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MS 1.2 – ENVRI White paper: Comprehensive analysis of emerging technology needs and service gaps in environmental Research Infrastructures

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Authors:

Jaana Bäck (UH/eLTER), Alex Vermeulen (ICOS CP), Elena Saltikoff (ICOS ERIC), Janne-Markus Rintala (ICOS ERIC), Giulia Saponaro (ACTRIS ERIC), Ulf Mallast (UFZ/eLTER), Allan Souza (UH/eLTER), Marco Galeotti (EMSO ERIC), Mariana Salgado (ICOS ERIC), Ville Kasurinen (ICOS ERIC), Martin Abbrent (UFZ/eLTER), Léonard Rivier (ICOS ATC)

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Foreword

ENVRINNOV aims at co-design, test, and validate a common Innovation Roadmap for the European Environmental and Earth System Research Infrastructures (ENVRI) community.

For this purpose, the current state-of-the-art in the used technologies, the key scientific and strategic challenges in implementing them, and the possibilities for better integration of the research infrastructure communities across the ENVRI were assessed and are compiled to a scientific white paper. The starting point has been the ESFRI Landscape report (2024) which outlined that in the Environmental Domain, comprehensive observations integrated with relevant experimental and modelling approaches, a federated approach to IT resources and e-Science facilities and reliable data policies compliant with FAIR principles are required.

1. Purpose and scope of the White paper

While the environmental effects and socio-economic impacts of the climate crisis continue to intensify, the definition, implementation, and monitoring of effective solutions to address them become increasingly more complex and urgent. To keep ensuring critical state-of-the-art support to the EU in this rapidly changing landscape, ENVRIs have to be able to continuously monitor emerging needs and gaps for new technologies and services to serve scientific and policy priorities from across the four environment subdomains.

The ENVRIs have been developed primarily to respond to the needs of specific research communities, following individual requirements and methods of specific disciplines (Figure 1). However, as the necessity of interdisciplinary cooperation became evident, the ENVRI community has increasingly cooperated as a cluster.

The ENVRIs are diverse and complex endeavors that integrate a variety of physical, digital, and collaborative components to advance environmental research. The ENVRIs cover, for example, observatories and field stations, laboratories and testbeds, in-situ or satellite sensor networks, data repositories and databases, modeling and simulation tools, or analytical platforms. Their users range from researchers and research networks to citizens, policy makers and technology developers.

Proper management and mitigation of environmental problems requires innovative solutions and interdisciplinary tools and services. The availability of comprehensive and high-quality data allows understanding of the main drivers, and the subsequent identification of options for measures. Such observations should be integrated with relevant experimental and modelling approaches. Data accessibility requires establishing reliable data policies compliant with FAIR principles.

While official monitoring networks are operated in the context of environmental regulations, the ENVRIs should be considered as a testbed or ‘precursor’ of such monitoring (i.e., innovating and testing of measurement technologies, co-designing novel methods). The ENVRIs engage in developing top-notch, user-friendly services that are available mostly for free for non-commercial purposes. They also contribute to knowledge sharing and training for users of their services.

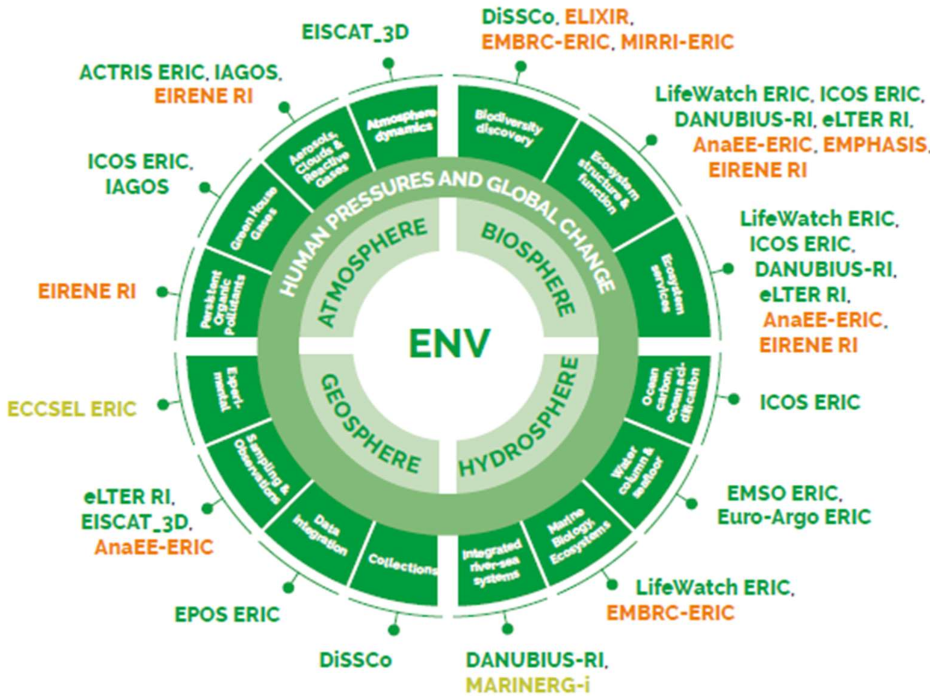

FIGURE 1.
The Landscape of
the Environment domain.

Figure 1. The four domains of the ENVRI landscape with the RIs in each domain. Source: ESFRI Landscape report 2024

2. Overview of current services of ENVRIs

The ENVRI Catalogue of Services (created by ENVRI-FAIR project) lists at the moment 71 services in its searchable database: ENVRI Catalogue of Services. The ENVRI-hub is work in progress under follow-up project ENVRI-Hub Next.

ENVRI-Hub is primarily focused on data management and services, reflecting the growing need for integrated and accessible environmental research data. While the Hub already provides valuable resources, such as the ENVRI Training Gateway and several science demonstrators, other key components are still in the early stages of development.

2.1. ENVRI Catalogue of Services primarily focused on data services

The ENVRI Catalogue of Services is today primarily focused on data services, which are designed to facilitate the aggregation, processing, and dissemination of environmental data. These services aim to improve the accessibility, interoperability, and usability of environmental data across various research infrastructures and user communities. The catalogue includes the following core data services:

- **Data Aggregation** – Consolidating data from multiple sources to create unified datasets.
- **Catalogues** – Centralized repositories for organized and searchable datasets.
- **Data Harvesting** – Automatic collection and integration of data from external sources.
- **EOSC Resource Description** – Providing metadata and resource information in line with the European Open Science Cloud (EOSC) standards.
- **Metadata Management** – Ensuring comprehensive and consistent data descriptions to facilitate discovery and reuse.
- **Plotting and Visualization** – Tools to create visual representations of complex datasets.
- **Processing and Analysis** – Offering computational resources and tools to enable advanced data analysis.
- **Publishing** – Supporting open-access dissemination of research data and findings.
- **Spatial Search** – Allowing data to be located and retrieved based on geographic parameters.

2.2. Beyond Data: Innovation and Research Services

A range of non-data services is currently being developed or implemented within the research infrastructures. These services can be grouped into three main categories: **Technological Services**, **Expertise and Consulting Services**, and **Research and Training Services**.

Technological Services

ENVRI RI's offer access to specialized technological services that include:

- **Specialized Environmental Analyses** – Access to advanced instrumentation for physical, biological, and chemical analysis, both in the field and in the lab (e.g., instrumented platforms, simulation chambers).
- **Testing, Validation, and Calibration** – Certification and calibration of technologies using reference instruments from research infrastructures. This includes joint instrument testing to ensure accuracy and performance consistency.
- **Mobile Laboratory Platforms** – Mobile quality control and testing platforms to enable field-based analysis.
- **Instrument Loan Service** – Facilitating access to specialized instruments in case of instrument failure, to avoid data gaps in the measurements or for short term campaigns.
- **Tool Development Support** – Providing computational and visualization tools to support the creation of new research instruments and analytical methods.

Expertise and Consulting Services

ENVRI RIs also offers high-level expertise and consulting services to support the development of new research methodologies and observation techniques. These services include:

- **Methodology and Protocol Development** – Creation of new protocols for specialized environmental applications.
- **Observation Techniques** – Development of innovative techniques for environmental monitoring and analysis.

- **Co-Design of Instrumentation** – Collaborative design and development of cutting-edge research instruments.
- **Expert Consulting** – Providing specialized expertise to support research and innovation projects.
- **Industry Interfacing and Collaborative Research** – Facilitating partnerships between research infrastructures and industry to drive innovation and technology transfer.

Research and Training Services

To support long-term capacity building and knowledge transfer:

- **Scientific Exploitation** – Promoting the use of new technologies and research outcomes through scientific publications and engagement with the research community.
- **On-Demand Training** – Offering tailored training services to meet the specific needs of research teams and industry partners.
- **Specialized Training Programs** – Developing structured training programs focused on the use of advanced research infrastructures and data analysis tools.

Moving forward, prioritizing the refinement and expansion of these services — particularly in the areas of data collection, sensing technologies, big data/AI/ML, interoperability and sustainability— will increase the impact and sustainability of the ENVRI RIs. These are further described in the rest of this document.

3. Emerging technology needs

This chapter will address the clear and recognized needs in ENVRI Community for improved technologies and services.

3.1. Data collection and sensing technologies

- Advanced sensors (air, water, soil quality, biodiversity, etc)

Advanced sensors: Advanced sensors are crucial tools in environmental observations, allowing for precise, real-time, and continuous data collection in a variety of environmental contexts. These sensors should be able to detect a wide range of environmental parameters, including air and water quality, temperature, humidity, soil conditions, and even biodiversity. They are needed, *among others*, in urban air quality monitoring, climate research, verifying environmental regulation compliance and mitigation efficiency, agriculture and aquaculture, wildlife conservation and detection of wildfires. The important characteristics is that they need to provide observations at unprecedented levels of detail and accuracy.

As an example, ocean carbon is still poorly understood due to lack of available sensors. The dissolved inorganic carbon has been measured from discrete water samples that were fixed with very toxic mercury chloride and later analyzed at home laboratories. Novel tools are based on lab-on-a-chip technologies that allow detection of e.g. the total alkalinity and dissolved organic carbon. There is a huge potential to increase observational capacities to regions not yet covered, outside the normal shipping routes or in extremely challenging conditions.

Autonomous and mobile sensors: drones, robots, and autonomous underwater vehicles (AUVs) can be used to gather environmental data in hard-to-reach or dangerous locations.

- IoT devices and real-time monitoring systems

Internet of Things (IoT): Environmental monitoring utilizing IoT technology, integrated with well-established methodologies and quality control mechanisms from scientific data management, facilitates the generation and maintenance of sustainable, long-term datasets. Low-cost, portable IoT devices are increasingly being deployed for real-time monitoring of environmental conditions. These connected sensors can measure e.g., air and water quality, temperature, and many other environmental parameters, providing up-to-the-minute data from remote or otherwise inaccessible locations. Machine-to-machine or machine-to-human interactions allow many novel applications and cost-efficient observational schemas and enable scaling from point observations to regions and beyond (Gaikwand et al 2021).

IoT technologies have already significantly enhanced environmental management practices by revolutionizing data collection and analysis across various ecosystems and in different environments (Katie 2024). For example, soil moisture sensors can be connected to a central system that automatically adjusts irrigation, improving water efficiency and crop yields in precision farming (ref). IoT sensors are already deployed in cities like London and Tokyo to collect continuous air quality data (e.g., particulate matter (PM2.5), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and carbon monoxide (CO)), and support localized pollution control measures (Tanaka & Yamada, 2021). By integrating IoT sensors with already existing monitoring frameworks, real-time data on air and water quality, agriculture, wildlife habitats, and urban green spaces can be gathered and thus facilitate proactive decision-making, early detection of environmental risks, and evidence-based policy formulation to address climate change, biodiversity conservation, and sustainable resource management challenges.

- Satellite and drone-based remote sensing technologies

Remote Sensing Technologies: Innovations in satellite and drone technology allow for high-resolution, large-scale environmental observations. These technologies are increasingly helping e.g., tracking impacts of climate change, deforestation, ocean temperature rise, and pollution on a regional and global scale. The novel technologies already in use include e.g. optical sensors detecting fluorescence or reflectance that can be used for assessing vegetation vitality and dynamics. The current Sentinel missions are supported by monitoring and verification capacities such as CO2MVS, for all of which in situ data are essential. The importance of reliable verification data increases, when the use of satellite data extends beyond the research community to society and policy making, especially monitoring the impacts of greenhouse gas emissions reduction and LULUCF management.

3.2. Big data: Data storage, processing and management

- Cloud computing and high-performance computing (HPC) for large datasets

Cloud-Based Platforms: Cloud computing allows for the storage and processing of large, complex datasets. Cloud-based platforms provide access to data in real-time and researchers can seamlessly access, analyze, and share data across geographical boundaries. Complex data analyzing and modelling are more efficiently handled by HPC systems, which facilitates and democratizes the access to high performance computers among the scientific community, facilitating the collaboration between different RI's and providing scalable resources for computationally intensive tasks (e.g., climate modeling, species distribution modeling).

- Big data analytics

Big Data Analytics: The volume, timeliness, and variety of environmental data are growing rapidly. Big data analytics enable researchers to manage and analyze these massive datasets, uncovering insights that were previously impossible to detect. With tools like data lakes, researchers can store raw data in an organized, accessible format, which can then be accessed and analyzed using advanced techniques like machine learning or AI. However, it is important to note that big data comes with high diversity, and to make better use of the data lakes, a clear data governance must be employed to ensure rich metadata description and to allow proper data lineage and provenance tracking. These steps are necessary to improve the usability of data lakes by the scientific community.

While the standardization of data in ENVRIs has improved during recent years, it still is challenging for machines to discover and access data based on persistent identifiers. This is problematic regarding the requirements for FAIR (Findable, Accessible, Interoperable, and Reusable) data, in general, and problematic for seamless integration of data and analysis, in particular. The data integration, or interoperability is essential not only in the FAIR data scope, but also to researchers and research infrastructures to make use of relevant information generated by third parties. To achieve this, it is crucial to provide semantic annotated data, ideally with crosswalks catalogues among the terms used by different ENVRIs. Without this step, big data and its integration becomes a bottleneck for the development of any initiative based on big data. Additionally, when well implemented, this step leverages the AI capabilities to harness the full potential of the datasets.

Another persistent challenge is the significant effort required to develop technologies that match the requirements of the many distinct application programming interfaces (APIs) implemented by data repositories with the many programming languages used by researchers for data analysis. There are several promising approaches that would improve the state-of-the-art, including e.g., software libraries that streamline reading data and metadata into computational environments (Huber et al 2021).

- Advances in computing power, database management solutions

Advanced and harmonized data quality control routines: Establishing harmonized quality control routines in scientific data management is essential to ensure data traceability, consistency, and reliability. Scientific data quality control mechanisms allow researchers to verify data integrity, detect errors, and maintain comparability across different datasets, infrastructures, domains and time periods. Integrated into the data streams real-time quality assurance enables high-quality real-time data.

Advances in Computing power: The development of the next generation of supercomputers as well as the advent of fully operational quantum computers, have the potential to revolutionize environmental research. These systems are expected to substantially expand the computing capabilities of environmental data, providing enhanced analytical and modeling capabilities that are currently not available for the scientific community. This could lead to breakthroughs in climate modeling, material science (e.g., for renewable energy technologies), and ecosystem predictions.

Data Management: Large volumes of heterogeneous data require the establishment of harmonized workflows and standardized processes to ensure consistency, accuracy, and traceability across datasets. Structured approaches avoid inconsistencies in data collection, processing, and storage, which can lead to errors, misinterpretations, and challenges in long-term usability. Well-defined and harmonized frameworks guarantee that the required metadata is systematically captured, documented, and maintained, allowing for seamless data integration, comparability, and reproducibility. Additionally, standardized quality control mechanisms ensure that data adheres to predefined quality standards, reducing uncertainties and enhancing reliability for scientific analysis and decision-making.

- Quality assurance

Advanced and harmonized data quality control routines: Establishing harmonized quality control routines in scientific data management is essential to ensure data traceability, consistency, and reliability. Scientific data quality control mechanisms allow researchers to verify data integrity, detect errors, and maintain comparability across different datasets, infrastructures, domains and time periods. Integrated into the data streams real-time quality assurance enables high-quality real-time data.

- Integration of various data sources

Global Data Repositories: Collaborative research networks and data repositories are becoming more advanced. Platforms like the European Open Science Cloud (EOSC) and the Global Earth Observation System of Systems (GEOSS) facilitate by improved discoverability the global data sharing and enable collaboration among researchers, institutions, and policymakers. By integrating metadata and datasets from multiple sources, these platforms create a more comprehensive view of environmental processes.

Examples of cloud-based data repositories and services for ENVRIs include, e.g.,

- PANGAEA (www.pangaea.de),
- ICOS Carbon Portal (https://www.icos-cp.eu).
- TERN (https://www.tern.org.au/)
- eLTER (https://www.elter-ri.eu)
- NEON (https://www.neonscience.org)
- EMSO Data Portal (https://data.emso.eu/home)
- European Network for Earth System Modeling Climate Data Infrastructure *(ENES CDI*, https://is.enes.org/)
- ACTRIS Data Portal (https://dc.actris.nilu.no/)

Citizen Science and Crowdsourcing: Technology now enables the participation of non-professional scientists and the citizen in data collection, especially in environmental domain. Platforms that allow citizen science can gather vast amounts of data on topics like biodiversity, pollution, and climate change from individuals worldwide, improving both data accuracy and research scalability. However, the quantity does not always compensate for quality, and special attention needs to be paid to quality control in general, and especially representativity of the data and potential of deliberate feeding of misinformation and disinformation.

Applications using AI based methods, where a software is used to confirm the observation between a person making the observation before the data is stored include, for example:

- iNaturalist: https://www.inaturalist.org/
- Pl@ntnet: https://plantnet.org/
- iEcology: http://www.i-ecology.org/

3.3. Artificial Intelligence and machine learning

- AI and machine learning models for predictive analytics and environmental modeling

Artificial Intelligence is an interesting and useful extension of the tools available to scientists to process and analyse big data. In the form of machine learning it already has been applied in the environmental sciences widely in the last 10 years, long before the current hype connected to LLM (chatGPT, Deepseek) started that inspires so many policy makers and funders. There are quite some ethical and philosophical issues around use of AI that should be considered when applying the techniques, and work is needed to prevent the major pitfalls and problematic areas, for example when AI systems are used as black box systems that seem to provide the right answers, but do not contribute to our understanding, the latter being the major reason of why we do research. There are however a lot of use cases where AI just works and is useful, and work is being performed on opening the black boxes to enable insights from the (causal) relations that AI methods identified between input and output.

Environmental observational data is essential as training data for AI in the field of environmental sciences, but the observations cannot be replaced by AI. AI is a useful tool in efficiently managing the ever growing amount of data and analysing it for patterns that can be used in for example quality control, gap filling, upscaling of in-situ data to spatially explicit gridded data and providing predictions. Any AI model however is only as good as its training data, and AI systems will not reliably predict outside of the conditions that were contained in the training dataset.

What is important for successful development of AI systems is the availability of high quality and trusted (true) training data though machine operable mechanisms. This requires FAIR and open methods to publish the data and a proper description of data quality, application area and other context like variable information (units, sensor type used etc), so that the right data can be used for the right application of AI. One disaster waiting to happen is AI systems trained by data generated (fabulated) by other AI systems or data provided for completely different contexts, one example of the latter would be cell phone back pocket temperatures to evaluate climate change.

Artificial Intelligence (AI) and Machine Learning (ML): AI and ML are increasingly being integrated into research infrastructures to analyze vast amounts of environmental data, to do quality control for large datasets and automate data processing, detect patterns, and provide predictive models for environmental change (e.g., climate models, biodiversity prediction). This requires protocols and public institutions on quality assurance, trustworthiness, etc., of data.

One example of initiatives combining earth observations (Remote sensing, Vegetation, Meteorological and Flux data) is FLUXCOM (https://www.fluxcom.org/) (Jung et al 2020). FLUXCOM machinery can create ensemble of data products for global carbon and energy over land and understanding and characterizing uncertainties in the fluxes. FLUXCOM has so far published ensembles based on Machine-Learning-Like Methos (MLL), Tree based methods, Regression Splines, Neural Networks and Kernel Methods or their usability is currently under investigation.

Digital Twins: The concept of digital twins involves creating virtual replicas of physical environmental systems (e.g., a forest, urban environment, or river). The use of supercomputers is a mandatory requirement in Digital Twin research. These models are used e.g., to simulate the impact of various changes or interventions, enabling researchers and policymakers to test different scenarios before implementing them in the real world.

Novel ways to combine data, models and interaction processes are required to predict e.g. biodiversity dynamics and offer solutions that promote sustainable management of the earth's biodiversity and its ecosystems and provide tools for advanced modelling, simulation and prediction capabilities. There are a handful of Digital Twin activities (e.g., Destination Earth, NVIDIA's Omniverse, the WCRP Digital Earths lighthouse activity, and the DITTO program of the UN Ocean Decade).

3.4. Connectivity and interoperability of services

- Standardization of data formats and communication protocols across ENVRIs
- Operational innovations (living labs, hierarchical networks etc)
- Integration of ENVRIs into global and regional networks for shared knowledge

Modular and Adaptive Infrastructures: Traditional research infrastructures are often inflexible and costly to upgrade, due to their origin and historical purposes. The trend toward modular, adaptable and interoperable infrastructures can allow for easier scaling and customization based on emerging research needs. This is particularly relevant for environmental research, where multi- and interdisciplinary data should be accessible and interoperable to address interlinked environmental challenges.

Living labs: Living labs are user-centered, open innovation ecosystems in real-life environments using iterative feedback processes throughout a lifecycle approach of an innovation to create sustainable impact. They focus on co-creation, rapid prototyping and testing, and scaling-up innovations, providing joint-value to the involved stakeholders. In this context, living labs can operate as intermediaries and facilitators among citizens, research organisations, companies and government agencies.

Hierarchical research networks and supersites: The global grand challenges require data on different domains from key ecosystems all over the globe. The current coverage of such observations is way too random and not dense enough. An attempt to solve this is the global observatory concept, introduced by Kulmala (2017), whereby the gaps in global coverage could be solved by a hierarchical station network, including ca 1000 supersites, a large number of less advanced observational sites and even larger number of sites that collect information on a few parameters only, but are needed for scaling up the observations from the less dense network of stations. Data from the hierarchical network would be linked to data from satellite-based remote sensing, laboratory experiments and computer models.

Innovations in the hierarchical station networks are fostering greater integration across disciplines, enabling researchers from various fields (e.g., environmental science, engineering, economics, social sciences) to collaborate more effectively. For instance, a single infrastructure platform might integrate environmental monitoring data, social impact assessments, and economic modeling to address complex environmental challenges. The supersite concept is created for addressing the global grand challenges in a comprehensive manner.

Cross-Domain Data Integration: Research infrastructures are increasingly capable of handling and integrating data across diverse domains, such as biology, ecology, chemistry, and socio-economics. This enables researchers to study environmental systems in a more holistic way, linking ecosystem health with human activities, policy, and economics.

Climate sciences require federated data structures that are not possible without close integration and collaboration between different regions and RIs (Stevens et al 2024). In addition to the re-analyses and climate projections, which provide the vast amounts of globally gridded data needed to train the most advanced weather- and climate-related AI models, a great many organizations and agencies collect and disseminate other forms of climate-related data (e.g., from satellites, networks of ground sensors, gliders, floats, and drones to integrative ecosystem super-sites) that could greatly enhance this training.

Many global networks have described essential variables in their domain. For example, an Essential Climate Variable (ECV) is a physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of Earth's climate. Global Climate observing system GCOS currently specifies 55 ECVs in areas of atmosphere, ocean and land. For the biodiversity domain, the EuropaBON is creating the Essential Biodiversity Variables (EBV), which are a starting point for the establishment of a concrete workflow for EBVs in Europe. The RIs should be involved in the definition of the essential variables, in standardization of their observation procedures and the required metadata, as well as crosswalks among the terms to facilitate the data integration. For further promotion of integration and interoperability, the commonalities between ECVs, EBVs and other harmonized observation systems should be explored and their common uses facilitated.

3.5. Sustainability, green technologies

- Technologies for reducing the carbon footprint of research infrastructures

Environmentally responsible operations of Research Facilities: Innovations in research infrastructures also aim to reduce the environmental impact of research itself. For example, green buildings, renewable energy sources, and energy-efficient computing systems are being incorporated into environmental research infrastructures to minimize the carbon footprint of research activities.

Usage of automated technologies, wireless sensor systems and remote observations reduce the need to travel to the sites and platforms. Co-location of measurement sites and collaborating in data management will not only enable interoperability but also create synergies in design and reduced costs and environmental impacts.

Circular Economy Principles: It should be a requirement for all ENVRIs that the operations are designed with circular economy principles, focusing on reducing waste, reusing resources, and recycling materials. High-performance computing requires substantial electricity resources. As a solution, innovations in solar photovoltaic cells, wind turbine design, and geothermal systems are making energy-demanding operations more efficient and cost-effective.

4. Service gaps in ENVRIs

This chapter will address the identified gaps and barriers/obstacles for uptake of novel services.

4.1. Access and equity issues

- Limited access to high-performance computing resources or remote sensors
- Barriers to data sharing and collaboration across different RIs
- data processing (shared protocols/schemes) in particular regarding the quality control and quality assurance across RIs
- data harmonisation/mobilization

Some existing services have limited outreach beyond the ESFRI community and specifically for other user groups than researchers. Some facilities may have limited open access for external users, particularly from outside the core research networks. The unperfect geographic balance forms a key challenge in the integration of ENVRI services. Most ENVRIs are located in wealthier EU countries for historical and financial reasons. Some countries have better funding to support engagement with ENVRIs, leading to disparities. Even when the transnational access programs are in place, the administrative and bureaucratic challenges make it difficult for researchers to access facilities across national borders and challenging for the in-situ sites for administer the access process. The current transnational access program budgets are mostly bound to third party funding which limits their uptake (would be optimised if continuous provision is guaranteed.

4.2. Skill and expertise gaps

Shortage of trained personnel to manage and analyze advanced technologies, manage research sites and platforms or facilities (needs a clear role that is often not acknowledged. Another issue that is seldom explored is the fact that there is a mismatch between the expected outputs of a person working in technical positions in RIs and the academic system where they are usually inserted. To maintain and advance in the career, the professional working in the technical components of RIs often need to produce scientific outputs that do not necessarily match their tasks. This creates focus dispersion and provides little incentives to retain staff for the long term.

Gaps in interdisciplinary training combining environmental science, technology, and data science: During the past decade the amount of data processing capacity has significantly increased, and it has partially led to the situation where researchers have a need to process larger and larger sets of data.

Virtual Research Environments (VRE) are currently existing as cloud-based services and there are several services providers in these markets. For example, google is providing free google lab service that has a limited memory and processing capacity. Also, universities provide such environments as well as high-computing capacity for the needs of research. Some examples of VRE's provided by RI's are at least ICOS Carbon Portal Jupyter Hub (https://www.icos-cp.eu/data-services/tools/jupyter-notebook), ACTRIS VRE (https://data.actris.eu/vre) and CERN VRE (https://vre-hub.github.io/).

The common service concept for Virtual Research Environments is that the user does not need to download large data sets to a local laptop and codes and workflows can be shared between project members enabling collaboration in cloud environments. However, the use of such services also requires new types of IT skills and without them such services are not accessible for scientific users. These kinds of gaps in interdisciplinary training combining environmental science, technology and data science are important to recognize.

- Gaps in interaction design and usability expertise for the creation of future services and the integration of new technologies

Lack of industry/business/government liaison during the preparatory phase results in insufficient collaboration with those partners at operational stage. Collaboration and co-creation with those partners need to be pursued actively from the start to ensure the infrastructures and services offered meet existing needs. It would be useful to have funding for an experienced industry/business/government liaison officer right from the start to establish contacts and collaborations early on.

Despite challenges like data security and interoperability in novel technologies, collaborative efforts among stakeholders can pave the way for more effective environmental monitoring and sustainable development initiatives globally.

4.3. Infrastructure limitations (governance, financial, operational)

Most European ENVRIs are federated organisations, some are national (e.g. AISBL, GmbH) or European (ERIC) legal entities and some organized as research networks or International Organisations. The applied governance model depends on many factors, but the important characteristics in legal entities are that no minimum capital is required, the liability of the members is limitable and economic activities are possible only on a small scale. In the current ESFRI Roadmap (2021) there are 5 (+1) ERICs, one AISBL, one international organisation and three projects among the Environmental Domain RIs.

The diverse landscape in Europe poses a challenge in the geographical coverage of ENVRIs. Lack of governmental support for national infrastructures results in gaps in data as well as heterogeneity in data quality and quantity, for pan-European RIs. The diverse landscape also hinders coordination between RIs, manifested in lack of systemic support for coordination, co-creation, and co-usage across RIs. This results in repeated parallel development of services, data platforms, etc. and limits the possible outputs and effectiveness of all RIs since time and resources are invested in establishing parallel structures.

Per European regulation, members of research infrastructures are the countries, not individual universities or researchers. However, countries delegate their participation to research funding organizations, which too often seem to treat a RI as another research project. The funding must be applied every few years, often in competitive calls, and the results are assessed with metrics not suitable for impact of RIs.

5. Strategic opportunities for advancing technologies

This chapter will address the key opportunities that could be explored for better services and more efficient use of resources.

5.1. Public-Private Partnerships

- Collaborations with industry leaders to drive innovation in environmental technology
- Encouraging the development of low-cost, high-efficiency scalable monitoring technologies
- Industries as users of RI data and data-related services
- Co-development and co-design of data-related services e.g. for agroindustry meaning RIs can act as innovation hubs

Research infrastructures can have two main types of industry cooperation: “upstream” where the RI uses products of industry (such as instruments), and “downstream” where industry uses output of RIs (such as data). Both types benefit from a two-sided model of “technology push and market pull”.

A research infrastructure can be a tempting customer for SMEs in the instrument industry, as a RI often requires tens if not hundreds of identical instrument installations, and marketing and user support can be provided to a concise group of users. However, operating a new type of instrument is a major investment of money and effort for the RI, so the expected long lifetime of support and spare part availability becomes a deciding factor.

Solving global challenges like climate change needs global data. Especially commitment to mitigating activities needs local observational data - there is no diet without a scale. Policymakers and administrators with no science background are easily tempted with the low purchase price of instrumentation, which can be very different from operational lifetime cost. With the multi-year experience from operational activities as well as development projects, the RIs can be a great source for sharing their experiences of operational costs of observations. E.g. the ICOS Handbook shares estimates of FTE needed for running an observational network. Similar analysis should be extended to suggested new technologies and platforms - and the resources needed are not to be assessed only as euros, but in megawatts of power and full-time equivalent of human power, because the cost of both can vary significantly between different areas of the world.

ICOS ERIC has experience based on the ICOS Cities (PAUL) project bringing together European citizens, policy makers and top scientist in co-designing pioneer greenhouse gas measurement methodologies and services for cities to support climate action (https://www.icos-cp.eu/projects/icos-cities). In Pilot cities the feasibility of different modelling approaches in various areas, three cities of different size have been selected as pilots: Paris (large), Munich (medium) and Zürich (small). In the project high, medium and low-cost sensors are used to investigate how to build an optimal GHG monitoring system in city scale.

Industries at any scale as well as government agencies are also potential customers of RI data and data-related services, e.g. of meteorological/atmospheric data to e.g. assess health thresholds and check the effectiveness of emission-control measures, or of carbon-content data from undisturbed soils in long-term observation plots to assess the effectiveness of carbon-farming measures. It is therefore crucial to create awareness and establish collaborations with such partners as early during the RI development as possible to ensure that data needs are met, and to establish data-access policies for industrial and governmental partners that encourage and enable the use of RI data by such partners.

5.2. Policy and regulatory support

- Role of governments and international bodies in providing funding and regulatory frameworks
- Aligning emerging technologies with sustainability goals
- Making data accessible to policy makers

5.3. Integration of new technologies into existing RIs

- Investment in skill development in new technologies
- Establishment of knowledge-sharing platforms and educational resources –> ENVRINNOV role as a broker
- Understanding new technology from the point of use of several stakeholders that could benefit RI's services.

Integrating new technologies into existing research infrastructures within the ENVRI Community is essential for maintaining their relevance, enhancing data quality, and expanding service capabilities. However, this integration must be approached strategically to ensure compatibility with existing systems, maximize efficiency, and align with the FAIR principles. Successful integration of new technologies into the ENVRI Community requires continuous dialogue, coordinated efforts across RIs, and alignment with European and global research strategies to ensure that environmental data remains at the forefront of scientific and societal advancements.

5.4. Global collaborations and data sharing networks

- Development of open-access repositories for data that are accessible and easy to use for a wide variety of stakeholders.
- Fostering international partnerships for addressing global environmental challenges

ACTRIS adheres to the European Commission's principle of being "as open as possible, as closed as necessary." This approach ensures that ACTRIS data and digital tools are freely accessible with minimal restrictions while complying with the FAIR principles. As a result, ACTRIS data remain available through international network portals while maintaining clear provenance. ACTRIS also aligns with the standards set by the WMO Integrated Global Observing System (WIGOS) and other international data repositories, with its policies reflecting the recommendations of Carmichael et al. (2023).

The EU HORIZON CARGO-ACT project fosters international partnerships by strengthening sustainable collaboration between key organizations in Europe and the United States. By enhancing access to high-quality atmospheric data on aerosols, clouds, and trace gases, the project supports global efforts to tackle climate and air quality challenges through shared expertise and coordinated monitoring strategies.

6. Recommendations for bridging technology needs and service gaps

This chapter will address the concrete actions that could be foreseen in near future.

6.1. Developing infrastructure roadmap for innovations

- Clear strategies for future-proofing ENVRIs with new technologies
- Recommendations for sustainable investments in infrastructure

Based on this collaborative report, the ENVRIs have reached a point in time where concrete and active work towards establishing joint strategies for nurturing and implementing innovations are urgently needed. many global grand challenges in the environmental domain are progressing in an unprecedented pace and working in silos will not provide the society the needed solutions.

This calls to action for stakeholders (governments, researchers, industry, and the public) to invest in and prioritise technological advancements in environmental research, for example the implementation of newly developed sensors on autonomous platforms to increase both the spatial and temporal coverage of observations (Schaap et al. 2025) as well as to include novel cost-efficient tools for wider accessibility of data. The increase in observational frequency, sustained analytical performance, and autonomous deployment in inaccessible or remote areas should be one of the priorities.

6.2. Strengthening collaboration and data sharing

- Promoting open-access and interoperable data systems

- Encouraging more inclusive and equitable access policies (incl data and other services)

Easy and rapid access to reliable, long-term, and high-quality environmental data is essential for advancing scientific understanding of the Earth and its environment. Such data also play a crucial role in developing mitigation and adaptation strategies, supporting fact-based decision-making, and fostering environmentally friendly innovations. As demand grows for integrated, interdisciplinary services beyond the atmospheric domain, ENVRIs must evolve to provide more comprehensive offerings, extending beyond atmospheric-specific data production to integrated global services. To achieve this, ENVRIs collaborate with research infrastructures both within and beyond the ENVRI cluster and the environmental sciences. Studying these interactions requires seamless access to multidisciplinary data across Earth's system, with FAIR digital (meta)data as a fundamental requirement.

6.3. Enhancing capacity building and training programs

Each ENVRI has their individual, disciplinary training and capacity building programs, required for harmonization of methods and quality assurance of data. However, multi- and transdisciplinary training programs should be pursued to expand the knowledge beyond the traditional disciplinary communities and promote innovation beyond the boundaries. Examples of such programs are the ENVRI-Hub Next training plan (Parisi & Vallo 2024).

7. Conclusion

- Recap of the major findings and key areas where emerging technologies can address service gaps

References

Carmichael, G., O. Tarasova, H. Hov, L. Barrie, and J. Butler, 2023: Global atmospheric composition observations, the heart of vital climate and environmental action. Bull. Amer. Meteor. Soc., 104, E666–E672, https://doi.org/10.1175/BAMS-D-22-0016.1.

ESFRI (2024) https://landscape2024.esfri.eu/

Eyre, B. D.; Cyronak, T.; Drupp, P.; De Carlo, E. H.; Sachs, J. P.; Andersson, A. J. Coral Reefs Will Transition to Net Dissolving before End of Century. Science 2018, 359 (6378), 908−911.

Friedlingstein, P.; Jones, M.; O'Sullivan, M.; Andrew, R.; Bakker,D.; Hauck, J.; Le Quéré, C.; Peters, G.; Peters, W.; Pongratz, J.; et al. Global Carbon Budget 2021. Earth Syst. Sci. Data 2022, 14 (4),1917−2005.

Gaikwand S.V., Vinbhute A.D., Kale, K.V & Mehrotra S.C: (2021) An innovative IoT based system for precision farming. Computers and Electronics in Agriculture. https://doi.org/10.1016/j.compag.2021.106291

Harvey, B. P.; Agostini, S.; Wada, S.; Inaba, K.; Hall-Spencer, J.M. Dissolution: The Achilles' Heel of the Triton Shell in an Acidifying Ocean. Front. Mar. Sci. 2018, 5, 371.

Hoegh-Guldberg, O.; Cai, R.; Poloczanska, E.; Brewer, P.; Sundby, S.; Hilmi, K.; Fabry, V.; Jung, S. The Ocean. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press; Cambridge, United Kingdom and New York, NY, USA, pp 1655−1731

Jung, M., Schwalm, C., Migliavacca, M., Walther, S., Camps-Valls, G., Koirala, S., Anthoni, P., Besnard, S., Bodesheim, P., Carvalhais, N., Chevallier, F., Gans, F., Goll, D. S., Haverd, V., Köhler, P., Ichii, K., Jain, A. K., Liu, J., Lombardozzi, D., Nabel, J. E. M. S., Nelson, J. A., O'Sullivan, M., Pallandt, M., Papale, D., Peters, W., Pongratz, J., Rödenbeck, C., Sitch, S., Tramontana, G., Walker, A., Weber, U., and Reichstein, M.: Scaling carbon fluxes from eddy covariance sites to globe: synthesis and evaluation of the FLUXCOM approach, Biogeosciences, 17, 1343–1365, https://doi.org/10.5194/bg-17-1343-2020, 2020.

Katie B (2024) Internet of Things (IoT) for Environmental Monitoring. International Journal of Computing and Engineering 6, 29 - 42, 2024

Parisi E & Vallo C (29024) ENVRI-Hub Next D3.2 Training Plan. DOI 10.5281/zenodo.14235708 (Accessed 31 March 2025)

Raven, J., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U., Shepherd, J., Turley, C., & Watson, A. (2005). *Ocean Acidification due to Increasing Atmospheric Carbon Dioxide*. The Royal Society. https://royalsociety.org/topics-policy/publications/2005/ocean-acidification/ pp 1-60

Schaap A.; Papadimitriou S.; Mawji E.; Walk J.; Hammermeister E.; Mowlem M.; Loucaides, S.: Autonomous Sensor for *In Situ* Measurements of Total Alkalinity in the Ocean. ACS Sensors 2025 10 (2), 795-803. DOI: 10.1021/acssensors.4c02349

Tanaka, H., & Yamada, S. (2018). Advances in climate change monitoring and management in Japan. Environmental Science & Policy, 80, 65-78. doi:10.1016/j.envsci.2017.12.001

Zanna, L.; Khatiwala, S.; Gregory, J. M.; Ison, J.; Heimbach, P. 2019: Global reconstruction of historical ocean heat storage and transport. *Proc. Natl. Acad. Sci. U.S.A.* 116, 1126–1131. doi: 10.1073/pnas.1808838115

Appendices

- **List of technologies in use in RIs**: Details of key technologies and platforms used
- **Glossary**: Definitions of key terms used in the white paper