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Long-term environmental monitoring infrastructures in Europe: observations, measurements, scales, and socio-ecological representativeness

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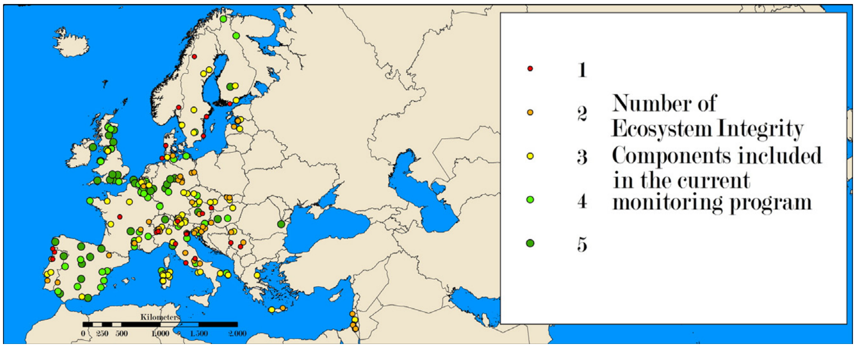
HIGHLIGHTS

- First study on conceptual and infrastructural comparability of LTER-Europe
- Analysis of biogeographical and socio-ecological representativeness of LTER-Europe
- Classification of LTER Europe sites based on the LTER framework of standard observations

GRAPHICAL ABSTRACT



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ABSTRACT

The challenges posed by climate and land use change are increasingly complex, with ever-increasing and accelerating impacts on the global environmental system. The establishment of an internationally harmonized, integrated, and long-term operated environmental monitoring infrastructure is one of the major challenges of modern environmental research. Increased efforts are currently being made in Europe to establish such a harmonized pan-European observation infrastructure, and the European network of Long-Term Ecological Research sites – LTER-Europe – is of particular importance. By evaluating 477 formally accredited LTER-Europe sites, this study gives an overview of the current distribution of these infrastructures and the present condition of long-term environmental research in Europe. We compiled information on long-term biotic and abiotic observations and measurements and examined the representativeness in terms of continental biogeographical and socio-ecological gradients. The results were used to identify gaps in both measurements and coverage of the aforementioned gradients. Furthermore, an overview of the current state of the LTER-Europe observation strategies is given. The latter forms the basis for investigating the comparability of existing LTER-Europe monitoring concepts both in terms of observational design as well as in terms of the scope of the environmental compartments, variables and properties covered.

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Nomenclature

DEIMS-SDR	Dynamic Ecological Information Management System – Site and Dataset Registry
EI	Ecosystem integrity
eLTER	European Long-Term Ecosystem, critical zone and socio-ecological Research Infrastructure
ESFRI	Policy European Strategy Forum on Research Infrastructures
EBV	Essential biodiversity variables
GEO	Group on Earth Observations
GEO BON	Group on Earth Observations Biodiversity Observation Network
GEOSS	Global Earth Observation System of Systems
ILTER	International Long-Term Ecological Research
LTER	Long-Term Ecosystem Research
RI	Formalized Research Infrastructure in the context of the European Strategy Forum on Research Infrastructures

1. Introduction

Human interactions with the environment, changes in climate and land use and their long-term impacts on ecosystems generate major global environmental risks and new scientific challenges of highest complexity. In order to provide answers to the great challenges facing humanity like changes in temperature and precipitation regimes, land use change and loss of biodiversity, eutrophication, or pollution, today's environmental science must gain comprehensive understanding about processes and cross-compartment feedbacks and their drivers across the appropriate temporal and spatial scales. The UN 2030 Agenda for Sustainable Development encompasses 17 sustainable development goals (SDGs) which are broken down in 169 associated targets (UNGA, 2015). As a prerequisite for achieving these goals, European policy must take into account the socio-economic significance of an array of well-functioning ecosystem services. Several of the 169 targets explicitly mention the sensible utilization of ecosystems, and a considerable number of them are directly related to ecosystem services, including genetic diversity, water quality, sustainable tourism, the use of natural resources, and environmentally related health issues and risks. Against this backdrop, the development and enhancement of integrated observation systems fostering inter- and transdisciplinary research is one of the Grand Challenges of Earth System Science for global sustainability (Reid et al., 2010) and also defined as one of the European Commission's Societal Challenges for Europe 2020 - Developing comprehensive and sustained global environmental observation and information systems (EC, 2017a).

The new challenges for Earth System Science are placing a number of new demands on observation designs and capabilities of monitoring technologies (Reid et al., 2010; Vihervaara et al., 2010, 2013; Zoback, 2001). There are the needs to describe and predict mass fluxes and energy balances at the systems level, to identify and describe the complex feedbacks between the different environmental compartments, to detect and evaluate signals of natural variability at a wide range of spatial and temporal scales, and finally to predict the consequences of human interaction at the scale of the natural system. In order to meet these needs, integrated multi-scale monitoring and modeling approaches are required (Ali et al., 2013; Banwart et al., 2013; Blöschl and Sivapalan, 1995; Haberl et al., 2006; Kirchner, 2006; Levin, 1992; Lin, 2003; Montgomery et al., 2007; Parr et al., 2002) and call for the “next generation of ecosystem research in Europe” (Mirtl, 2010). This situation is compounded by the fact that biodiversity monitoring schemes are mostly separated from abiotic monitoring and consistent strategies for greater integration between both sides are needed (Haase et al., 2018; Vihervaara et al., 2013). Furthermore, many environmental systems react with considerable delay to changes in the environmental conditions requiring long-term monitoring efforts to identify the major drivers like climate change (Dalton, 2000; Nisbet, 2007; Vihervaara et al., 2013; Zacharias et al., 2011).

These issues are tackled by Long-Term Ecosystem Research (LTER), an essential component of worldwide efforts to better understand ecosystems. Through long-term research and monitoring, LTER seeks to improve our knowledge of the structure and functions of ecosystems and their response to environmental, societal and economic drivers.

The International Long-Term Ecological Research (ILTER; Vanderbilt and Gaiser, 2017) network currently covers approximately 900 LTER sites globally. Within ILTER, LTER-Europe is a regional (continental) network representing the European LTER sites and 24 countries with well-established national and European governance structures.

Since its launch in 2003, LTER-Europe has sought to better integrate traditional natural, more disciplinary sciences and more holistic ecosystem research approaches including the impact of humans on environmental systems. LTER-Europe was heavily involved in developing the concept of Long-Term Socio-Ecological Research (LTSER). As a result, LTER Europe now comprises not only LTER sites but also larger LTSER platforms, where long-term interdisciplinary research is encouraged.

LTER-Europe builds on an in-situ infrastructure of 477 formally accredited ecosystem research sites (65% terrestrial, 26% aquatic and 9% transitional waters) and 35 LTSER Platforms for socio ecological research. The infrastructures are operated by around 100 institutions. LTER-Europe brings together research sites originally set up in varying contexts (projects and networks driven by national/institutional strategies and domain specific requirements) and provides an excellent setup to establish Pan-European research focusing on entire ecosystems.

One of the key requirements towards continental-scale environmental in-situ research infrastructures is a representative coverage of the socio-environmental gradients addressing environmental and geographical characteristics (e.g. altitude, climate, landforms, geology, land cover, biogeography), as well as social and economic gradients (e.g. demography, economic density). The majority of the existing ecological research activities is still performed on smaller spatial scales (e.g. plot scale, field scale, research stations), representing a large variety of funding schemes. However, an overarching concept to integrate such activities is still missing. In Europe, the development and provision of such a concept to transform the existing in-situ research sites into a continental-scale, harmonized, integrated, inter and cross-disciplinary research infrastructure is one of the key objectives of two EC-funded projects: “eLTER H2020” (Integrated European Long-Term Ecosystem & Socio-Ecological Research Infrastructure; duration 2015–2019) and “Advance_eLTER” (Advancing the European Long-Term Ecosystem, Critical Zone and socio-Ecological Research Infrastructure towards ESFRI; 2017).

Within the aforementioned EU projects a comprehensive survey was conducted to investigate the status of the monitoring programs of European LTER sites. Based on this survey the objectives of this study are to evaluate the current status of the observation strategies of LTER sites in Europe by: (i) providing an overview on biotic and abiotic observations across LTER-Europe sites, (ii) identification of gaps in the observation concepts, (iii) identification of gaps in the socio-ecological coverage, and (iv) provision of recommendations on how to overcome existing deficits and option towards future joint developments of infrastructural components for integrated long-term environmental research in Europe.

2. Methods

2.1. LTER framework of standard observations

LTER sites and national networks have mainly been developed in a bottom up manner (Haase et al., 2016). As a consequence, sites were established for different research and monitoring reasons and their research and design is largely driven by institutional and program-related needs. These sites cover a wide variety of ecosystem types, plot sizes, infrastructures, instrumentation, and individual sites measure a wide range of biotic and abiotic variables according to site-specific requirements.

One of the key challenges is the transformation of existing in-situ research sites into a harmonized, high-performance, complementary, and interoperable socio-ecosystem research infrastructure. To tackle this challenge, the provision of standardized top-down mechanisms and benchmarks to produce comparable baseline data is of central importance. Accordingly, there is a common agreement on the necessity to harmonize, coordinate and synthesize long-term biotic and abiotic data to enable comparisons within and between international monitoring activities, ecosystems, and scales (Hoffmann et al., 2014). Currently, we see parallel developments of data harmonization and integration mechanisms driven by different scientific communities and facilities (e.g. National Ecological Observatory Network - NEON, Group on Earth Observations Biodiversity Observation Network - GEO BON, ILTER; Haase et al., 2018).

Within the eLTER H2020 project and in cooperation with GEO BON experts a framework of standard observations has been developed. Haase et al. (2018) suggested to combine the Ecosystem Integrity (EI) and the Essential Biodiversity Variables (EBV; Pereira et al., 2013) frameworks and to derive standard observations for next-generation site-based, long-term ecosystem research and monitoring. The idea of EI is to assess the complexity and ability for self-organisation of an ecosystem in order to safeguard sustainability in terms of functions, processes and related ecosystem services. This is seen as a precondition to be prepared for unforeseen ecological risks. Thus, EI framework is based on a comprehensive set of biotic and abiotic indicators enabling to identify drivers of biodiversity changes within the context of ecosystem structures and processes (after Müller, 2005). However, the way how to come to such an EI assessment by evaluation of indicators against justified baselines still needs some clarification. Definitely this will not end up in a single EI value. In contrast, GEO BON and the EBV framework are dealing with global biodiversity change issues and propose a globally applicable monitoring system able to map the complexity of biodiversity change. Thus EBV's are addressing in detail the different biodiversity levels from genetic up to habitat. While the EI framework is aiming at whole ecosystems with its structures and processes, its biotic indicators lack sufficient detail and standardization to be applicable to within- and among network harmonization (Brown and Williams, 2016). An ideal monitoring site should however be able to provide data suitable for both, the EI and the EBV frameworks (Haase et al., 2018).

The LTER framework of standard observations (Table 1) has been developed based on experiences and outcomes of discussion between experts from different disciplines in the context of LTER Europe, and national expert groups. The framework aims to provide a harmonized guiding principle for the design of a pan-European infrastructure and for future infrastructural enhancements of LTER Europe sites. It focusses on variables which are (i) frequently measured in environmental monitoring, (ii) highly sensitive to environmental change, or of (iii) critical relevance for environmental modeling. The selected biotic measurements address basic and frequently recorded elements of biotic diversity like plants, butterflies and birds (Schmeller et al., 2009). The selected abiotic variables and properties consist of basic environmental variables and properties describing abiotic heterogeneity and different environmental budgets in terms of e.g. weather, hydrological runoff and water quality, groundwater and groundwater quality, soil properties and energy balance. The demand to address the energy and water balance of a research site necessitates the hydrological catchment scale to be considered in the monitoring concept. In the present study, the current state of infrastructural development of the LTER-Europe sites was compared with the LTER framework of standard observations. This comparison provides an overview about the given level of monitoring and the basis to evaluate the conceptual comparability in LTER Europe.

Table 1
The recommended LTER framework of standard observations considering core environmental variables and observation components; for further details see also Haase et al. (2018).

EI components	LTER standard observations
Abiotic heterogeneity	Air temperature
	Windspeed and wind direction
	Air humidity
	Barometric pressure
	Precipitation
	Incoming shortwave radiation
	Soil characterization (e.g. texture)
	Soil moisture
Water budget	Surface water temperature
	Surface water discharge
	Surface water pH
	Surface water specific conductivity
	Groundwater elevation
	Groundwater temperature
Matter budget	Groundwater specific conductivity
	Surface water nutrients and ions
	Soil water chemistry
	Atmospheric deposition
	Surface water dissolved organic carbon (DOC)
Energy budget	Soil heat flux
	Radiation budget
	Leaf area index (LAI)
	Concentration of CO_2 and water vapor
Biotic diversity	Abundance and identity of birds
	Abundance and identity of insects
	Abundance of vascular plants

2.2. DEIMS-SDR and used datasets

The data used in this paper were compiled, stored and queried using the LTER DEIMS-SDR (Dynamic Ecological Information Management System – Site and Dataset Registry; https://data.lter-europe.net/deims/). DEIMS-SDR is the site catalogue of both LTER-Europe and ILTER. In addition to storing site records it serves as a data node for dataset publication. All related information of a site, i.e. affiliated personnel and networks, datasets and research activities (data products) can be combined and exposed using the INSPIRE EF (Environmental Monitoring Facilities) application scheme (EC, 2017b) as a means of a standardized metadata interchange format.

As of June 12th 2017 DEIMS-SDR hosts a total of 1006 published site records ranging from LTSER platforms covering a wide range from socio-ecological research topics to point-based research plots with very particular research topics. This number includes both formally accredited LTER sites and other observation and research sites (partly also experimental sites). This makes DEIMS-SDR the globally most comprehensive catalogue of long-term environmental research facilities, featuring foremost but not exclusively information about all ILTER sites and provides this information to science, politics and the public in general. As a consequence, DEIMS-SDR was adopted by the Group on Earth Observation (GEO) as pilot for a global observation site registry.

For the purpose of the present study an “infrastructure survey” was carried out, aiming at the collection of more detailed site information beyond the standard DEIMS-SDR site metadata, specifically concerning observations and instrumentation covered by the sites. It addressed all LTER-Europe site managers and was entirely integrated as an extension into DEIMS-SDR, using a comprehensive pre-defined list of observations and related infrastructures (e.g. sensors). This list was consistently implemented in the standard DEIMS-SDR site metadata form and the site managers or other eligible metadata providers were asked to update their site metadata accordingly, securing seamless and global usability beyond the original purpose. The goal of the survey was to perform a parameter-driven state-of-art-analysis of the design elements at the site level and to collect the appropriate metadata (e.g. about sensors, sample rates). In the end, 224 LTER-Europe sites from 24 countries participated in the infrastructure survey.

The results presented in this study are based on two datasets created by using (i) the information available in DEIMS-SDR and (ii) the information gained by the infrastructure survey:

- Dataset A – Formally accredited LTER-Europe sites: Information of 477 accredited LTER sites from 26 national LTER networks. The formal accreditation by ILTER requires full site documentation and the formal acknowledgement by the respective national LTER network.
- Dataset B – Sites with available in-depth information on standard observation and instrumentation gained by the infrastructure survey: Information of 224 LTER-Europe sites from of 24 countries participating in the infrastructure survey.

2.3. Site classification

In order to evaluate suitability and representativeness of LTER-Europe for long-term socio-ecological monitoring both at the network level and the level of individual sites, two classification approaches were applied in this paper: analysis (i) of geographical distribution of sites at the network level according to bioclimate, landcover, landforms, biogeographical and socio-ecological regions in comparison to the given relative share of these geographical units in Europe, and (ii) of the actual level of instrumentation and site design (e.g. scale of observation). The latter was done based on information gained in the infrastructure survey among the LTER-Europe network. In order to deal with conceptual approaches like Ecosystem Services (ES) across larger spatial units (e.g. scale of countries or continents), a consistent framework of geographical classification (e.g. land cover, biogeographical regions) is needed in which ES can be assessed (Stoll et al., 2015). Input layers of the map of global ecological land units (bioclimate, landforms and land cover classes; Sayre et al., 2014) and the map of the biogeographical region classification provided by the European Environment Agency (EEA, 2016) were assigned to LTER-Europe sites. Information about 477 formally accredited LTER sites (excluding off-shore sites) in Europe have been included in this analysis. Additionally, a socio-ecological stratification integrating economic density zones and environmental attributes based on the method applied by Metzger et al. (2010) has been considered.

2.4. Geographical distribution analysis

All data included in the geographical distribution analysis (see Sections 2.4.2 to 2.4.5) have been processed in ArcGIS (ESRI, 2016). If available, the precise information about extent and geometrical shape (polygon data) of the LTER sites were imported into ArcGIS. For all other sites, center coordinates were used adding circular buffers calculated from of the specific size of the individual LTER site. In the next step, the site polygons were intersected with the input layers of different strata (e.g. bio-climatic zone, land cover class). This allowed determining the area covered by LTER-Europe facilities for each geographical, ecological, or socio-ecological unit. A summary of all imported strata data is shown in Table S1. To include coastal, onshore sites in the overall statistics an additional “Coastal Area” class has been considered by calculating a 3 nautical miles (5556 m) buffer at the sea boundaries in each input layer. The relative coverage per stratum is expressed by:

$$r_{A_{\mathrm{LTER-stratum}}} = \frac{A_{\mathrm{LTER-stratum}}}{A_{\mathrm{LTER-total}}} \tag{1}$$

where $A_{\text{LTER-stratum}}$ is the area of LTER-sites per stratum and $A_{\text{LTER-total}}$ is the total area of LTER-Europe facilities used for the analysis ($N_{total} = 477$). The relative area of a strata is calculated by:

$$r_{A_{\mathrm{stratum}}} = \frac{A_{\mathrm{stratum}}}{A_{\mathrm{total}}} \tag{2}$$

where A_{stratum} is the area of the stratum and A_{total} the total area of the data set. High representativeness is assumed if the number and distribution of LTER sites covers different environmental strata evenly.

2.4.1. Biogeographical regions

The biogeographical regions Europe 2016 dataset (a product of the EEA, 2016) provided the basis for biogeographical analysis with a scale of 1:10,000,000. It contains the official delineations used in the Habitats Directive (92/43/EEC, 1992) as well as for the EMERALD Network (Fernandez-Galiano, 2002) design under the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention, 1979).

2.4.2. Bioclimates

The Global Environmental Stratification (GEnS) produced by Metzger et al. (2013) was used as basis and overall context for the bioclimate stratification and provides a global context for comparative research and analysis (Zomer et al., 2015). The GEnS was developed to support global biodiversity monitoring and ecosystem research within the GEO BON Network (Scholes et al., 2008, 2012), as part of the Global Earth Observation System of Systems (GEOSS). This dataset has also been recently used to develop a new map of global ecological land units using an ecophysiographical stratification approach (Sayre et al., 2014). The GEnS classifies the world's land surface into 125 relatively homogeneous bioclimate strata, which cluster areas with similar climates together, based upon a statistical analysis of recent climate data (namely air temperature, precipitation and seasonality), i.e. as average of 1950 to 2000 (Hijmans et al., 2005; Ramirez and Jarvis, 2010; Zomer et al., 2015). These units were aggregated into 18 bioclimate zones with a resolution of a 30 arcsec (approximately 1 km^2 at the equator; Metzger et al., 2013).

2.4.3. Land cover

The GlobCorine product (Bontemps et al., 2009) has been used to describe the global land cover. This product is mainly based on a composition of MERIS (Medium Resolution Imaging Spectrometer; Rast et al., 1999) Full Resolution Full Swath (FRS) data and was collaboratively produced by the European Space Agency (ESA) and the Université Catholique de Louvain (Belgium). By using the processing chain of GlobCover (Arino et al., 2008; Bicheron et al., 2008, 2011; Vancutsem et al., 2007) the delivered product represents the global distribution of 13 land cover classes as interpreted from 300 m spatial resolution (Bontemps et al., 2009; Sayre et al., 2014).

2.4.4. Landform units

The landform mapping methodology used in this study (modified from True, 2002) was originally developed by the Missouri Resource Assessment Partnership (MoRAP) and is described in Sayre et al. (2009). The data source for this landforms classification model which is mainly based on an analysis of slope and local relief (Sayre et al., 2013) was the USGS GMTED2010 digital elevation model (Danielson and Gesch, 2011).

2.4.5. Socio-ecological regions

According to Metzger et al. (2010) the two most critical factors identified causing and describing anthropogenic ecosystem changes are economic power and human population pressure (see also Dietz and Rosa, 1994; Ehrlich et al., 1971; Redman et al., 2004). Hence the fusion of available data about Gross Domestic Product (GDP) and population density is appropriate for defining socio-economic regions as well as for identifying characteristics in socio-economic gradients across Europe (Metzger et al., 2010).

For the preparation of a consistent dataset for all LTER-Europe countries the two major limitations to be dealt with are (i) data availability and (ii) distortions by using administrative regions (Metzger et al., 2010). To overcome both we decided to base the socio-economic dimension on the economic density (ED) after Metzger et al. (2010), an indicator defined as the income generated per square kilometer:

$$\mathrm{ED} = \text{Economic Power} \cdot \text{Population Density} \tag{3}$$

$$\mathrm{ED} = \frac{\mathrm{GDP}}{\mathrm{Capita}} \cdot \text{Population Density} \tag{4}$$

where economic power, defined as GDP per capita, was available for European Union LTER-Europe countries (except Norway) from the EU statistical bureau (Eurostat, 2015). For Norway and countries outside the EU the GDP data were obtained from various sources (Israel, Serbia and Turkey from WEO, 2017; Norway from SSB, 2017; all other European countries from UNstats, 2017). These datasets have been resampled to 1 km^2 resolution. Population density data was available at a 1 km resolution level through the Gridded Population of the World dataset from the Center for International Earth Science Information Network (CIESIN, 2016). Following the suggestions of Metzger et al. (2010) an economic density map (€ per km^2) was constructed by applying Formula 4 on the economic power and population density datasets (see also Sachs et al., 2001). The resulting map with 1km^2 spatial resolution was aggregated to four economic density zones.

3. Results

3.1. Geographical and ecological distribution of LTER sites in Europe

An overview about the countries and the relative share per country in comparison to all formally accredited sites in LTER-Europe included in the analysis (dataset A) is given in Fig. S1. With >10% relative area per country Italy and the United Kingdom provide approximately 30% of all formally accredited LTER-Europe sites. With 5%–10% area share per country Austria, Germany and the Czech Republic contribute around 20%. Although there is a higher concentration of sites in the central part of Europe, the distribution of LTER-Europe sites is well balanced across the four European regions following the continental classification of the UN Statistics Division (UNSD) (Table 2).

3.1.1. Biogeographical regions

The area of Israel was not considered in the dataset used for the description of the biogeographical regions (EEA, 2016). For the analysis of the biogeographical coverage the decision was taken, to classify the Israel region as Mediterranean (Fig. 1). Three of the five main biogeographical regions (representing >9% up to 26% of the total area) are well covered by the existing LTER Europe network – Alpine, Atlantic and Boreal stratum (Table S2). The other two larger regions – the Mediterranean and Continental region – are underrepresented mainly due to a sparse distribution of sites in the eastern areas.

3.1.2. Bioclimates

Table S3 provides an overview of the geographical allocation as well as the distribution across the bioclimatic zones of Europe. Due to the high concentration of sites in the central part of Europe and the large extent of the 'cold wet' and 'cool wet' bioclimate approximately 50% of all sites are located in these two bioclimatic zones. This leads to a good representation of these main zones compared to the distribution in Europe (including Israel and Turkey; excluding Russia). In contrast, 'cool moist' and 'cool semi-dry' regions are slightly underrepresented. It is expected that Turkey, which only recently became a member of the LTER-Europe network, will provide sites within the 'cool semi-dry' zone in the near future. Overall, the distribution of LTER-Europe sites represents well the bioclimatic characteristics of Europe.

Table 2
Overview of continental units and relative share of sites in comparison to formally accredited sites in LTER-Europe included in the analysis of geographical and ecological representativeness (dataset A) after the UNSD classification.

Regions	Relative share	Number of sites
Eastern Europe	17.40%	83
Northern Europe	24.32%	116
Southern Europe & Israel	29.35%	140
Western Europe	29.35%	138

3.1.3. Landcover

The summary presented in Table S4 indicates that the major land cover classes covered by LTER Europe sites are forests (26.7%) and rain fed croplands (25.1%). The site distribution reflects well the overall distribution of these land cover classes in the LTER-Europe countries. Mosaic cropland, representing the third major European land cover class, is slightly underrepresented within the network. All other classes except 'permanent snow and ice' are sufficiently covered.

3.1.4. Landform units

The characteristic landforms of LTER-Europe sites (Table S5) are 'Flat or nearly Flat Plains' (24.1%), 'High Mountains' (12.4%) and 'High Hills' (12.1%). The latter two can be attributed to the high concentration of sites in the European Alps. Besides a slightly underrepresentation of 'scattered Low Mountains' and 'Low Mountains' the network mirrors approximately the distribution of major landform units of Europe.

3.1.5. Socio-ecological regions

The socio-ecological regions of Europe (Fig. 2) were defined by intersecting the biogeographical regions dataset (Fig. 1) with the economic density zones (Table 3) following the method proposed by Metzger et al. (2010). A detailed evaluation of these zones shows in various aspects economic structures - e.g. by highlighting higher economic density around metropolitan areas or the clearly visible increase in economic density in tourist areas along the Mediterranean coast (see also Metzger et al., 2010). The several mountain regions and the regions in the far north are much less influenced by human impact, expressed by lower economic density. Differences in economic development between central regions of Europe and more eastern regions are also reflected in the map.

In combination with the biogeographical stratification the spatial details of the socio-economic stratification can be interpreted in a broader context. For instance, the low economic density of the Alpine region includes the higher hillsides in the Alps, the Carpathians, and the Scandes. By contrast the high economic density Atlantic zone covers the metropolitan areas of the United Kingdom, northern France, Belgium, Netherlands, northwest Germany and Denmark.

3.2. Observational designs in LTER-Europe - analysis of current state

3.2.1. LTER-Europe and the LTER framework of standard observations

To provide an overview about the given level of monitoring and conceptual comparability, a survey on the current state of monitoring/observation technologies in LTER-Europe was designed (see also Section 2). The following results are based on the information gathered by an "infrastructure survey". In total, 224 LTER-Europe sites provided information on infrastructure, mode of infrastructure operation, spatial and temporal scale of measurements (dataset B).

These data have been used to compare the current monitoring program of each site with the proposed LTER framework of standard observations (Table 1). The LTER framework of standard observations comprises measurements focusing on the five components of ecosystem integrity (EI) as described by Haase et al. (2018) - biotic diversity, abiotic heterogeneity, energy budget, water budget, matter budget). Each of the sites was classified in terms of the number of EI components covered by the current monitoring program. To be assigned to one of the five EI components, the respective proposed measurement (see Table 1) must not be completely covered. Rather, the allocation of the EI components indicate

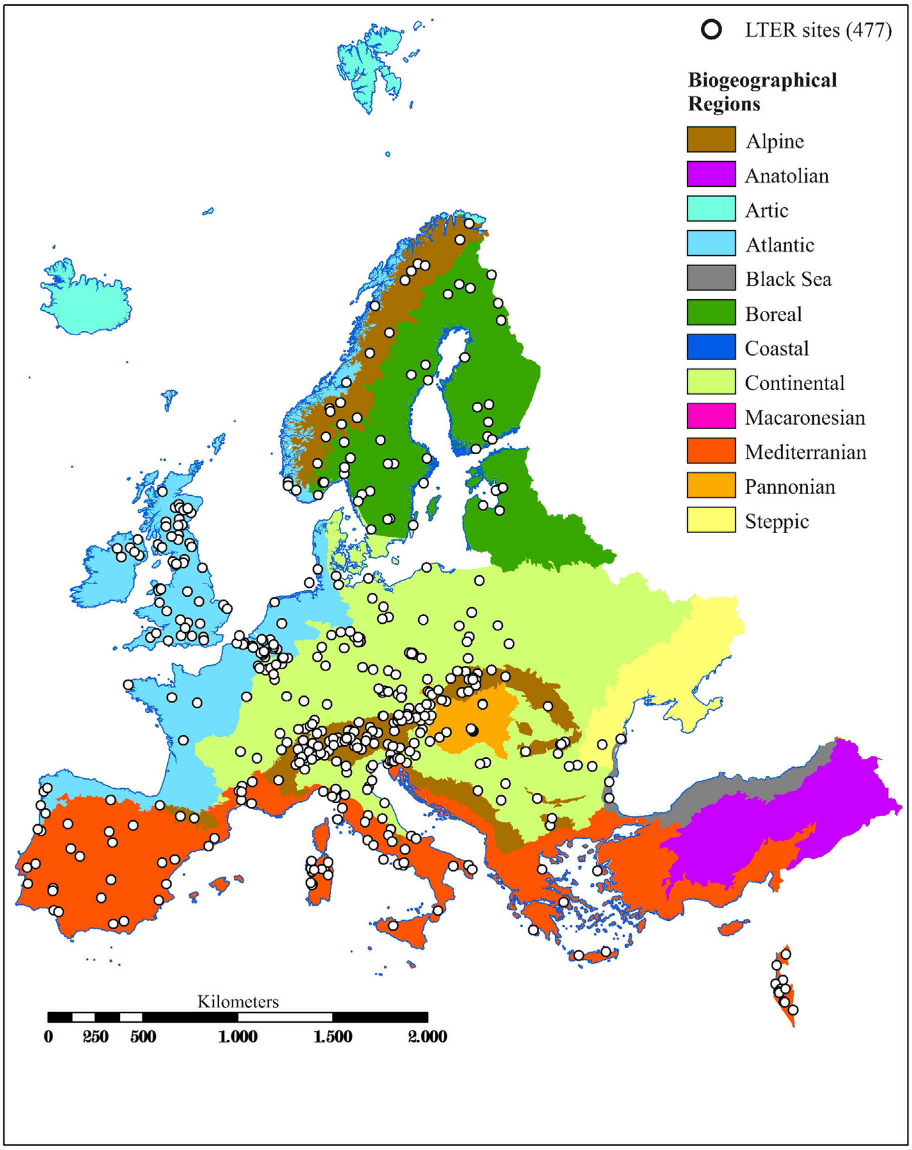

Fig. 1. Distribution of formally accredited LTER-Europe sites (dataset A, excluding offshore sites) within the European biogeographical regions.

that at least parts of the recommended measurements of the respective EI component are already included in the current monitoring program of the specific site (see Fig. S2).

Following this approach of site classification, 40% of all LTER-Europe sites included in the analysis can be classified as sites running a monitoring program which includes environmental variables targeting at four or five EI components respectively (see Fig. S3). In contrast, about 50% of the analyzed LTER-Europe sites monitor only variables out of two or even only one EI component. As expected a general trend illustrating the relation between monitoring effort and level of interdisciplinarity/integration can be postulated: the more EI components are included in the monitoring concept of an individual site the higher proportion of the LTER framework of standard observation is already covered by this monitoring concept (Fig. S4).

As anticipated, weather data are among the most frequently measured abiotic data. More elaborated monitoring methods – both in terms of infrastructure costs but also in terms of required expertise and workload – like measurement of energy, water and matter budget are much less widespread (Fig. 3). Among the three monitoring targets of biotic diversity evaluated, monitoring of plants is most frequently done.

3.2.2. Classification of representativeness

A new level of information emerged from combining the results from the assessment of geographical representativeness with the results from the site classification regarding the LTER framework of standard observations. As can be seen from Fig. 4, the different levels of site categories are rather evenly distributed along two transects from North-East to the South-West as well as North-West to South-East.

A more differentiated picture is given when only the distribution of sites monitoring four or even all five EI components (class 4 and 5 in Fig. 4) is taken into consideration. 89 sites (out of 224 included in this analysis, dataset B) fall in these two categories and constitute the LTER-Europe sites with the highest level of already existing monitoring components according to the LTER framework of standard observations (Table 1). These sites may play a key role in the further development of LTER-Europe towards a harmonized, pan-European infrastructure for long-term environmental monitoring and research.

Fig. 5 gives an overview about the distribution and relative share of the sites monitoring four or even all five EI components (see also Fig. 4) across the main European biogeographical regions and the regions of economy density. The numbers in Fig. 5 give the number of

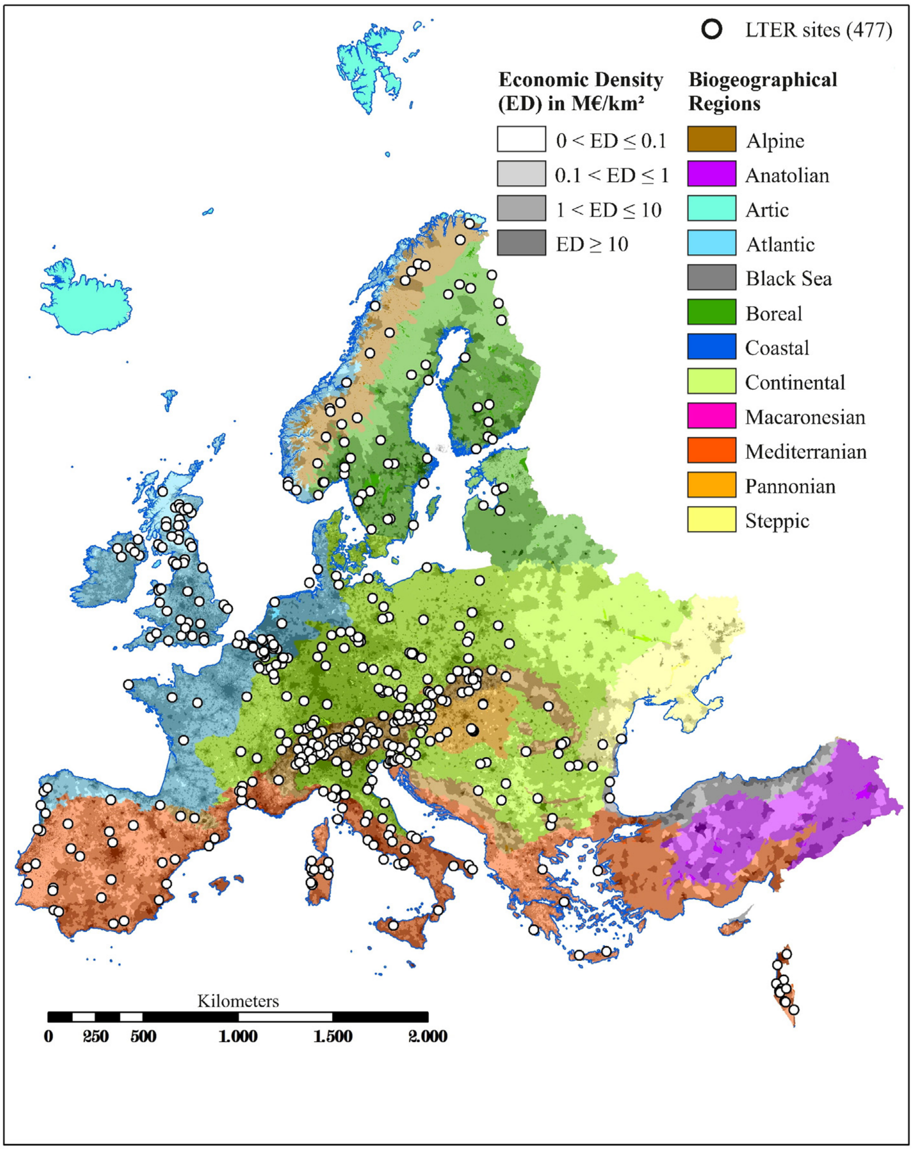

Fig. 2. Distribution of formally accredited LTER-Europe sites (dataset A, excluding offshore sites) within 44 European socio-ecological regions derived by intersecting biogeographical regions with economic density zones.

sites covering a specific socio-ecological stratum. For very large LTER sites it may occur that more than one stratum is covered. As can be seen, the by far highest density of highly equipped European LTER sites is established in the Atlantic region followed by the Continental and the Mediterranean region. Alpine, Boreal, Pannonian, Coastal, and Steppic region are underrepresented.

Table 3
Distribution of relative share of area of formally accredited LTER-Europe sites (dataset A, excluding offshore sites) within the calculated economic density zones and comparison with the proportional coverage in the LTER-Europe area.

Economic density (ED) in M€/km^2	LTER-Europe countries share in %	LTER-Europe sites share in %
ED < 0.1	26.5	16.9
0.1 ≤ ED < 1	47.7	47.4
1 ≤ ED < 10	21.7	30.1
ED ≥ 10	4.2	5.6

4. Discussion

Global environmental issues, including the impacts of land use, climate change, and biodiversity loss are to the core of humanity's grand challenges (Chapin et al., 2000; Haase et al., 2018; Rockström et al., 2009). To tackle these challenges, environmental change needs to be tracked at multiple spatial and temporal scales. Results of fundamental importance for policymakers, environmental managers and scientists can only be provided on the basis of sound data. Generating such data requires well-tuned, long-term biotic and abiotic research and observation programs (Parr et al., 2002; Peters et al., 2014). Many of the current monitoring systems are only inadequately suited in addressing the grand challenges in particular with respect to the continental or global scale. Representativeness and adequate coverage (geopolitical, environmental gradients) might not be tested or might be difficult to achieve, e.g. for political reasons or due to the mechanisms of programs for infrastructure development such as ESFRI, which build on national contributions resulting in patchy RI designs depending on varying country participations across RI's. Data are often gathered at scales incompatible

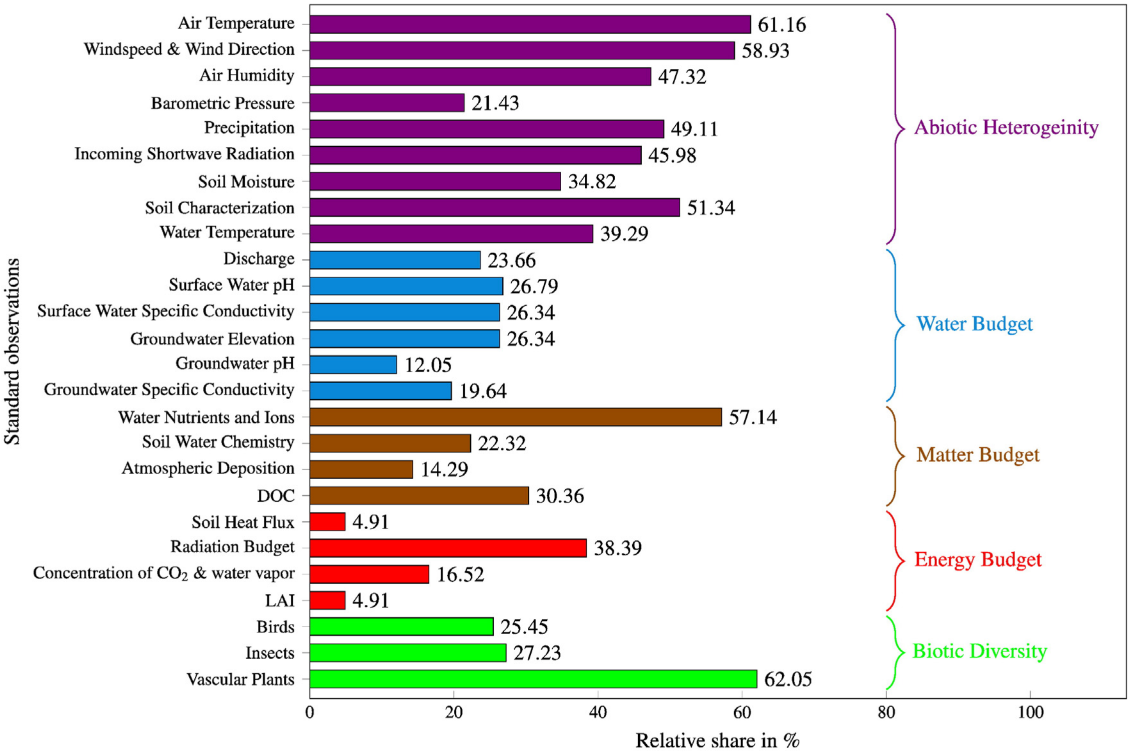

Fig. 3. Frequency of LTER framework of standard observations assigned to EI components.

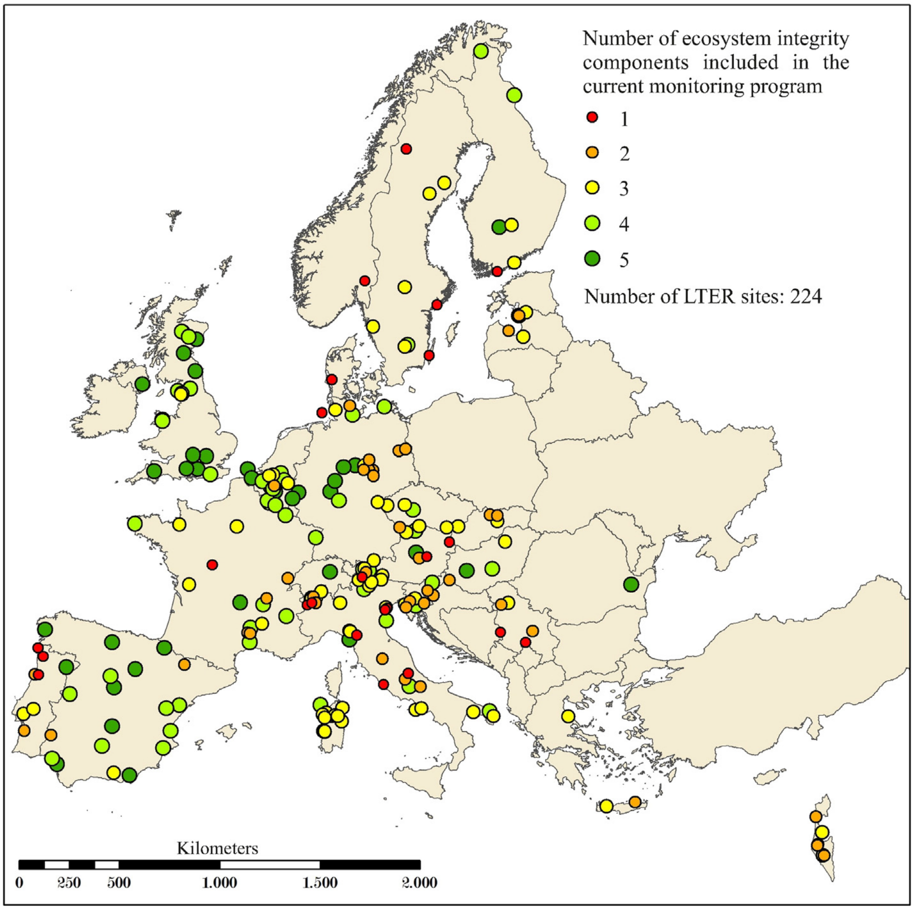

Fig. 4. Distribution of LTER-Europe sites with detailed documentation available (dataset B, 224 sites; excluding offshore sites) and classification following the Framework of Standard Observation and the EI concept (number of EI components included in the current monitoring program).

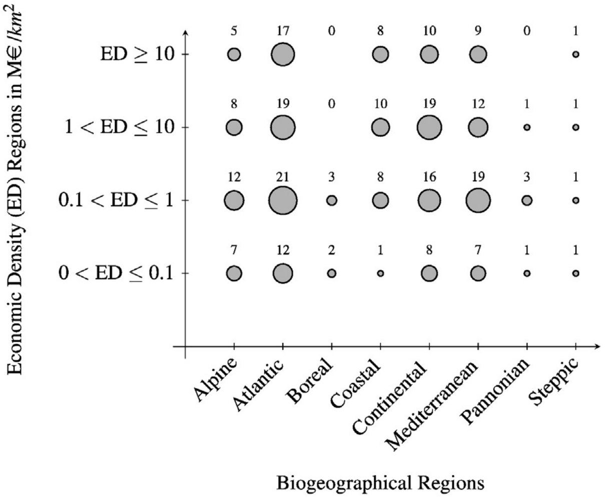

Fig. 5. Distribution and number of LTER Europe sites with detailed documentation available (dataset B) per socio-ecological stratum. Only those sites are displayed whose monitoring concept covers elements from four or even all five EI components. The size of the bubbles represents the number of sites (at the top of each bubble) in the corresponding category.

to be linked with policy-relevant decision making. Interdisciplinary and transdisciplinary research is often hampered by a lack of integrated infrastructures enabling capacity building in bringing researchers from different disciplines together. The lack of methodological standardization impairs cross-site comparability and scalability specifically in the long term (Pereira and Cooper, 2006). Therefore Haase et al. (2018) postulated feedback-loops of site-based measurements and local, regional and global data requirements to harmonize, coordinate and synthesize long-term environmental data.

One key challenge in this process is to upscale local site-based data from many LTER sites to the European scale. The clear majority of the analyzed LTER sites (approximately 60%) are operating on the plot level. Approximately 40% of the sites have implemented a monitoring concept including the catchment scale or focus on larger regions beyond the catchment level, allowing for the closure of water or matter balances and budgets. In addition, the actual LTER sites´ designs are frequently coupled with observation schemes at larger spatial scales (e.g. regional or national monitoring grids or National Parks inventories), supporting reliable up- and downscaling.

The distribution of formally accredited LTER sites in Europe (dataset A) does represent the given main gradients in biogeography, land use and even in the socio-ecological dimension (Tables S2, S4 and 3). However, there are some differences revealed by the analysis of the representation of formally accredited 477 LTER sites in comparison to Metzger et al.'s (2010) results (based on the analysis of 958 sites). The majority of the analyzed sites are located in medium and high economic density areas. Sites in natural or semi-natural areas with a low economic density are, by contrast, slightly underrepresented. Comparable to Metzger et al.'s (2010) findings for the biogeographical coverage, Mediterranean regions are still slightly underrepresented. But overall and in comparison the results of Metzger et al. (2010), the impact of strategic efforts made by LTER-Europe in recent years to (i) inform and encourage national LTER site network developments to close gaps or (ii) support the development in countries located in underrepresented areas (e.g. eastern Mediterranean area, LTER Greece) can be seen.

The combination of the analysis of geographical representation with the information about the current state of observation design introduces a further level of interpretability (Fig. 5). This analysis reveals a greater need for infrastructural upgrades (with respect to the LTER framework of standard observations, see Table 1) for the Northern, East-Mediterranean, and the East-European regions. It is noticeable, that the majority of highly equipped sites have a focus on regions with medium or high economic density, while regions with low or very high economic density are less represented. Some differences in the distribution of highly equipped sites may also convey differences in the national funding situation. Long-term environmental research relies mainly on national funding and sustaining a long-term, ground-based monitoring program puts high demands on the securing of financial resources. For the purpose of the future development of LTER in Europe and – specifically – a formalized European LTER research infrastructure, national differences in the funding situation must be borne in mind and should be adequately reflected in the design strategy.

5. Conclusion and outlook

In a recent paper Rose et al. (2017) addressed the key importance and implications of heterogeneities in regulating variables governing ecological interactions across space and time. To be able to describe these relations adequately, harmonized high quality data are required and tools need to be developed to meet the new challenges of technological advances, scientific progress, and the massive growth in available data. The scope of the challenge is clearly beyond the capability of individual sites in a network and can be met only through the synergies offered by a pan-European network that provides the respective infrastructure for environmental monitoring and research. The present study focused on the evaluation of the geographical representativeness and the observational design of LTER in Europe as a basis for filling a critical gap in the European research infrastructures landscape.

Overall, the network of LTER-Europe sites represents an excellent foundation for developing a research infrastructure featuring internally consistent design and standardized measurements with the purpose to (i) support world class ecosystem research at benchmark sites covering the major European environmental and socio-ecological gradients, (ii) run a high-level observation program across sites covering important ecosystem structures and functions as well as critical driving forces, and (iii) to provide the European counterpart to other continental-scale ecological research infrastructures like NEON, the US National Ecological Observatory Network (NEON, 2017), or TERN, the Australian Terrestrial Ecosystem Research Network (TERN, 2017).

Although the results do not allow direct conclusion to be drawn with regard to the comparability of monitoring methods or technologies, the present study is of key importance especially in the light of developing strategies towards a formalized, high-performance Research Infrastructure for integrated Long-Term Ecosystem, critical zone and socio-ecological Research (eLTER RI, Mirtl et al., 2018). This comprises the assessment of required amendments of the physical network, instrumentation and related upgrade costs. Thus, the study provides a valuable contribution for the future design of the emerging eLTER RI network both at the continental and the level of the national LTER networks.

Rapid biophysical, societal and technological developments may cause unforeseen environmental problems that pose new questions to be addressed and require adjustments of existing research strategies and infrastructures. Due to its geographical representativeness and the integrated observation concept, LTER-Europe represents an enormous potential for serendipitous science. While serendipity – the "propensity for making surprising discoveries" (Michener et al., 2009) – is a major component of scientific discoveries, the ability to draw useful and correct conclusions depends always on the access to facts. Translated into environmental science and the purposes of LTER, processes, cause-effect relationships and mechanisms eventually driving our socio-ecological systems and significantly affecting ecosystem services can only be identified on the basis of well-documented long-term data reflecting the functioning of entire ecosystems impacted by multiple driving forces over decades and centuries. LTER has the ability to provide such data for a representative network of locations and to securing the sustainable use of legacy information. An important strategy is to offer a generic infrastructure to serve the needs of various scientific and other user communities such as Critical Zone research. Synergistic interaction with related environmental research infrastructures comprises the co-location of LTER sites with other large-scale environmental, representative environmental monitoring schemes dedicated to monitoring specific elements of the environmental system, e.g. ICOS sites with respect to carbon fluxes (Integrated Carbon Observation System; ICOS, 2017) or UNECE ICP Forest (ICP, 2017) in order to maximize the potential application and informative value of data collected by LTER. Options to co-locate with experiments (AnaEE, 2017; AQUACOSM, 2017) have also to be explored.

Results of this study provide major input to the identification of focal areas for such co-located sites, aiming at a network of joint, highly developed sites ("Master Sites") representing European environments as well as a well-balanced composition of the actual LTER network of sites comprising site categories, which represent a hierarchy of spatial scales and hierarchical level of instrumentation as elements of a nested design (LTSER Platforms, LTER Master Sites, LTER Regular Sites, LTER Satellite Sites; see Mirtl et al., 2018).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.12.095.

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