth?

Both internal and external considerations are helping to shape the future of ILTER, including three major activities: 1) strategic dialogues with global and major regional related partner organizations, which commenced prior to and during the ILTER OSM 2016 in South Africa; 2) a series of mission and goals workshops of member network representatives; and 3) an "ILTER Futures" survey. In addition, regional group level analyses on the relevance of LTER for various systems of societal and research Grand Challenges feed future strategies. The various results from strategic dialogues and internal workshop outcomes (1, 2) are reflected in related sections of this article. Given their importance to a broad scientific community-based network such as ILTER, we briefly summarize the internal survey results here.

In 2015 an "ILTER Futures" survey was carried out among the entire global ILTER community with the explicit targets of revisiting goals and activities in an increasingly competitive research environment and helping bridge the gap between vision and achievable goals, considering two decades of experience in operating ILTER. The results of this survey (see Supplementary material, Chapter 9) and ILTER Coordinating Committee workshops in 2016 and 2017 led to the major fields of activities and roles currently suggested for the next phase of ILTER strategic planning:

- **A global community of researchers and research institutes:** This has been first and foremost the foundation and driver of ILTER, accounting for most of the achievements and still linking innovation strategies across all ILTER levels and component elements (organization, communication and capacity development);
- **A strategic global framework and partner**: ILTER has become a platform for various user groups and stakeholders, supporting collaborative efforts towards innovative ecosystem research. This comprises conceptual developments, harmonization across national and regional LTER networks and the division of work with related networks and research infrastructures;
- **A Global Research Infrastructure GRI:** the physical network of LTER Sites and LTSER Platforms forms part of major RI developments in their countries and regions. ILTER has become a unique umbrella to serve as GRI (site network, data management, standardization, issues of global coverage and representativeness);
- **A scientific knowledge factory for societally relevant information on sustainable natural resources:** site-based and cross-disciplinary research at sites committed to the "whole system approach", enabling a unique contextualization, proper interpretation and embedding of individual findings in the ecosystem context.

5.2. A global community of researchers and research institutes

The basic assets of ILTER are in-situ research sites and research teams working at these sites. The hierarchical structure of ILTER as an international network, however, led to a situation in which the main actors directly involved in actual ILTER activities have been largely elected representatives, who typically have had significant experience conducting research at an LTER Site. The "ILTER Futures" survey showed an increasing interest in more direct interactions and networking to the level of site research teams in addition to providing data enabling high-level global cooperation, analyses and syntheses (interoperability, sharing). This was a major driver behind launching global scientific bottom-up initiatives and organizing the first global ILTER OSM 2016 in South Africa (Fig. 17). At the OSM also partner organizations presented options for future collaboration, which were discussed in plenary sessions.

ILTER catalyzes and facilitates effective communication among the many participants involved, which would not be possible without this organizational framework. To improve information flows, the ILTER website was updated and re-launched in August 2017 (https://www.ilternet.edu/). Based on an updated global LTER contact data base, more direct interaction with the community has started, involving new social media, and increased visibility of sites, their teams and operating institutions in their countries, regions, and across communities. The continuously improved site documentation (DEIMS) will play an increasingly important role by presenting the sites, their teams, data and

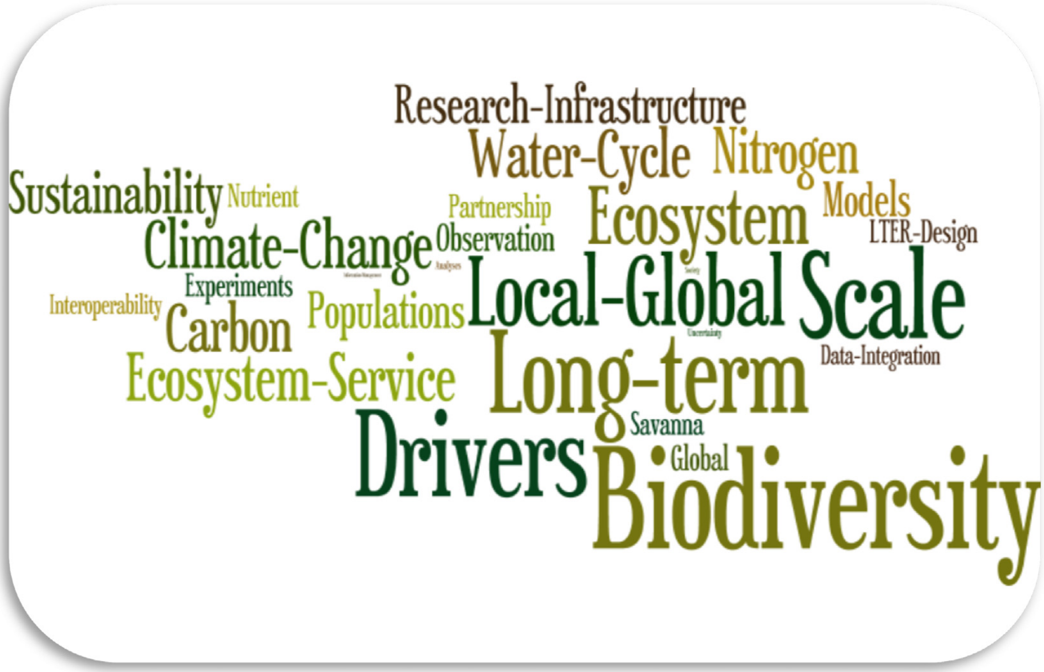

Fig. 17. Word cloud of 160 presentation titles of the 2016 ILTER Open Science Meeting, South Africa.

related institutions to a global audience (DEIMS site URLs can serve as LTER Site "business cards"). The quick identification of appropriate sites for research projects via DEIMS forms a major step in supporting cross-site activities in a bottom-up manner.

Due to the fact that LTER science is a collaborative endeavor with distributed information production, there is an intrinsic difficulty in arguing, for instance, the policy impact of one individual finding or site, as scientifically valuable as it might ever be. Efforts will be made to strengthen the visibility of the collective role and impact to contextualize individual sites´ achievements within a larger framework. From the sites' perspective, addressing Grand Challenges and strategy building are important, but excellent research done at the sites must remain the core concern.

Another important community related aspect of ILTER is taking advantage of comparably long-lasting engagement of key staff, underpinning the importance of training and specialization in response to new technical and managerial requirements (e.g. information management, high-technology field instruments), and leading to new job profiles, a new working culture and an overall more proficient Research Infrastructure.

5.3. Strategic global framework and partner

ILTER focuses on what its component elements cannot achieve in isolation and has thereby become both a strategic framework and structuring process at all levels, which, in recent years, has also become strongly related to the Research Infrastructure component outlined in the following section. This role touches the challenge of balancing the perspectives and needs of various user groups and stakeholders within and outside ILTER. Expectations towards LTER across all levels comprise:

Consolidation of research infrastructures in the terrestrial and aquatic in-situ domain for most effective usage of public funding with the best outcomes with highest relevance for societies

Data harmonization across the globe

Bridging the gap from short-term observations to long-term trends

Upscaling or working across scales and biomes (from individual sites/plots to landscape and large biogeographic zones and the globe)

Providing observational and experimental data for predictive modeling and scenario testing

Free, open, and easily retrievable data for multiple use, including distributed data curation repositories (the data architecture foresees data exposure at distributed storages in standard formats, which can be searched and harvested by various data and access brokers (e.g. GEO Data and Access Broker, GEO-DAB)

Ensuring that ILTER outcomes are translated into implementable policies

Several of these issues have been addressed by LTER activities and services, but overall the underlying causality chain and workflow from knowledge production to assessments, options for mitigation measures, and translation to political action need to be more explicitly considered in the future. This supports (1) developing an increasingly well-defined niche for LTER activities and outputs and (2) identifying priority areas for collaboration. Chapter 4.1 provides an overview of current global partnerships and envisaged collaborative activities.

There are excellent examples of how ILTER has served as an important reference for re-organizing Member Networks and Regional Networks of environmental research. The EAP Region (see Chapter 4.2.1) members closely interact in advancing their networks and have been active in hosting important global level meetings (e.g. High-level Round Table on Earth Observation in Brisbane, March 2016, and the planned 2018 workshop on highly integrated ecosystem RIs in China). The LTER-Europe Regional Group has recently submitted the eLTER Research Infrastructure proposal to form part of the European Strategy Forum on Research Infrastructures Roadmap 2018, considering trend-setting examples from around the globe (see Chapter 4.2). The European case is a good example showing how regional-scale strategies can align funding from primarily country-specific resources.

ILTER also provides a framework for streamlining ecosystem research across member networks. Globally tested and approved site designs (site categories) and standard observation variables are provided in order to achieve maximum convergence in spite of necessary local/regional modifications. Members and candidates can meet, exchange ideas, initiate research and conduct comparative studies, which are important elements of LTER related mobility and training activities (bottom-up). Exemplary network developments are promoted and the global and regional level activities have an increasing influence on national research and research infrastructure strategy building (see next chapter).

5.4. A Global Research Infrastructure (GRI)

5.4.1. Towards a Global Research Infrastructure (GRI)

Research Infrastructures (RI) are increasingly recognized as key elements in research and innovation policies, for boosting scientific knowledge generation, for accelerating technology development, for enhancing both technological and social innovation, and for providing advanced scientific training for new generations of scientists and science managers. In some cases, the complexity of RIs, as well as their high development, construction and operation costs or simply the global nature of the scientific challenge addressed, make it impossible for one country or region alone to build and operate these facilities. In such cases it becomes crucial to make concerted efforts at the international level for the realization of "Global RIs" (GRI). The interest in a GRI arises based on its capacity to address the research needs of worldwide scientific communities by combining the best available knowledge, human capital and resources in one specific scientific area with multi-source funding. Furthermore, GRIs provide an enabling environment for established researchers to improve their performance and knowledge and innovation outputs.

The potential for increased international cooperation on issues related to GRIs has been recognized during international high-level meetings on science policy and in different fora since 2007. At the first G8 Ministerial meeting, held in Okinawa on 15 June 2008, it was decided to form a Group of Senior Officials (GSO) to take stock and explore cooperation on global research infrastructures (GSO 2013). The mandate of the GSO includes identifying research infrastructures of global interest, analyzing how countries evaluate and prioritize the construction of large scale research infrastructures, identifying possible new areas of cooperation, and promoting transnational access to research infrastructures of global interest. The GSO is composed of representatives from Australia, Brazil, Canada, China, the European Commission, France, Germany, India, Italy, Japan, Mexico, Russia, South Africa, UK and USA and has been active since 2011.

The GSO agreed on three broad GRI:

1. Real single-sited global facilities are geographically localized unique facilities whose governance is fundamentally international in character, e.g. the Large Hadron Collider (LHC) in Switzerland.
2. Globally distributed research infrastructures are research infrastructures formed by national or institutional nodes, which are part of a global network and whose governance is fundamentally international in character.
3. National facilities of global interest are national facilities with unique capabilities that attract wide interest from researchers outside of the host nation. Antarctic or ocean drilling facilities are typical examples.

ILTER clearly belongs to the second category, which underpins the high relevance of the GSO framework and GRI aspects for ILTER's scope and challenges.

Among its main achievements is the agreement on a reference framework for GRIs (the GSO framework) depicting the criteria to be addressed in establishing a truly global initiative. So, policy requires GRIs to comply with specific criteria (GSO, 2013), which can by definition only be met on the basis of appropriate and permanent global funding mechanisms. In absence of such funding mechanisms, one should not be surprised that the probability of full compliance with such criteria is low.

Nonetheless, numerous ILTER member networks and regional groups have been actively involved and form part or represent even core elements of National Research Infrastructures (NRI) or continental environmental RI development (SAEON/EFTEON/SMCRI, TERN, CERN/TEREX, eLTER RI, Chapter 4.2). In support of global level advancements, ILTER has provided a platform for information exchange, multi-lateral consultations, and training of experts and has organized high-level workshops for spreading state-of-the-art concepts and technologies from these leading networks.

Considering ILTER's networking potential, strategic position, financial possibilities and distributed in-kind contributions in light of GSO recommendations, we suggest that those of highest relevance and applicability are R1–3 (anchoring of purpose and scope in a global landscape & partnerships), R9 and R10 (collaborative service development to allow seamless data exchange). The ILTER strategic plan till 2030 will refer in detail to all 14 GSO recommendations.

5.4.2. Further development of ILTER's in-situ network

The ambition of being a global network for ecosystem research demands a proper coverage of global biomes and socio-ecological regions. Detailed representativity and gap analyses have been carried mainly in continental Regional Groups and Member Networks (e.g. Metzger et al., 2010; Mollenhauer et al., 2018), where most siting decisions are taken.

Regarding global coverage, ILTER is facing a situation that has been addressed inter alia in the IPCC reporting (e.g. Rosenzweig et al., 2005, IPCC AR4 WG2). The locations of terrestrial observatories, which delivered data for climate change analyses, are unevenly distributed across latitudes. Secondly, there is a bias with an increasing number of observatories and available data with increasing GDP. Fig. 18 shows the latitudinal representativity of ILTER in-situ facilities in relation to the land mass. As in earlier studies, and strongly correlated with economic conditions, the comparison of land mass and number of ILTER facilities over latitude reveals oversampling in the northern hemisphere (specifically mid-latitude) and undersampling in the southern hemisphere.

Efforts to fill the gaps and achieve a more proportional distribution comprise (1) the optimization of Member Networks and (2) new Member Networks in critical regions. This endeavor regards how LTER Sites were established and how they are selected to form part of LTER component networks. Sites have emerged over time from different projects and network contexts and represent substantive cumulative investments. In addition to financial constraints, setting up entirely new sites increases LTER coverage only after a delay, once long-term time series have been gathered. The main impact of LTER consists in awareness raising and advising national funding stakeholders in siting decisions towards closure of network gaps at the national, regional or even global scale.

Secondly, ILTER puts regional emphasis in recruiting new ILTER member networks. Current candidates under discussion are India, Argentina, Ecuador, Turkey, Estonia and Canada. In the coming decade, ILTER will engage in capacity building in countries that are not yet participating in concerted long-term ecosystem research. This represents one of the focal areas in cooperating with the UNESCO World Network of Biosphere Reserves (WNBR). Plans were discussed with UNESCO WNBR at the 10-years WNBR conference in Lima (March 2016) to collaborate at the level of national Biosphere Reserves and LTER coordination towards increasing ILTER's coverage.

5.4.3. ILTER as a global environmental data infrastructure

The successful implementation of a distributed global data infrastructure relies on the buy-in and contributions across user groups and stakeholders, which strictly depend on the infrastructure's utility. The networking platform provided by ILTER plays a significant facilitating role in (1) collecting requirements across stakeholders, (2) coordinating distributed service development and (3) technical training, promoting best practices, and providing guidance across organizational levels (site-country-region-globe). This concerns the different stakeholders in various respects, namely individual researchers (e.g. willingness to contribute quality metadata and publish outputs with the most liberal license that applies), institutions and projects (e.g. develop data policy and select licenses to support Open Data and Open Science),

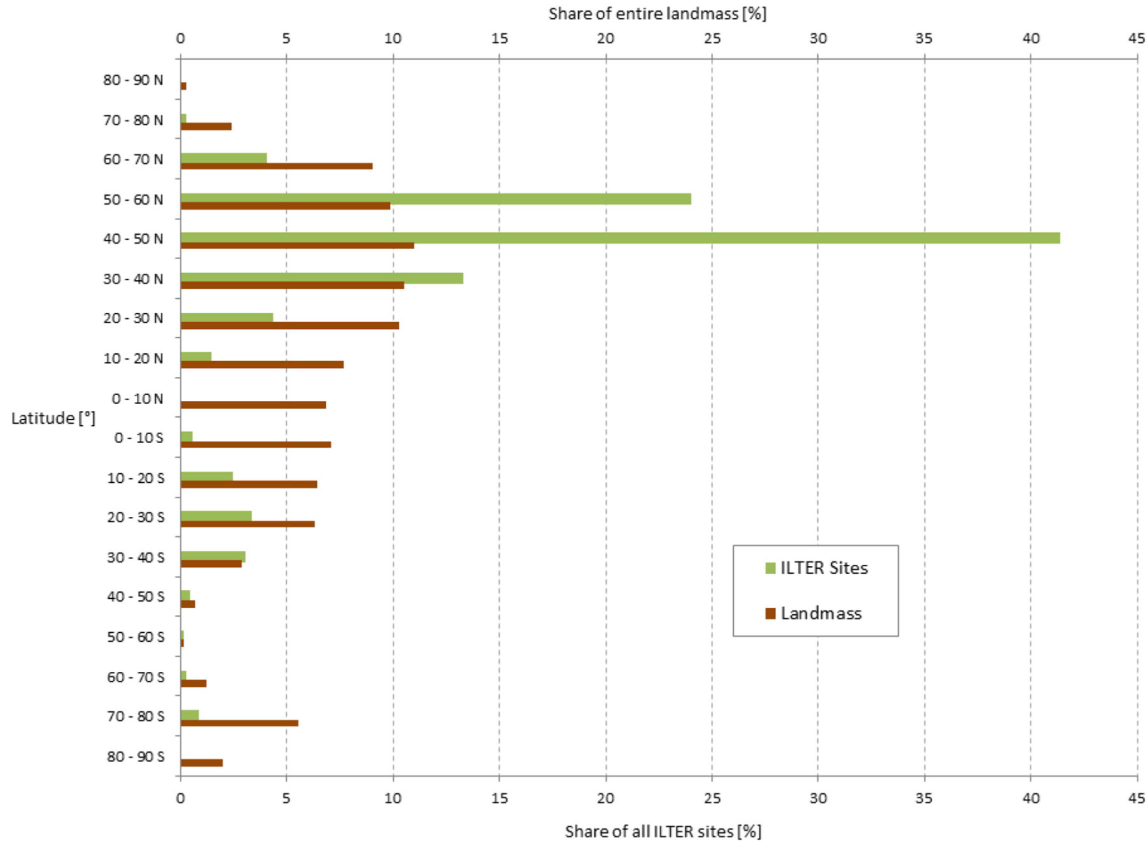

Fig. 18. Latitudinal representativity of ILTER in-situ facilities in relation to the land mass ($n = 691$). Latitude values of all LTER Sites were aggregated in 10° classes and the share of each latitude class was calculated relative to the total number of LTER Sites. The same approach was applied to the global landmasses (openstreetmap boundaries of continents). In a second shape file, the global landmass was split in 10° latitude polygons. Both layers were intersected, the total area of landmass in each 10° strip calculated, and the relative share of each strip was compared to the total mass to get the percentage values used in this graph.

developers and infrastructure managers (e.g. implement measures to ensure schematic, syntactic, and semantic interoperability), and community or domain initiatives (e.g. develop guidance, standards, specifications, and reference implementations).

Relevant common requirements for building a resilient data infrastructure in support of ILTER are:

- Open Data and Open Science, including initiatives such as 'FAIR' (Findable, Accessible, Interoperable, and Reusable);
- Emerging consensus on the fundamental building blocks of research data infrastructure (including links to DataOne, GEOSS, EUDAT, LifeWatch, GBIF, or GEO-BON), and the push for standardization and collaboration (for example via Research Data Alliance (RDA)) between RI and e-infrastructures;
- Advances in semantic sensor networks (SensorThings) and new ways of publishing the data;
- Requirements in respect of trusted repositories - increasingly required from funders;
- Broad consensus that a loosely coupled, standards-based system of systems is a scalable and feasible solution for a network such as ILTER;
- Increasing availability of crowdsourcing methods, non-traditional sensor networks and platforms of opportunity, overlapping with citizen science contributions (Fritz et al., 2017);

ILTER has started tackling a number of e-infrastructure challenges of relevance for global implementation roadmaps, dealing with business and governance (e.g. roles and responsibilities, oversight, management of consensus on standards and specifications), standards and specifications (e.g. recommendations of selected standards and specifications), systems and components (based on existing open source projects or member infrastructure and initiatives), data (detailing the modes of integration of distributed data sources and services), outreach and capacity building (e.g. framework for development and maintenance of best practice and guidance), and stakeholder and network (e.g. rules whereby networks, institutions, and projects participate in ILTER from an e-infrastructure point of view need to be developed). As for detailed considerations concerning interoperability and the ILTER e-infrastructure design, see the Supplementary material (Chapters 4 and 6).

5.4.4. Standardization

Given their heterogeneous origin, LTER facilities often differ in instrumentation and methods used to measure biotic and abiotic variables. Recently more emphasis has been put on developing a core set of biotic and abiotic variables (Haase et al., 2018). The development process of this core set of variables reflects intensive discussions among ILTER and other scientists, site managers, reflect realistic observation of site conditions, and were further adjusted towards already existing standards in other monitoring approaches (e.g. ICOS, NEON; Haase et al., 2018).

These core variables allow for better comparisons across spatial scales and increase the usage of ILTER data. This is true, in part, because these core variables not only take the Ecosystem Integrity Framework (Müller, 2005) into account but also the Essential Biodiversity Variables (EBV, Pereira et al., 2013) and the Essential Climate Variables (GCOS, 2016) frameworks. Thus, such data could be used for different purposes. On the other hand, the semantic aspects and vocabularies associated with ILTER observation data needs to be standardized to allow interoperability of data sets.

The core variables suggested by Haase et al. (2018) do not yet include the socio-economic status to capture human wellbeing. Such a development may start from Land Use Land Cover (LULC) data, Green and Blue Infrastructure availability, and more standard social, demographic and economic variables (accessible from standard statistical bureaus, though not always at the correct scales as needed). ILTER will consider recent developments such as the emerging framework for Essential Variables for Sustainable Development Goals - linking socio-economic and environmental concerns (Reyers et al. 2017). A set of core variables will reflect Ocean Observation Variables (EOVs; Constable et al., 2016). Finally, will ILTER align its observations protocols with existing initiatives.

Overall, these measures have been improving and will further foster the availability of LTER data to complementary observation networks coordinated by, e.g. the WMO, the UN, and GEO, specifically as LTER data are exposed, searchable and harvestable by any data integration portal like the GEO Data Access Broker (GEO DAB).

5.5. A scientific knowledge factory for societally relevant information on sustainable natural resources

One of the greatest challenges for the coming decades will be to scale from local to global ecological patterns and processes in order to address pressing global issues such as global change, ecosystem conversion, and species loss (Lambin and Meyfroidt, 2011; Bellard et al., 2012; Reis et al., 2016). LTER helps in tackling a wide range of Grand Challenges for society and research. Based on the anchoring of LTER in the major Grand Challenge classifications (see Supplementary material, Chapter 8), the following four focal LTER research challenges can be summarized as:

(1) Climate change and greenhouse gases.
(2) Biodiversity loss and land use change.
(3) Eutrophication and pollution.
(4) Environmental protection, sustainable management of natural resources, water, biodiversity & ecosystems.

Collaborative ecological research networks have been amassing data relevant for these research challenges from sites spanning regions and continents and increasingly using these data to gain novel insights into the generality and site- or regional-scale contingencies of ecological responses to global changes (Borer et al., 2014; Borer et al., 2017). In the absence of such collaborations, many new insights would not have been possible. A key ambition of ILTER has been to increase the usability and re-use of these data by improving their interoperability (Chapters 3.4 and 5.4) across sites, country and regional networks.

However, even as these contributions to the observational system of systems are acknowledged, the fundamental characteristic of ILTER must not be forgotten. Each of the LTER Sites has been designed to deepen our understanding of ecosystem functioning at its location in a given ecosystem type and biome. Usually much care was taken to choose sites, which are representative for this ecosystem type to enable exemplary system research that best represents neighboring and similar ecosystems. A major asset of ILTER and its site network has thus consisted of its ability to place the information obtained at a given site in a broader regional or continental context. This context provides the ability to detect ecosystem processes and their linkages across ecosystem compartments and scales, and thereby link traditional site-based ecosystem ecology with macroecology. ILTER data and contextualized findings have revealed the diversity of ecosystems and resulting variability across spatial transects and in time that was not captured in previous coarse-scale assessments. This applies to both the environmental or biogeophysical system and the socio-ecological system, where decision making towards sustainable resource use heavily depends on such thorough understanding of land use management impact on a given system with its specific environmental history and current status.

For this reason the ILTER research challenges translate in a hierarchical cascade from overarching questions such as the impact of eutrophication, to more detailed research questions for individual climatic zones, biomes, ecosystem types and – finally - sites. In order to detect eutrophication trends and impact signals at specific ecosystem types or the very site level, for example, we will always need to customize experimental designs and methods according to locally relevant factors, e.g. nitrogen input paths, affected ecosystem compartments, indicator organisms and affected ecosystem services. Therefore, ILTER typically stands for the trade-off between standardization in favor of cross-site comparability and the necessity of modifications dictated by site conditions and development of experimental designs suited to test small-scale scientific hypotheses. This trade-off has frequently been considered as a weakness. However, recent interactions of ILTER with Remote Sensing service developers have evidenced the high value of contextualized environmental information as gathered at LTER Sites for RS service validation.

The continuous improvement of ecosystem models represents another important field of LTER data usage. The mechanistic understanding of ecosystem processes as reflected in models and model clusters (e.g. Kuemmerlen et al., 2016) is indispensable for complying with the political request for predictive modeling to test future environmental scenarios. Accordingly, LTER standard observation variables have also been selected with respect to their critical relevance as parameters for ecosystem models.

Scenario testing and improving the underlying system understanding touches upon another important development in ILTER's scope: While the focus of most multi-site research collaborations has been observational (e.g., Baldocchi et al., 2001; Weathers et al., 2013), some networks are demonstrating the power of pairing experiments with long-term observations (Arft et al., 1999; Duffy et al., 2015; Borer et al., 2017; Jourdan et al., 2018). ILTER provides a platform positioned to take advantage of this important tool, thus generating both large-scale and long-term observational and experimental insights into global change, a key challenge for this discipline (Soranno and Schimel, 2014). This comprises two major approaches: (1) The co-location of standardized small-scale and highly instrumented experimental treatments with LTER Sites in order to test future scenarios along environmental and site characteristics gradients. This approach, as promoted in the Chinese emerging TEBEX and in the planning for European co-located experimental AnaEE and LTER Sites, requires well-thought-out integrated designs to avoid unintended interference of experimental treatments with the long-term observation of natural forcing, and; (2) The alignment of large-scale, low-intensity treatments.

As part of this awareness, the ILTER Distributed Experiments Task Group was established in 2017. As a first step, this initiative takes advantage of the organization, communication and growing collaborative nature of the ILTER as an opportunity to pair long-term observations with experiments replicated at many sites. By working with existing experimental networks manipulating global change factors, namely the Nutrient Network (http://nutnet.org, Borer et al., 2014; Borer et al., 2017) and DroughtNet (http://wp.natsci.colostate.edu/droughtnet/), as well as an international observational decomposition network, TeaComposition (Chapter 3.6.2). Through this prototypical globally concerted experiment across ILTER and even other networks´ sites, the ILTER is testing its potential to contribute to large-scale, long-term replicated experiments and observations. By replicating the identical methodology of the existing networks, ILTER will allow direct comparisons of conditions and responses (e.g., diversity, productivity, edaphic characteristics, etc.) of single LTER Sites to other sites in the world as well as allowing direct comparisons among LTER Sites. Importantly, by contributing to ongoing network projects, the ILTER Network will be able to significantly add to the growing understanding of the context-dependence of future global changes and their effects on local environments (Borer et al., 2017).

5.5.1. Engagement with a Wider Research Community and Societal Benefit

A significant gap often exists between scientific evidence and policy advice: not only are the variables observed by science not always directly applicable to the questions that are asked by policy-makers, but a synthesis from various disciplines is usually required. ILTER's increasing alignment with interoperability standards for data services and position in contributing to portfolios of essential variables, promotes the use of its data beyond traditional direct research applications. In particular, one should consider the role it may play in global monitoring and evaluation frameworks such as the Aichi targets, UN Sustainable Development Goals, and the Sendai Framework. Such contributions belong to innumerable jigsaw pieces shaping formalized societal benefit through re-use in a cross-disciplinary context. Outreach to Citizen Science networks may also be beneficial in both directions: Provided that the hurdles involving protocols and quality can be addressed, citizen contributions to scientific data (and harnessing of a large and growing availability of informal sensors) have obvious benefits to the research community, but equally, citizens can benefit from packaging and dissemination of research data in ways that interest or benefit them.

5.5.2. Inter- and transdisciplinary science

LTER Sites, LTSER Platforms, and data holdings represent cornerstone research infrastructure for planetary management towards sustainability. The Socio-Ecological Research Platforms, usually containing several LTER Sites, define themselves as infrastructures for multi-, inter- and cross-disciplinary research that are required to answer the wicked problems of what global policies for sustainable living on Earth should entail. This includes the mentioned testing of future scenarios with options for adaptation to a changing environment and the thresholds of no-return. ILTER has advanced well, but is far from realizing its potential concerning inter- and transdisciplinary research (Dick et al., 2018). Therefore, ILTER will further strengthen socio-ecology as a crucial component for fulfilling its vision of “a world in which science helps prevent and solve environmental and socio-ecological problems” (ILTER, 2006). The network's definition of socio-ecology is drawn not only from its disciplinary focus, studying human-nature interactions (Fisher-Kowalski and Weisz, 2016), but it also adopts socio-ecology in its transdisciplinary form, which is problem-oriented and advocates for tapping into a broader network of knowledge sources (i.e. stakeholders; Grove et al., 2015; Singh et al., 2013; Haberl et al., 2006). In this way, ILTER broadens its network of partners to assure the societal relevance of its research, the utilization of all available perspectives and insights, and strengthening of the potential for policy uptake.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.12.001.

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