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Special Collection:
The Future of Critical Zone Science: Towards Shared Goals, Tools, Approaches and Philosophy

Key Points:

- Integrated observatories ensure a holistic Earth Systems perspective, offering data for current and future ecological challenges
- The scientific and societal value of observatories is invaluable, but their design, construction and operation require considerable effort
- For assured long-term data collection, research infrastructure must have flexible design for adapting to changing research needs

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Fifteen Years of Integrated Terrestrial Environmental Observatories (TERENO) in Germany: Functions, Services, and Lessons Learned

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Abstract The need to develop and provide integrated observation systems to better understand and manage global and regional environmental change is one of the major challenges facing Earth system science today. In 2008, the German Helmholtz Association took up this challenge and launched the German research infrastructure TERrestrial ENvironmental Observatories (TERENO). The aim of TERENO is the establishment and maintenance of a network of observatories as a basis for an interdisciplinary and long-term research program to investigate the effects of global environmental change on terrestrial ecosystems and their socio-economic consequences. State-of-the-art methods from the field of environmental monitoring, geophysics, remote sensing, and modeling are used to record and analyze states and fluxes in different environmental disciplines from groundwater through the vadose zone, surface water, and biosphere, up to the lower atmosphere. Over the past 15 years we have collectively gained experience in operating a long-term observing network, thereby overcoming unexpected operational and institutional challenges, exceeding expectations, and facilitating new research. Today, the TERENO network is a key pillar for environmental modeling and forecasting in Germany, an information hub for practitioners and policy stakeholders in agriculture, forestry, and water management at regional to national levels, a nucleus for international collaboration, academic training and scientific outreach, an important anchor for large-scale experiments, and a trigger for methodological innovation and technological progress. This article describes TERENO's key services and functions, presents the main lessons learned from this 15-year effort, and emphasizes the need to continue long-term integrated environmental monitoring programmes in the future.

Plain Language Summary This paper discusses the importance of creating comprehensive environmental observation systems to better understand and address global and regional environmental changes. In 2008, a German research infrastructure named Terrestrial Environmental Observatories (TERENO) was established to build and maintain a network of observatories. The goal is to conduct interdisciplinary, long-term research on the impacts of global environmental changes on terrestrial ecosystems and their socio-economic effects. The TERENO network employs advanced methods from environmental monitoring, geophysics, remote sensing, and modeling to study various environmental aspects. Over the past 15 years, four

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observatories have been part of this network, contributing to valuable experience in overcoming challenges and exceeding expectations. Today, TERENO is a crucial component for environmental modeling and forecasting in Germany, serving as an information hub for practitioners and policymakers. It also fosters international collaboration, supports large-scale experiments, and drives methodological and technological advancements. The article highlights key lessons learned from this 15-year effort and emphasizes the importance of continuing such integrated environmental monitoring programs in the future.

1. Introduction

Global environmental change and it's continued acceleration has dramatic impact on all natural systems and human societies. Recent data show that 2023 was the hottest year on record (Copernicus, 2023). The resultant challenges for science to address are immense, which includes the need for improved understandings, predictions, and adaptation solutions. Moreover, today's global environmental change includes changes in ecosystem processes, land-use and management, biodiversity loss, and the services they provide to society. Hence, a more holistic approach is needed to tackle these challenges at the same pace and pattern in which they occur. There is widespread scientific consensus that integrated and systemic approaches are needed to address these complex environmental problems (Haase et al., 2018; Lin et al., 2011; Paola et al., 2006; Zoback, 2001). A holistic approach to address these environmental challenges requires accurate and precise monitoring at a whole new level of long-term integrated Earth observations (Beck et al., 2009; Kulmala, 2018; Parr et al., 2002; Reid et al., 2010).

The list of motivations and justifications to develop and operate long-term environmental monitoring programs is long. Systematically collecting and analyzing environmental data can help to tackle unanswered questions about biodiversity loss, climate change impacts, pollution, and sustainable resource management, and ultimately inform decisions for the benefit of today's and future generations. All natural and human-managed systems respond to changing environmental conditions at different time scales and time lags. As a result, many of the trends, impacts and consequences of anthropogenic climate change on the environmental components of the Earth system (pedosphere, biosphere, hydrosphere, atmosphere, cryosphere) only become apparent after several years or even decades of observation (e.g., Sierra et al., 2009). Discovery of these changing trends often comes too late to apply effective mitigation or adaptation strategies, which also increases the risk of reaching tipping points when system processes change irreversibly, for example, the ability for an ecosystem not to return to a pre-perturbed state (Chapin et al., 2009). Conversely, most socio-economic and political processes occur over much shorter timescales than the domino effect they trigger in the environment.

Long-term environmental monitoring programs help detect changes and assess trends early, and support mitigation and adaptation strategies. They do so by providing data to inform Earth system models, predictive models, and to validate remote sensing applications. Their data also inform and track the effectiveness of land-use planning and management decision-making, and agronomic and natural resource management economies. In situ terrestrial observatories ensure and protect soil health, biodiversity and the availability of clean and sufficient water resources (e.g., Chabbi et al., 2017; Gonzalez et al., 2023; Kulmala, 2018; Montgomery et al., 2007; Tetzlaff et al., 2017). Monitoring data are the basis of early warning systems for potential natural disasters to facilitate adaptation and mitigation efforts. Lastly, these long-term data provide the evidence needed to track slower and/or stochastic processes of climate and environmental change, to refine and improve our corresponding environmental policies, to raise public awareness of environmental protection and sustainability, and to further inform adaptive management strategies.

While fully recognizing the political and scientific will to invest in a long-term environmental monitoring program, these programs also require substantial and sustained financial and human resources to ensure long-term operation. Operating, maintaining, and upgrading these technical systems is costly, and training and retaining skilled staff is an ongoing challenge. To assure data reliability, accuracy, and precision over time requires rigorous data quality control and standardization, and skilled "observatory" data scientists. Establishing standardized methodologies and protocols is key to assure that the phenomena of interest are observed consistently and provides trusted comparable data over time, space, and across programs. Applying standardized methodologies can reduce operational costs by efficiently applying a consistent level of effort. However, it remains a challenge to apply these methodologies across different institutions and networks.

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Securing funding for technical and human resources for long-term operations is difficult, as maintaining operations beyond the initial investments is often not seen as a high priority compared to other, more immediate funding needs. This is exacerbated by the fact that political decision-making is often reactive and based on a short-term agenda (Willis et al., 2022). Because it may take years-to-decades to detect a significant change in an environmental process, long-term monitoring programs require a sustained commitment. It is precisely this contrast between the multi-decadal or longer time scales inherent in environmental processes and the short-term agenda of political decisions which often makes long-term environmental monitoring programs seem politically unattractive (Lovett et al., 2007), being viewed as “Cinderella science” (Nisbet, 2007). Taken together, funding bodies such as ministries and agencies may be more inclined to focus on demonstrating short-term results rather than embracing the value of long-term data that may have high-impact on societal well-being (Willis et al., 2022).

In 2008, the German Helmholtz Association addressed these challenges and launched a German infrastructure: TERrestrial ENvironmental Observatories (TERENO, Zacharias et al., 2011). The aim of TERENO was to create an observatory network as foundation for an interdisciplinary and long-term research programme and to investigate the effects of global environmental change on terrestrial ecosystems and their socio-economic consequences. To date, five Helmholtz institutions (Research Centre Jülich (FZJ), Helmholtz Centre for Environmental Research (UFZ), German Research Centre for Geosciences (GFZ), Karlsruhe Institut of Technology (KIT), German Aerospace Center (DLR)) are committed to this integrative observatory network. TERENO enables excellent research in the field of environmental sciences as part of their science mission of each participating Helmholtz Centre and is at the heart of their respective research programs. Developing, building and operating complex research infrastructures and making them available to the national and international research community is another key element of the mission of the Helmholtz Centers. TERENO conducts environmental science research and also provides several community functions and services. Over the past 15 years, the TERENO-operating institutions and their respective managers have gained experience by operating this long-term monitoring network, which also includes facing unexpected operational and institutional challenges as well as exceeding many expectations, and facilitating scientific understandings. Here, we describe TERENO's designs, and key services and the functions it provides, (Chapter 2). This is followed by the four most crucial lessons learned from 15-years of operating TERENO (Chapter 3). Throughout this paper, the authors advocate the benefits from—and the challenges in—operating long-term integrated environmental monitoring programmes.

2. TERENO—A Network of Four Integrated Environmental Observatories

Today, four TERENO observatories form a network stretching from the North German Lowlands to the Bavarian Alps (as illustrated in Figure 1), representing different landscape characteristics and focuses on areas which are particularly sensitive to climate change:

- Northeastern German Lowland Observatory, operated by the German Research Centre for Geosciences GFZ (Heinrich et al., 2018)
- Harz/Central German Lowland Observatory, operated by the Helmholtz Centre for Environmental Research UFZ (Wollschläger et al., 2017).
- Eifel/Lower Rhine Valley Observatory, operated by the Research Centre Jülich FZJ (Bogena, Montzka, et al., 2018),
- Bavarian Alps/Pre-Alpine Observatory, operated by the Karlsruhe Institute of Technology KIT (Kiese et al., 2018).

TERENO was awarded a budget of approximately 24 M€ to construct its observational and data infrastructure. TERENO defined the terrestrial system under observation as the subsurface environment (pedosphere and subsurface hydrosphere), the land surface including the biosphere, the lower atmosphere and the anthroposphere. TERENO has a geographically distributed design that combines monitoring with modeling to make inferences at a regional scale. Measurements of these systems are designed along a hierarchy of spatial and temporal scales that range from the local scale (i.e., ~1 m^2) to the regional scale (i.e., > 1,000 km^2), and with temporal scales that range from directly observable periods (i.e., sub-hourly to several years) to much longer time scales (centennial to multi-millennial) derived from geoarchives (e.g., Brauer et al., 2022). Thus, the spatial scale ideally covers the landscape scale (>100 km^2), to capture the given climatic and land use gradients, terrestrial processes, atmospheric feedbacks, socioeconomic disparities, and demographic gradients. By combining data from TERENOs' individual observatories, the processes, feedbacks and impacts can be investigated at even larger scales, for

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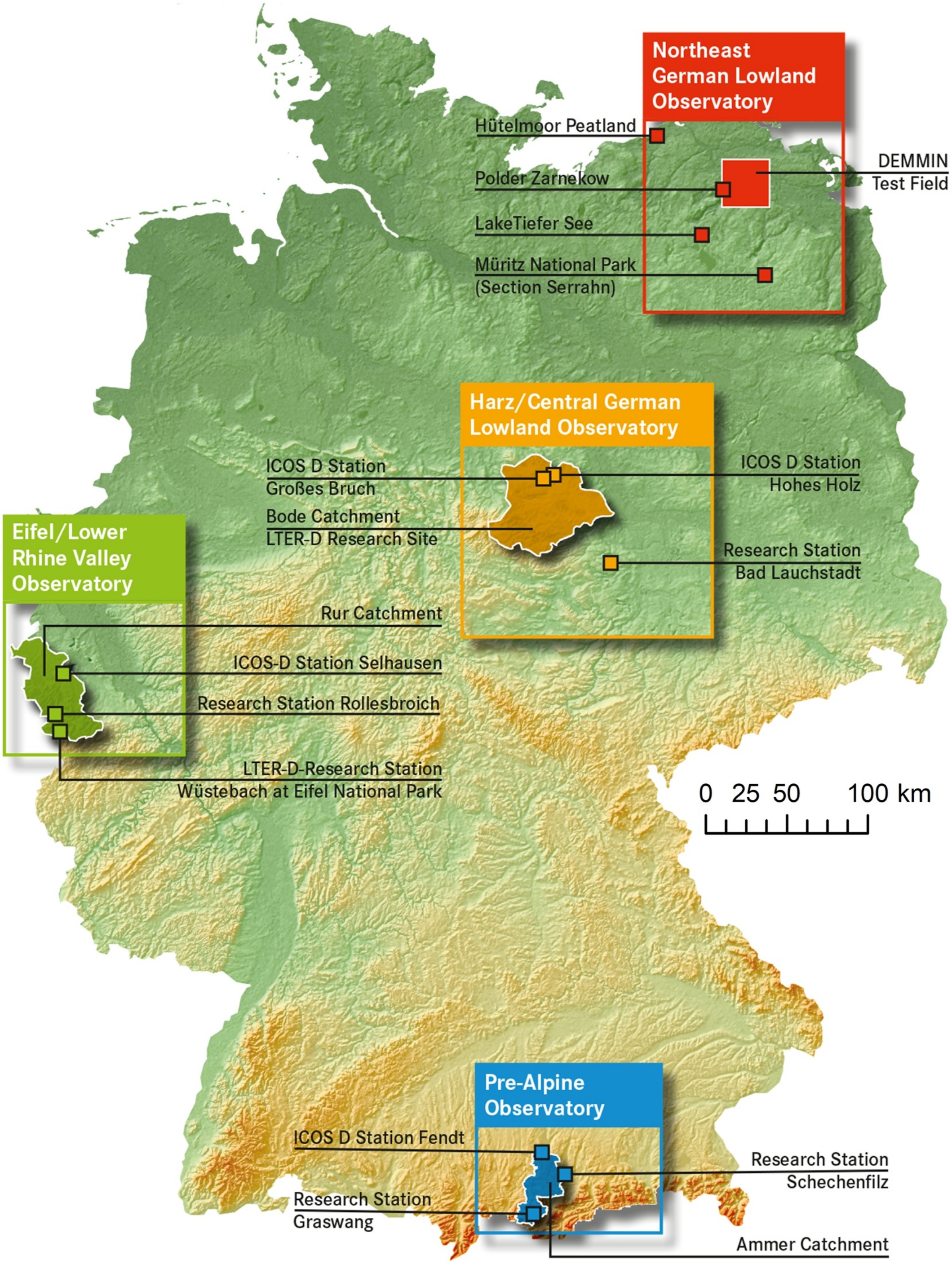

Figure 1. Map of Germany, showing location and extent of the four TERENO observatories, including the experimental catchments and associated research stations, source: TERENO.

example, country-wide, and thus foster combined and scientifically robust terrestrial and atmospheric research communities. TERENO also combines observations with comprehensive integrated modeling (Section 2.1) and larger scale experiments (Section 2.4) to increase our understanding of terrestrial system functioning and their complex interactions and feedback mechanisms among different ecological processes.

A typical TERENO observatory covers the main land cover types in Germany (forest, grassland, cropland and wetlands). All four observatories are equipped with a combination of in situ ground-based instrumentation as well as airborne remote sensing techniques, and consist of the following measurement systems:

- Comprehensive bottom-up, hydrologic observation systems (e.g., sap flow sensors, lysimeters, soil moisture sensor networks, Cosmic Ray Neutron Sensors (CRNS, see also Section 2.5), groundwater observations, river runoff gauges) to quantify the water balance dynamics and mass transport (solutes and particulates) at the catchment-to-regional scale that are used for various intensive research studies and to better inform resource management and decision-making,
- Micrometeorological measurements that monitor in real time how whole ecosystems exchange (i.e., breathe) water vapor, energy, carbon dioxide, nitrogen oxides, and other trace gases (e.g., by eddy-covariance), together with their environmental drivers,
- Weather radars and/or an increased spatial density of precipitation gauging networks to improve our accuracy and precision in the input of water from precipitation at field-to-regional scales
- Wireless sensor networks to measure environmental climate and soil variables at high spatial and temporal resolution, that inform the appropriate scales of environmental heterogeneity to better address research questions,
- Ground-based and airborne remote sensing platforms (e.g., microwave radiometers, sensor-equipped drones) to scale point-based observations to larger spatial scales, and to develop precision agriculture tools for the emergent bio-economy and climate-smart agriculture,
- Robust data acquisition, processing, and merging of field observed data with external data sets (e.g., satellite-born data) to create novel, accessible data products for research, decision-makers, and the public.

In addition to the design elements that are common to all observatories, each of the four TERENO facilities has additional environmental measurements that are either specific to the local site conditions or specific to the scientific needs of the Helmholtz Centre operating it. These include, for example, biodiversity monitoring plots, lake observatories, geoarchive monitoring (lake sediments, tree rings), atmospheric chemistry, underground laboratories, etc.

TERENO infrastructure also includes high-capacity data acquisition, processing and communication systems to ensure rapid access to the collected environmental data sets. TERENO data are collected, processed and made available through the central TERENO Data Discovery Portal TEODOOR* (internet addresses for projects, initiatives or databases referenced are listed in Appendix A and marked with an asterisk). This portal, introduced by Kunkel et al. (2013), is open access, FAIR compliant (following Wilkinson et al., 2016) and allows TERENO scientists and external users to search, view and download data by specific categories (topics, keywords, sensor type, variables and parameters), and time period and regions. TERENO's open data policy is also the gateway to networking with other national or international data repositories and observing programs: For example, the weather radar operated by the TERENO "Eifel/Lower Rhine Valley" observatory complements the operational radar network of the German Weather Service (Chen et al., 2023), TERENO soil moisture data are part of the International Soil Moisture Database (ISMN)*, and data from the TERENO insect monitoring are regularly fed into the German butterfly monitoring* program.

Today, the TERENO observatories are primary in situ research infrastructures of the participating Helmholtz Centres and provide a key role in academic training, and outreach to the public. The data and associated research have resulted in more than 1,200 peer-reviewed publications* and more than 100 successfully completed PhDs since 2010.

2.1. Regional Modeling and Forecasting

Observational data are indispensable for Earth system modeling. Existing models are continually being improved based on the evolution of our understanding–and new data, and observational data inform and refine the model behavior, validate model output, and enhance our understanding of the complex interactions within the Earth system (see also Lesson 3). Archived observational data is permanent and of high value also for the future model developments. Since its inception, TERENO has provided the in situ data as a backbone for a number of integrated models to improve the prediction of environmental processes of water, energy and nutrient cycling and their drivers. These long-term TERENO data have been essential to calibrate and validate models performance, and form the basis for various regional, national and continental data products. Four of the large system models,

Table 1
Integrated Earth System Models (Further) Developed or Advanced With TERENO Support

Model	Main characteristics	Spatial extent	Key reference
TerrSysMP: Terrestrial Systems Modeling Platform	Fully integrated soil-vegetation-atmosphere modeling system with a focus on the terrestrial hydrological and energy cycles	Regional, continental	Shrestha et al. (2014)
mHM: mesoscale Hydrologic Model	Fully integrated distributed hydrological model with a focus on the terrestrial hydrological cycle	Regional, continental, global	Samaniego et al. (2010)
WRF-Hydro: Weather Research and Forecasting hydrological modeling system	Fully coupled atmospheric-hydrological modeling systems with a focus on atmospheric and hydrologic processes	Regional	Gochis et al. (2020)
LandscapeDNDC	Terrestrial ecosystem model with a focus on carbon, nitrogen, and hydrological cycles	Site, regional	Haas et al. (2013)

which were significantly advanced with TERENO support, are summarized in Table 1. In combination with data assimilation approaches, these models can forecast terrestrial hydrologic and/or biogeochemical processes on weekly to seasonal time scales. One insight gained from the use of these models is that there are still certain knowledge gaps, particularly about the deeper subsurface of the critical zone. Data would be essential for a more accurate characterization of underground flow and transport processes. There is a pressing need to increase the number of direct measurements and improve the methods and technologies used to collect this information. These considerations should be taken into account in the further development of observation approaches. Another lesson learned from executing these large models is the importance of a priori design for data management that can more easily facilitate the integration of data and models for forecasting and reanalysis (see also Lesson 3).

TERENO data are not only key for the model development but also for the creation of regional and supra-regional data products. A prominent example is the German Drought Monitor (GDM)* (Zink et al., 2016), which serves as a reference drought monitoring system for the general public, agronomic and forest economies, and regional and water resources planning. Presently, it assesses daily the soil moisture from the top soil horizons (up to 1.8 m in depth) by integrating meteorological observations provided by the German Weather Service (DWD) as drivers in its process-based model mHM (Samaniego et al., 2010). The GDM offers two key drought indices: (a) the Soil Moisture Index (SMI) (Samaniego et al., 2013) and (b) the soil plant water availability. Both indices are derived through the hydrological model (mHM) spanning the past 70 years. The SMI is a probabilistic indicator for a typical drought event at a given location and over a time integral. In other words, it estimates the probability of drought if a threshold value (SMI <20%) has been exceeded at least 80% of the past years on record. The second indicator, on the other hand, is used to inform agronomic and forest management decision-making, for example, fire risk, planting dates, irrigation demand, etc. The GDM was originally launched in 2014 as an experimental initiative after the first soil moisture reconstruction for Germany was concluded (Samaniego et al., 2013). Since that time, the GDM has garnered substantial attention and popularity among prominent news outlets, including national magazines, television and radio stations, propelling it to become one of the most widely cited UFZ webpages (with more than 1 million webpage visits per year).

The genesis of the GDM drew inspiration from other contemporaneous models and data products, notably the US Drought Monitor (Est. 1999), as well as others pioneered by Washington and Princeton Universities in the US. What set the GDM apart, however, was its innovative utilization of a high-resolution hydrological model. Initially, the GDM data output had a spatial resolution of 4 km (v1), and has since evolved to finer 1.2 km resolution since 2021 (v2). This contrasts with the US drought monitor that operates at a coarser 1/8° spatial resolution, equivalent to approximately 13.75 km. Another notable advantage of GDM lies in its exceptional water closure performance for daily soil moisture estimation (Zink et al., 2017, 2018). Moreover, the GDM's robust performance across diverse locations and scales is attributed to the use of the Mulitscale Parameter Regionalization technique MPR (Samaniego et al., 2010). This approach enables the model to be applied at various resolutions without necessitating the re-calibration of its transfer function parameters.

The evaluation of mHM-simulated soil moisture was unfeasible during the initial phase of the GDM (v1 from 2014 to 2021) due to the absence of long-term soil moisture observations for Germany. Recent advancements in evaluation techniques made possible through sustained TERENO efforts, also provided the observational soil moisture data (alongside a few German FLUXNET* sites for the mHM evaluation). Drawing from TERENO observations, the evaluation of the soil moisture anomalies was possible for the first time. The advancements made by mHM in the high-resolution GDM v2 showed notable improvements in the simulated soil moisture during fall (+0.07 compared to the median of correlation R) and winter seasons (+0.12 compared to the median of correlation R) compared to previous results from GDM v1. Moreover, a good agreement has been found between the simulated and observed soil moisture anomalies in the uppermost horizon (0–25 cm) during the active growing season from April to October, a median correlation R of 0.84 (Boeing et al., 2022). These results demonstrate the GDM's ability to provide highly reliable, trusted, quality data for both mean trends and specific anomalies. In addition, this evaluation also informs how to best improve the model through refinement in mHM soil parameterization. It also provides comparative data to better access our ability to describe a process-level understanding.

Two other examples of TERENO data products are (a) the German *Wasser-Monitor** (water monitor), and (b) SUSALPS grassland assessment system based on the LandscapeDNDC* biogeochemical model. The *Wasser-Monitor* provides daily 9-day forecasts of the soil moisture content and plant water availability. The SUSALPS system (see Section 2.7) is a grassland management tool to assess yield, organic matter formation, and other environmentally relevant emissions of nitrate, nitrous oxide, and ammonia.

2.2. Linking In Situ Infrastructure With Remote Sensing

The advancements and integration of airborne and space-borne environmental data are paramount to scale our in situ observational- and model-data to larger spatial scales, (i.e., region-to-country-to-continent), and support frontier environmental research. The integration of space-borne data is three-fold. First, to assess the accuracy of remotely sensed data and data products ground-based in situ biophysical information is required to vicariously validate processes. Vicarious validation of airborne data using ground-based observations occurs for every flight, because of changing daytime atmospheric conditions and changes in ecosystem phenology. Similarly, space-borne validations using ground based observations are performed throughout its operational period and across a range of changing atmospheric conditions, changes in sun angle, etc. In all cases, the use of high-quality TERENO observational data is essential for remote sensing validation.

Second, integrating the remotely sensed data and in situ data provides new process-level understandings and is an active area of research and education. Since its inception, TERENO aims to better understand how to scale ecological processes by identifying sources of spatio-temporal disparities among remotely sensed or in situ observations, and model results (Bogena, 2016). Remotely sensed data also provide model input, both state variables and environmental drivers, resulting in estimates of agronomic yield prediction, forecasts of ecosystem productivity, soil processes, and flood protection (Mollenhauer et al., 2023; Wolf et al., 2017). However, challenges remain in our ability to integrate these two sources of data, for example, develop uncertainty estimates, account for long periods of cloudiness, estimate covariance spatial scales, etc. (GEO, 2016).

More detailed examples of recent TERENO studies bringing together in situ observation and remote sensing are:

- retrieval of soil moisture from Sentinel-1 C-band Synthetic Aperture Radar (SAR) with multi-orbit capabilities, addressing dynamic vegetation contributions to the SAR signal (Mengen et al., 2023).
- T. Schmidt et al. (2024) assessed the quality of 15 commonly-used satellite/model-based soil moisture products through comparison with COSMOS network data in TERENO (Bogena, Schrön, et al., 2022), highlighting the utility of in situ cosmic-ray neutron data for satellite product validation.
- Blasch et al. (2015) used multispectral RapidEye data to estimate changes in soil organic matter under bare conditions, and Leaf Area Index, which is used in turn for land surface simulations (Ali et al., 2015; Reichenau et al., 2016).
- Vallentin et al. (2022) used various sources of multispectral satellite data to evaluate how well they estimate agronomic crop yield, highlighting the variability in yield estimates among different satellite sources and the need for groundtruthing with in situ observations.
- Mollenhauer et al. (2023) developed a spectral reference target in a mobile wireless ad hoc sensor network to validate Sentinel-2 multispectral observations, as an approach to standardize vegetation characterization.
- In the atmospheric domain, Wloczyk et al. (2011) utilized Landsat data to estimate air temperature over vegetated and bare regions.

And lastly, because TERENO sites have a long history of past experiments, long timeseries of trusted in situ observations, and extensive site knowledge and expertise, they have become ideal collaborative test-beds for airborne and satellite-borne campaigns. These campaigns leverage TERENO capabilities and investments primarily to test and validate new, novel, state-of-the art satellite capabilities, for example, to test a new sensors' ability to extract environmental variables before their official launch and implementation. TERENO's infrastructure provided the test-bed for new remote sensing technologies, such as:

- The F-SAR airborne sensor (German Aerospace Center) has a SAR capable to acquire data from 3 different wavelengths at the same time (Reigber et al., 2012). When used over different TERENO sites, this sensor was not only able to estimate soil and vegetation parameters over a specific site, but also to compare and validate electromagnetic methods over different test sites under different contrasting conditions.
- New and innovative imaging modes have been tested on TERENO sites, for example, the multi-baseline technique of the Tomographic SAR approach which combines multiple-acquisitions with slightly different acquisition angles wherein the scattering within a volume can be determined and removed, resulting in the ability to process the data into a 3D image (Joerg et al., 2018). This technique has utility because it separates the soil from the vegetation volume to better estimate soil moisture beneath the vegetation.
- Hyperspectral observations over TERENO sites were made to validate the German EnMAP satellite data used to infer grassland drought stress, and determine the contributions of different spectral bands to estimate changes in plant and soil traits due to environmental (drought) stress (Hermanns et al., 2021).
- The retrieval of solar-induced plant fluorescence was tested before the launch of ESA's upcoming Fluorescence Explorer (FLEX) (Morata et al., 2021).

Detailed estimates of soil moisture across the globe is key to understand the potential effects of climate change, and used for extensive decision-making across a wide range of science disciplines, policies, and economies. As such there are numerous satellite borne efforts underway to better address this challenge and for several of them TERENO in situ data and supporting infrastructure were leveraged to support the testing and validation of these missions: (a) the European Space Agency's Soil Moisture and Ocean Salinity (SMOS; Hasan et al., 2014), (b) Copernicus Sentinel-1 (Hajnsek et al., 2009), (c) ROSE-L (launch planned for 2028) (Mengen et al., 2021), (d) US NASA's Soil Moisture Active Passive (SMAP; Montzka et al., 2016), and (e) a proposed German bistatic L-band SAR mission (Tandem-L; Jiang et al., 2015).

2.3. Fostering International Collaborations

There is a growing awareness among the public, decision-makers and researchers that solving today's global environmental challenges requires new solutions, as evidenced by the COP28 commitments, and other international reports, (e.g., IPCC, 2022). Part of that solution is to leverage and combine the capabilities from existing research projects, infrastructures and collaborations beyond their original design for both, an added value and to accelerate our current system understanding (D. P. C. Peters et al., 2014). Because we know ecological systems can telecommunicate across large regions of the globe and beyond geopolitical borders, establishing stronger international collaborations is just a natural logical progression (Kulmala, 2018; Loescher et al., 2022). Also, by bringing together each single or multi-site observatory, and/or each single- or trans-disciplinary research infrastructure (RI) approach the respective strengths are combined toward a more integrative global understanding (Futter et al., 2023; Kulmala, 2018; Loescher et al., 2022). Fostering international collaborations then creates new challenges that center around; (a) harmonizing data and technical setup, (b) training and building an equitable international user community, and (c) organizationally establishing the flexibility to tackle future, as yet unknown, environmental problems globally. It is also important to note that each international partner has their own science and social cultures that should be managed explicitly when addressing each challenge (Loescher et al., 2022).

FAIR data policies are an important building block for promoting international co-operation. Great advances have been made in informatics to harmonize and apply accreditation to data (Wilkinson et al., 2016). However, making the data useful to the international user communities also goes beyond standardized metadata formats (e.g., ISO 19115, Darwin core) and must include the original rationale for the observations. This is because the ecological context and inferences inherent in the data itself has bearing on how they can be integrated with other data. Same can be said for the technical approach and the time and space domains of the data. Standardization of procedures and traceability of the observations to known standards are a historical approach toward harmonization, such as, the co-location of observations, or the harmonization of measurement protocols across RIs. But estimating all sources of observational uncertainty a priori can facilitate the harmonization of data and make integrated statistical inferences through emergent machine learning, Bayesian, and artificial intelligence approaches.

Addressing global environmental problems by using integrated observations and data across networks internationally has created a new discipline of researchers (SanClements et al., 2022). Harmonizing the respective network-to-network data and research communities also provides added value and accelerates current understandings and predictability. Yet, building a new cohort of researchers to use these ensembled network-to-network data requires new training, as well as development of platforms (e.g., Github, Docker, Python) to work across virtual communities. This also includes the establishment of early career networks (e.g., eLTER* or critical zone community) to nurture the new generation of scientists and to promote cross-site and cross-network collaboration from the onset (Arora et al., 2023). Because environmental problems of today will be different in the future, it requires developing critical problem solving skills in these new user communities (Roberts et al., 2022), as many of the future's environmental problems will be considered “wicked” (Grewatsch et al., 2023). Moreover, creating new means of accessibility to the data, actual and virtual environments, and training for new researchers have shown to make the solutions more relevant, bring in different perspectives, and foster retention of underserved communities (Emery et al., 2021; Giles et al., 2020). This is particularly true when collaborating internationally. For example, the successful European provision of transnational access* to sites for joint research projects is novel, and should be encouraged elsewhere.

Lastly, we know global environmental change will continue at rates unprecedented in human history with impacts on all sectors of society and well-being. Having international network-to-network collaborations provide a flexible and adaptable platform to address emergent, so far unknown environmental problems. For example, in situ observational design must be flexible and capable enough to meet these new challenges as they may arise, for example, the necessary extension of measurement programs, or adjustments to the selection of measurement sites. But not only does that come with the need to be conceptually adaptive in the ability to make new observations, but also with the need to add resources and decision to do so must come from the public and decision-makers. Hence, a frequent and open communication is needed by all stakeholders to address future environmental problems.

By their very nature, integrated environmental observatories like TERENO offer many opportunities for research collaboration, and over the years, cooperation among other existing international environmental research networks to foster a better understanding of the impact of global change. A few examples are following.

The Integrated Carbon Observation System (ICOS-RI), is a European-scale research infrastructure and a European Strategy Forum on Research Infrastructures (ESFRI)* Landmark. The aim of ICOS is to measure and create regional greenhouse gas balances for Europe. Toward this end, ICOS was established to continuously monitor trace gas exchange between different ecosystems and the atmosphere. The main method used for this is the Eddy Covariance, which is also used at all TERENO sites. Therefore, the standardized designs of the ICOS network created the opportunity to co-locate their efforts with TERENO sites, and leverage these investments and scientific capital. Today, three TERENO observatories are members of ICOS and operate 7 of the 20 German ICOS Ecosystem Stations*. In this way, (a) TERENO benefits from the standardized state-of-the-art instrumentation of ICOS and its scientific expertise, (b) the ICOS measurements can be combined with TERENO's multi-discipline measurement systems, and (c) extend TERENO's sphere of inference, for example, to close the local water balance across regional scales (A. Graf et al., 2014).

In 2003 the US National Science Foundation (NSF) launched the Critical Zone Observatory and associated concepts (Richter & Billings, 2015) which rapidly created new opportunities for international collaboration among national networks in Europe. The critical zone approach aims to connects different disciplines interested in understanding the connectivity between hydrological, geomorphological, biogeochemical and ecological processes over time scales that range from seconds to eons. CZOs are defined by their ability to observe scientific convergence where interoperable data sets are required and the use of predictive models to elaborate the associated processes to the Earth's life zone, “between the rock and the sky” and anthropogenic pressures (Feder, 2018). There are currently seven CZOs established within the TERENO observatories, which are part of the Critical Zone Exploration Network (CZEN)*.

The EC-funded SoilTrec network brings together 15 European partners to develop an integrated soil process model to describe key soil functions, as defined by the EC soil Thematic Strategy (Banwart et al., 2019). In 2016, Observatoires de la zone critique, applications et recherche (OZCAR) was formalized as a French network of existing hydro-geochemical long-term observatories (Gaillardet et al., 2018) and strongly promoted the scientific collaboration with TERENO and European Long-Term Ecological Research (LTER) observatories (Baatz et al., 2018; Bogena, White, et al., 2018). Furthering this collaborative relationship, an EC training network (ENIGMA ITN)* was funded between 2016 and 2020, and a series of co-organized TERENO-OZCAR international conferences (held in 2021 in Strasbourg, in 2023 in Bonn, in 2025 scheduled for Paris) was initiated that fosters strong engagement with early career scientists (Arora et al., 2023).

In 2020, the Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research Infrastructure (eLTER RI)* was launched, of which TERENO is a founding partner. Supported by several EC Horizon 2020 projects, this led to a successful inclusion of eLTER into the ESFRI Roadmap 2018. This marked a globally unique milestone, because a large and integrated scientific community came together to advocate a "whole system approach" at a scale and complexity that has never been attempted before. These communities will benefit from eLTER's common physical network of in situ infrastructure and a comprehensive set of services (Mirtl et al., 2021). eLTER RI leverages 26 formal national LTER networks (∼550 sites and platforms), which also represents the European contribution to the international LTER (ILTER), and related CZOs. The formal eLTER RI will consist of ∼200 distributed eLTER sites (natural earth sciences) and eLTSER Platforms (socio-ecological research in focal regions). After the formal eLTER ESFRI process (in 2020), the follow-on construction and engagement projects eLTER Preparatory Phase Project (eLTER PPP) and eLTER Advanced Community Project (eLTER PLUS), respectively, were initiated. In 2023, the Ministerial representatives from 21 countries decided to fund 8 M€ annually, for eLTER's Central Services that includes data management, standards and interoperability, technological innovation, analytical tools and modeling, centralized analytics, and syntheses that lead toward actionable knowledge. TERENO has been involved in the eLTER initiative from the very beginning and has been an important reference for the conceptualization of a feasible eLTER RI, including the standardization of the eLTER observation program.

Finally, international cooperation is essential for addressing significant data gaps, particularly in developing countries. West Africa is one of such data scarce regions and susceptible to the effects of global warming and climate change. Since 2012, TERENO has collaborated with the WASCAL* project to establish a hydrometeorological observatory in Sudan Savanna of Burkina Faso and Ghana, and has been in continuous operation since (Bliefernicht et al., 2018). The design and technical realization were motivated by TERENO, and made possible via TERENO's experience from the prealpine at KIT Campus Alpin. Currently, 5 Eddy-Covariance stations are being operated along a land use gradient, along with complementary water, energy, and carbon balance devices. It was found by, for example, Berger et al. (2019), that only the woody pristine natural Savanna is a prominent CO_2 sink, while sites at degraded Savanna are net sources with a complex relationship to annual rainfall amounts. Since the establishment of the WASCAL observatory, its instrumentation and measurements were continuously used in several African PhD studies (e.g., Quansah et al., 2015).

TERENO's international recognition goes beyond that of typical research collaborations through its support and provision of data to international repositories. Notably, TERENO is a major German contributor of data to the International Soil Moisture Network (ISMN, Dorigo et al., 2011). The ISMN serves as a primary repository to validate remotely-sensed and modeled soil moisture products (Montzka et al., 2021). Numerous studies also rely on TERENO's soil moisture data to evaluate and validate new and novel methods evaluations (e.g., Colliander et al., 2021; Ebrahimi-Khusfi et al., 2018; Hongtao et al., 2019; Ma et al., 2019; Mazzariello et al., 2023; Montzka et al., 2012; T. Schmidt et al., 2024). As international collaboration among research entities continue to grow, the need for reference databases, and standardized repository capabilities also continues to grow. As such, the ongoing contributions of data, results, and outreach from TERENO to these repositories exceed current design and capabilities and require updates and re-tooling, as with all large-scale environmental research infrastructures.

2.4. Enabling Large-Scale Experimentation

Long-term monitoring provides insight into the behavior of ecological processes and their environmental controls as a scientific baseline understanding and to elucidate the chronic, ongoing pressures on these processes by climate change (Smith et al., 2009). Large-scale experimentation allows researchers to elucidate future ecological behavior not yet experienced in the natural world through the manipulation of environmental drivers and processes (Schimel et al., 2011). By combining our understanding from both long-term monitoring and experimentation, researchers can better predict and model future ecosystem states, trajectories, functions, and services (Chabbi et al., 2017; Dietze et al., 2018).

Conducting large-scale ecosystem-level experiments within long-term environmental observatories is not always straightforward. The main focus of observatories, such as TERENO, is to capture and record long-term environmental trends, their magnitude, variance, and periodicity, and to make these data accessible and discoverable. Because experiments directly manipulate the ecosystem under observation, they can affect nearby natural interactions of areas that we wish to remain undisturbed. For example, experimental nitrogen additions or experimental irrigation to natural systems may change the vegetation composition, thereby also affecting for example, pollinator abundances in nearby areas, where we wish to assess them under existing conditions. So, careful consideration has to be evaluated before an ecosystem manipulation is applied in the field or outside environment. Ways in which TERENO addresses this issue are through careful a priori review, and providing experimental facilities that remove or minimize any impact to surrounding ecosystems, such as, the lysimeter design (see below). Alternatively, there are a number of experimental approaches that do not involve large-scale perturbation of natural site conditions, and can clearly benefit from applying the experiment across a range of sites that have existing long-term environmental observations. For example, the Global Teabag Experiment, which investigated the influence of climate on litter decomposition using the same substrate, which included the TERENO sites (Djukic et al., 2018). Another way to address this issue is to outsource experiments to another location, and link them mechanistically to the in situ observations (e.g., by controlling the experimental boundary conditions). And finally, even within operating an observatory, changes may occur, for example, changes in land management, which are beyond the control of the observatory operator, and provide new opportunities to study the effects on environmental systems from sudden changes in boundary conditions.

In addition to the ecosystem approach, TERENO also incorporates the experimental catchment scale into the observational design. This also makes it possible to examine scale-appropriate questions of future changes in the water and nutrient cycles at the landscape scale. One experimental example is the Wüstebach catchment experiment, initiated in 2013 at the Eifel/Lower Rhine Valley observatory in Western Germany. The Wüstebach experiment investigates the effects of deforestation on ecohydrological processes (Bogena et al., 2015). In 2008, the catchment was instrumented to capture unmanipulated baseline data. Then in 2013, 9 ha of spruce forest were clearcut to initiate the regeneration of a near-natural forest (Bogena, Montzka, et al., 2018). To date, >100 peer-reviewed publications* have emerged from this TERENO catchment, demonstrating the value and the knowledge gained from this experimental approach. For example, Wiekenkamp et al. (2016) found that deforestation led to an increase in soil water storage, which in turn increased the frequency and volume of runoff rates. In another study, Ney et al. (2019) showed that clearcut areas become strong sources of CO_2 in the first year of deforestation, while in the following years, the albedo effect of clearcut out-weighed the potential warming effect of increased CO_2 release.

In 2010, the TERENO SOILCan lysimeter network was initiated, which installed high precision lysimeters at TERENO sites. The SOILCan lysimeter network is based on the concept of "space for time" substitution, in which intact soils were transferred along temperature and precipitation gradients within and between TERENO observatories to investigate the expected impacts of climate change on grassland or arable soils (Pütz et al., 2016). SOILCan comprises 132 lysimeters at 13 different TERENO sites, each paired with a suite of meteorological measurements. The weighable, cylindrical, high precision lysimeters (surface area: 1 m^2, depth: 1.5 m, precision: $\pm$10 g), have also been instrumented to measure matrix potential, soil water content, soil temperature, soil heat flux and chemical composition of soil solutions throughout the profile (see Figure 2). The lysimeters have a controlled bottom boundary condition to match the flow of water to that of the undisturbed soil in the field. In this way, the manipulated processes, effects, and feedback mechanisms match what we would expect from the non-disturbed field soils as close as possible.

TERENO-derived algorithms assure data quality and compute the water fluxes across the upper and lower boundaries of the lysimeters (e.g., Hannes et al., 2015; A. Peters et al., 2017). Lysimeter data was used to determine the impact of changing climate and land use management on terrestrial hydrology and nutrient cycles for grasslands (Fu et al., 2017), and arable land (Groh et al., 2022). The temporally highly resolved measurements of hydraulic state variables and water fluxes have allowed to (a) advance the understanding of soil hydrology and inform new models (Hannes et al., 2016; Herbrich & Gerke, 2017), (b) evaluate energy balance closure of eddy-covariance stations (Mauder et al., 2018), (c) test crop yield models (Kamali et al., 2022), (d) predict impacts of

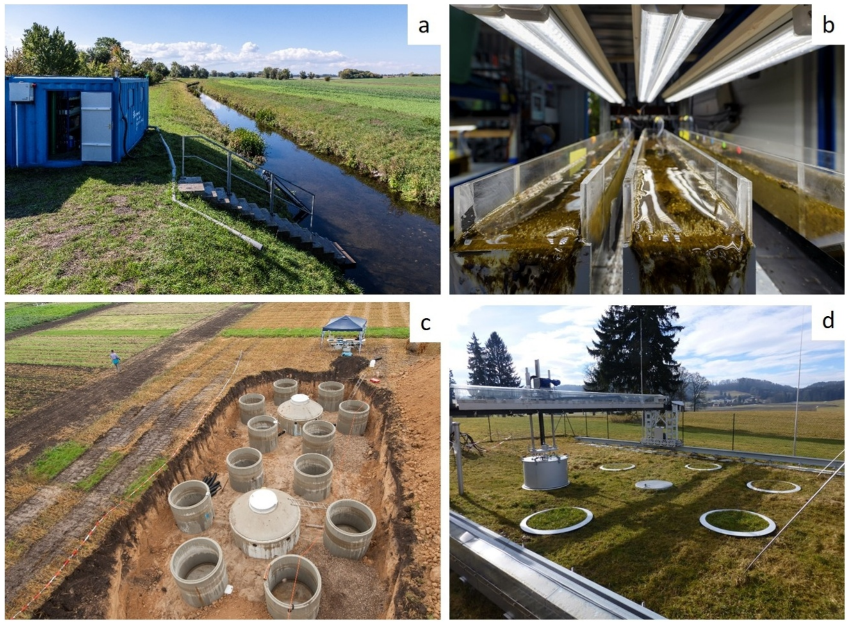

Figure 2. Examples of some of the TERENO experimental infrastructures: (a) MOBICOS container at an agricultural river side, (b) linear flumes within a MOBICOS container, (c) construction of a SoilCan lysimeter site, and (d) robotic system to measure soil greenhouse gas exchange on SoilCan lysimeters. Image sources: (a)–(c) André Kuenzelmann and UFZ, (d) TERENO.

climate change water use efficiency and plant growths (Jarvis et al., 2022), and (e) validate large scale model simulations of the German Drought Monitor (Boeing et al., 2022) and remotely sensed products (Trigo et al., 2018).

The TERENO design also extends the experimental catchment concept to stream reaches for improved understanding of aquatic ecosystem functions. As an example, the MOBICOS (mobile aquatic mesocosms) was developed (Fink et al., 2020) and integrated into the "Harz/Central German Lowland" TERENO observatory. MOBICOS is designed to observe and apply experiments that span the stream reach adopting a gradient approach of disturbed and undisturbed environmental conditions and local attributions across multiple stressors (Weitere et al., 2021). MOBICOS consists of a set of 8 stream-side mobile mesocosms (see Figure 2) using bypass flumes to/from surface waters, thereby bridging the gap between controlled laboratory experiments and field studies (Fink et al., 2020). Installed along remarkable anthropogenic land use gradient, MOBICOS combines in situ real-time biogeochemistry monitoring with the manipulation of different ecosystem processes (Jäger et al., 2017). Its compact and modular design also allows the MOBICOS infrastructure to easily be transferred between sites or operated at multiple sites simultaneously. Between-site replication of the same experimental design under different initial environmental conditions improved the understanding of causal relationships between natural environmental oscillations of aquatic ecological states and water quality (Anlanger et al., 2021; Graeber et al., 2021), anthropogenic stressors (Sunjidmaa et al., 2022), and their combined ecological impacts on these aquatic ecosystems (Iannino et al., 2021; Weitere et al., 2021).

2.5. Triggering Technological Innovation and Methodological Progress

Over the last decade, environmental monitoring technologies continue to evolve, partly due to a number of reasons that include:

1. Increasing need to address environmental problems requiring new solutions and technologies,
2. Technological advances in other application areas, such as information technology and materials science, that transfer well, such as, the Internet of Things improving our ability to continuously monitor, and quality control data, or the use of AI and machine learning techniques to rapidly analyze vast amounts of data efficiently and make new discoveries,

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3. Increasing need for observational data to improve model and/or other cyberinfrastructure capabilities, for example, satellite technology offering higher and higher resolution imagery increasing spatial resolution and temporal coverage
4. New technologies specifically designed to capture new or more phenomena, for example, mid-range IR techniques that measure multiple scalar gases simultaneously, or DNA barcoding and eDNA approaches that have revolutionized species identification, and
5. Applying Moore's law (according to which the number of transistors on integrated circuits will double approximately every 2 years) to make instruments more compact, efficient and affordable.

Environmental Observatories are always striving to update themselves both in terms of replacement or upgrades to existing infrastructure, and reducing or optimizing operational costs. Operational decisions combine these reasons to assure the uninterrupted, continuous, long-term, cost-efficient observations that meet the required data quality. To do so falls under the rubric of having to continuously evaluate: new capabilities, methodologies, and technologies; development opportunities; the strategies to adopt them; risk and benefits, while optimizing the cost of initial purchase and operating them. Long-term operated, integrated environmental observatories have several advantages when it comes to the development or the introduction of new technological infrastructures (instruments) or methodologies. First, they have long-term data sets and ongoing data-streams that enable the detection of trends, patterns, and changes in the phenomena of interest. In other words, they have the data to demonstrate how a sensor/methodology is expected to behave in the real environment, that is, ability to assess the signal/noise ratio, required measurement accuracy, timescale of the phenomena of interest. Subsequently, the statistical inferences of the natural phenomena can be used to test, evaluate, and validate the ability of a new technology or method in the field or laboratory environments. Today's observatories offer real-time data and remote sensing capabilities, allowing researchers to test new measurement techniques under various conditions against these data sets. Overall, the long-term nature of operating observatories naturally employs adaptive approaches for new technology or methodology transfer. In the following we outline five examples from TERENO research of applying this approach:

In 2010, TERENO was one of the first European observatories to test the then novel Cosmic-Ray Neutron Sensing (CRNS) technology to measure integrated soil moisture at the hectare-scale. CRNS is based on the moderation of naturally-occurring neutrons by hydrogen atoms present in water and snow. The concentration of neutrons detected can be related to the amount of hydrogen within the sensor's footprint, which can cover several hectares, and soil depths down to several decimeters. Initially, 50 CRNS stations were established in the US as the first CRNS network (Zreda et al., 2012). Over the past decade, the number of CRNS probes deployed in research projects, environmental observatories, and other long-term monitoring efforts have increased 100-fold.

The testing and adoption of the CRNS within TERENO exemplifies the approach outlined above. When the first CRNS sensors were deployed at TERENO, there were a number of methodological unknowns with this new method (e.g., sensitivity and dynamics of the footprint, influence of biomass water on the measurement signal, factors affecting site-specific calibration). The TERENO observatories provided an excellent test bed to address these methodological issues. The existing TERENO observatories study plots included spatially distributed soil moisture data over large areas, commensurate with the CRNS footprint. TERENO developed specific research projects to assess the comparative field designs that combined CRNS with these networks, and to evaluate how and where it can be adopted as a new technology. This led to a number of other research projects and collaborations worldwide that resolved several of the issues around adopting this technology, while many new methodological solutions were developed. The CRNS field application is now a worldwide standard. TERENO research projects advanced the use of CRNS by further developing the theory and applications: redefine the sensor footprint (Köhli et al., 2015; Schrön et al., 2023); assess "road effects," which can lead to an underestimation of soil moisture at complex sites or in mobile CRNS operations (Schrön et al., 2018); assess the influence of water in the litter layer or biomass on the CRNS signal (Baatz et al., 2015; Bogena et al., 2013); develop a new CRNS sensor downhole method (Rasche et al., 2023); or assess soil moisture measured along transects using permanent CRNS installations on trains for the first time (Altdorff et al., 2023). Since 2008, ISI Web of Science (WoS) listed a total of 186 published articles with German Helmholtz Association members contributing the largest share of publications and citations (29%, according to WoS where "abstract" includes "cosmic" and "ray" and "neutron" and "soil" or "snow," accessed 18 November 2023). Over the last 5 years (2018–2023), the German Helmholtz Association has contributed >34% of all CRNS publications and had >42% of all citations (174, excluding self-citations). This is a good example of how the adoption of a new technology (see also Figure 3) or methodology can

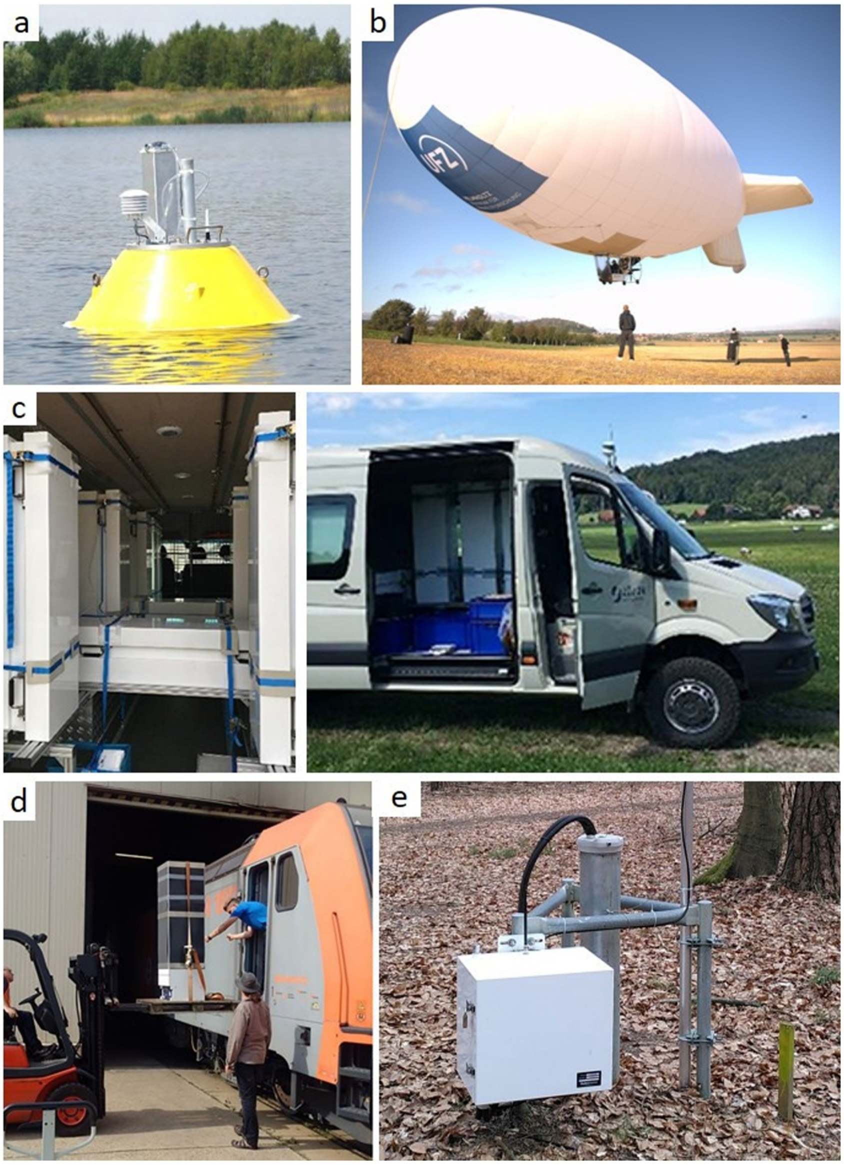

Figure 3. Examples of technological and methodological Cosmic Ray Neutron Sensors (CRNS) innovations and research supported by TERENO: (a) buoy-based CRNS on a lake to monitor atmospheric conditions and space weather, (b) airborne CRNS using a hot-air blimp, (c) dual-channel high-performance CRNS rover with thermal and epithermal detectors using different orientations, (d) railway CRNS system for permanent long-range spatial mapping of soil moisture along national rail tracks, and (e) the downhole CRNS system.

be part of ongoing upgrades in TERENO, and how they can be used to educate and grow the global user communities, and become an academic effort in itself.

A second example of technical/methodological evaluation and transfer by TERENO were in using commercial microwave links (CMLs) operated by mobile network providers to estimate bulk precipitation. This effort was carried out at the Bavarian Alps/pre-Alps observatory (Fendt site), which hosted two dedicated microwave transmission experimental designs specifically built to support the emergent research on the use of CMLs to estimate rainfall.

Important new insights were made by these studies that showed that (a) droplet size influenced the CML's ability to estimate rainfall, and (b) the temporal dynamics of "wet antenna attenuation" (WAA) is the source of significant error in CML-derived rainfall estimates (Moroder et al., 2019; Tiede et al., 2023). These findings provided the basis for model improvements. When the experiment was started (Chwala et al., 2014), the ability of CML to estimate rainfall was still nascent. Currently, this technique has matured to be applied country-wide (M. Graf et al., 2020), and the German Weather Service has applied these data to refine their weather radar estimates. The success of these microwave experiments was only possible by the TERENO's provision of reference data, along with TERENO's continued support during the long-term field campaign.

A third example is the wireless sensor network (WSN) technology that enables distributed monitoring of environmental variables (e.g., soil moisture) near real-time to not only measure catchment-level seasonal and short-term dynamics but also the spatial heterogeneity scales (Bogena et al., 2010; Mao et al., 2020). In the early 2000s, technical WSN solutions were still being developed and not robust for long-term applications as needed in TERENO. For this reason, TERENO developed, tested, and adopted a new WSN system (SoilNet*; Bogena et al., 2010; Bogena, Weuthen, & Huisman, 2022). To date, over 30 SoilNet applications worldwide have been deployed that address a wide range of research questions (e.g., A. Graf et al., 2014; Metzger et al., 2017; Rosenbaum et al., 2012).

Fourth, in the past, biodiversity assessments and species identifications in an environmental observatory setting was challenging because it mostly relied on taxon-specific trained experts, who were not always available. Nowadays, however, AI is developing rapidly concurrent with abundant available materials (images, soundscapes) to train reliable detection algorithms for certain species groups, for example, birds, moths, frogs, etc. Using sound as an identifier, a popular and inexpensive acoustic logger, AudioMoth (Hill et al., 2019) can be configured to record specific periods of the day or night when birds (or other animals) are expected to sing, for example, morning cacophony. The audio frequency spectrogram (sonograph), can be stored and analyzed for identification purposes using AI approaches, for example, BirdNET (Kahl et al., 2021). In 2023, the AudioMoth devices and identification approach got extensively tested in the Harz/Central German Lowland observatory. The aim was to test: (a) the use of AudioMoth under field conditions and validate BirdNet identifications, (b) the results of different recording times and lengths, and (c) the technological feasibility for TERENO network-wide use. The AudioMoth-Birdnet method was compared with the conventional transect-based point-stop method (expert observation, manually counting all bird individuals seen and/or heard) at defined sites in the TERENO observatory. At the same sites, AudioMoth units were mounted on trees and programmed to record for 3 hr in the morning, 2 hr in the evening and 1 hr at night for 14 days over 1 month. The performance of each method was compared by testing the AutoMoth-BirdNet results against expert validation. The preliminary results (publication in preparation) indicate that the comparison of bird species identification between taxon experts and machine detection showed a high-level of accuracy and reliability. However, audio recordings can only provide a proxy for bird abundance, which is much more accurate with expert observation. Furthermore, it was also found that by increasing the amount of AudioMoths sampling time, more species were detected than that found by field experts alone. Operationally, an advantage of an acoustic logger is the ability to increase sampling time (can be 24/7) compared to that of a field expert. Hence, combining acoustic loggers with AI provides the opportunity to increase sampling time, and identify more bird species with high levels of accuracy. The technological approach can also be supported by field technicians alone, without the inclusion of taxon experts, showing promise for more broader TERENO applications, and use for other taxon in addition to avifauna.

Lastly, other examples of TERENO using the approach to develop, assess, and adopt new technologies and methods include; (a) mobile wireless ad hoc sensor networks (Mollenhauer et al., 2023), (b) development of in situ gravimetry to measure water storage dynamics (Heistermann et al., 2022), (c) development of automated quality assessment for eddy-covariance measurements (Mauder et al., 2013), (d) robotic systems for automated GHG measurements (Grace et al., 2020), and (e) the development of DNA-based approaches to interpret ancient lake sediments (Nwosu et al., 2021).

Linking technology and methods are the data they produce and making them available. The large variety of sophisticated sensors and data streams generate very large data volumes, variety, and velocity from the TERENO monitoring systems, along with system health data from the field. This necessitates the need for innovative data management solutions. As observatory capabilities grow and scale up, traditional methods (e.g., researcher lab methods) become inadequate to handle this large influx of data and manage the system that transforms these data into data products, information, and knowledge. Effective data management is also critical to assure the trust, quality, accuracy, and reliability in the collected environmental observations. Hence, meticulous organization, acquisition, transformation, and storage of data are essential to preserve the integrity of this information, and to provide it to future generations of researchers. The data that TERENO collects has large historical and archival importance.

At TERENO's inception, an interoperable data infrastructure was developed and operationalized (Kunkel et al., 2013). In recent years, novel data management solutions have advanced (e.g., edge computing bringing the processing to the sensor, data lakes and fabrics to store vast amounts of data, machine learning for data management). Testing and validating new technologies includes the adoption of transferable and universal cloud-based solutions that operate independently of the partner's cyberinfrastructures. TERENO's novel digital, FAIR-compliant, data ecosystem consists of the following components: the Sensor Management System SMS that easily registers sensors and their associated metadata; new open-source software framework time.IO (Schäfer et al., 2023) that connects and merges the data streams from different data sources; an automated Quality Control (SaQC) system that automates data quality assurance; and the capability to transform "raw" data into higher level secondary data products (L. Schmidt et al., 2023). The TERENO novel data management solution provides near-real-time data stream processing, which is particularly relevant to identify and predict, extreme events, for example, frost, floods, ice storms, heat waves, etc.

Taken together, each one of these examples differ in how TERENO can test, validate and adopt new technologies and methods. This is important to be demonstrated because each example reaches a different community of interest, a different end user, and uses different abilities TERENO applies to augment its infrastructures and services that it provides. It also highlights the explicit need for RIs (like TERENO) to provide these services, not only to be able to update antiquated technologies, but also demonstrates the necessity to be flexible, innovative, and provide relevancy to tackle future environmental problems (see also Lesson 2).

2.6. Creating Potential for Annex Projects

TERENO is first and foremost a RI and thrives on being used for—and to enable other—research projects. In this sense, infrastructures such as TERENO are naturally a seedbed for third-party funded research and the successful acquisition of annex projects (ancillary-funded, adjacent science). Since its inception, dozens of annex projects have been funded, implemented, and partnered with TERENO. Annex projects not only fund external partners to use the RI's data, but also provide resources for direct scientific (physical) access and use of the infrastructure itself. Annex projects also provide additional resources to train and educate (PhD projects) that are essential to maximize the scientific potential of the RI, and to build the new cohort of users that will tackle future, yet unknown environmental problems. Annex projects allow the RI itself to maintain its relevancy by effectively and sustainably being linked and embedded in the regional, national and international scientific landscapes. Last but not least, such projects also provide another *raison d'etre*, providing additional justification for operational renewal and expansion of the infrastructure itself.

One example of a large annex project is the Transregional Collaborative Research Centre 32 (TR32) "Patterns in Soil-Vegetation-Atmosphere-Systems: Monitoring, Modeling and Data Assimilation," during 2007–2016. TR32 main research site was in the Rur catchment area, which in 2008, also became part of the TERENO Eifel/Lower Rhine Valley observatory. Most TR32 sub-projects utilized TERENO data (e.g., test sites Rollesbroich, Wüstebach and Selhausen). TR32 fostered numerous PhD and postdoc projects in collaboration with TERENO that resulted in >350 publications (Simmer et al., 2015). The Terrestrial Systems Modeling Platform (TerrSysMP) (see Section 2.1) was developed jointly with the Forschungszentrum Jülich, the TR32, and the Collaborative Research Center DETECT "Regional Climate Change: disentangling the Role of Land Use and Water Management."

TERENO has been a nucleus for fundamental research groups, such as "CosmicSense"*. This project unites 9 Universities and the Helmholtz Centres in Germany and Austria, collaborating across science and engineering disciplines to enhance the technological and methodological development of CRNS, and to create a quantitative, adaptable approach for observing root-zone soil moisture at the field scale. In Phase I, the research group joined forces to create 2 field clusters of high-density CRNS stations, roving, modeling, remote sensing, hydrogravimetry, and detector development at the TERENO intensive research sites Fendt (Fersch et al., 2020) and Wüstebach (Heistermann et al., 2022) in order to identify scale-specific sensor combinations to represent soil moisture variability at different scales. In the ongoing Phase II, the research goal is to extend capabilities to monitor and model soil moisture and snow to the 10–100 km^2 scales, for example, in the TERENO pre-alpine observatory and in the Selke river catchment, part of TERENO Central Germany.

ScaleX was an intensive interdisciplinary observation campaign in a region of complex topography and variation across land-use/land-cover types in the TERENO pre-Alpine Observatory (Wolf et al., 2017). It explored the question of how well measured and modeled components of biogeochemical and biophysical cycles match at the interfaces of soils, vegetation, and the atmosphere, and across various spatial and temporal scales. The overarching concept of ScaleX combined the objectives of long-term ecosystem research with those of intensive campaigns, to stimulate collaborative, interdisciplinary research and synergistic interactions to understand what is gained by expanding the resolution and scale of observations. TERENO's interdisciplinary approach offered excellent conditions and proving grounds to carry out its campaign and discovery for innovative instruments, methods, and techniques to measure quantities that cannot (yet) be automated or deployed over long periods of time.

The mobile observation system MOSES* (Modular Observation Solutions for Earth Systems) was designed as a complement to long-term observatories (Weber et al., 2022). While TERENO focuses on long-term trends in the environment, MOSES investigates the evolution and impacts of short-term events and targets of opportunity, such as, heavy precipitation and flooding, heatwaves, and droughts. Because of TERENO's comprehensive infrastructure, both physical and information resources, they served as anchor points for MOSES implementation. The integration of the event-based MOSES data sets and the long-term recordings also further complements TERENO's long-term environmental monitoring.

2.7. Providing Information Hubs for Regional Stakeholder Engagement

Engagement with others outside the research environment takes several forms. Engaging stakeholders is crucial for the long-term success of environmental observatories, as it demonstrates our ability to provide impactful science that can be used by non-scientists, or local decision-makers, and to better society (as opposed to just providing basic research). Here, we define stakeholders as "non-scientists" and those having a voice and "stake" in the outcomes provided by TERENO. Moreover, because TERENO is a long-term endeavor and the host observatory institutions are permanent, the natural relationship among TERENO, its researchers and staff, and stakeholders are infused together in the communities, local economies, and as being good neighbors. Further developing these relationships within the context of formal TERENO projects and efforts further strengthens the communities in which they sit, and fosters stronger sustainability (in all meanings of the word). The degree to which TERENO is able to engage stakeholders ultimately determines how these activities are perceived by the public.

On purely practical terms, TERENO's operation would be impossible without the cooperation, support, and acceptance of landowners, land users, regional stakeholders and local communities. Because TERENO observation facilities and projects are located on private or public land requiring land use permits, or in protected areas (nature reserves or national parks), which often requires special permissions, as they cannot occur without the support, involvement, and close coordination of stakeholders throughout all stages of planning, construction and operations. Through this direct engagement. TERENO must demonstrate the worth of the facility or project to science and stakeholders, alike.

Local-to-regional agricultural enterprises can take advantage of TERENOs' ability to test new technologies and approaches (Section 2.5). Agriculture can increase their productivity/yield while also protecting the environment and increasing biodiversity by using biogeo-referenced data, in particular those from satellites, aircraft and UAVs (Karnelli, 2017; Pilar Cendrero-Mateo et al., 2017). TERENO tested such approaches by the "AgriSens DEMMIN 4.0" project* at the Northeastern German Lowland Observatory. It brought together remotely sensed geoinformation (e.g., Copernicus satellite, UAV data) and field information (e.g., crop growth, meteorological variables, soil moisture) and derived field-scale information on crop growth, yield, vitality, irrigation requirements, etc. (BMEL, 2023). Led by GFZ, in 2020–2025, this technological approach is being tested with- and evaluated by- regional stakeholders, farms, agricultural advisors, and the local pre- and post-processing agricultural market chain (industry).

Dovetailing TERENO's science and engagement activities together, directly benefits local water managers and the public. A flagship project of the TERENO Harz/Central Germany observatory is the Rappbode Reservoir Observatory (Rinke et al., 2013), founded in 2011 in close cooperation with two relevant regional stakeholders: The State Reservoir Authority of Saxony-Anhalt* and the drinking water provider Fernwasserversorgung Elbaue-Ostharz*. The Rappbode Reservoir is Germany's largest drinking water reservoir supplying water to >1 million

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people in Central Germany, and a high priority water resource. The observatory measures water quality and discharges from all major inflows and pre-dams. It also monitors biological, chemical and physical water quality variables at high temporal resolution (<1 hr) and at high vertical resolution (<1 m) of the main reservoir. Today, TERENO's real-time measurements and data transfer are an integral part of the control room's suite of data used by the reservoir operator(s) to manage the water works. This project was initially funded by TERENO, but has evolved with stakeholders sharing the efforts and costs. Since 2023, the stakeholders have even signed a long-term commitment with UFZ to finance all sensor maintenance, repairs and renewal. The UFZ is responsible for scientific exploration of the data, and all field and lab support, for example, sensor cleaning, data quality assurance, and field-borne maintenance. The evolution of this project and its engagement activities successfully demonstrates a mutual value-added partnership among stakeholders, UFZ, and TERENO, which has led to a joint sustainable operational model. TERENO and UFZ continue to explore and innovate around this project for other value-added services, such as long-term data analysis (Wentzky et al., 2018), optimization of reservoir operation (Zhan et al., 2022) and climate impact and adaptation assessments (Mi et al., 2020). As a timely example serves the recent widespread forest dieback in the reservoir's catchment due to a severe drought from 2018 to 2020, culminating in a loss of >70% of forest cover. TERENO's products enabled fast scientific analysis that provided key information on the consequences of the drought on water quality (Kong et al., 2022) and potential future developments.

TERENO's stakeholder engagement also extends to being better prepared for extreme events, and developing the tools for planning, mitigation, and adaptation. For example, the 2021 flood disaster in Western Germany caused >180 deaths and billions of euros in property damage. During this event, it became apparent that there is still a lack of fast, reliable and efficient data that could have assisted the disaster response. In this case, there was a lack of information about the behavior of smaller streams, which played a major role in this flood disaster. To fill this gap, the HÜProS project* is developing an improved forecasting system to provide a more spatially and temporally detailed understanding of these hydrological dynamics using new TERENO soil moisture and water level sensors, as part of the Eiffel/Lower Rhine valley observatory.

In partnership with the North Rhine-Westphalia Chamber of Agriculture, TERENO with stakeholders co-designed an applied knowledge transfer project to support the regional agricultural economy as a measure to adapt to climate change. Here, the ADAPTER project* is developing a suite of innovative sensor- and simulation-based data products for use by local farmers to make more informed decisions. In one instance, the CRNS (discussed above) is combined with numerical modeling approach to provide high-resolution spatial predictions of soil moisture. This, in turn, better informs the practitioner of when and how much to irrigate, when to plow, plant, fertilize, etc. (Ney et al., 2021).

Alpine and Pre-Alpine ecosystems and the economies they support are some of the first to be affected by climate change. Hence, a large regional project, SUSALPS, has brought together stakeholders, TERENO, the Technical University of Munich, the Universities of Bayreuth and Würzburg, the Helmholtz Centre Munich and the Bavarian State Research Centre for Agriculture, to address this issue. The project stakeholders are local authorities, farmers, and the dairy industry that require better tools and data to sustainably manage these grassland ecosystems, that is, how to optimize productivity, nutrient use efficiency, better sequester soil carbon and nitrogen, ecosystem services, and manage biodiversity, etc. SUSALPS and TERENO are also developing early warning systems based on agro-ecological indicators that identify potential negative impacts on grassland ecosystem services, and a practical model-based decision support tool. These efforts are co-designed to help these stakeholders assess the potential impacts and better manage these grasslands, their soil functions, and ecosystem services. Based on TERENO's stakeholder engagement and research with SUSALPS, has led for TERENO to join the EU's "Living Lab and Lighthouses' initiative to lead the transition to healthy soils by 2030 as part of the mission "A Soil Deal for Europe."

Lastly, TERENO's also has a comprehensive outreach and education program that engages regional and local stakeholders, and provides information and communications particularly with regard to the regional impacts from environmental research. TERENO-Observatories further anchors stakeholder engagement locally through webpages, public events (e.g., open days), providing field trips and summer schools opportunities with local schools and universities, and providing advise to local stakeholders and decision-makers, etc.

3. The Lessons Learned

Lesson 1: Interdisciplinarity does not happen by itself

Given the complexity and inherent interrelationships governing today's "wicked" environmental problems, the need for interdisciplinary research is now largely unquestioned, and the term "interdisciplinarity" has become very much *en vogue*. But working across the boundaries of scientific disciplines is still largely uncharted territory for many researchers today. Hence, interdisciplinary research places unique demands on the research setting, as well as the design of in situ Earth observations. While environmental monitoring within a particular discipline has long been the tradition, integrated environmental observatories are still rare (Hari et al., 2016; Kulmala, 2018; Lin et al., 2011; Loescher et al., 2022), which calls for a paradigm shift.

There are several barriers that need addressing to achieve interdisciplinarity. Barriers within and among RIs are most often associated with; (a) the ability to transfer technology or methods, (b) how an institution is structured and what programmatic constraints are inherent in a project, and (c) not accounting for different cultures, for example, the culture within/among a particular research disciplines, differing cultures across countries, differences between the research culture and by the user communities (farmers, natural resource managements, decision-makers), etc. (Sorvari et al., 2015). To successfully achieve interdisciplinarity, each of these barriers have to be explored and explicitly accounted for in the design and execution of an RI, or RI-related research projects.

Institutions that house individual science or engineering disciplines can be a good example of often being rigid and siloed that find it difficult to engage outside their comfort zone. This boundary is certainly more prevalent at universities than at large research centers, for example, TERENO Helmholtz centres. However, these are also committed to specific research programs and are subject to scientific competition and need to publish often requiring a high level of scientific productivity, which is easier to achieve within a specific disciplinary focus. Further highlighting the need to address cultural barriers. Breaking down these barriers and working integratively across disciplinary boundaries is real work and takes determination to derive truly successful interdisciplinary solutions. Even though recent progress has been made in this area, "large" interdisciplinary research still faces challenges to obtain funds or publish its results in high-impact journals (Ledford, 2015). Key to careful planning and consideration is the team willingness to address these barriers and the communication skills to bridge these challenges.

To achieve TERENO's design goals of creating an observing platform that could serve a wide range of research interests, it was necessary to overcome the limitations of disciplinary in situ observatories. The solution was to first assess and accommodate the different requirements of the scientific disciplines and the user communities to determine suitable sites and the needed standards. This led to one solution in TERENO; to design and implement a multi-scale and multi-site design with hydrological catchments (>100–1,000 km^2) that serve as a central reference areas. Designing an observatory site that covers large areas with a number of smaller embedded sites, significantly increases the scientific and engagement options available for long term local, intensive and interdisciplinary studies. With this design, a reference watershed scale that ensures all the data collected can be spatially referenced and regionally scaled, thereby meeting both the scientific directives and a regional engagement with decision-makers (e.g., water regulations or land management districts). Furthermore, intensive study sites within a watershed allows different simultaneous investigations at the same time and location. Examples include flux tower sites where trace gas exchange between the ecosystems and the atmosphere, biological surveys and hydrological measurements are carried out at the same time, or the co-location of hydrological measurements with aquatic ecological sampling. Ultimately, however, integration and co-location always require a willingness to compromise on set-ups and location.

The spatial integration of long-term environmental observations is certainly a requirement for interdisciplinary environmental research, but it is by no means sufficient. To make interdisciplinarity a reality, active, explicit management of these goals must also be a requirement, for example, having an research strategic environment. Schmoch et al. (1994), classified a distinction between "small" and "large" interdisciplinarity, the latter describing scientific cooperation between more dissimilar disciplines, whereas "small" interdisciplinarity describes working within narrower disciplinary boundaries, for example, among "nearest neighbor" sub-disciplines (Kutílek & Nielsen, 2007). With regard to the list of scientific publications in the field of "small" interdisciplinarity, the suite of TERENO scientific publications are a strong representation of cross-science disciplines for example, in the fields of hydropedology, biogeochemistry or geophysics. This is also reflected in an analysis

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Table 2
Top 15 Web of Science Categories and Relative Distribution of Articles Related to TERENO and (Co-)authored by Members of the German Helmholtz Association[a]

Web of Science category	Share of 387 articles (%)
Environmental Sciences	21.0
Geoscience Multidisciplinary	18.3
Water Resources	18.2
Soil Science	6.8
Meteorology Atmospheric Sci.	5.5
Limnology	4.6
Remote Sensing	4.5
Imaging Sci. Photographic Technology	3.9
Geography Physical	3.3
Civil Engineering	2.9
Ecology	2.7
Forestry	2.6
Agronomy	2.1
Engineering Environmental	2.0
Engineering Electrical	1.6

Note. The broad range of Earth System disciplines, but also note the lack of socio-ecological, policy-relevant, and data science disciplines. Web of Science analysis from 14 December 2023. [a]Search: "all fields = TERENO" and "affiliation = Helmholtz*."

using the WoS core collection from December 2023, which yielded 387 results for a query limited to titles with the restrictions "all fields = TERENO" AND "affiliation = Helmholtz*." This number represents about 30% of the approximately 1,200 articles produced so far using TERENO-data. The analysis of the WoS categories shows that 18% of these publications fall into the category "Geoscience Multidisciplinary" (see Table 2). On the other hand, the outcome with regard to "large" interdisciplinarity is much more modest and respective scientific articles are missing.

Building blocks for progress toward "large" interdisciplinarity could be, for example, doctoral programs that specifically encourage interdisciplinary collaboration, training programs that specifically impart knowledge and tools for interdisciplinary work, and finally a funding and research policy that specifically requires interdisciplinarity and makes it an evaluation criterion. Another nuance to fostering interdisciplinarity is not only having the cross-disciplinary skills to collect, process, analyze, store, and maximize the utility of data, but also being able to communicate the results in a way that non-experts can understand.

Lesson 2: Keep balance between service and science flexible

Even though there is widespread accepted importance of long-term data providing knowledge on the state of our environment, the long-term maintenance of environmental monitoring programs remains difficult. Each RI has a life cycle that begins with the development of a concept, followed by the construction and formation of the RI, and subsequently the start of its operations. The acquisition of the measurement infrastructure is costly, but it also requires secure financial resources for its operation. Any compromise to sustained and adequate funding also compromises the value of long-term data and the knowledge it provides. Operational funding support includes human resources (e.g., technical staff, field engineers, data scientists), cost for land leases and electricity supply, contract management, data infrastructure maintenance and upgrades, and, last but not least, replacement or re-engineering of outdated technologies and/or adapt the RI to new frontier requirements.

Over 15-years of TERENO operations show that annual base operating budget (personnel costs for technical support, costs for power supply, land leases) is in the order of 10%–15% of the initial investment. This estimate does not include depreciation costs or costs for unforeseen expenses due to incidents such as loss of equipment due to flooding or fire. At the same time, there is constant competition for funding resources at the national policy, and institutional levels. Moreover, it is not uncommon to continually have to justify resources on the value of long-term observations, and making the distinction between "pure monitoring" and "discovery science" (Nisbet, 2007).

In order to keep an RI vibrant in the face of these challenges, it is therefore essential to continuously demonstrate the relevance of its science and engagement (see also Lesson 4). Toward this end, it is necessary to keep the underlying scientific RI concept and design under constant review and, if necessary, adapt it. Research at the Helmholtz centres that operate TERENO is organized within the framework of multi-year research programs that are regularly evaluated internationally. The research funded by these programs forms the basis to ensure TERENO's operation, but also requires that TERENO has sufficient flexibility to respond to new challenges that arise in the context of current and future research agendas.

At first sight, this "flexibility" may seem contradictory as one of the most important *service* activities of TERENO is the generation and continuous provision of long-term, uninterrupted and high quality-assured time series of environmental data. However, this contradiction only becomes important when the required *flexibility* affects a long-term task/data. Key to overcome this contradiction is to avoid an overly complex design in the choice of baseline measurements. In the selection of the baseline monitoring variables, a balance must be made between long-term scientific relevance and utility with the general feasibility to maintain the measurements and its associated data. In the case of TERENO, there is a whole range of environmental variables that have been selected

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following this philosophy, and these data are continuously acquired by all the observatories since their inception, for example, water discharge, water quality, groundwater, climate data, soil moisture and temperature, and greenhouse gas concentrations and fluxes.

The basis for this selection was an implementation plan designed jointly by all TERENO partners in the year it was founded. Over the 15 years of operation, the suite of measurements have also been continuously expanded to that take into account and align with the specific research programs at each of the respective Helmholtz Centres. Most of these additional measurements have now been in operation for many years and the data are accessible via the TERENO data infrastructure. Managing the balance between *service* and *flexibility* preserves the original TERENO scope and also demonstrates its ability to respond and adapt to other initiatives over the years. For example, several TERENO sites are part of the European-wide ICOS RI, the German LTER Network, and the international network of Critical Zone Observatories (CZEN) (see also Section 2.3). The flexibility to accommodate these new measurements, infrastructure, data, as well as many annex projects (described above), demonstrates TERENO's ongoing relevancy to society and science.

Any long-term environmental monitoring project requires community-accepted measurement standards and data harmonization. Maintaining these standards, for example, in terms of sensor types and/or processing methods, over many years can be a challenge. Instruments that become obsolete, defective, or have short time between failures, need to be replaced. Sometimes, however, a particular instrument is no longer available, there are new technical developments, or the price of measurement technology is no longer feasible. The more complex the infrastructure and the more demanding the measurement standards, the greater the operational challenge. Henry Janzen, one of the pioneers of LTER, summed up the situation well with: "A design too complex increases the risk of premature demise" (Janzen & Ellert, 2014).

To overcome this dilemma, it is helpful to base the standardization strictly on the desired measurement accuracy (signal-to-noise ratio) rather than on specific sensor types. Then, when it comes to replace a particular sensor, the selection of a new, replacement device can be based on its ability (accuracy and precision) to observe the specific phenomena of interest, and its feasibility for maintenance. If possible, new sensors are then operated alongside old sensors to assess how they preform in the natural environment and to understand, if any, differences in uncertainty occur in the new time series, re. critically reviewed redundancy testing. Adopting new technology means changes in the documentation, Standard Operating Procedures, and metadata. The associated raw data and informatics of the entire series are open and freely available for all to compare. Taken together, this approach allows for the flexible choice of new replacement technology to be adopted within TERENO, and assures the sustainable continuity and value of the long-term data set.

Lesson 3: Models drive monitoring drives models

Ultimately, the measure of an observatory's value is not the amount of data it produces, but the amount of knowledge it generates. The aim of an environmental observatory is to use the data it produces to gain a better understanding of the state and behavior of the environmental system. Linking models with data is therefore an intrinsic feature of observatories, just as conversely, observations are the basis of any Earth system modeling (see also Section 2.1). The integration of the modeling perspective is therefore essential in all phases of the RI life cycle.

The selection criteria for baseline observations for an RI are a balance among: (a) variables to be measured and the definition of the corresponding observed phenomena (variable), (b) the science and operational requirements for the measurement (methods), and (c) and the feasibility to make the measurement (protocols). Part of the selection assessment is to determine the signal-to-noise of the measurement device/approach against the signal-to-noise of the phenomena of interest, for example, assess Akaike Information Criteria. In this way, the observation design can determine how long and where a measurement must be made to statistically determine a trend or change in behavior, that is, inform the observatory's temporal and spatial resolution, and better prioritize which variables to be measured. In the design phase, the modeling perspective provides critical information regarding the prioritization of variables to be measured, as well as the required accuracy and spatial and temporal resolution of the measured data.

Models can optimize the spatial design of the observatory. The *robustness* of the spatial design can be increased with the help of models, especially in the case of spatially large observatories. While it is not always possible to

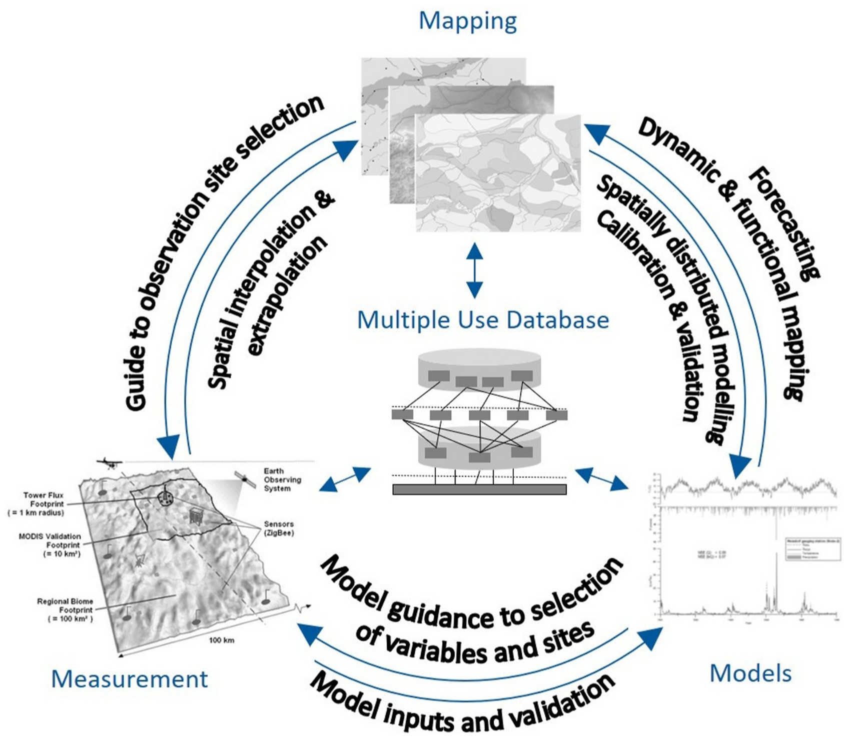

Figure 4. Integrative loop of measuring, modeling, mapping, and data mining as an integrated and evolutionary approach to address the complexity and dynamics of environmental systems across scales (modified 3M approach from Lin (2010)).

find an "optimal" observation site, it is important to choose a site that will provide the best possible data under the given conditions. This involves selecting a site that is generally representative of a large region, allowing for broader spatial extrapolation of inferences. Alternatively, choose a site that provides information on the sources of variance for a specific phenomenon. For example, TERENO used model-based optimization to inform the spatial design for a precipitation monitoring network at one of the observatories. This model coupled a mesoscale hydrological model with geostatistical approaches, and a sensitivity analysis was performed to identify possible locations for a precipitation radar to optimize its ability to assess the variance sources (Zacharias et al., 2011).

Observed environmental data is integral to the development and testing of Earth system prediction models. These data inform our ability to describe how to model how whole systems behave. They are used for input variables into models, to validate the behavior of the model outputs, and/or to calibrate the model, that is, particularly in light of AI, Bayesian, or machine learning techniques which require a priori data as inputs (Dietze et al., 2018). Multi-site model calibration is a method of choice to reduce uncertainties in predictions (Beven, 2006), and regional observatories with a measurement design adapted to these modeling needs make this approach more feasible (Jiang et al., 2015). Then, when models use new data, we learn how well we can describe that system, and how they can improved. How the model itself is structured also represents our understanding of the system in question. Observed environmental data can also test the model's ability to structurally represent the system in question and our understanding of that system, for example, the functional relationships described within the model (Wellen et al., 2015). Since the inception of the TERENO-Observatories, they have served as regional platforms to test a wide variety of models (e.g., Bogena, Montzka, et al., 2018; Ghaffar et al., 2021; Kamjunke et al., 2013; Musolff et al., 2015; Wolf et al., 2017). In all examples, testing the model behavior and its structure attributes, are always under improvement.

Observational data informs mapping (spatial representation), mapping informs models, models inform what data to observe, and so forth (see Figure 4). It is exactly this iterative approach that develops new knowledge, increases the precision in our ability to predict Earth System behavior, and is used to increase forecast precision by weather services around the globe (Loescher et al., 2017). In addition, Lin (2010) spoke of this as an *evolutionary* approach among these three elements *monitoring, modeling* and *mapping* as a basis to develop adaptive strategies

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and the continuous optimisation of model and observational data to increase our knowledge. However, as a role of observatories as data providers, a fourth component to this concept needs to be added (see Figure 4). Effective and adaptive *data management* is essential for the successful implementation of this integration strategy (see also Section 2.5).

For example, the requirements for real-time data provision are constantly increasing. Recent developments in big data science and AI are creating new data management requirements, specially for Earth system observatories. New measurement systems must be integrated quickly and effectively into existing data infrastructures. Automated data quality assurance processes need to be integrated into databases. As we advance interdisciplinary, integrated environmental observatories, for example, TERENO, we also face challenges that arise from the differing requirements from different scientific disciplines, such as data availability, storage and archive, latency, accessibility, and visualization and discovery tools for observational and model data and their data products. Provision of long-term data continues to prove challenging, both conceptually and operationally, as the infrastructure and human resources costs to sustain existing and new requirements continue to increase. Only by ensuring that the data management needs are well understood and implemented can we facilitate new knowledge being produced through this data-model-mapping approach (see Figure 4).

Lesson 4: Observatory culture is key

The success of infrastructure projects relies on the commitment of the scientists, technicians, field engineers, data managers, and stakeholders involved. All stakeholders must identify with the RIs scientific vision and strategic mission. This is essential and of utmost importance to secure the resources needed for its operations. Long-term RIs face the challenge of building a mission-based culture, and nurturing it over the long lifetime of the RI.

The longer the life of an RI, the greater the risk that its culture will be eroded, for example, staff turnover, distractions from other projects, shifting personal priorities, etc. TERENO site PIs have been successful in attracting new third-party projects at the individual observatories, but not applied to the whole RI. New research projects may lead to augmenting the observatory infrastructure, but externally funded colleagues come and go, new research collaborations emerge, or the foci of the participating scientists change. In contrast to single-site and single-discipline RIs, the risk of culture erosion is probably even more pronounced in the case of TERENO with its geographically dispersed infrastructures, diverse research activities, and its wide range of scientific disciplines. A concerted effort is needed to manage and maintain the overarching observatory culture.

To address these risks, the observatory vision, mission, and culture must anchored in and aligned with the long-term scientific strategy of the operating institute. This begins with a strong, trusted, efficient, and constant level of communication with - and engagement by - senior management. As this is often accompanied by a need for a high level of visibility into the observatory affairs for the managing institutions, it is necessary to enhance the visibility of the observatory far beyond the boundaries of the operating institute.

Fostering a strong observatory culture goes hand-in-hand with a communication strategy. Our scientific commerce and our own personal value in the project is derived from providing quality data, new knowledge in the form of publications, and being part of a larger research community. Hence, developing a strong sense of belonging comes from the timely publication of the measurement data and the results. This can be further enhanced by building a community of technicians, students, scientists and managers through center-based, national or even international workshops and conferences. In the case of TERENO, this has been achieved through annual national workshops and a biennial international conference co-organized with OZCAR. Ongoing reporting and outreach activities, for example, the TERENO newsletter*, also contribute to this effort. Having a strong, trusted, observatory identity and culture also increases the potential to network and opportunities for third-party funding from student projects to international cooperation and integration into flagship consortia.

4. Conclusions

TERENO started in 2008 with the vision of creating an interdisciplinary and scientific cross-cutting observation network to study the long-term impacts of Global Change on terrestrial ecosystems and their socioeconomic implications, to support the development of mitigation and adaptation measures in response to Global Change, and to provide a federated database to the science community. This led to a holistic design approach to observe the

Earth system, from the subsurface to the vegetated surface and the lower atmosphere. Today, TERENO is one of Germany's leading environmental research infrastructures and a partner in many other international networks.

TERENO has been designed as an infrastructure platform to bring together scientists from a wide range of disciplines, to facilitate interdisciplinary research and to provide the data basis to validate, integrate and advance terrestrial Earth System models (Lesson 3). The co-location of disciplinary infrastructures and observations is a necessary condition, but falls short to fully establish sustainable interdisciplinary or even transdisciplinary research (Lesson 1). TERENO's ability to co-design and execute projects with stakeholder communities continues to demonstrate its relevancy and contributions to society (Lesson 2). To achieve long-term success, it is also necessary to balance the provision of long-term environmental data with the flexibility to accommodate new research questions and their associated design requirements (Lesson 2). Advancing knowledge and scaling through the data-model-paradigm requires visionary alignment with the institutional research agendas and their respective funding programs (Lesson 3). Maintaining a strong sense of observatory culture is essential to sustain the science, research and education (Lesson 4). Increased collaboration with and between disciplinary research infrastructures, for example, through joint research projects, is another way to better promote interdisciplinarity. International projects, such as the European Research Infrastructures for Ecological Challenges (ENVRI)*, which aims to improve the networking of existing environmental RIs, are important building blocks, as they often come with further efforts to harmonize the RI landscape with regards to methods, protocols, and new user communities.

The TERENO infrastructure is well embedded in the individual host institutional research agendas whose long-term, secure funding is directly linked to TERENO's performance. For multi-institutional RIs, such as TERENO, long-term data collection can only be guaranteed if the RI and its design are flexible enough to adapt to the changing research needs, some of which may be institution specific. Environmental science is not limited to our geo-political borders, hence it is particularly important to continue international efforts to harmonize interdisciplinary measurements and concepts, like those being implemented by the Global Ecosystem Research Infrastructure (GERI)*, a federation of environmental RIs globally (Loescher et al., 2022), or eLTER* (Futter et al., 2023) that already offers robust sustainable structure and proven approaches.

Reid et al. (2010) states "Develop, enhance, and integrate observation systems to manage global and regional environmental change," is the greatest challenge of Earth system science. Some of TERENO's key lessons learned from operating a network of integrated environmental observatories over the last 15 years are described in this paper. The scientific and social value of observatories is priceless, but their design, construction, and operations require significant effort. Cooperation at regional, national, and international levels is essential to sustainably secure and use the wealth of data, and to generate new knowledge for future generations.

Appendix A: Weblinks for Projects, Initiatives, Databases Associated With the Asterisk Symbol * in the Main Text

- ADAPTER, https://www.adapter-projekt.de/
- AgriSense DEMMIN, https://www.agrisens-demmin.de/index.html
- Butterfly monitoring, https://web.app.ufz.de/tagfalter-monitoring/
- CosmicSense, https://www.uni-potsdam.de/en/cosmicsense
- CZEN, https://www.czen.org/
- eLTER RI, https://www.elter-ri.eu/
- ENIGMA ITN, https://enigma-itn.eu/
- ENVRI, https://envri.eu/
- ESFRI, https://www.esfri.eu/about-esfri
- Fernwasserversorgung Elbaue-Ostharz, https://www.feo.de/
- FLUXNET, https://fluxnet.org/about/
- GERI, https://global-ecosystem-ri.org/about/
- GDM, https://www.ufz.de/droughtmonitor
- HÜProS, https://www.iww.rwth-aachen.de/cms/iww/forschung/forschungsgruppen/nachwuchsforschungsgruppe-hochwasservorh/aktuelle-projekte/~bejvfi/huepros/?lidx=1
- ICOS stations, https://www.icos-cp.eu/observations/ecosystem/stations
- ISMN, https://ismn.earth/en/

- MOSES, https://www.ufz.de/moses/
- LandscapeDNDC, https://dss.susalps.de/demo2/
- SoilNet, http://www.soilnet.de
- State Reservoir Authority of Saxony-Anhalt, https://www.talsperrenbetrieb-lsa.de/
- TEODOOR, https://ddp.tereno.net/ddp/
- TERENO newsletter, https://www.tereno.net/joomla4/index.php/resources/tereno-newsletter
- TERENO publications, https://www.tereno.net/joomla4/index.php/resources/publications
- Transnational access, https://research-and-innovation.ec.europa.eu/partners-networking/access-research-infrastructure/access-european-research-infrastructures_en
- WASCAL, https://wascal.org/
- Wasser-Monitor, https://wasser-monitor.de
- Wüstebach publications, https://experimental-hydrology.net/wiki/index.php?title=W%C3%BCstebach_long-term_experimental_catchment#References

Data Availability Statement

Not applicable. The exemplary research findings that are highlighted in this manuscript refer entirely to studies previously published within the framework of TERENO, whereby the relevant sources are referenced at the appropriate positions in the manuscript.

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