AGU ADVANCING EARTH AND SPACE SCIENCES

Earth's Future

RESEARCH ARTICLE
10.1029/2025EF006743

Key Points:

- Harmonized environmental observation systems are key to inter- and transdisciplinary research on Earth system and sustainability challenges
- eLTER uses a Whole System Approach to monitor Europe's ecosystems through long-term, cross-scale observation of all system components
- eLTER defines essential ecosystem variables and protocols to unify data and support cross-disciplinary collaboration

Correspondence to:
S. Zacharias,
steffen.zacharias@ufz.de

Citation:
Zacharias, S., Lumpi, T., Weldon, J., Dirnböck, T., Gaillardet, J., Haase, P., et al. (2026). Achieving harmonized and integrated long-term environmental observation of essential ecosystem variables - The eLTER framework of standard observations. *Earth's Future*, *14*, e2025EF006743. https://doi.org/10.1029/2025EF006743

Received 17 JUN 2025
Accepted 12 MAR 2026

Author Contributions:
Conceptualization: Steffen Zacharias, Theresa Lumpi, James Weldon, Thomas Dirnböck, Jérôme Gaillardet, Peter Haase, Ingolf Kühn, Harry Vereecken, Jaana Bäck, Michael Mirtl
Writing – original draft: Steffen Zacharias
Writing – review & editing: Steffen Zacharias, Theresa Lumpi, James Weldon, Thomas Dirnböck, Jérôme Gaillardet, Peter Haase, Ingolf Kühn, Harry Vereecken, Jaana Bäck, Caterina Bergami, Bastian Bertsch-Höermann, Isabelle Braud, Nathalie Cools, Jan Dick, Shayli Dor-Haim, Martin Forsius, Martyn N. Futter, Veronika Gaube, Elli Groner, Lubos Halada, Laura Kauppi,

Achieving Harmonized and Integrated Long-Term Environmental Observation of Essential Ecosystem Variables - The eLTER Framework of Standard Observations

Steffen Zacharias[1], Theresa Lumpi[2], James Weldon[2], Thomas Dirnböck[3], Jérôme Gaillardet[4], Peter Haase[5,6], Ingolf Kühn[1], Harry Vereecken[7], Jaana Bäck[8], Caterina Bergami[9], Bastian Bertsch-Höermann[10], Isabelle Braud[11], Nathalie Cools[12], Jan Dick[13], Shayli Dor-Haim[14], Martin Forsius[15], Martyn N. Futter[2], Veronika Gaube[10], Elli Groner[16], Lubos Halada[17], Laura Kauppi[8], Andrea Lami[18], Tanja Lindholm[8], Carmela Marangi[19], Giorgio Matteucci[20], Pablo F. Méndez[21], Christin Mueller[1,22], Don Monteith[13], Jens C. Nejstgaard[23], Nikolaos P. Nikolaidis[24], Alessandro Oggioni[25], Daniel E. Orenstein[26], Christophe Piscart[27], Marie-Noëlle Pons[28], Robert Ptacnik[29], Karsten Rinke[1], Taru Sandén[30], Marcus Schaub[31], Martin Schrön[1], Claudia Schütze[1], Christian Siebert[1], Adelheid Spiegel[30], James M. Thornton[32,33], Hans-Jörg Vogel[1], and Michael Mirtl[1]

[1]Helmholtz Centre for Environmental Research - UFZ, Leipzig, Germany, [2]Swedish University of Agricultural Sciences, Uppsala, Sweden, [3]Environment Agency Austria, Vienna, Austria, [4]Université Paris Cité, Paris, France, [5]Senckenberg Research Institute and Natural History Museum Frankfurt, Frankfurt, Germany, [6]Faculty of Biology, University of Duisburg-Essen, Essen, Germany, [7]Forschungszentrum Jülich, Jülich, Germany, [8]University of Helsinki, Helsinki, Finland, [9]Institute of Marine Sciences CNR-ISMAR, National Research Council of Italy, Milan, Italy, [10]University of Natural Resources and Life Sciences, Vienna, Austria, [11]INRAE, RiverLy, Villeurbanne, France, [12]Research Institute for Nature and Forest, Geraardsbergen, Belgium, [13]UK Centre for Ecology & Hydrology, Lancaster, UK, [14]Israel National Forest Service and Land Development Authority - KKL-JNF, Jerusalem, Israel, [15]Finnish Environment Institute, Helsinki, Finland, [16]Dead Sea and Arava Science Center, Mizpe Ramon, Israel, [17]Institute of Landscape Ecology, Slovak Academy of Science, Nitra, Slovakia, [18]Water Research Institute - CNR-IRSAVB, National Research Council of Italy, Verbania, Italia, [19]Institute for Applied Mathematics - CNR-IAC, National Research Council of Italy, Bari, Italy, [20]Institute of BioEconomy - CNR-IBE, National Research Council of Italy, Rome, Italy, [21]Institute of Innovation and Knowledge Management - INGENIO, CSIC-Universitat Politècnica de València, Valencia, Spain, [22]Geotop-UQAM, Université du Québec à Montréal, Montréal, QC, Canada, [23]Department of Plankton and Microbial Ecology, IGB- Leibniz Institute of Freshwater Ecology and Inland Fisheries, Stechlin, Germany, [24]School of Chemical and Environmental Engineering, Technical University of Crete, Chania, Greece, [25]Institute for Electromagnetic Sensing of the Environment - CNR-IREA, National Research Council of Italy, Milan, Italy, [26]Technion - Israel Institute of Technology, Haifa, Israel, [27]Université de Rennes, CNRS, ECOBIO - UMR 6553, Rennes, France, [28]Université de Lorraine, CNRS, LRGP, Nancy, France, [29]Department of Natural Sciences and Environmental Health, University of South-Eastern Norway, Bø, Norway, [30]Department for Soil Health and Plant Nutrition, AGES - Austrian Agency for Health and Food Safety, Vienna, Austria, [31]Swiss Federal Institute for Forest, Snow and Landscape Research - WSL, Birmensdorf, Switzerland, [32]Mountain Research Initiative, University of Bern, Bern, Switzerland, [33]PartnerRe, Zurich, Switzerland

Abstract The development of harmonized, standardized, and integrated environmental observation systems is a key challenge in Earth system science. Such capability is essential for advancing the interdisciplinary research needed to improve understanding of the Earth system and support global sustainability. The Integrated European Long-Term Ecosystem, Critical Zone and Socio-ecological Research Infrastructure (eLTER RI) is a recently developed pan-European network of in situ research sites that facilitates the collection long-term, comprehensive observation, analysis, and modeling of environmental and ecosystem change. This initiative focuses on Europe's primary ecosystems, encompassing the atmosphere, geosphere, hydrosphere, biosphere, and their socio-ecological interactions with the anthroposphere. A fundamental prerequisite for effective environmental monitoring and observation is a standardized and harmonized design that facilitates consistent and comparable environmental data across diverse spatial and temporal scales. The objective of this paper is to introduce the eLTER Framework of Standard Observations (eLTER SO) as a harmonized conceptual and operational standard for long-term, integrated in situ environmental observations, and to demonstrate how it supports consistent cross-sphere monitoring and international collaboration in environmental research. The eLTER SO delineates essential ecosystem variables, their measurement methods, and protocols. These Standard

Andrea Lami, Tanja Lindholm, Carmela Marangi, Giorgio Matteucci, Pablo F. Méndez, Christin Mueller, Don Monteith, Jens C. Nejstgaard, Nikolaos P. Nikolaidis, Alessandro Oggioni, Daniel E. Orenstein, Christophe Piscart, Marie-Noëlle Pons, Robert Ptacnik, Karsten Rinke, Taru Sandén, Marcus Schaub, Martin Schrön, Claudia Schütze, Christian Siebert, Adelheid Spiegel, James M. Thornton, Hans-Jörg Vogel, Michael Mirtl

Observations (SOs) constitute the conceptual foundation of eLTER RI and provide a basis for overcoming existing disciplinary barriers to the international harmonization of environmental research and a foundation for cross-sphere observation concepts. The eLTER SO combines the scientific-academic perspective, as known from "classical" Essential Variable concepts, with the operational perspective required for the establishment and long-term operation of in situ observatories.

Plain Language Summary In order to better understand and protect the environment, we need observation systems that are standardized, coordinated, and integrated. These systems support transdisciplinary research and address key challenges in Earth system science and sustainability. The eLTER Research Infrastructure (eLTER RI), a Europe-wide network of long-term research sites, enables scientists to observe, analyze, and model ecosystem changes over time. eLTER RI applies a comprehensive approach that considers air, land, water, living organisms, and human societies as interconnected parts of the environment. This approach is: (i) Integrative—combining multiple scientific disciplines and stakeholder input, (ii) Place-based—focusing on site-specific features, (iii) Long-term—tracking changes over decades, (iv) Cross-scale—connecting insights from local to global levels and across time frames. To ensure consistency, eLTER developed the Framework of eLTER Standard Observations (eLTER SO), a set of key variables with harmonized protocols for environmental observation. These cover physical, biological, and socio-ecological aspects of ecosystems and aim to bridge disciplinary gaps. The eLTER SO balance scientific and practical needs, making them essential for long-term, globally relevant research. They strengthen collaboration across the environmental research community and support efforts toward sustainability.

1. Introduction

Human interactions with the environment have caused diverse and long-term transformation of ecosystems. Today, humanity is confronted with a *triple planetary crisis* comprising the closely interlinked threats of climate change, biodiversity loss, and pollution (Desai & Desai, 2025). Soil degradation, deforestation and an increasing frequency of weather extremes exacerbate these threats and can lead to environmental and societal disasters (Group on Earth Observations (GEO), 2023). In order to more effectively understand and manage the risks and consequences posed by these threats, which are of utmost importance to both ecosystems and humanity, it is vital to develop a profound and comprehensive scientific understanding of ecosystem processes and the feedbacks that operate between societal drivers and environmental systems. This ultimately requires the adoption of an inter- and transdisciplinary (including socio-ecological) approach to environmental observations (Hadorn et al., 2006; Steelman et al., 2015).

The aforementioned challenges confronting the scientific community today are accompanied by novel and continually expanding demands for the design of environmental observation and monitoring technologies (Brantley et al., 2016; Global Climate Observing System, 2010; Hari et al., 2016; Lawford, 2014; Mollenhauer et al., 2018; Reid et al., 2010; Shapiro et al., 2010; Zacharias et al., 2024; Zoback, 2001).

In order to understand the multiple interactions between global change and the thin veneer of the planet where life (including humans) is concentrated, it requires appropriately designed research infrastructures (RIs), where scientists and research communities collaborate across domains in the long term at in situ research sites and regional platforms. Long-term forecasting and projections of ecological (ecosystem functioning and dynamics) and socio-ecological developments (dynamic society-nature interactions) are increasingly called upon to ensure effective environmental policy and planning, while promoting equity and justice in environmental policies. This requires a framework agreed upon not only by the scientific community but also by policymakers, environmental managers, and other societal stakeholders, to improve our ability to observe the long-term dynamics of ecosystems, their coupled biotic-abiotic processes, and the coupled social-biophysical drivers. Despite years of discussion about the necessity for international harmonization of systemic, integrated environmental observation and monitoring, however, consensus over the specifics of such a holistic assessment framework has remained elusive (Kulmala, 2018).

The creation and enhancement of harmonized, standardized, and integrated observation systems is essential for fostering system-wide and transferable inter- and transdisciplinary research. This is one of the major challenges in

Earth system sciences aimed at achieving global sustainability (Arora et al., 2023; Kulmala, 2018; Reid et al., 2010; Zoback, 2001). The European Commission defined the *Development of comprehensive and sustainable global environmental observation and information systems* as one of the grand societal challenges (European Commission, 2016). Despite considerable progress in the development of concepts for the harmonization of in situ environmental monitoring, as expressed, for example, in the various *Essential Variable* concepts, there is still a lack of internationally coordinated and harmonized concepts for the standardization of integrated long-term environmental monitoring and observation that focuses on all compartments (”spheres”) of the natural environment (atmosphere, hydrosphere, geosphere, biosphere) including socio-ecological conditions at a given place.

In 2020, the initiative to establish the Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research Infrastructure (eLTER RI: https://elter-ri.eu/) was launched. eLTER represents a historical convergence of different research communities and their observation infrastructures, originating from a variety of perspectives. These communities share a necessity for a more integrated (systemic) approach and an enhanced connection to society during the critical period of the Anthropocene (Richter et al., 2024). eLTER gathers different community networks: the well established Long-Term ecological research observatories (Parr et al., 2002) with a prominent focus on ecology, Critical Zone observatories with a focus on Earth sciences and long-time scales (Brantley et al., 2017), and socio-ecological approaches, that associate the stakeholders into the research practices (Haberl et al., 2006).

eLTER aims to advance ecosystem and critical zone research and to reveal and integrate the effects of various societal and environmental stressors on European terrestrial, freshwater, transitional water ecosystems, and the critical zone dynamics. The overarching goals of the eLTER RI design are twofold. First, it seeks to promote excellence in scientific research by facilitating access to and enhancing the utility of comprehensive environmental and socio-ecological data. Second, it aims to provide the most comprehensive observational coverage possible of key biogeographical and socio-ecological regions of Europe (Ohnemus et al., 2024, 2025). Together, these objectives advance our understanding of ecosystem functioning in a changing environment and society. The insights derived from this research are intended to inform solutions to 21st-century sustainability challenges across diverse spatial scales, ranging from local to global (Holzer & Orenstein, 2023).

The conceptual foundation of eLTER RI is based on the “Whole System Approach for in situ research on Life Supporting Systems in the Anthropocene” (WAILS). This approach largely encompasses the Earth System comprising the four biophysical spheres geosphere/pedosphere, hydrosphere, biosphere, and lower atmosphere as well as socio-ecological and socio-economical interactions with the antroposphere. WAILS seeks to comprehend ecosystems as intricate, dynamic systems, aligning itself with the Press Pulse Dynamic Model of (Collins et al., 2011). Concurrently, it draws upon the multi-directional feedbacks and interactions that span over temporal and spatial scales in order to follow the spatially-nested hierarchical feedback paradigm of Macrosystem Ecology, as articulated by Heffernan et al. (2014). By embedding empirical findings in their full ecological, spatial, and social context, it enables the detection and interpretation of both gradual and extreme changes in ecosystem functioning (i.e., presses and pulses)—particularly in response to diverse environmental drivers, pressures, and human interventions (Collins et al., 2011).

A central anchoring element and the in situ foundation for the establishment of eLTER RI is the Long-Term Ecosystem Research network in Europe (LTER-Europe). LTER-Europe comprises over 650 nationally acknowledged in situ sites and platforms for ecosystem and socio-ecological research (https://deims.org/) and sites from closely related projects and networks (incl. Critical Zone Observatories). These sites and platforms, which are primarily funded by institutional or national bodies, represent the basis for developing the eLTER RI. The LTER concept has historically centered on single sites (Holzer et al., 2018). Hence, each LTER facility represents different levels of infrastructural development and typically covers smaller spatial scales (single research stations, plot or field scale). The establishment of each LTER site and platform was accompanied by the development of specific research portfolios. Consequently, the characterization of these sites and platforms has been determined by observation programs and protocols that are non-uniform in nature (Mirtl et al., 2018). Critical zone observatories have been implemented more recently at the global scale in order to gather Earth scientists from different disciplines to work together at highly instrumented places, very often using the watershed as an integrating unit (Brantley et al., 2017). Furthering these structures toward a continental, harmonized, inter- and transdisciplinary research infrastructure, the eLTER RI, is the central goal of two projects funded by the European Union, the eLTER Preparatory Phase Project (https://elter-ri.eu/elter-ppp) and the eLTER PLUS project (https://elter-ri.eu/elter-plus). Such transformation requires a standardized and harmonized observation design that covers variables essential to characterize the status and trends of the observed systems as a key prerequisite for data exchange between sites. A major challenge for eLTER is hence to establish transferable and harmonized monitoring designs on the one hand but allow site-specific monitoring targets on the other hand. The observation design should include a description of the specific recorded environmental variables, along with an outline of the methodology to be employed.

Against this background, a process for iteratively selecting and defining *eLTER Standard Observations* (SOs) across 25 European countries has been launched. This paper provides a comprehensive overview of the eLTER Framework of Standard Observations (eLTER SO), including its conceptual foundations, the criteria and rationale underlying the selection of SO variables, and the structured, community-driven development process through which the framework was established. The paper outlines the scientific and operational considerations that guided the definition of essential variables, describes the methodological principles applied to ensure harmonization and comparability across sites, and provides an explanation of how the framework supports integrated, long-term in situ ecosystem observation within eLTER RI.

The eLTER SO, a major building block for the eLTER RI, represent a novel approach for a cross-domain prioritization of the environmental variables to be measured. They create links between existing disciplinary international standards of environmental observation and monitoring to bring together the perspectives of biotic, abiotic and socio-ecological environmental long-term observation.

2. eLTER and the Process for Defining Standard Observations

2.1. The eLTER Standard Observations Concept

As a first step in the development of the eLTER SO, an analysis was carried out to identify and compare existing environmental research infrastructure networks and related standardization concepts. Based on this analysis, conceptual interfaces between environmental research infrastructures, and thus the potential for international and cross-network harmonization, were identified.

One of the most pivotal concepts for international standardization and harmonization of environmental observation is the concept of *Essential Variables* (EVs). The EV concept was developed in response to the need to effectively capture and understand critical aspects of environmental systems. In the 1990s, the Global Climate Observing System (GCOS) started to identify environmental variables that would allow for the collection of targeted, harmonized and standardized measurements, to systematically record and describe the state of the environment with a focus on the climate system (Houghton et al., 2012). This process led to the definition of the Essential Climate Variables (ECVs), and 55 ECVs are currently defined by GCOS Global Climate Observing System (2022). The concept of EVs has been extended in recent years to many other domains, such as the marine environment (Essential Ocean Variables, Miloslavich et al., 2018), the biosphere and biodiversity (Essential Biodiversity Variables, Pereira et al., 2013), the geosphere (Essential Geodiversity Variables, Schrodt et al., 2024), the hydrosphere (Essential Water Cycle Variables, Huffman et al., 2021), mountain ecosystems (Essential Mountain Climate Variables, Thornton et al., 2021), or ecosystem services (Essential Ecosystem Service Variables, Balvanera et al., 2022). These frameworks continuously develop with additional new variables, domains and networks being considered (Hummel et al., 2022; Pacheco-Romero et al., 2020; Patias et al., 2019).

Despite the undoubted value of the various EV concepts for targeted environmental observation and monitoring, there are significant obstacles to their utilization as the foundation for a long-term operated, integrated, holistic and interdisciplinary Research Infrastructure. The development of the various EV concepts has been initiated from a disciplinary perspective, with many EVs linked to specific monitoring objectives (e.g., biodiversity vs. climate). EV concepts usually function as a guidance for system design rather than as a “checklist” for sites. Instead, the focus is on reference-quality observation and principles rather than claiming full site implementation anywhere. Furthermore, when integrating different EV concepts, one is often confronted with differences in disciplinary standards and methodologies, as different scientific disciplines often use their own established methods, units or standards for data collection, not to speak of spatial and temporal scales of observation or the focus on qualitative or quantitative information. A further challenge is the diverse and frequently changing requirements of practitioners working in dynamic ecosystems. In this sense, EV concepts are of course an important basis for the selection of relevant variables and were also decisive for the assessment of the “essentiality” of the variables for the eLTER SO. However, they are only of limited use as a direct guide for the development of a concrete in situ design for a long-term network of integrated environmental observatories. This situation emphasizes the need for a well-thought out and harmonized definition of methods on the one hand but also the need to consider flexibility, adaptive observation, and differing temporal or spatial resolutions on the other.

The development of eLTER SO required translating the scientific agenda of the eLTER RI into a framework of requirements for the observatories. This involved determining what needs to be measured and how, while taking existing approaches to standardization and environmental monitoring, such as those provided by the EV concepts or existing protocols of sibling infrastructures such as ICOS (Integrated Carbon Observation System), into account. Hence, a novel conceptual approach was developed to facilitate this translation by extending the EVs concept and linking it with the *Ecosystem Integrity* (EI) concept (Haase et al., 2018; Müller et al., 2000). The idea of EI is to assess the complexity and ability for self-organization of an ecosystem to safeguard sustainability in terms of functions, processes, and related ecosystem services. The EI concept provides a holistic approach to ecosystem assessment of biotic and abiotic fluxes and states, describing the energy, water, and matter budgets, as well as abiotic heterogeneity and biotic diversity. This approach enables excellent tracking of ecosystem services but falls short of capturing human-nature interactions in detail. In order to comply with the WAILS approach, the EI concept had to be extended to incorporate social-ecological indicators. With this expansion, the EI concept, in combination with a set of selected EVs, fits very well into the scientific perspective of eLTER's WAILS approach and was used to structure the process of selecting variables for the eLTER SO. At the beginning of the selection process, the following criteria for eLTER SO variables were defined:

- Representation of key elements of the Ecosystem Integrity concept
- Critical relevance for understanding the coupled human-nature system
- High sensitivity to environmental changes and anthropogenic pressures
- Critical relevance for ecosystem modeling

These four criteria determined the scope of the SOs, while the eLTER RI scientific objectives provided the foundation for selecting the variables. The main research foci of eLTER RI—climate change, biodiversity loss, soil degradation, pollution, unsustainable resource use, and ecosystem and critical zone functioning across Europe's terrestrial, freshwater and transitional water ecosystems—are intentionally linked to selected SOs.

eLTER RI will generate information accessible to a wide range of stakeholders, including scientific users, governmental and non-governmental organizations, industry (e.g., sustainable resource management, environmental risk assessment, assessment of compliance with ecological regulations) and high-level decision makers. This service is challenged by the fact that the operation of the observatories is funded by institutional research organizations with specific research agendas and funding agencies with their specific time frames. To maintain the scientific vibrancy of the eLTER RI, the SO framework must allow for flexibility to be integrated into existing research agendas or to be adapted or expanded as new research questions emerge. Achieving a balance between this science-driven flexibility and the service provision, which constitutes a fundamental aspect of the core task of an RI (Zacharias et al., 2024), such as routine measurements and mandatory data provision, was of paramount importance when selecting and defining eLTER SO. The more complex the design and the more extensive the operational requirements, the more challenging and difficult it becomes to ensure long-term operation (see also Section 3.3.2).

Another criterion that had to be taken into account, especially for the definition of methods and protocols for the measurement of variables, was the coordination with other existing environmental RIs and standards (e.g., Integrated Carbon Observation System—ICOS, World Meteorological Organization—WMO, UNECE International Cooperation Programs—ICPs such as Forests, Waters and Integrated Monitoring, EV concepts). Harmonization of methods and protocols with other networks and initiatives is essential to leverage existing long-term data, create new and improve existing synergies, increase scientific impact and catalyze international scientific networking. Further criteria for the selection of variables included the general feasibility of measurement and associated costs as well as the potential of automatized measurements to reduce personnel effort and gain higher temporal resolution. Moreover, with respect to a considerable number of socio-economic SOs, the existence of readily available data at the required spatial and temporal scales was also considered. Indicators that had been systematically collected by census bureaus, statistical offices, or satellite imagery were given priority.

Table 1
Criteria and Ranking Principles for Selection of Standard Observations Variables, Methods, and Protocols (Criteria Based and Adapted From Costa et al. (2016) and GEO BON (2017))

Criteria	Description	Ranking principles	Ranking
Relevance	The degree to which the variables represent key elements of the ecosystem integrity concept; response to driving pressures of environmental change. *What to measure?—Variable(s)*	Based on expert judgment; the variable is highly relevant across several research disciplines; variable is highly sensitive for detecting/measuring current and potential future drivers of environmental change	High
		Relevant only for one or few research themes/disciplines or not highly sensitive for detecting/measuring environmental change	Low
Cost efficiency	Describes required investment and operation costs. *How to measure?—Method*	Measurement is already available at many locations; instrumentation can be implemented at relatively low cost; fully automated measurements (low personnel costs) possible; low follow-up costs; high durability (withstand storms, extreme and low temperatures)	High
		Very expensive instrumentation; high follow-up costs (laboratory, cooling costs etc.); labor-intensive; low durability	Low
Operative feasibility	Describes potential for operational implementation at a large number of sites with respect to usual lab/field equipment and practical realization. *How to implement?—Protocol*	Well established standards available, part of routine measurements in international networks; easy to apply; high probability of being harmonized	High
		Extensive expertise needed for operation; logistically difficult, for example, complex measurement campaigns needed; lack of widely accepted/applied protocols; low probability of being harmonized	Low

According to these criteria, the eLTER SO defines the (a) minimum set of eLTER SO variables, (b) the associated methods, and (c) the protocols to characterize adequately the state of the Earth systems, including the human dimension. SOs have to be able to determine the system's state and development and, furthermore, have a high feasibility, relatively low cost of implementation, and sufficient spatiotemporal coverage (Masó et al., 2020; Reyers et al., 2017). In summary, the SOs should enable characterization of an environmental system from groundwater to the land surface to the lower atmosphere, including its socio-ecological characteristics, in an affordable, reliable, and methodologically appropriate manner (Guerra et al., 2017).

The eLTER SO has several commonalities with frameworks of EVs as developed within various scientific communities and described above. They take into account the most complete scientific understanding available of states, fluxes and dynamics of the environmental system under consideration, as well as its link to society, as also reflected in concepts of EVs. Furthermore, the definition of SOs aligns with the design of the eLTER RI by considering cost-effectiveness and operative feasibility as preconditions for selecting methods and protocols (Table 1). These latter two aspects are of particular importance with regard to the long-term implementation of SOs, exerting a direct consequence on the definition of the measurement method. In this sense, an eLTER SO is defined as a combination of three elements (see Figure 1):

1. Definition of the variable/variable combination to be measured,
2. Definition of the measurement method to be applied,
3. The protocol for measuring the variable/variable combination.

2.2. Selection and Adaptive Development of eLTER Standard Observations

The selection of eLTER SO variables was one of the most fundamental decisions for implementing the systemic, cross-domain perspective of eLTER in the in situ design and the services eLTER RI will provide. The eLTER SO significantly impact costs and are therefore critical for both science-driven decisions and economically constrained decision-making processes in the formal construction of the European eLTER network.

Sustainable implementation of the network design and associated measurement protocols can only succeed if both are developed with close consideration of the users' perspectives. Therefore, a multi-stage process of successive,

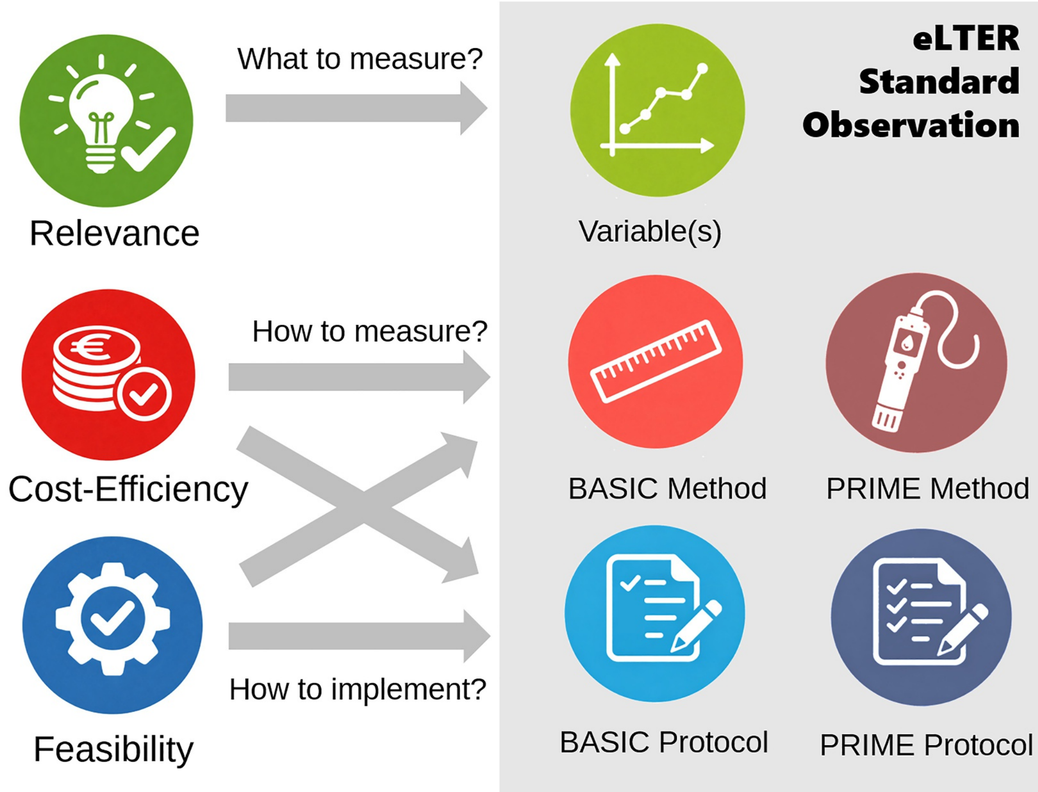

Figure 1. Definition of Standard Observations (variable + method + protocol) based on consideration of scientific relevance, cost and operative feasibility (The concept underlying the BASIC/PRIME classification of methods and protocols is delineated in Section 2.3).

iterative consultation and feedback rounds provided various opportunities for users to participate directly in defining the eLTER SO. Direct participation and the contribution of expertise from internal and external experts, as well as eLTER site/platform managers and users, occurred through iterative consultation rounds, ultimately resulting in the final selection of the eLTER SO (for further details see Weldon et al. (2024)).

Although eLTER needs a properly defined spectrum of SOs for its implementation, the process of identifying SOs is dynamic and should allow for adjustments and further development. This can become relevant, for example, whenever new methods emerge. One example of this are novel approaches for recording biological variables. Traditional quantitative observation methods, such as the microscopic analysis of plankton or the identification of birds in the field, are time-consuming and require a significant degree of expert knowledge. Conversely, methods supported by emerging technologies, such as eDNA or soundscape analyses, can be automated. However, making methodological adjustments often raises challenges and needs through expert review. This is in particular the case when quantitative methods (e.g., microscopy) are substituted by qualitative methods (e.g., eDNA, see also Section 3.3.6).

2.3. The Linkage Between eLTER Standard Observations and the Design of eLTER's In Situ Research Facilities

The physical backbone and fundamental building blocks of the spatially distributed eLTER RI are its in situ *facilities*, which comprise *eLTER Sites* and *eLTSER Platforms*—locations where instruments, sensors, and standardized protocols are deployed to collect data continuously over years to decades.

eLTER Sites are well-instrumented individual research locations where long-term environmental observation takes place. Usually eLTER Sites are designed to cover specific ecosystems or landscape units and provide baseline data sets for larger-scale integration. "eLTER Sites Category-1" are designed for the highest operational level ("highly instrumented sites") and capture ecosystem processes in great detail and serve as reference sites for calibration, method development, or model validation. "eLTER Sites Category-2" provide a measurement program, that is, either reduced or less intensive in nature when compared to that of Category-1 (see also Figure 3). Nevertheless, these sites are still required to adhere to the eLTER standards, thereby ensuring the comparability and quality of the data. The combination of eLTER Sites Category-1 and Category-2 supports up- and downscaling of information to achieve sufficient spatial coverage.

A further element of eLTER's in situ design are "eLTSER Platforms" for socio-ecological research. Platforms represent a "higher-level" structure that integrates eLTER Sites and usually cover a broader spatial scale, often a region or a cluster of habitats. eLTSER Platforms are place-based scientific infrastructures defined by explicit geographical and administrative boundaries, providing the scientific, administrative and human infrastructure necessary for observing, analyzing and co-producing knowledge across academic disciplines, institutions and local communities. Platform prerequisites include the development of robust data collection, the integration of at least one Category-2 eLTER Site, with particular emphasis on the extensive and sustainable integration of and communication with a diverse range of stakeholders. While the eLTER Sites Category-1 and Category-2 correspond to the concept of classical environmental in situ observatories, the eLTSER Platforms are a novel concept that aims at cross- and transdisciplinary research by bringing together different scientific disciplines with stakeholders beyond science (e.g., policymakers, land managers, local communities) and at the same time providing long-term observations (quantitative and qualitative data) on societal interactions (Bretagnolle et al., 2019; Dick et al., 2018; Haberl et al., 2006; Holzer et al., 2019; Méndez et al., 2022; Mirtl et al., 2012). Similar to eLTER Sites, eLTSER Platforms can be designed as Category-1 and Category-2. As for the eLTER Sites, the difference between both Platform categories is mainly driven by the methods and level of detail and accuracy of eLTER SO performed in the Platform (see Section 3.2).

To accomplish the two eLTER RI design goals, that is, (a) fostering integrated science by providing access to comprehensive environmental information and (b) reaching a representative geographical coverage, a concept of a two-tier, modular categorization of the in situ facilities was adopted. This categorization, for which the SOs play a pivotal role, pursues three main objectives:

1. To describe the "quality," that is, the observational breadth, and focus of in situ research facilities in terms of scope and instrumentation,
2. To describe the relevance of specific scientific questions,
3. To facilitate networking with related monitoring networks.

The creation and provision of data embedded in eLTER's WAILS context implies integrated long-term observation at selected sites. This must be balanced with the challenge of achieving large-scale, systematic coverage of the major European terrestrial, freshwater, and transitional water ecosystems, taking socio-ecological aspects into account. The two-tier categorization of in situ facilities ensures both high scientific quality and broad coverage across Europe while keeping the system practical and cost effective. The classification is directly linked to a definition of the mandatory measurement program, which is reflected both in different compositions of the environmental variables to be measured and in differences in the standards for the measurement methods to be used.

A central element for the operation of eLTER Sites and eLTSER Platforms is the set of SOs, which are obligatory to be measured for each Site or Platform category. These are subsets of SOs that allow an integrated (where possible) characterization of key ecological processes in terms of water, energy and material balances, as well as characterization of abiotic site properties, selected elements of biodiversity, and socio-ecological conditions.

To facilitate the utilization of the SO concept within eLTER's Site and Platform hierarchy (i.e., categories), two sets of methods and protocols were defined for the majority of SOs. The *PRIME* set of methods and protocols represents the highest standard (in terms of measurement accuracy, quantification of processes, spatial and temporal resolution). The second is the *BASIC* set, a less elaborate (and in most cases less resource-demanding) combination of methods and protocols, which does not compromise the quality and diversity of the measurements, but allows data to be collected from a larger number of sites with a wider spatial and broader temporal coverage. The definition of this hierachical methodological design, *PRIME* and *BASIC*, facilitates considerably greater flexibility in transferring eLTER SO definitions to the eLTER Site and Platform categories.

Putting the eLTER WAILS approach into practice, eLTER Category-2 Sites are the fundamental units of the eLTER RI network. Category-2 Sites observe the ecosystem at a basic level and enable the coverage of all five Earth system spheres and their associated core set of SOs as defined by the *BASIC* combination of methods and protocols. This core set of SOs delineates the minimum requirements concerning the composition of the environmental variables to be recorded, as well as the minimum requirements for measurement methods and measurement protocols. eLTER Category-1 Sites represent the highest site category in the eLTER RI design and are developed based on the design of Category-2 Sites. Advancing an eLTER Site from Category-2 to Category-1 requires the expansion of the observation and research foci and expansion of the in situ measurement design for a minimum two out of the four biophysical spheres (geo-, hydro-, bio-, atmosphere) that are delineated as Category-1 focal spheres for the designated site. This comprises additional SOs on the focal spheres (see also Figure 3 in Section 4). The operation of a Category-1 Site is accordingly more demanding and involves greater effort since (a) the number of mandatory variables is higher and (b) in many cases, a more demanding *PRIME* combination of method and protocol applies. The clear advantage of this hierarchical site concept is the possibility of transferring previously existing specializations of sites seamlessly into the eLTER RI and directly integrating already existing expertise while encouraging expansion toward new research fields. In many cases, this will guarantee uninterrupted compliance with existing institutional obligations and increases the opportunities for collaboration with other existing RIs.

To be applicable at eLTER Sites and eLTSER Platforms across European environments and socio-ecological regions, a thorough consideration of habitat-specific requirements was needed. Not all variables can be measured meaningfully in every habitat type, nor are they all necessarily relevant to that particular habitat. It must be acknowledged that a requirement that is met, for example, for a forest site, may not be feasible or reasonable for an aquatic site and vice versa. Furthermore, specific adaptations to measurement protocols may be required in certain habitats, necessitating the definition of distinct sampling protocols despite measuring the same variable. The EUNIS (European Nature Information System) Habitat Classification (https://eunis.eea.europa.eu/index.jsp), developed by the European Topic Center on Biological Diversity of the European Environment Agency (EEA), was used as a foundation for the classification of habitats. This system provides a comprehensive pan-European hierarchical classification of habitats, covering both marine and terrestrial ecosystems (Chytrý et al., 2020) and serves as the guiding framework for eLTER. It is important to note that the following habitat list does not constitute a complete adoption of the EUNIS nomenclature but rather comprises selected EUNIS habitat types and subtypes that, within the context of the eLTER RI design, facilitate the derivation of a minimum set of required SOs. Accordingly, the following habitat types were imposed for classifying habitat-specific requirements for eLTER Sites:

- Wetlands (mires, bogs, fens)
- Grasslands and lands dominated by forbs, mosses or lichens
- Heathlands, shrub and tundra
- Forests and other wooded land
- Vegetated human-made habitats (regularly cultivated agricultural, horticultural and domestic habitats)
- Inland surface standing waters
- Inland surface running waters
- Coastal (transitional) waters, including coastal littoral zones
- Sparsely vegetated habitats and deserts

3. eLTER Standard Observations

3.1. Overview

As a result of the multi-stage process of identifying and selecting the SOs described in Section 2.2, a final number of 63 SOs was defined. Thirty-three of these SOs represent bundles of variables to be measured. This logic of "bundling" variables into one SO reflects more clearly the requirements of practical on-site implementation of measurement requirements. The underlying principles are illustrated schematically in Figures 2a–2c. This aggregation of SO variables has been done in cases where different variables either:

1. Can be captured by a "standardized" sensor combination (e.g., meteorological station, Figure 2a)
2. Can be captured by a single sensor system (e.g., multi-parameter probe for physical and chemical water variables, Figure 2b) or analytical methods providing concentrations of several substances through a single measurement (e.g., ion chromatography), or
3. Where the required sampling (e.g., soil inventory) resp. Data collection (e.g., acquisition of socio-ecological data) can be done in one step or operation (Figure 2c).

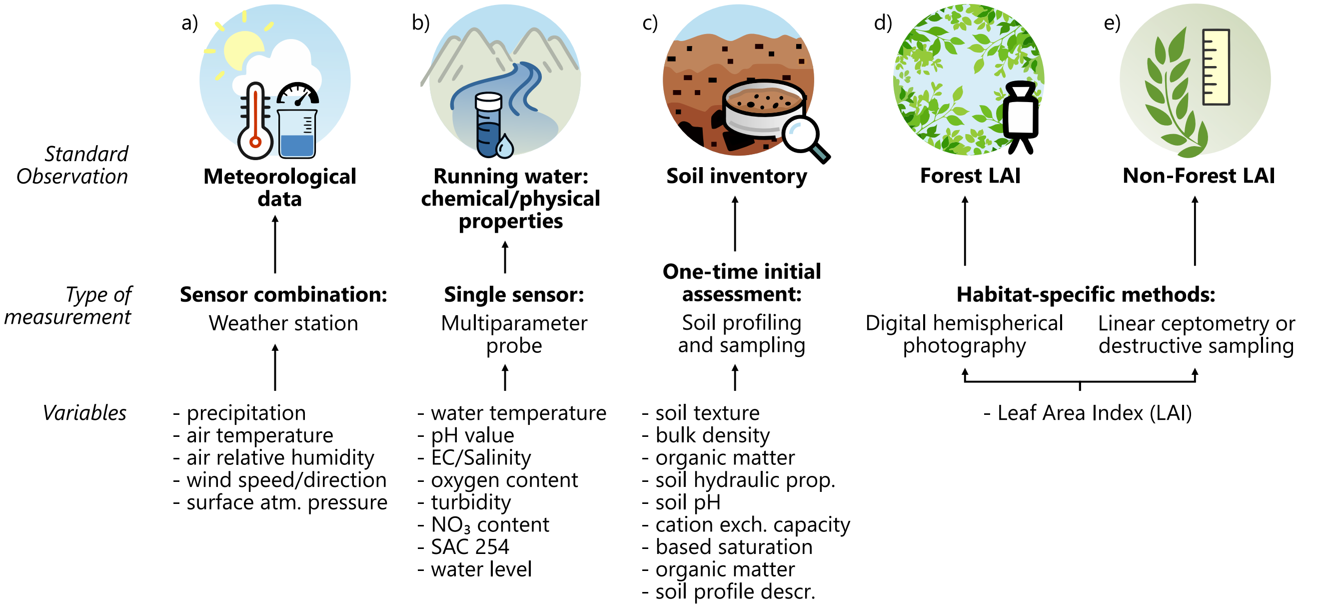

Figure 2. Schematic representation of the principles of (i) bundling Standard Observation variables into single Standard Observations (a–c) and (ii) defining different Standard Observations for the same Standard Observation variable (d, e) (see Sections 3.1 and 3.2 for details).

The nine defined habitat types represent ecosystems that require specific sets of observation in the sense of a holistic description of the ecosystem, that is, WAILS-compliant. As previously outlined, the term 'SO' is defined as the combination of the definition of the variable(s) to be measured and the measurement method and measurement protocols that have been specified (see Figure 1). In accordance with this definition, differences in measurement methods or measurement protocols (e.g., due to habitat-specific differences in requirements) result in the definition of a new SO. Consequently, the same environmental variables can also be part of multiple SOs. For example, measuring the leaf area index (LAI) in grasslands and forests is covered by two SOs due to the different methods applied in these habitats (Figures 2d and 2e).

A list of all SOs required with regard to the habitat type and the site classification is provided in Appendices Tables A1–A9. A graphical representation of the sphere-specific composition of the SOs is given in Figure 3.

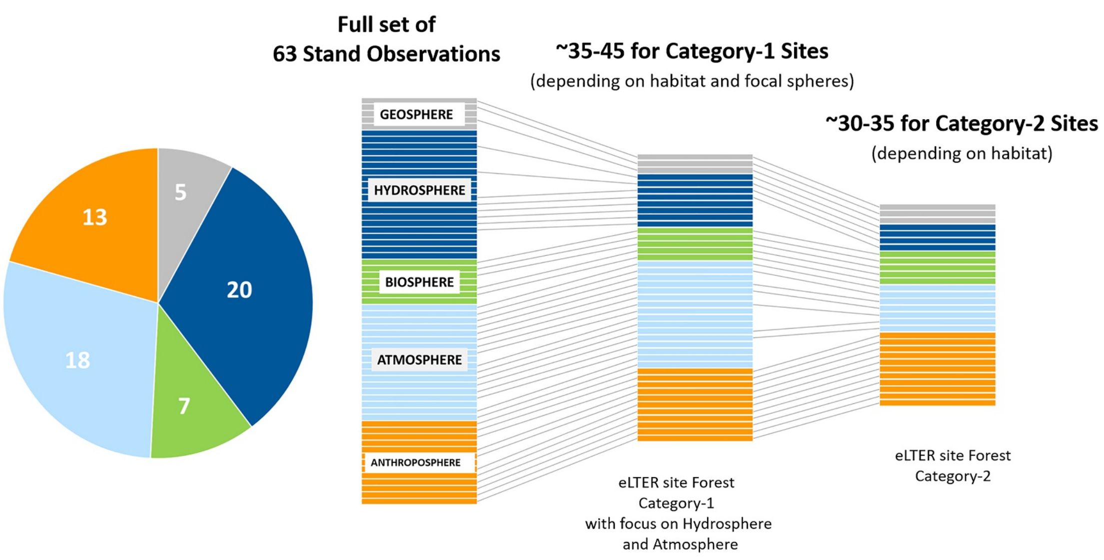

Figure 3. Customization of the observation program of eLTER Sites specific to the habitat and Site Category (example shown for Category-1 and Category-2 forest sites).

The 63 SOs are presented in more details in the following sections. When translating the requirements from the eLTER SO into a concrete in situ measurement design, it is imperative to consider the specific on-site conditions. This is particularly relevant to determine the number of measurement points and locations, taking into account the size of the site and spatial heterogeneity. Consequently, the implementation of specific measurements should be based on what is feasible at reasonable costs and what makes sense in the context of the environmental conditions of the given habitats. Examples of site conditions that are not appropriate for the implementation of certain SOs are, for example, groundwater levels that are too deep to allow the drilling of groundwater monitoring wells at reasonable costs, or the location of sites that are too far away from watercourses or other surface water bodies to relate discharge or other surface water related measurements directly to the area under investigation.

3.2. The Standard Observation Variables

It is important to emphasize that the eLTER SO does not seek to propose or endorse any specific conceptual model of ecosystems. The WAILS sphere concept is foundational to the eLTER Site hierarchy. The categorization of spheres should not be interpreted as a scientifically validated definition of the Earth system; rather, it is employed to organize the SOs according to content and the research objectives that they address:

- Geosphere: SOs to describe lithological/soil/sediment characteristics and pedo-chemical fluxes
- Hydrosphere: SOs to describe water balance and hydro-chemical fluxes
- Biosphere: SOs to describe biodiversity
- Atmosphere: SOs to describe atmospheric conditions, energy balance, greenhouse gas and other atmospheric fluxes, carbon cycling
- Anthroposphere: SOs to describe socio-ecological characteristics

The allocation of SOs to the WAILS spheres is directly informed by the research objectives delineated above. For instance, certain biotic properties, such as vegetation growth data, are directly relevant as variables of carbon turnover or plant transpiration, but possess minimal relevance in the context of biodiversity assessment. Consequently, these properties are designated as "Atmosphere" SOs.

In addition to these aspects, practical requirements resulting from the operational implementation were also considered when assigning the SOs to the "spheres," as expressed, for example, in merging variables into SO bundles. Consequently, the allocation of SOs to the WAILS spheres is not always straightforward. In the case of precipitation, which can also be considered as a variable of the "Hydrosphere" whilst also being a variable recorded by conventional weather stations, it was decided to allocate the corresponding measurement to the SO bundle "Meteorological data," which is categorized within the "Atmosphere" SOs.

In order to increase observational width and interlinkages between sites, Category-1 Sites are required to commit to an additional observation and research focus on a minimum of two of the four biophysical spheres (geosphere, hydrosphere, biosphere, atmosphere, see also description in Section 2.3). This additional research focus is reflected in the implementation of higher standards for SO measurements in these focal spheres, applying the *PRIME* combination of method and protocol.

3.2.1. Geosphere - Describing Soil/Sediment Characteristics and Pedochemical Fluxes

The objective for recording *Geosphere* variables is to facilitate the characterization of the properties of abiotic site elements, including those of a physical, chemical and hydrological nature, concerning soil and sediment. These properties are strongly controlled by geological features. This group contains five SOs. Several *Geosphere* SOs require a spatially explicit mapping of soil or sediment variables, which can usually only be realized for smaller areas (plot, sub-sites). Decisions should be made about which areas the SO can generate the greatest additional benefit. This could be, for example, highly instrumented areas within Sites such as soil moisture monitoring plots or areas that have an explicit focus on soil- or groundwater-related research.

1. *Soil inventory*: retrieval-based (BASIC), sample-based (PRIME), one-time initial classification of soil texture, soil hydraulic properties, bulk density, soil pH, Cation Exchange Capacity (CEC), base saturation, organic matter, pedological characterization (or soil profile description), and soil type classification. Furthermore, the geological site conditions and chemical weathering regimes need to be characterized.

2. *Soil chemical and physical properties*: sample-based, total organic C concentration, CEC, total nitrogen, total phosphorus, plant available phosphorus, pH, soil base saturation, bulk density, and volume of coarse fragments (at fixed sampling depths).
3. *Soil water chemistry*: sample-based, soil water pH; soil nutrient concentration per horizon: NH_4-N, NO_3-N, dissolved organic nitrogen (DON), dissolved organic carbon (DOC), concentration of major ions Cl^-, SO_4^{2-}, Na^+, K^+, Mg^{2+}, Ca^{2+}, Fe, Mn
4. *Soil infiltration*: retrieval-based (BASIC), sample-based (PRIME) one-time assessment of soil infiltration rates to determine soil saturated hydraulic conductivity
5. *Sediment (aquatic/marine)*: sample-based, physical and chemical characterization (particle size distribution, pH, carbon, sulfur).

3.2.2. Hydrosphere - Describing Water Balance and Hydrochemical Fluxes

The *Hydrosphere* group of the eLTER SO focuses on groundwater and surface water, including standing waters (such as lakes and reservoirs), running waters (such as creeks, streams, and rivers), transitional waters, soil hydrological variables, snow, and water quality variables. This group comprises 20 SOs. All variables are explicitly quantitative and thus ideal indicators of the effect of climate and land use change on the hydrological state of sites. Several SOs represent bundles of variables (see also Section 3.1), which can either be measured by multi-parameter probes or whose measurement can be combined into one operation (e.g., water level and multi-parameter probes). This joint collection reduces cost compared to individual purchases of single sensors for each variable. Furthermore, the application of differing measurement methods and protocols for running waters and standing waters results in separate SOs for the same environmental variables. In certain instances, the same environmental variables may be encompassed by multiple SOs, a consequence of the habitat-specific delineation of SOs. To illustrate this, the water level of watercourses represents a fundamental hydrological variable that, in accordance with eLTER's WAILS approach, ought to be recorded for terrestrial habitats, as well, provided that a watercourse is directly associated with the habitat under investigation. At the same time, the water level measurement is a mandatory component of eLTER's measurement program for running waters. However, the measurement here is part of a more extensive bundle of variables, that is, only mandatory for running waters and includes additional running water SO variables such as water temperature, turbidity, and pH value. Consequently, the water level variable is included in two separate SOs.

1. *Standing water—Profiles of chemical/physical waters properties*: sample-based (BASIC) and sensor-based (PRIME), water temperature, pH, electrical conductivity (EC), turbidity, oxygen concentration, water depth
2. *Running water—chemical/physical properties*: sample-based (BASIC), sensor-based (PRIME), water temperature, pH, EC/salinity, turbidity, oxygen, NO_3-N, SAC 254, water level
3. *Groundwater—chemical/physical properties*: sensor-based, water temperature, pH, water level and EC
4. *Running water level*: retrieval-based (BASIC), sensor-based (PRIME), water level (input for stage-discharge relationship, optional velocity measurements recommended)
5. *Running water—nutrients*: sample-based, total phosphorus (TP), soluble reactive phosphorus (SRP), total dissolved nitrogen (TDN), NO_3-N, NO_2-N, NH_4-N
6. *Standing water—profiles nutrients*: sample-based, total phosphorus (TP), soluble reactive phosphorus (SRP), total dissolved nitrogen (TDN), NO_3-N, NO_2-N, NH_4-N of water as a measure for eutrophication
7. *Standing water—Ice cover/thickness*: retrieval-based (BASIC), sample-based (PRIME), ice cover, ice thickness
8. *Snow*: retrieval-based (BASIC), sample-based (PRIME), snow cover, snow height/density, first and last days of snow
9. *Soil water content/temperature*: sensor-based, soil water content, soil temperature
10. *Running water—carbon concentration*: sample-based, concentration of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC)
11. *Standing water—carbon concentration*: sample-based, profiles of concentration of DOC, DIC
12. *Groundwater—nutrients*: sample-based, concentration of total phosphorus (TP), soluble reactive phosphorus (SRP), total dissolved nitrogen (TDN), NO_3-N, NO_2-N, NH_4-N, DOC, DIC
13. *Running/Standing water—Major ion concentrations*: sample-based, concentration of major ions Cl^-, SO_4^{2-}, Na^+, K^+, Mg^{2+}, Ca^{2+}, and dissolved silica.

14. *Groundwater—Major ion concentrations*: sample-based, concentration of major ions Cl^-, SO_4^{2-}, Na^+, K^+, Mg^{2+}, Ca^{2+} and dissolved silica.
15. *Running/Standing water—Stable isotopes*: sample-based, $\delta^{18}O$ and $\delta^{2}H$ signatures
16. *Groundwater—Stable isotopes*: sample-based, $\delta^{18}O$ and $\delta^{2}H$ signatures
17. *Standing water—Secchi-depth*: retrieval-based, Water transparency
18. *Glacier front variation*: retrieval-based, temporal variation of glacier front
19. *Glacier mass balance*: retrieval-based, geodetic mass balance of glaciers
20. *Glacier area*: retrieval-based, temporal variation of glacier area extent

3.2.3. Biosphere - Describing Biotic Diversity

The *Biosphere* SO group addresses the biotic diversity of eLTER Sites. In total, this group comprises currently seven SOs. Biodiversity monitoring often requires the detailed expertise of trained researchers and technicians and is often difficult or impossible to automate. Consequently, the automation of such monitoring protocols often proves challenging, if not unfeasible. This presents a significant obstacle to the implementation of these protocols, particularly in the context of BASIC methods across all sites.

Despite the existence of a large number of standardized protocols for numerous biological variables and recent progress toward international harmonization, such as through the European Water Framework Directive for water quality assessment, many of the used protocols vary between or even within countries. Accordingly, harmonizing these protocols across countries or replacing these protocols with new, largely automated protocols would not only be very difficult and most likely impossible but also interrupt existing time series. Nevertheless, these protocols generally have a long tradition, have provided highly valuable legacy data (and offer opportunities to compare respective data across sites).

In light of this context, the chosen variables aimed to identify those for which automated and standardized collection and observation appear feasible (e.g., sound recorders, Malaise traps, bulk samplers for air, soil, and water eDNA) and thus providing a good basis for standardization, especially for sites that have not yet focused specifically on collecting biological data. These proposed SOs are intended to complement but not replace existing in situ non-automated measurements or established on-site protocols.

In order to ensure consistency for existing time series, it is mandatory to support the parallel use of new and established methods. This is to ensure that breakpoints in valuable time series are avoided. Furthermore, and crucially, classical approaches offer quantitative data that can be linked to specific organisms and processes in a manner, that is, not currently feasible with molecular approaches, continuation of established methods is required at sites that provide quantitative data on biological processes. The combination of establishing the new SOs and continuing existing biodiversity monitoring protocols provides a unique opportunity to inter-calibrate these protocols and make them interoperable. Hence, both protocol types can and should be analyzed jointly and a posteriori (see also discussion on innovative approaches in biodiversity monitoring in Section 3.3.6).

1. *Flying insects*: sample-based, species-level identification based on DNA metabarcoding of flying insects samples.
2. *Vegetation composition—plot scale*: sample-based vegetation composition.
3. *Acoustic recording*: sensor-based, recording of soundscapes to identify birds and other vocalizing animals (e.g., bats, amphibians, locusts).
4. *Pollen and spores*: sample-based, concentration of pollen and spores in air (DNA metabarcoding).
5. *eDNA Water*: sample-based, DNA in water.
6. *eDNA Soil*: sample-based, DNA in soils.
7. *Surface water—Pigments*: sensor-based, sample-based, concentration of chlorophyll A, concentration of phycocyanin (in freshwaters), concentration of phycoerythrin (in saltwater).

3.2.4. Atmosphere - Describing, Energy Balance, Greenhouse Gas and Other Atmospheric Fluxes, and Carbon Cycling

The eLTER SO group of the *Atmosphere* comprises 18 SOs and addresses (a) the atmospheric conditions of sites and (b) properties quantifying energy, atmospheric fluxes and carbon balance. Plants function as primary controllers of carbon, water, and energy exchanges between ecosystems and the atmosphere. It is evident that variables such as leaf area index and plant height have a significant impact on the processes of photosynthetic carbon cycling and transpiration. Flux measurements are indicative of the rate of exchange of greenhouse gases or water; however, they do not provide a detailed explanation of why these fluxes vary over time or space. Biotic traits (e.g., plant growth or phenology) provide critical information that facilitates the connection of observed fluxes with mechanistic drivers, such as species-specific drought responses. In order to address these aspects by the *Atmosphere* SOs, a number of the following SOs capture also biotic variables and traits associated with plant growth and ecosystem productivity.

1. *Meteorological data*: sensor-based, relative air humidity, precipitation, air temperature, wind speed/wind direction, surface atmospheric pressure.
2. *Radiation*: sensor-based, Photosynthetically active radiation (PAR), Global radiation (diffuse and direct shortwave incoming radiation), longwave radiation (PRIME only).
3. *Soil heat flux*: sensor-based, soil-ground heat flux.
4. *Atmospheric deposition in precipitation*: sample-based, bulk NH_4-N, NO_3-N, NO_2-N, total nitrogen (N_{tot}), SO_4^{2-}, PO_4-P, Cl^-, Na^+, K^+, Mg^{2+}, Ca^{2+}, DOC, pH, electrical conductivity (EC).
5. *Dry deposition of N-components*: sample-based, dry N-deposition (gaseous compounds and particulates).
6. *Eddy covariance*: sensor-based, CO_2-flux and concentration, latent heat flux, sensible heat flux.
7. *Forest—Aboveground biomass*: retrieval-based, annual aboveground vegetation biomass at the site scale.
8. *Non-forest—Aboveground biomass*: sample-based, annual aboveground vegetation biomass at the site scale.
9. *Forest—Tree growth*: sensor-based, annual aboveground tree biomass at the site scale.
10. *Gross primary productivity*: retrieval-based, gross primary productivity (GPP) calculated from Eddy-Covariance measurements.
11. *Transpiration*: retrieval-based, transpiration rate calculated from sap flow.
12. *Forests—Litterfall*: sample-based, litterfall in forests.
13. *Phenological traits (Remote Sensing)*: retrieval-based, vegetation phenology (phenological parameters including start, maximum, end of season) at the continental scale based on satellite-based remote sensing.
14. *Phenological traits (on-site)*: sensor-based (Phenocam), on-site vegetation phenology (phenological parameters including start, maximum, end of season).
15. *Forest—LAI*: sensor-based (hemispherical photography), annual LAI.
16. *Non-forest—LAI*: sensor-based (ceptometry), annual LAI.
17. *Leaf—Elements*: sample-based, content of C, N, K, P, Ca, Mg, Mn in leaves.
18. *Vegetation—LiDAR*: sensor-based, vegetation structure derived from LiDAR measurements.

3.2.5. Anthroposphere - Describing Socio-Ecological Characteristics

The eLTER SO group for the *Anthroposphere* includes qualitative and quantitative data characterizing the socio-ecological system and interactions. It generally includes bundles of variables describing demography, economy, consumption, land use, resource use, governance structures, and ecosystem services. A total of 13 SOs are assigned to this variable group.

Some variables (e.g., demography or farm structure) can be retrieved from official statistical sources, while others require the production of primary data. Due to this approach, the spatial resolution of data in this group will vary by variable and method. In the BASIC method, statistical data will be retrieved from official, institutional statistical sources (e.g., EUROSTAT, OECD Data Portal, United Nations data portal UNdata) at the spatial resolution of national or subnational levels (based on the NUTS classification—*Nomenclature of Territorial Units for Statistics*, i.e., NUTS-2 or NUTS-3), depending on individual availability. In the PRIME method, national or regional sources potentially provide data with a higher spatial resolution up to the LAU-2 level, representing the smallest local administrative units (such as municipalities). Since the production of primary data is mostly qualitative, its spatial precision is directed to cover the extent of the respective eLTSER platform boundaries.

The provision of data is in quantitative or qualitative formats, depending on individual variables (e.g., statistical variables are always quantitative, while variables describing stakeholders or governance structure are largely qualitative and require textual explanations). Some SO bundles contain quantitative *and* qualitative variables.

1. *Agricultural yield*: retrieval-based, a bundle of statistical variables depicting harvest and production from cropland, grasslands, forests, livestock and fisheries/aquaculture.
2. *Land-based income*: retrieval-based, a bundle of statistical variables depicting average income form farms, forestry, aquaculture etc. and wages.
3. *Livestock*: retrieval-based (BASIC) and sample-based (PRIME), a bundle of statistical and qualitative variables depicting past and future developments and challenges in the livestock sector, including head counts, manure production, breeds, feed and grazing management, as well as climate change impacts and adaptation strategies.
4. *Governance structure and character*: retrieval-based, qualitative data describing key land use, environmental and ecosystem changes and their potential causes and drivers (focusing on governance actors, institutional dynamics, the political-economic context and power relationships).
5. *Land cover*: retrieval-based, description of land cover based on Satellite-based Land Cover data products.
6. *Land use statistics and stakeholders*: retrieval-based and sample-based (BASIC, PRIME),a bundle of quantitative and qualitative variables describing land use and management systems (including farm structure, land tenure, labor input, fertilizer/soil/pest management), as well as drivers of land-use change, key land use actors and related stakeholders, environmental protection and sustainability challenges, and climate change impacts and adaptation strategies.
7. *Ecosystem services profile*: retrieval-based (BASIC) and sample-based (PRIME), a bundle of semi-quantitative variables describing 21 ecosystem services (not already included as a SO in another eLTER sphere).
8. *Economics*: retrieval-based, a bundle of statistical variables including gross domestic product (GDP) and per-capita income.
9. *Demography*: retrieval-based, a bundle of statistical variables including total population size and density, population age structure and sex composition, educational attainment, and residential density.
10. *Employment*: retrieval-based, a bundle of statistical variables including employment rate, employment by sector, and unemployment.
11. *Consumption*: retrieval-based (BASIC) and sample-based (PRIME), a bundle of quantitative and qualitative variables describing regional consumption.
12. *Resource use*: retrieval-based, a bundle of statistical variables describing national economy-wide material flows of solid, gaseous, and liquid materials (except for bulk flows of water and air), including biomass, metal ores, non-metallic minerals, fossil energy carriers, waste and emissions.
13. *Subsidies*: retrieval-based, a bundle of statistical variables for monitoring of payments from the Common Agricultural Policy (CAP) for direct support, rural development, and market measures.

3.3. The Standard Observation Protocols

3.3.1. Development Process

The process of developing the methods and protocols for SOs was carried out in a top-down manner according to the five WAILS spheres (geosphere, hydrosphere, biosphere, atmosphere, anthroposphere). For each of the spheres, a recognised expert in each domain was responsible for coordinating the respective writing teams. The aim was to include a wide range of different viewpoints, institutions, and countries. In this way, some of the potential controversies and disagreements on decisions about methods and protocols could be discussed early to produce a draft protocol that could be widely accepted.

A general principle when writing the SO protocols was to avoid creating novel approaches unless needed, but rather to adopt or adapt existing and tested methods and protocols already in use within other RIs, research programs or communities. Given the high degree of co-location with other RIs, the desire to minimize costs for sites when becoming part of the eLTER RI, and the aim of harmonizing protocols with other RIs, some obvious candidates for protocols emerged that could be adopted/adapted. UNECE ICPs (Forests, Integrated Monitoring and Waters) and ICOS have many sites co-located with eLTER and were important resources. Apart from cost and practical advantages, this approach allows long-term data series for many key variables to be continued and contribute to the eLTER RI with minimal harmonization issues. Although a time-limited project rather than a research infrastructure, Lifeplan protocols were an important resource for several Biosphere SOs with a focus on newer methods for monitoring biodiversity, such as eDNA and audio recording. Protocols from the WMO, the EU Water Framework Directive, Soil BON (Soil Biodiversity Observation Network), TERENO (TErrestrial ENvironmental Observatories, Germany), ACTRIS (Aerosol, Clouds and Trace gases Research Infrastructure), SITES (Swedish Infrastructure for Ecosystem Science), INBO (Instituut voor Natuur-en Bosonderzoek, Belgium) and others also played an important role in the writing process for selected SOs. ISO standards were extensively referred to in the SO protocols, but at a more granular, variable-specific level. For example, an ISO method for measuring levels of a chemical parameter may be recommended. Finally, the definition of specific SOs was also based on published methods from the scientific literature. It is important to note that these SO protocols are still in the finalization stage. They are scheduled for immediate dissemination via the eLTER website (https://elter-ri.eu/standard-observations-spheres/) once finalized.

3.3.2. Balancing Standardization and Flexibility

The harmonization of existing methodologies is influenced by the bottom-up process through which LTER sites, platforms and national networks have been developed historically Haase et al. (2016). LTER and co-located sites were established with different research and monitoring strategies in mind, and their design is motivated by institutional and program-related requirements. The sites are therefore characterized by a wide variety of individual site measurement variables, ecosystem types, infrastructures and instrumentation, challenging their transformation into one coherent, large-scale comparable monitoring structure (Mollenhauer et al., 2018). Sites following national protocols or protocols of other RIs or networks for these variables are understandably reluctant to apply new methods, either replacing the previous method (and so harming time-series continuity) or complementing it (with added effort and expense). To address this challenge, top-down harmonization and agreement on common parameters and methods were necessary. The challenge here is to strike a fine balance between establishing a common standard for all measurements and allowing enough flexibility to accommodate site-specific requirements (Holzer et al., 2018). A very strong top-down standardization would inevitably severely limit the number of sites willing and able to participate in the RI, but standardization is, at the same time, required to distinguish the eLTER RI from the looser bottom-up network of LTER Europe. The resulting harmonization of existing and established methods in the SO protocols is thus a pragmatic attempt at gathering comparable and integrable data sets while coming as close as possible to having one method as the standard. In many ways, the story of this tension in the production of SO protocols can be summarized as "as standardized as possible, as flexible as necessary." For example, this flexibility is evident in sample-based protocols such as for the "Atmospheric deposition in precipitation," which specifies that samples at collectors must be kept cool and dark. Several common methods for achieving this are described, but the final implementation is left to the site—a decision likely influenced by existing infrastructure. Another strategy pursued by eLTER RI is to base standardization strictly on a predefined measurement accuracy (signal-to-noise ratio) rather than on specific sensor types. This approach enables the continued use of existing sensors that meet the required accuracy and, in the event that sensor replacement becomes necessary, allows purchasing decisions to be made solely on the basis of performance (accuracy) and potential follow-up costs.

3.3.3. Differences in Measurement Techniques

Different sensors and equipment may produce measurements that are not directly comparable, and sites may have long-term data sets collected with older equipment (or a range of equipment over time). Moving forward, the SO protocols specify the requirements for equipment to be used (while not mandating a specific model), but intercalibration is required where data collected with different equipment will be combined. Where it has proven impossible to adopt standard protocols in international monitoring due to existing commitments to national protocols (such as in the Water Framework Directive), extensive efforts in intercalibration were needed (Poikane et al., 2015), highlighting the importance of standardizing equipment and methods as much as possible right from the beginning. There are three categories of data gathering processes in the protocols:

- *Sensor-based methods* are characterized by minimum requirements for instrument parameters such as the sensitivity, accuracy, and frequency of measurements.
- *Sample-based measurements* involve information on both the procedure for taking samples and subsequent analysis (e.g., laboratory procedures based on ISO methods).

- *Retrieval-based protocols* apply to SOs where existing data such as satellite images or economic statistics are obtained from third-party providers and specify reproducible methods of downloading and processing these data (e.g., scripting code via an API).

3.3.4. Taxonomic Issues

A significant number of eLTER Sites possess extensive data sets on biodiversity data, collected through the utilization of well-established methodologies to quantify biological communities. These legacy data are of significant importance as a data source. However, the methods employed at various sites are frequently based on different and often inconsistent taxonomic references and protocols, which poses considerable challenges to standardization and limits the ability to conduct network-wide meta-analyses.

3.3.5. Semantics and Standardized Vocabularies

By bringing together various materials from a wide range of existing protocols and incorporating legacy data from sites with a long operational history, there is great potential for confusion based on unclear use of terms, and there is an urgent need to use a controlled vocabulary, defining terms, protocols and SO definitions in a standardized manner. The use of a controlled and standardized vocabulary or thesaurus as an initial step toward enabling semantic harmonization has been established practice within the eLTER community for several years. Initially, the Environmental Thesaurus (EnvThes: https://vocabs.lter-europe.net/EnvThes) was created to compile a set of terms to describe data resulting from observations and measurements across different domains (Schentz et al., 2013). This was followed by the eLTER Controlled Lists (eLTER CL: https://vocabs.lter-europe.net/elter_cl) thesaurus, which was made available to ensure consistent terminology across multiple environmental projects within the eLTER community. Most recently, a thesaurus for SOs (https://vocabs.lter-europe.net/so) was also implemented, making extensive efforts to ensure consistency despite the SO protocols leaning on a diverse range of existing materials.

3.3.6. Innovative Approaches - Socio-Ecological Methods and New Methods to Address Biodiversity

The implementation of newer methods avoided some of the difficulties associated with harmonizing existing protocols. These innovations fall into two categories: socio-ecological methods and novel biodiversity monitoring techniques. eLTER's socio-ecological SOs describe aspects of the anthroposphere and human-environment interactions, covering demography, economy, consumption, land use, resource use, governance structures, and ecosystem services. This is achieved through a combination of centralized data services based on data collection from European or national statistics and site-specific assessments. Novel protocols have been developed for governance structure characterization, consumption profiling, land use monitoring, ecosystem services profiling, and livestock management assessment. These approaches employ document analyses, surveys, interview panels and expert assessments—established social science methods that have not previously been implemented as standardized protocols in this scientific context and at the European scale. Some of these methods, as defined in the protocols, primarily produce qualitative (or non-numerical) data that adhere to specific requirements concerning their collection, processing and analysis, as well as their archiving and sharing. The integration of social science methodologies and data into the eLTER RI's natural science-based logic, structures and systems, even considering the embedding of such methods in a holistic socio-ecological perspective, constitutes a challenging task that will be subject to further development and harmonization efforts in the future. This integration process bridging "the great divide" between social and environmental sciences is also a testament to the commitment of eLTER RI to deliver cutting-edge inter-and transdisciplinary sustainability research within the WAILS approach.

Traditional approaches employed in biodiversity monitoring frequently encounter challenges related to methodological standardization and taxonomic variation. These methods are often labor-intensive and necessitate a substantial degree of expertise, which can impede the acquisition of high-spatio-temporal resolution data. The eLTER SO implement novel methods for cost-effective, large-scale biodiversity monitoring across Europe. Acoustic recording for specific insects, amphibians, birds, and bats offers promising capabilities with the implementation of machine-learning approaches for species identification (Kershenbaum et al., 2025). Automated sampling via Malaise traps and molecular methods such as metabarcoding and eDNA

10.1029/2025EF006743

analysis provide good taxonomic resolution and cost-efficient application and processing. However, such methodological alternatives to classical approaches often give rise to pertinent issues of their information content. The eDNA method has been demonstrated to have significant advantages, including its capacity to detect rare species (Rees et al., 2014). Consequently, it has been employed in the context of species inventories to facilitate comprehensive assessments. However, the method has also been the subject of criticism from ecologists, who have expressed concerns regarding its lack of quantitative abundance information (Beng & Corlett, 2020). This limitation restricts the utility of eDNA in population dynamics, food web studies and budget analyses. Notwithstanding the progressive advancements witnessed in metabarcoding methodologies, persistent challenges remain with regard to the establishment of transnational laboratory standards and the formation of reference libraries. eLTER will play an important role in aligning these guidelines and testing them at a continental scale.

4. Putting eLTER Standard Observations Into Practice

The eLTER SO is a central building block for developing the eLTER RI network design. It represents one of the main foundations to transform existing and mainly "principal investigator (PI)"-driven in situ research sites into a harmonized, high-performance, complementary, and interoperable ecosystem research infrastructure. The two-level categorization of eLTER Sites and Platforms (see also Section 2.3) is supposed to cover significantly heterogeneous site conditions, including varying habitat and terrain properties. The staged specification of categories allows for customization and adaptation, enabling the categories to be applied to a wide range of structural and organisational settings. It has been developed in response to the need to minimize ambiguity.

The common denominator of all eLTER Sites is that they implement a holistic observation approach, the WAILS approach, which covers essential ecosystem variables from all environmental spheres. Depending on the habitat being observed, 30–35 SOs must be implemented to fulfill the requirements for "holistic" observation in the sense of eLTER (see Figure 3). In this case, only the implementation of BASIC methods and protocols is required (criterion for eLTER Site Category-2). To develop a Category-2 Site into a Category-1 Site, the eLTER RI design requires an additional specialization of the observation program for a minimum of two of the four biophysical spheres (Category-1 focal spheres). This therefore requires an increase in the number of environmental variables to be monitored for these two focal spheres and, in most cases, requires the implementation of the higher measurement standard defined by the PRIME methodology. The number of SOs to be implemented increases to 35–45 SOs, depending on the habitat type and the selected focal spheres of the Category-1 Site (see Figure 3). An overview of the required measurement scopes for each of the nine habitat types defined in eLTER can be found in the Appendix A, Tables A1–A10. As a consequence of the development of the eLTER SO, national discussion and planning processes were initiated in the European LTER, Critical Zone, and LTSER networks, and these continue to the present. An online tool, accessible to all site and platform operators, was utilized to facilitate a comparison between the existing site- and platform-specific observation and monitoring programs and the criteria and requirements for eLTER Sites and Platforms. This analysis also yielded data pertaining to the resources necessary for the transfer of existing sites and platforms to the eLTER RI. These resources encompass costs for additional measurement equipment, operating costs, and laboratory costs. This information was then used to obtain a Europe-wide overview of the current status of the eLTER RI partners and eLTER RI development potential, and enabled the assessment of the biogeographical and socio-ecological representativeness of the future network (Ohnemus et al., 2024, 2025).

The eLTER SO enables the establishment of clear criteria to facilitate the comparability of Sites and Platforms (mandatory measurement program, harmonized measurement standards). At the same time, it also introduces a degree of flexibility to accommodate the heterogeneity present within the European landscape of long-term ecological, socio-ecological and critical zone research. This flexibility enables the preservation and continuation of existing specializations in research in eLTER while further accounting for variations in site conditions, such as spatial design.

A major challenge for eLTER is in realising its over-arching concepts within a concrete design applicable to individual eLTER sites. Two challenges are particularly central to this:

- *Scale discrepancies between processes and measurement*
  - It is evident that environmental and socio-ecological processes exhibit considerable variability in terms of their spatial and temporal scales (Dirnböck et al., 2013). These processes range from microscopic levels, such as the activity of soil microorganisms, to macroscopic levels encompassing hydrological, hydrogeological, and weather systems.
  - Measuring systems are generally designed for a specific spatial resolution. For instance, in situ soil sensors typically record volumes of only a few cubic centimeters. In contrast, river discharge measurements can capture the dynamics of runoff events within catchment areas extending over several hundred square kilometers.
- *Natural spatial heterogeneity*
  - The terrestrial surface of the Earth is characterized by significant heterogeneity. Topography, vegetation, or microclimate of an ecosystem can differ even on short distances (Kolasa and Pickett, 1991).
  - Measurements obtained from a limited number of points may not accurately represent the entire area. This, in turn, complicates the process of extrapolation and interpretation of the data.

It is imperative to acknowledge that these two challenges must be tackled by any environmental monitoring program, irrespective of the eLTER SO. In addition to multi-scale observation designs, potential solutions to the aforementioned challenges include the integration of in situ measurements with environmental observations from remote sensing or applying citizen science approaches (Fraisl et al., 2022). The most important tool, however, is the close networking with modeling approaches such as statistical or process-based models for upscaling or downscaling data, geostatistical approaches and, above all, the coupling of measurement data with environmental models to close scale gaps (Baatz et al., 2021). In this sense, coupling models with data is an intrinsic feature of any environmental observatory, just as environmental observation is the basis of any Earth system modeling (Zacharias et al., 2024). The overarching objective of the development of any concrete, site-specific in situ design is to identify a *robust* solution. The term *robust* in this context refers to the fact that a measurement design rarely, if ever, represents an *optimum* from a numerical point of view. However, in the vast majority of cases, it represents the best compromise that can be achieved under the given conditions (Zacharias et al., 2011). Models have been proven to be a vital instrument in optimizing the concrete in situ design and enhancing the *robustness* of measurement designs. Model-driven analysis of uncertainty helps to increase the robustness of the observation design by identifying *best* locations for sensors by minimizing the total estimation variance, minimize the observation effort (i.e., number of sensors), maximize the predictive efficiency of model and last but not least to maximize the observed spatio-temporal variability with a given number of sensors.

It is also evident that larger-scale data are needed for supporting development and evaluation of policy measures, which in most cases are conducted at scales ranging from regional to global. Examples of such efforts using eLTER RI data are already available (Dirnböck et al., 2018; Forsius et al., 2021a, 2021b). One of eLTER's central objectives is the provision of gap-free, comparable data across diverse spatial scales. Such data is crucial for facilitating scientific advancement and providing informed support to decision-makers. Data sets from eLTER RI are available to the scientific community according to FAIR-principles (Findable, Accessible, Interoperable, and Re-usable). However, observational data on water cycle components, such as soil moisture, actual evapotranspiration, river discharge, water temperature and river metabolism, and ecosystem functions, including gross primary production, water use efficiency, biomass and net ecosystem exchange, will invariably be constrained by the scarcity and scale discrepancy of ground measurements. In addition to other centralized services, such as the management of data and the analysis of samples in a centralized laboratory setting (e.g., eDNA laboratory), eLTER RI will provide a centralized service for the analysis and modeling of environmental data. The objective of this service is to produce and provide access to synthesized, harmonized, consistent, and gap-free data for key SOs on the basis of hydrological and ecosystem reanalyses. Consequently, a multi-model ensemble approach will be established for significant SOs, including soil moisture, riverine discharge, water temperature and ET. The service is fundamentally based on fully coupled model systems that encompass the entire terrestrial system, from groundwater and land surface processes to the atmosphere. It will provide gap-filled, regionalized, integrated fields for numerous abiotic and biotic SOs, representing pivotal processes, states, and fluxes at and below the land surface. The primary focus is on large-scale simulations, such as those involving main catchments and ecosystems on a European scale. This modeling service, which is being developed in parallel with the in situ infrastructures, offers direct support for the entire life cycle of the research infrastructure, from the development of the specific in situ design through to operation.

The implementation of integrated cross-sphere environmental observation is dependent on the collaboration of experts from diverse disciplinary backgrounds. A salient risk that must be addressed pertains to the fragmentation of data sets, stemming from the fragmentation of expertise and from divergent focal points in the design of measurement protocols, challenging the desired integrated analysis of the data. The challenges that arise when combining SOs for water quantity and water quality are mentioned here as illustrative examples. Sensor-based water quantity measurements (e.g., gauging stations and measurement protocols) are optimized for hydrological accuracy (e.g., temporal resolution, long-term sensor robustness). In contrast, water quality measurements, such as the SO for recording nitrogen and phosphorus components in water bodies are sample-based and require additional laboratory analysis and focus primarily on traceability and the accuracy of chemical measurements. Differences in spatial resolution or quality control protocols for water quantity and quality can lead to inconsistencies. For example, nutrient pulses during high-flow events may be missed due to insufficient water sampling frequency. The challenges arising from the variety, fragmentation of disciplinary requirements and sphere-specific SOs are addressed in eLTER by various strategies, including in situ design, measurement protocols and data handling:

- Co-location of sensors and sample sites is imperative to ensure the effective correlation of data,
- Cross-calibration of sensor and sample-based measurements,
- Joint logging of different sensors to synchronise time stamps,
- High temporal resolution of sensor-based measurements to obtain high-quality time series data,
- Coordination and synchronisation of protocols for different SOs across various disciplines,
- Centralized data management and QA/QC for all SOs and consistent connection of data via timestamp and location ID (Bumberger et al., 2025).

Whilst the challenges mentioned above are pertinent to the design of environmental monitoring in general, a further challenge arises in the case of eLTER. First, eLTER Sites exhibit a wide array of historical backgrounds, ranging from those with highly focused monitoring programs that are characterized by explicit protocols to those with highly individualized designs that are the result of diverse research programs. Second, the definition of the mandatory monitoring program for eLTER Sites is based on a habitat-specific perspective. However, several eLTER Sites encompass larger regions where diverse habitat types are present. This is particularly true for critical zone observatories which are often hydrological units chosen for their integrating properties to determine matter and energy budgets. Conversely, most present (and future) sites focus on monitoring specific habitats, so the proposed classification can be used to determine the appropriate requirements for the composition of SOs. In such cases, establishing a multi-scale observation design is recommended. A focus habitat is defined for which the in situ measurement program can largely adhere to the habitat-specific eLTER SO requirements. Depending on the available resources, such a habitat-targeting intensive observation site can be complemented by measurements conducted in additional habitats. Such an approach may involve implementing additional measurement instruments, such as water level measurements to broaden the catchment perspective, or installing additional meteorological stations to provide more comprehensive regional coverage for selected environmental variables.

It is evident that the eLTER SO also serves as a pivotal interface with other initiatives that pursue the objective of further harmonizing international in situ environmental monitoring. Various "essential variable" frameworks (EVs) have been developed in recent years to describe changes in processes and trends in water systems, oceans, climate systems or biodiversity. Many of these EV frameworks have strong interconnections and show overlaps in variables. Such overlaps offer excellent opportunities for better networking or co-location of existing research infrastructures (Futter et al., 2023; Loescher et al., 2022). Identifying and testing such overlaps is an important step toward developing more coherent concepts for in situ environmental research (Lehmann et al., 2023). The interdisciplinary and systemic nature of eLTER's WAILS approach, which encompasses the (lower) atmospheric, terrestrial, aquatic, coastal and socio-ecological domains, consequently establishes direct links to various EV frameworks. An in-depth analysis of the connections between the eLTER SO and various EV concepts for environmental monitoring shows a high degree of direct overlap ranging from 48% to 85%. The results of this comparison for five EV concepts (climate, water cycle, biodiversity, geodiversity, ecosystem services) are presented in the Appendix B, Tables B1–B5. In detail, these comparisons resulted in the following coverage of the respective EV frameworks by the eLTER SO:

- *Essential Climate Variables (ECV)* (WMO, 2022)
  - ECVs of Upper Air Atmospheric Composition, Ocean, Anthroposphere have been excluded from the comparison
  - 18 out of the 27 ECV are directly covered by the eLTER SO (=67%)
  - 5 more ECVs are partially covered
- *Essential Water Cycle Variables (EWV)* (Huffman et al., 2021; Unninayar & Lawford, 2022)
  - 16 out of 19 EWVs are directly covered by the eLTER SO (=84%)
  - 2 more EWVs are partially covered
- *Essential Biodiversity Variables (EBV)* (Pereira et al., 2013)
  - 10 out of 21 EBVs can be directly related to the eLTER SO (=48%)
  - 9 more SOs are related to remaining EBVs
- *Essential Geodiversity Variables (EGV)* (Schrodt et al., 2019)
  - 4 out of 8 EGVs are directly covered by eLTER SO (=50%)
  - 2 more EGVs can be related to remaining SOs
- *Essential Ecosystem Service Variables (EESV)* (Balvanera et al., 2022)
  - 17 out of 20 EEV are directly covered by eLTER SO (=85%)

The EVs not covered by the eLTER SO include variables that (a) fall outside the classical "Critical Zone" perspective of eLTER, which encompasses environmental domains from groundwater and the vadose zone through the vegetated land surface to the lower atmosphere, including the socio-economic dimension (e.g., ECV "Clouds and Aerosols"); (b) require continuous instrumental monitoring associated with high costs and highly specialized expertise (e.g., ECV "Ozone"); or (c) involve data acquisition with substantial measurement effort that cannot currently be automated and/or for which no established international standards exist (e.g., ECV "Soil Carbon").

5. Summary and Outlook

The European eLTER consortium is in the final stages of establishing a formal pan-European in situ research infrastructure to provide a comprehensive representation of the state and evolution of the most significant European ecosystems, critical zone and socio-ecological systems. The eLTER RI initiative is concerned with two interconnected sets of complex adaptive systems. The first of these is that of the natural and human environments, conceptualized by the different spheres targeted by the eLTER's whole systems approach, WAILS. The second is the ensemble of eLTER Sites and eLTSER Platforms that collectively constitute the RI. The establishment of a *common language* is imperative for the effective communication across the multiple levels of complexity inherent in these two systems. This was the main motivation for the development of the SOs. Today, the world of environmental observations is characterized by the utilisation of disparate observation and measurement techniques across various sites and platforms. eLTER's Framework of Standard Observations will not overcome the institutional and biogeophysical differences between sites and platforms; however, it will provide the basis for facilitating communication, which is the fundamental prerequisite for a better understanding of complex environmental problems.

The present eLTER SO concept has been developed as a conceptual framework for implementing a science-driven, long-term operated, standardized and harmonized in situ observation concept. It combines both, the scientific-academic perspective, as known from "classical" Essential Variable concepts, with the operational perspective required for the establishment and long-term operation of in situ observatories. The purpose of this concept is to capture critical aspects of biological diversity and abiotic characteristics, in addition to variables of the energy, matter and water balances and fluxes of the most important ecosystems in Europe as well as key socio-ecological information, and it defines the habitat-specific variables to be recorded for this purpose, including the measurement methods to be used.

The eLTER SO builds on previous approaches in environmental and socio-ecological research paving the way for future progress. Notwithstanding the successful and viable solutions that have been achieved in certain scientific disciplines (e.g., the World Meteorological Organization's standards for climate observations or the established standards for recording greenhouse gases as part of the European ICOS initiative), there is a still a lack of internationally coordinated and harmonized concepts for the standardization of integrated environmental monitoring. Such concepts should focus on all spheres of the natural environment (atmosphere, hydrosphere, geosphere, hydrosphere) as well as socio-ecological conditions. Although there have been successful disciplinary attempts to implement concepts for international harmonization, such as the *Essential Climate Variable* concept, over many years, the implementation of a cross-sphere observation concept that includes both the biotic and abiotic components, as well as socio-ecological elements has not yet been realized on an international scale. The concept of the eLTER SO closes this gap and offers excellent opportunities for stronger international collaboration among RIs.

Even though the elements of cost efficiency and feasibility, in relation to the methodological requirements, were of pivotal significance in the selection and definition of the SOs, the final realization of an adequate in situ design and a secured long-term operation is very resource-demanding and remains a challenge. Many of the future eLTER Sites and eLTSER Platforms were originally created to address specific ecological or Earth science research questions and comprise different degrees of existing infrastructural equipment. To address this issue, the eLTER SO possesses characteristics that permit a certain level of flexibility in the configuration of the measurements, thereby facilitating practical implementation. For most SOs, two quality levels were defined for the required instrumentation, thereby enabling a balancing between a cost-effective variant and a more cost-intensive and elaborate measurement method. In relation to the precise requirements for measurement accuracy, minimum requirements have been defined to allow greater flexibility in selecting the suitable measurement equipment. On the one hand, Category-2 sites have the option of choosing between the mandatory, more cost-efficient (BASIC) method for measurement or data collection and a more complex (PRIME) method for almost all measurements. Concurrently, this enables the integration of measurement concepts already implemented in the eLTER design. On the other hand, the implementation of an extended and more specialized measurement program in specific environmental domains is a further possibility, as is the development of a site or platform in accordance with the habitat-specific requirements for Category-1. The latter presents a valuable opportunity to adjust existing specializations of sites and platforms to the eLTER RI.

Emerging technological advancements, for example in imaging and automated image analysis for biosphere observation, machine-learning or cloud-based analytics, real-time sensor networks, are rapidly transforming environmental observation across a wide range of research domains and have the potential to further reshape environmental in situ research in the near future. Jointly coordinating future or evolving standards, enhancing the harmonization of current protocols to assess environmental and other variables, and continuously screening and testing new technologies are essential prerequisites for uniting the international landscape of in situ ecosystem and socio-ecological research.

As articulated in this paper, the eLTER SO resulted from an iterative, multi-year community effort comprising scientists from several disciplines, 25 European countries, as well as several hundred site and platform coordinators. In addition to the well-founded scientific arguments, it was necessary to consider the aspects of long-term feasibility across all eLTER Sites and eLTSER Platforms and cost efficiency. Consequently, this also demanded compromises, and not all proposals for extensions to the framework that had been substantiated could ultimately be considered. In the course of the consultative discussions, some environmental variables were identified that are of high scientific relevance, but where no consensus had yet been reached regarding network-wide standardization. Examples are variables to quantify biological processes in aquatic and transitional water habitats. This is also related to the tradeoff between existing specializations of sites and platforms and commonly mandatory criteria. To enable ongoing development, including the incorporation of additional SOs, mechanisms for regular reviews have been adopted. This encompasses targeted pilot studies and expert assessments to generate options for future development (see e.g., parallel implementation of conventional quantitative methods and assessment of eDNA, Section 3.2.3). Consultation with the relevant partners is imperative to ensure the incorporation of experience from implementation into potential revisions. In this sense, the framework must also be regarded as a robust compromise and consequently, it is essential to view the eLTER SO as one that will further evolve. Concurrently, it is essential to engage in further exchange with other RIs and the international scientific community.

10.1029/2025EF006743

Appendix A: eLTER Core Sets of Standard Observations per Habitat

B = BASIC combination of method and protocol

P = PRIME combination of method and protocol

Explanation see Section 2.3

Table A1
Geosphere Standard Observations Across Different Habitats for Category-2 Sites

SO-ID	Standard observation	Habitat								
		Wetlands	Grasslands	Heathlands, shrub, tundra	Forests, other wooded land	Vegetated man-made habitats	Inland surface standing waters	Inland surface running waters	Coastal (transitional) waters	Sparsely vegetated habitats, deserts
SOGEO_001	Soil inventory	B	B	B	B	B	B	B	B	B
SOGEO_003	Soil chemical and physical properties		B	B	B	B				B
SOGEO_167	Soil water chemistry									
SOGEO_048	Soil infiltration		B	B	B	B				B
SOGEO_155	Sediment (aquatic/marine)						B	B	B	

Table A2
Geosphere Standard Observations Across Different Habitats for Category-1 Sites

		Habitat								
SO-ID	Standard observation	Wetlands	Grasslands	Heathlands, shrub, tundra	Forests, other wooded land	Vegetated man-made habitats	Inland surface standing waters	Inland surface running waters	Coastal (transitional) waters	Sparsely vegetated habitats, deserts
SOGEO_001	Soil inventory	P	P	P	P	P	B	B	B	P
SOGEO_003	Soil chemical and physical properties		P	P	P	P				P
SOGEO_167	Soil water chemistry	P	P	P	P	P				P
SOGEO_048	Soil infiltration		P	P	P	P				P
SOGEO_155	Sediment (aquatic/marine)						P	P	P	

10.1029/2025EF006743

Table A3
Hydrosphere Standard Observations Across Different Habitats for Category-2 Sites

		Habitat								
SO-ID	Standard observation	Wetlands	Grasslands	Heathlands, shrub, tundra	Forests, other wooded land	Vegetated man-made habitats	Inland surface standing waters	Inland surface running waters	Coastal (transitional) waters	Sparsely vegetated habitats, deserts
SOHYD_004	Standing water—Profiles chemical/physical waters properties	B					B		B	B
SOHYD_005	Running water—chemical/physical properties					B	B	B		B
SOHYD_006	Groundwater—chemical/physical properties	B	B	B	B	B	B			B
SOHYD_010	Running water level	B	B	B	B				B	
SOHYD_172	Running water—nutrients							B		
SOHYD_173	Standing water—Profiles nutrients						B		B	
SOHYD_011	Standing water—Ice cover/thickness						B		B	
SOHYD_012	Snow	B	B	B	B	B	B	B		B
SOHYD_168	Soil water content/temperature	B	B	B	B	B	B	B		B
SOHYD_169	Running water—Carbon concentration							B		
SOHYD_170	Standing water—Carbon concentration	B					B		B	
SOHYD_064	Groundwater—Nutrients						B		B	
SOHYD_171	Running/Standing water—Major ion concentrations						B	B	B	
SOHYD_062	Groundwater—Major ion concentrations						B		B	
SOHYD_058	Running/Standing water—Stable isotopes									
SOHYD_059	Groundwater—Stable Isotopes									
SOHYD_174	Standing water—Secchi-depth						B		B	
SOHYD_164	Glacier—front variation									B
SOHYD_165	Glacier—mass balance									B
SOHYD_166	Glacier—area									B

10.1029/2025EF006743

Table A4
Hydrosphere Standard Observations Across Different Habitats for Category-1 Sites

SO-ID	Standard observation	Habitat								
		Wetlands	Grasslands	Heathlands, shrub, tundra	Forests, other wooded land	Vegetated man-made habitats	Inland surface standing waters	Inland surface running waters	Coastal (transitional) waters	Sparsely vegetated habitats, deserts
SOHYD_004	Standing water—Profiles chemical/physical waters properties	P					P		P	P
SOHYD_005	Running water—chemical/physical properties					P	P	P		P
SOHYD_006	Groundwater—chemical/physical properties	P	P	P	P	P	P	P		P
SOHYD_010	Running water level	P	P	P	P				P	
SOHYD_172	Running water—Nutrients							P		
SOHYD_173	Standing water—Profiles nutrients						P		P	
SOHYD_011	Standing water—Ice cover/thickness						P		P	
SOHYD_012	Snow	P	P	P	P	P	P	P		P
SOHYD_168	Soil water content/temperature	P	P	P	P	P	P	P		P
SOHYD_169	Running water—Carbon concentration							P		
SOHYD_170	Standing water—Carbon concentration	P					P		P	
SOHYD_064	Groundwater—Nutrients	P	P	P	P	P	P	P	P	
SOHYD_171	Running/Standing water—Major ion concentrations						P	P	P	
SOHYD_062	Groundwater—Major ion concentrations	P	P	P	P	P	P		P	
SOHYD_058	Running/Standing water—Stable isotopes		P	P	P	P	P	P	P	
SOHYD_059	Groundwater—Stable Isotopes	P	P	P	P	P	P	P		P
SOHYD_174	Standing water—Secchi-depth						P		P	
SOHYD_164	Glacier—front variation									P
SOHYD_165	Glacier—mass balance									P
SOHYD_166	Glacier—area									P

Table A5
Biosphere Standard Observations Across Different Habitats for Category-2 Sites

SO-ID	Standard observation	Habitat								
		Wetlands	Grasslands	Heathlands, shrub, tundra	Forests, other wooded land	Vegetated man-made habitats	Inland surface standing waters	Inland surface running waters	Coastal (transitional) waters	Sparsely vegetated habitats, deserts
SOBIO_014	Flying insects	B	B	B	B	B	B	B	B	B
SOBIO_017	Vegetation composition	B	B	B	B	B				B
SOBIO_018	Acoustic recording	B	B	B	B	B				B
SOBIO_019	Pollen and spores									
SOBIO_021	eDNA Water	B	B	B	B	B	B	B	B	
SOBIO_022	eDNA Soil	B	B	B	B	B	B	B		B
SOBIO_096	Surface water—Pigments						B	B	B	

Table A6
Biosphere Standard Observations Across Different Habitats for Category-1 Sites

SO-ID	Standard observation	Habitat								
		Wetlands	Grasslands	Heathlands, shrub, tundra	Forests, other wooded land	Vegetated man-made habitats	Inland surface standing waters	Inland surface running waters	Coastal (transitional) waters	Sparsely vegetated habitats, deserts
SOBIO_014	Flying insects	P	P	P	P	P	P	P	P	P
SOBIO_017	Vegetation composition	P	P	P	P	P				P
SOBIO_018	Acoustic recording	P	P	P	P	P				P
SOBIO_019	Pollen and spores	P	P	P	P	P				
SOBIO_021	eDNA Water	P	P	P	P	P	P	P	P	
SOBIO_022	eDNA Soil	P	P	P	P	P	P	P		P
SOBIO_096	Surface water—Pigments						P	P	P	

Table A7
Atmosphere Standard Observations Across Different Habitats for Category-2 Sites

		Habitat								
SO-ID	Standard observation	Wetlands	Grasslands	Heathlands, shrub, tundra	Forests, other wooded land	Vegetated man-made habitats	Inland surface standing waters	Inland surface running waters	Coastal (transitional) waters	Sparsely vegetated habitats, deserts
SOATM_027	Meteorological data	B	B	B	B	B	B	B	B	B
SOATM_028	Radiation	B	B	B	B	B	B	B	B	B
SOATM_098	Soil heat flux									
SOATM_103	Atmospheric deposition in precipitation	B	B	B	B	B	B	B	B	B
SOATM_108	Dry deposition of N-components	B	B	B	B	B	B	B	B	B
SOATM_176	Eddy covariance									
SOATM_023	Forest—Aboveground biomass				B					
SOATM_024	Non-forest—Aboveground biomass	B	B	B		B				B
SOATM_177	Tree growth									
SOATM_090	Gross primary production									
SOATM_091	Transpiration									
SOATM_092	Forests—Litterfall				B					
SOATM_015	Phenological traits (Remote Sensing)	B	B	B	B	B	B	B	B	B
SOATM_016	Phenological traits (on-site)									
SOATM_025	Forest—LAI									
SOATM_026	Non-forest—LAI									
SOATM_095	Leaf—Elements									
SOATM_140	Vegetation—LiDAR									

Table A8
Atmosphere Standard Observations Across Different Habitats for Category-1 Sites

		Habitat								
SO-ID	Standard observation	Wetlands	Grasslands	Heathlands, shrub, tundra	Forests, other wooded land	Vegetated man-made habitats	Inland surface standing waters	Inland surface running waters	Coastal (transitional) waters	Sparsely vegetated habitats, deserts
SOATM_027	Meteorological data	P	P	P	P	P	P	P	P	P
SOATM_028	Radiation	P	P	P	P	P	P	P	P	P
SOATM_098	Soil heat flux	P	P	P	P	P				P
SOATM_103	Atmospheric deposition in precipitation	P	P	P	P	P	B	B	B	P
SOATM_108	Dry deposition of N-components	P	P	P	P	P	P	P	P	P
SOATM_176	Eddy covariance	P	P	P	P	P				P
SOATM_023	Forest—Aboveground biomass				P					
SOATM_024	Non-forest—Aboveground biomass	P	P	P		P				P
SOATM_177	Tree growth				P					
SOATM_090	Gross primary production	P	P	P	P	P				P
SOATM_091	Transpiration	P	P	P	P	P				P
SOATM_092	Forests—Litterfall				P					
SOATM_015	Phenological traits (Remote Sensing)	P	P	P	P	P	P	P	P	P
SOATM_016	Phenological traits (on-site)	P	P	P	P	P				P
SOATM_025	Forest—LAI				P					
SOATM_026	Non-forest—LAI	P	P	P		P				P
SOATM_095	Leaf—Elements	P	P	P	P	P				P
SOATM_140	Vegetation—LiDAR	P	P	P	P	P				P

Table A9
Anthroposphere Standard Observations Across Different Habitats for Category-2 and Category-1 Sites

		Habitat								
SO-ID	Standard observation	Wetlands	Grasslands	Heathlands, shrub, tundra	Forests, other wooded land	Vegetated man-made habitats	Inland surface standing waters	Inland surface running waters	Coastal (transitional) waters	Sparsely vegetated habitats, deserts
SOSOC_031	Agricultural yield	B	B	B	B	B	B	B	B	B
SOSOC_030	Land-based income	B	B	B	B	B	B	B	B	B
SOSOC_114	Livestock	B	B	B	B	B	B	B	B	B
SOSOC_032	Governance structure and character									
SOSOC_036	Land cover	B	B	B	B	B	B	B	B	B
SOSOC_037	Land use statistics and stakeholders	B	B	B	B	B	B	B	B	B
SOSOC_040	Ecosystem service profile									
SOSOC_042	Economics—GDP	B	B	B	B	B	B	B	B	B
SOSOC_043	Demography	B	B	B	B	B	B	B	B	B
SOSOC_044	Employment	B	B	B	B	B	B	B	B	B
SOSOC_045	Consumption	B	B	B	B	B	B	B	B	B
SOSOC_183	Resource use	B	B	B	B	B	B	B	B	B
SOSOC_184	Subsidies	B	B	B	B	B	B	B	B	B

Note. BASIC Standard Observations of Anthroposphere for Sites do not require direct data collection but can be derived from freely available data sources such as European statistics.

Table A10
Anthroposphere Standard Observations Across Different Habitats for Category-2 and Category-1 Platforms

SO-ID	Standard observation	Platform Category-2	Platform Category-1
SOSOC_031	Agricultural yield	B	B,P
SOSOC_030	Land-based income	B	B,P
SOSOC_114	Livestock	B	B,P
SOSOC_032	Governance structure and character	B	B,P
SOSOC_036	Land cover	B	B,P
SOSOC_037	Land use statistics and stakeholders	B	B,P
SOSOC_040	Ecosystem service profile	B	B,P
SOSOC_042	Economics—GDP	B	B,P
SOSOC_043	Demography	B	B,P
SOSOC_044	Employment	B	B,P
SOSOC_045	Consumption	B	B,P
SOSOC_183	Resource use	B	B,P
SOSOC_184	Subsidies	B	B,P

Appendix B: Overview of Various Essential Variable Frameworks and Their Coverage in eLTER Standard Observations

Connections between eLTER Standard Observations and five Essential Variable Frameworks (climate, water cycle, biodiversity, geodiversity, ecosystem services).

Table B1
Overview of the Essential Climate Variables (ECVs, Exluding ECVs of Upper Air Atmospheric Composition, Ocean, Anthroposphere) and Their Coverage in eLTER Standard Observations; X: Directly Covered by eLTER SO, (X): Partially Related to eLTER SO

Essential climate variable	eLTER SO
Air Pressure	X
Surface Temperature	X
Surface Wind Speed and Direction	X
Surface Water Vapor	X
Precipitation	X
Surface Radiation Budget	X
Greenhouse Gases	(X)
Ozone	–
Aerosol Properties	–
Groundwater	X
Lakes	X
River Discharge	X
Soil Moisture	X
Terrestrial Water Storage	(X)
Snow	X
Glaciers	X
Ice Sheet and Ice Shelves	(X)
Permafrost	(X)

Table B1
Continued

Essential climate variable	eLTER SO
Above-ground Biomass	X
Albedo	–
Evaporation from Land	X
Fire	(X)
FPAR	X
Land Cover	X
Land Surface Temperature	X
Leaf Area Index	X
Soil Carbon	–

Table B2
Overview of the Essential Water Cycle Variables (EWVs) and Their Coverage in eLTER Standard Observations; X: Directly Covered by eLTER SO, (X): Partially Related to eLTER SO

Essential water cycle variable	eLTER SO
Precipitation	X
Evaporation/Evapotranspiration	X
Snow/Ice Cover	X
Soil Moisture/Temp	X
Groundwater	X
Runoff/Streamflow/River Discharge	X
Lakes/Reservoir Levels, water extent	X
Surface water extent; surface water elevation	(X)
Glacier/Ice Sheet Balance	X
Water Quality	X
Water Use/Demand	X
Surface Meteorology	X
Surface radiation budget SW, LW	X
Clouds & Aerosols	–
Soil Moisture/Temp	X
Vegetation cover/type	X
Land cover, Land use	X
Elevation/topography, geology	X
Permafrost	(X)

Table B3
Overview of the Essential Biodiversity Variables (EBVs) and Their Coverage in eLTER Standard Observations; X: Directly Covered by eLTER SO, (X): Partially Covered by eLTER SO

EBV class	Essential biodiversity variable	eLTER SO
Genetic composition	Intraspecific genetic diversity	(X)
	Genetic differentiation	X
	Effective population size	–
	Inbreeding	–
Special population	Species distributions	X
	Species abundances	(X)
Species traits	Morphology	(X)
	Physiology	–
	Phenology	X
	Movement	–
	Reproduction	X
Community composition	Community abundance	(X)
	Taxonomic/phylogenetic diversity	X
	Trait diversity	X
	Interaction diversity	(X)
Ecosystem functioning	Primary productivity	X
	Ecosystem phenology	X
	Ecosystem disturbances	(X)
Ecosystem structure	Live cover fraction	X
	Ecosystem distribution	X
	Ecosytem vertical profile	(X)

Table B4
Overview of the Essential Geodiversity Variables (EGVs) and Their Coverage in eLTER Standard Observations; X: Directly Covered by eLTER SO, (X): Partially Related to eLTER SO

Essential geodiversity variable	eLTER SO
Hardrock/Fossils/Minerals	–
Unconsolidated deposits	X
Geophysical activities	–
Landform distribution	(X)
Soil chemistry	X
Soil physical state	(X)
Surface water distribution/quality	X
Groundwater distribution/quality	X

Table B5

Overview of the Essential Ecosystem Service Variables (EESs) and Their Coverage in eLTER Standard Observations; X: Directly Covered by eLTER SO, (X): Partially Related to eLTER SO

Essential ecosystem services variable	eLTER SO
Food	X
Water	X
Materials	X
Genetic resources	X
Medicinal resources	–
Air quality regulation	X
Climate regulation	X
Water regulation	X
Erosion regulation	X
Water purification	X
Disease regulation	–
Pest regulation	–
Pollination	X
Natural harzard regulation	X
Recreation and tourism	X
Aesthetic values	X
Cultural heritage	X
Spiritual and Religious Values	X
Educational Values	X
Sense of Place	X

Acknowledgments

The development of the Framework of eLTER Standard Observations would not have been feasible without the active contribution of countless European colleagues from the European LTER network. We would therefore express our utmost gratitude to the many colleagues not explicitly mentioned, without whose professional expertise and collegial contribution it would not have been possible to develop the concept. A special thanks also goes to colleagues from other European RIs and research networks, in particular ICOS, ICP Forests, ICP Integrated Monitoring, TERENO, RZA (Réseau des Zones Ateliers), and OZCAR (Observatoires de la Zone Critique: Application et Recherche), who provided invaluable advice and support during the variable selection and method definition process. This research has been supported by the European Commission, Horizon 2020 (Projects eLTER PPP, Grant 871126 and eLTER PLUS, Grant 871128). We are grateful to the three anonymous reviewers and the editor for their careful and thorough evaluations. Their insightful comments have significantly contributed to improving the content and structure of this article. The authors used ChatGPT (OpenAI) to create the icons used in Figure 1. The Plain Language Summary was drafted by the authors and subsequently edited using ChatGPT (OpenAI) to improve clarity, readability, and adherence to plain language principles. All content was critically reviewed and approved by the authors. Open Access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Data were not used, nor created for this research. A comprehensive overview of the emerging eLTER Research Infrastructure (eLTER RI) can be found on the eLTER RI website (https://elter-ri.eu/elter-ri).

References

Arora, B., Kuppel, S., Wellen, C., Oswald, C., Groh, J., Payandi-Rolland, D., et al. (2023). Building cross-site and cross-network collaborations in critical zone science. *Journal of Hydrology*, *618*, 129248. https://doi.org/10.1016/j.jhydrol.2023.129248

Baatz, R., Hendricks Franssen, H. J., Euskirchen, E., Sihi, D., Dietze, M., Ciavatta, S., et al. (2021). Reanalysis in Earth system science: Toward terrestrial ecosystem reanalysis. *Reviews of Geophysics*, *59*(3), e2020RG000715. https://doi.org/10.1029/2020rg000715

Balvanera, P., Brauman, K. A., Cord, A. F., Drakou, E. G., Geijzendorffer, I. R., Karp, D. S., et al. (2022). Essential ecosystem service variables for monitoring progress towards sustainability. *Current Opinion in Environmental Sustainability*, *54*, 101152. https://doi.org/10.1016/j.cosust.2022.101152

Beng, K. C., & Corlett, R. T. (2020). Applications of environmental DNA (eDNA) in ecology and conservation: Opportunities, challenges and prospects. *Biodiversity & Conservation*, *29*(7), 2089–2121. https://doi.org/10.1007/s10531-020-01980-0

Brantley, S. L., DiBiase, R. A., Russo, T. A., Shi, Y., Lin, H., Davis, K. J., et al. (2016). Designing a suite of measurements to understand the critical zone. *Earth Surface Dynamics*, *4*(1), 211–235. https://doi.org/10.5194/esurf-4-211-2016

Brantley, S. L., McDowell, W. H., Dietrich, W. E., White, T. S., Kumar, P., Anderson, S. P., et al. (2017). Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth. *Earth Surface Dynamics*, *5*(4), 841–860. https://doi.org/10.5194/esurf-5-841-2017

Bretagnolle, V., Benoit, M., Bonnefond, M., Breton, V., Church, J. M., Gaba, S., et al. (2019). Action-orientated research and framework. *Ecology and Society*, *24*(3).

Bumberger, J., Abbrent, M., Brinckmann, N., Hemmen, J., Kunkel, R., Lorenz, C., et al. (2025). Digital ecosystem for fair time series data management in environmental system science. *SoftwareX*, *29*, 102038. https://doi.org/10.1016/j.softx.2025.102038

Chytrý, M., Tichý, L., Hennekens, S. M., Knollová, I., Janssen, J. A. M., Rodwell, J. S., et al. (2020). EUNIS Habitat Classification: Expert system, characteristic species combinations and distribution maps of European habitats. *Applied Vegetation Science*, *23*(4), 648–675. https://doi.org/10.1111/avsc.12519

Collins, S. L., Carpenter, S. R., Swinton, S. M., Orenstein, D. E., Childers, D. L., Gragson, T. L., et al. (2011). An integrated conceptual framework for long-term social–ecological research. *Frontiers in Ecology and the Environment*, *9*(6), 351–357. https://doi.org/10.1890/100068

Costa, L., Hildén, M., Kropp, J., Böttcher, K., Fronzek, S., Swart, R., et al. (2016). Assessing climate impact indicators: Evaluation criteria and observed strengths and weaknesses. *Reports of the Finnish Environment Institute*, *41*, 2016.

Desai, B. H., & Desai, J. B. (2025). Ideating on the planetary future: Prognosis and prospects. *Environmental Policy and Law*, *54*(4-6), 18785395241312433. https://doi.org/10.1177/18785395241312433

Dick, J., Orenstein, D. E., Holzer, J. M., Wohner, C., Achard, A.-L., Andrews, C., et al. (2018). What is socio-ecological research delivering? A literature survey across 25 international LTSER platforms. *Science of the Total Environment*, *622*, 1225–1240. https://doi.org/10.1016/j.scitotenv.2017.11.324

Dirnböck, T., Bezák, P., Dullinger, S., Haberl, H., Lotze-Campen, H., Mirtl, M., et al. (2013). Critical scales for long-term socio-ecological biodiversity research. In *Long term socio-ecological research: Studies in society-nature interactions across spatial and temporal scales* (pp. 123–138).

Dirnböck, T., Pröll, G., Austnes, K., Beloica, J., Beudert, B., Canullo, R., et al. (2018). Currently legislated decreases in nitrogen deposition will yield only limited plant species recovery in European forests. *Environmental Research Letters*, *13*(12), 125010. https://doi.org/10.1088/1748-9326/aaf26b

European Commission. (2016). Horizon 2020 work programme 2016-2017.

Forsius, M., Kujala, H., Minunno, F., Holmberg, M., Leikola, N., Mikkonen, N., et al. (2021). Developing a spatially explicit modelling and evaluation framework for integrated carbon sequestration and biodiversity conservation: Application in southern Finland. *Science of the Total Environment*, *775*, 145847. https://doi.org/10.1016/j.scitotenv.2021.145847

Forsius, M., Posch, M., Holmberg, M., Vuorenmaa, J., Kleemola, S., Augustaitis, A., et al. (2021a). Assessing critical load exceedances and ecosystem impacts of anthropogenic nitrogen and sulphur deposition at unmanaged forested catchments in Europe. *Science of the Total Environment*, *753*, 141791. https://doi.org/10.1016/j.scitotenv.2020.141791

Fraisl, D., Hager, G., Bedessem, B., Gold, M., Hsing, P.-Y., Danielsen, F., et al. (2022). Citizen science in environmental and ecological sciences. *Nature Reviews Methods Primers*, *2*(1), 64. https://doi.org/10.1038/s43586-022-00144-4

Futter, M. N., Dirnböck, T., Forsius, M., Bäck, J. K., Cools, N., Diaz-Pines, E., et al. (2023). Leveraging research infrastructure co-location to evaluate constraints on terrestrial carbon cycling in northern European forests. *Ambio*, *52*(11), 1819–1831. https://doi.org/10.1007/s13280-023-01930-4

GEO BON. (2017). *GEO BON strategy for development of Essential Biodiversity Variables* (Technical Report). Group on Earth Observations Biodiversity Observation Network (GEO BON).

Global Climate Observing System. (2010). Implementation plan for the Global Observing System for Climate in support of the UNFCCC (2010 update).

Global Climate Observing System. (2022). The 2022 GCOS ECVs requirements (GCOS 245). Technical Report GCOS-245.

Group on Earth Observations (GEO). (2023). *Geo post 2025 strategy* (Technical Report). Group on Earth Observations.

Guerra, C., Drakou, E., Pereira, H., Pendleton, L., Marques, A., Freyhof, J., et al. (2017). *Review of existing Essential Variables (EVs) relevant to PAs studies* (Report). European Union Horizon 2020 ECOPOTENTIAL Project.

Haase, P., Frenzel, M., Klotz, S., Musche, M., & Stoll, S. (2016). The long-term ecological research (LTER) network: Relevance, current status, future perspective and examples from marine, freshwater and terrestrial long-term observation. *Ecological Indicators*, *65*, 1–3. https://doi.org/10.1016/j.ecolind.2016.01.040

Haase, P., Tonkin, J. D., Stoll, S., Burkhard, B., Frenzel, M., Geijzendorffer, I. R., et al. (2018). The next generation of site-based long-term ecological monitoring: Linking essential biodiversity variables and ecosystem integrity. *Science of the Total Environment*, *613–614*, 1376–1384. https://doi.org/10.1016/j.scitotenv.2017.08.111

Haberl, H., Winiwarter, V., Andersson, K., Ayres, R. U., Boone, C., Castillo, A., et al. (2006). From LTER to LTSER: Conceptualizing the socioeconomic dimension of long-term socioecological research. *Ecology and Society*, *11*(2), art13. https://doi.org/10.5751/es-01786-110213

Hadorn, G. H., Bradley, D., Pohl, C., Rist, S., & Wiesmann, U. (2006). Implications of transdisciplinarity for sustainability research. *Ecological Economics*, *60*(1), 119–128. https://doi.org/10.1016/j.ecolecon.2005.12.002

Hari, P., Petäjä, T., Bäck, J., Kerminen, V.-M., Lappalainen, H. K., Vihma, T., et al. (2016). Conceptual design of a measurement network of the global change. *Atmospheric Chemistry and Physics*, *16*(2), 1017–1028. https://doi.org/10.5194/acp-16-1017-2016

Heffernan, J. B., Soranno, P. A., Angilletta, M. J., Buckley, L. B., Gruner, D. S., Keitt, T. H., et al. (2014). Macrosystems ecology: Understanding ecological patterns and processes at continental scales. *Frontiers in Ecology and the Environment*, *12*(1), 5–14. https://doi.org/10.1890/130017

Holzer, J. M., Adamescu, C. M., Cazacu, C., Díaz-Delgado, R., Dick, J., Méndez, P. F., et al. (2019). Evaluating transdisciplinary science to open research-implementation spaces in European social-ecological systems. *Biological Conservation*, *238*, 108228. https://doi.org/10.1016/j.biocon.2019.108228

Holzer, J. M., Adamescu, M., Bonet-García, F. J., Díaz-Delgado, R., Dick, J., Grove, J., et al. (2018). Negotiating local versus global needs in the international long term ecological research network's socio-ecological research agenda. *Environmental Research Letters*, *13*(10), 105003. https://doi.org/10.1088/1748-9326/aadec8

Holzer, J. M., & Orenstein, D. E. (2023). Organizational transformation for greater sustainability impact: Recent changes in a scientific research infrastructure in Europe. *Landscape Ecology*, *38*(12), 4275–4289. https://doi.org/10.1007/s10980-023-01624-y

Houghton, J., Townshend, J., Dawson, K., Mason, P., Zillman, J., & Simmons, A. (2012). The GCOS at 20 years: The origin, achievement and future development of the global climate observing system. *Weather*, *67*(9), 227–235. https://doi.org/10.1002/wea.1964

Huffman, G., Unninayar, S., Gutierrez, A., & Lawford, R. (2021). Essential water variables (EWVs) for water cycle research and water sustainability applications. Retrieved from https://ntrs.nasa.gov/citations/20210015754

Hummel, H., Kalle, V., Bienfait, L., Boyer, Y., Heurich, M., Svajda, J., et al. (2022). A bottom-up practitioner-derived set of essential variables for protected area management. *Environmental and Sustainability Indicators*, *14*, 100179. https://doi.org/10.1016/j.indic.2022.100179

Kershenbaum, A., Akçay, Ç., Babu-Saheer, L., Barnhill, A., Best, P., Cauzinille, J., et al. (2025). Automatic detection for bioacoustic research: A practical guide from and for biologists and computer scientists. *Biological Reviews*, *100*(2), 620–646. https://doi.org/10.1111/brv.13155

Kolasa, J., & Pickett, S. T. (1991). *Ecological heterogeneity* (Vol. 86). Springer-Verglag.

Kulmala, M. (2018). Build a global Earth observatory. *Nature*, *553*(7686), 21–23. https://doi.org/10.1038/d41586-017-08967-y

Lawford, R. (2014). *The GEOSS water strategy: From observations to decisions*. Japan Aerospace Exploration Agency.

Lehmann, A., Giuliani, G., Jarvis, I., Serral, I., Masò, J., Lacroix, P. M. A., & Gilliams, S. (2023). *Geo community activity report: Mainstreaming EVS across geo* (Technical Report). Université de Genève.

Loescher, H. W., Vargas, R., Mirtl, M., Morris, B., Pauw, J., Yu, X., et al. (2022). Building a global ecosystem research infrastructure to address global grand challenges for macrosystem ecology. *Earth's Future*, *10*(5), e2020EF001696. https://doi.org/10.1029/2020ef001696

Masó, J., Serral, I., Domingo-Marimon, C., & Zabala, A. (2020). Earth observations for sustainable development goals monitoring based on essential variables and driver-pressure-state-impact-response indicators. *International Journal of Digital Earth*, *13*(2), 217–235. https://doi.org/10.1080/17538947.2019.1576787

Méndez, P. F., Fajardo-Ortiz, D., & Holzer, J. M. (2022). Disrupting the governance of social-ecological rigidity traps: Can pluralism foster change towards sustainability? In *Advances in ecological research* (Vol. 66, pp. 243–291). Elsevier.

Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Global Change Biology*, *24*(6), 2416–2433. https://doi.org/10.1111/gcb.14108

Mirtl, M., Borer, E. T., Djukic, I., Forsius, M., Haubold, H., Hugo, W., et al. (2018). Genesis, goals and achievements of long-term ecological research at the global scale: A critical review of ilter and future directions. *Science of the Total Environment*, *626*, 1439–1462. https://doi.org/10.1016/j.scitotenv.2017.12.001

Mirtl, M., Orenstein, D. E., Wildenberg, M., Peterseil, J., & Frenzel, M. (2012). Development of LTSER platforms in LTER-Europe: Challenges and experiences in implementing place-based long-term socio-ecological research in selected regions. In *Long term socio-ecological research: Studies in society-nature interactions across spatial and temporal scales* (pp. 409–442). Springer.

Mollenhauer, H., Kasner, M., Haase, P., Peterseil, J., Wohner, C., Frenzel, M., et al. (2018). Long-term environmental monitoring infrastructures in Europe: Observations, measurements, scales, and socio-ecological representativeness. *Science of the Total Environment*, *624*, 968–978. https://doi.org/10.1016/j.scitotenv.2017.12.095

Müller, F., Hoffmann-Kroll, R., & Wiggering, H. (2000). Indicating ecosystem integrity—theoretical concepts and environmental requirements. *Ecological Modelling*, *130*(1–3), 13–23. https://doi.org/10.1016/s0304-3800(00)00210-6

Ohnemus, T., Dirnböck, T., Bäck, J., Gaube, V., Kühn, I., Mirtl, M., et al. (2025). Fitness for future: eLTER RI's representation of climate and land use change. *Ecological Indicators*, *171*, 113159. https://doi.org/10.1016/j.ecolind.2025.113159

Ohnemus, T., Zacharias, S., Dirnböck, T., Bäck, J., Brack, W., Forsius, M., et al. (2024). The eLTER research infrastructure: Current design and coverage of environmental and socio-ecological gradients. *Environmental and Sustainability Indicators*, *23*, 100456. https://doi.org/10.1016/j.indic.2024.100456

Pacheco-Romero, M., Alcaraz-Segura, D., Vallejos, M., & Cabello, J. (2020). An expert-based reference list of variables for characterizing and monitoring social-ecological systems. *Ecology and Society*, *25*(3), art1. https://doi.org/10.5751/es-11676-250301

Parr, T., Ferretti, M., Simpson, I., Forsius, M., & Kovács-Láng, E. (2002). Towards a long-term integrated monitoring programme in Europe: Network design in theory and practice. *Environmental Monitoring and Assessment*, *78*(3), 253–290. https://doi.org/10.1023/a:1019934919140

Patias, P., Verde, N., Tassopoulou, M., Georgiadis, C., & Kaimaris, D. (2019). Essential variables: Describing the context, progress, and opportunities for the remote sensing community. In *Seventh international conference on remote sensing and geoinformation of the environment (RSCy2019)* (Vol. 11174, pp. 97–106). SPIE. https://doi.org/10.1117/12.2533604

Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., et al. (2013). Essential biodiversity variables. *Science*, *339*(6117), 277–278. https://doi.org/10.1126/science.1229931

Poikane, S., Birk, S., Böhmer, J., Carvalho, L., de Hoyos, C., Gassner, H., et al. (2015). A hitchhiker's guide to European lake ecological assessment and intercalibration. *Ecological Indicators*, *52*, 533–544. https://doi.org/10.1016/j.ecolind.2015.01.005

Rees, H. C., Maddison, B. C., Middleditch, D. J., Patmore, J. R., & Gough, K. C. (2014). The detection of aquatic animal species using environmental DNA–a review of eDNA as a survey tool in ecology. *Journal of Applied Ecology*, *51*(5), 1450–1459. https://doi.org/10.1111/1365-2664.12306

Reid, W. V., Chen, D., Goldfarb, L., Hackmann, H., Lee, Y. T., Mokhele, K., et al. (2010). Earth system science for global sustainability: Grand challenges. *Science*, *330*(6006), 916–917. https://doi.org/10.1126/science.1196263

Reyers, B., Stafford-Smith, M., Erb, K.-H., Scholes, R. J., & Selomane, O. (2017). Essential variables help to focus sustainable development goals monitoring. *Current Opinion in Environmental Sustainability*, *26*, 97–105. https://doi.org/10.1016/j.cosust.2017.05.003

Richter, D. D., Billings, S. A., Brantley, S. L., Gaillardet, J., Markewitz, D., Schlesinger, W. H., et al. (2024). Earth sciences are the model sciences of the anthropocene. *Perspectives of Earth and Space Scientists*, *5*(1), e2024CN000237. https://doi.org/10.1029/2024cn000237

Schentz, H., Peterseil, J., & Bertrand, N. (2013). EnvThes–interlinked thesaurus for long term ecological research, monitoring, and experiments. In *Proceedings of the 27th conference on environmental informatics-informatics for environmental protection, sustainable development and risk management*. Shaker Verlag.

Schrodt, F., Bailey, J. J., Kissling, W. D., Rijsdijk, K. F., Seijmonsbergen, A. C., van Ree, D., et al. (2019). To advance sustainable stewardship, we must document not only biodiversity but geodiversity. *Proceedings of the National Academy of Sciences*, *116*(33), 16155–16158. https://doi.org/10.1073/pnas.1911799116

Schrodt, F., Vernham, G., Bailey, J., Field, R., Gordon, J. E., Gray, M., et al. (2024). The status and future of essential geodiversity variables. *Philosophical Transactions of the Royal Society A*, *382*(2269), 20230052. https://doi.org/10.1098/rsta.2023.0052

Shapiro, M., Shukla, J., Brunet, G., Nobre, C., Béland, M., Dole, R., et al. (2010). An Earth-system prediction initiative for the twenty-first century. *Bulletin of the American Meteorological Society*, *91*(10), 1377–1388. https://doi.org/10.1175/2010bams2944.1

Steelman, T., Nichols, E. G., James, A., Bradford, L., Ebersöhn, L., Scherman, V., et al. (2015). Practicing the science of sustainability: The challenges of transdisciplinarity in a developing world context. *Sustainability Science*, *10*(4), 581–599. https://doi.org/10.1007/s11625-015-0334-4

Thornton, J. M., Palazzi, E., Pepin, N. C., Cristofanelli, P., Essery, R., Kotlarski, S., et al. (2021). Toward a definition of essential mountain climate variables. *One Earth*, *4*(6), 805–827. https://doi.org/10.1016/j.oneear.2021.05.005

Unninayar, S., & Lawford, R. (2022). Exploring the role of Essential Water Variables (EWVs) in monitoring indicators for the sustainable management of the water-energy-food (WEF) nexus, UN-SDGS & Climate Change GC031B-06: Earth science for advancing national implementation of the sustainable development goals. *Authorea Preprints*. https://doi.org/10.1002/essoar.10512995.1

Weldon, J., Lumpi, T., Villwock, H., Gaube, V., & Bertsch-Hoermann, B. (2024). eLTER PLUS Deliverable D3.3 - Assessment of international standardisation and harmonisation of environmental observation: eLTER RI Standard Observations Protocols. https://doi.org/10.5281/zenodo.18769077

WMO. (2022). *The 2022 GCOS ECVs requirements* (Technical Report GCOS-245). World Meteorological Organization.

Zacharias, S., Bogena, H., Samaniego, L., Mauder, M., Fuß, R., Pütz, T., et al. (2011). A network of terrestrial environmental observatories in Germany. *Vadose Zone Journal*, *10*(3), 955–973. https://doi.org/10.2136/vzj2010.0139

Zacharias, S., Loescher, H. W., Bogena, H., Kiese, R., Schrön, M., Attinger, S., et al. (2024). 15 years of integrated terrestrial environmental observatories (TERENO) in Germany: Functions, services and lessons learned. *Earth's Future*, *12*(6), 1–42.

Zoback, M. (2001). *Grand challenges in earth and environmental sciences: Science, stewardship, and service for the twenty-first century* (pp. 41–47). GSA today.