CONTENTS

PART2

LANDSCAPE ANALYSIS - SECTION1

ENVIRONMENT

ENVIRONMENT

Environmental sciences are traditionally divided into four research and study domains: **ATMOSPHERE**, **HYDROSPHERE**, **BIOSPHERE** and **GEOSPHERE**. These different *spheres* are closely interlinked, and therefore environmental sciences can also be presented according to *Grand Challenges*, such as loss of biodiversity, pollution, depletion of natural resources, risks, hazards and climate change.

Atmosphere, hydrosphere, biosphere and geosphere are closely interlinked spheres of environmental sciences responding to big human challenges from loss of biodiversity to climate change.

Many of the most critical and urgent issues that human society faces are linked to key environmental challenges. Managing and responding to natural and anthropic environmental changes need to be understood at the Earth System level. The effect of pollution and climate change, including associated impacts on biodiversity and ecosystem integrity, need to be fully understood urgently. The sustainable and responsible use of key natural resources and ecosystem services such as food, water, energy and minerals by a more demanding and growing population is vital. Modern society is progressively vulnerable to the increased frequency of natural hazards such as extreme weather, earthquakes, space weather, epidemic disease outbreaks, which can cause loss of life and have an enormous impact on the society with large economic deficits. Tackling environmental challenges is crucial for mankind and for life on Earth and given the scale, complexity and the interlinkages of the challenges, a multidisciplinary approach is essential. Layers of complexity to carrying out environmental research are added by the multidisciplinary aspect amongst the main Earth system domains and by the considerable range of spatial and temporal scales involved.

Because of its complexity, the environmental research as a whole should be facilitated by comprehensive observations with an integrated approach including experiments and modelling which are essential for understanding and predicting the Earth's environmental system. A federated approach to IT resources and e-science facilities – including liable data policies according the FAIR principle – is also necessary. The objective of achieving a comprehensive multidisciplinary approach to improve our scientific understanding of the Earth's system can be obtained with the realisation of the current ensemble of RIs in the Environmental domain which are highly integrated in respective global efforts. The existing Environmental RIs already adopt this approach; many include observing systems which generate key data for the European and the international scientific communities, and contribute to global data systems, among them Global Atmosphere Watch (GAW)[1] and the European component of GEO[2] in creating a Global Earth Observation System of Systems (GEOSS)[3] that will link Earth observation resources world-wide across multiple Societal Benefit Areas – agriculture, biodiversity, climate, disasters, ecosystems, energy, health, water and weather – making those resources also available for better informed decision-making. Their main objectives are:

- achieving national and international objectives for a resilient society, sustainable economies and a healthy environment worldwide;
- addressing global and regional challenges by deepening the understanding of Earth system processes and improving the link between scientific understanding and policy-making;
- fostering new economic opportunities, improving efficiency, and reducing costs to public sector budgets through innovation and collaboration.

Several RIs in the Environmental domain are also feeding in the European Union's flagship Copernicus[4] programme, focusing on operational monitoring of the atmosphere, oceans and land services, whose main users are policy-makers and public authorities. Copernicus is providing validated information services in six areas: land monitoring, marine monitoring, atmosphere monitoring, emergency management, security and climate change.

Other linkages with the Joint Programming Initiatives (JPI's)[5] such as JPI Climate, JPI Oceans, JPI Water, JPI-FACCE as well as with other initiatives such as EMODNET[6], the European Environment Agency (EEA)[7] and the INSPIRE Directive[8] should be strengthened.

The ESFRI environmental RIs play also a key role at global scale in the UN framework, contributing to the UN Sustainable Development Goals[9], the UN Framework

1. GAW aims to understand and control the increasing influence of human activity on the global atmosphere. *http://www.wmo.int/pages/prog/arep/gaw/history.html*

2. GEO, established in 2005, is a voluntary partnership of governments and organizations that envisions "a future wherein decisions and actions for the benefit of humankind are informed by coordinated, comprehensive and sustained Earth observations and information". GEO Member governments include 96 nations and the European Commission, and 87 Participating Organizations comprised of international bodies with a mandate in Earth observations *https://www.earthobservations.org/index2.php*

3. Global Earth Observation System of Systems (GEOSS) *http://www.earthobservations.org/geoss.php*

4. Copernicus – European Programme for the establishment of a European capacity for Earth Observation *http://www.copernicus.eu/*

5. Joint Programming Initiative (JPI) *http://ec.europa.eu/research/era/joint-programming-initiatives_en.html*

6. EMODNET *http://www.emodnet.eu/*

7. European Environment Agency (EEA) *https://europa.eu/european-union/about-eu/agencies/eea_en*

8. INSPIRE Directive *https://inspire.ec.europa.eu/*

9. UN Sustainable Development Goals *https://sustainabledevelopment.un.org/*

Convention on Climate Change (UNFCCC)[10] and the Convention on Biological Diversity (CBD)[11].

Environmental RIs play an important role for the scientific community and the society at large by:

- providing centres of frontier scientific research as focal points for education and training of researchers and contributing significantly to the European skills base;

- delivering essential data for more reliable communication to the general public on events such as volcanic eruptions, earthquakes, poor air quality and extreme weather as well as information on biodiversity impacts;

- generating coherent, comparable and sustained time-series of key environmental variables;

- producing accurate data and scientific and technical knowledge that underpin the construction of tools supporting decision making and development of efficient regulations and policies;

- opening access to environmental *big data* from space-based and *in situ* observations as key driver for the development of new services and for promoting activities in the private sector;

- developing new technologies, such as laser-based sensors, high resolution wireless networks and remotely operated autonomous systems, which leads to additional co-benefits.

Environmental Research Infrastructures have multiple roles in tackling the *Societal Challenges* as listed in the EU Horizon 2020[12] program with *Climate action, environment, resource efficiency and raw materials* being closest connected to them. *Health, demographic change and wellbeing* as well as *Food security, sustainable agriculture and forestry, marine and maritime and inland water research, and the Bioeconomy* are strongly dependent on the whole environment, particularly when it comes to climate change adaptation, pollution, or overuse of ecosystem services. Environmental catastrophes can shutter societal security and cause migration with related security problems. The *Societal Challenges Secure, clean and efficient energy* and *Smart, green and integrated transport* even directly respond to environmental necessities and can receive guidance from a comprehensive understanding of the Earth System. Needless to say that societies that concern their environment are inclusive, innovative and reflective.

There is an urgent need to sustain, integrate and further develop a diverse set of Environmental RIs in a way that Europe can address both the key societal and economic challenges as well as improve our basic scientific knowledge.

10. UN Convention on Climate Change (UNFCCC) https://unfccc.int/

11. UN Convention on Biological Diversity (CBD) https://www.cbd.int/

12. H2020 Societal Challenges https://ec.europa.eu/programmes/horizon2020/en/h2020-section/societal-challenges

ATMOSPHERE: FROM NEAR GROUND TO THE NEAR SPACE ATMOSPHERE

The atmosphere hosts many physical and chemical processes and represents a major part of the environment to which the life on Earth is sensitively responsive. The atmosphere is part of the larger connected global environment and is central for climate, weather, and transport of chemical species over large distances.

Perturbation of the atmosphere impacts on different thematic areas like climate change, air quality, environmental hazards, environmental risks, food security and the water cycle.

The research on the atmosphere is multidisciplinary, embracing atmospheric chemistry, physics, dynamics and radiation; and it combines observations and modelling. It also has to cover the full altitude range from the planetary boundary layer near the surface across the tropopause and stratosphere up to the middle atmosphere – i.e from ground to 50 km altitude and beyond. The atmospheric domain interacts with marine, terrestrial, freshwater, solid earth systems and the near space.

The atmosphere contains a wide range of trace species. The identification and quantification of their properties, atmospheric transport and transformation processes and life cycles require highly interdisciplinary approaches. Both natural and man-made gases and aerosols may be transported from emission to receptor sites over long distances in the atmosphere across national borders and continents. Thus, atmospheric research and monitoring requires close international collaboration. Climate change poses a foremost scientific challenge because of large uncertainties in our current knowledge on climate change processes. Particularly, the understanding of climate feedback mechanisms requires considerable joint research where enhanced cooperation of existing Research Infrastructures has to play an important role.

Atmospheric Research Infrastructures do not only provide monitoring, but exploratory infrastructures are also needed to study the processes. Atmospheric processes are multiscale in time and space, from the sub-second, sub-micron scale of microscopic processes to the decadal global scale characteristic of climate change. In this context, the atmospheric infrastructures should be sufficiently equipped to be able to inform across a similar range of scales.

II CURRENT STATUS

The European atmospheric landscape covers a wide range of actions ranging from the establishment of ESFRI long-term atmospheric Research Infrastructures to EU-funded projects such as Integrating Activities (IA), Design Studies, and other projects.

- Long-term atmospheric observation platforms: the **ESFRI Project ACTRIS** (Aerosols, Clouds and Trace gases Research Infrastructure); the **ESFRI Landmark IAGOS** (In-service Aircraft for a Global Observing System) (Airborne, lower atmosphere); the **ESFRI Landmark ICOS ERIC** (Integrated Carbon Observation System); ARISE (Atmospheric dynamics Research Infrastructure in Europe) and the **ESFRI Landmark EISCAT_3D** (Next generation European Incoherent Scatter radar system) (upper atmosphere); SIOS (Svalbard Integrated Arctic Earth Observing System) (Integrating all observations, terrestrial, marine and atmosphere at Svalbard).

- Exploratory process oriented research, atmospheric chemistry including aerosols: the **ESFRI Project ACTRIS**; EUROCHAMP 2020 (laboratory studies); EUFAR (Airborne platforms for field experiments).

- Modelling development and experiments: IS-ENES (global climate and earth system models).

The atmospheric subdomain landscape is sketched in **Figure 1** in a topic (x-axis) versus altitude (y-axis) graph.

The European atmospheric research community is well recognised at an international level and in many specific research topics it has an undisputed leadership. Atmospheric RIs have a fundamental role to strengthening the EU position and leadership in this research area by providing unique informa-

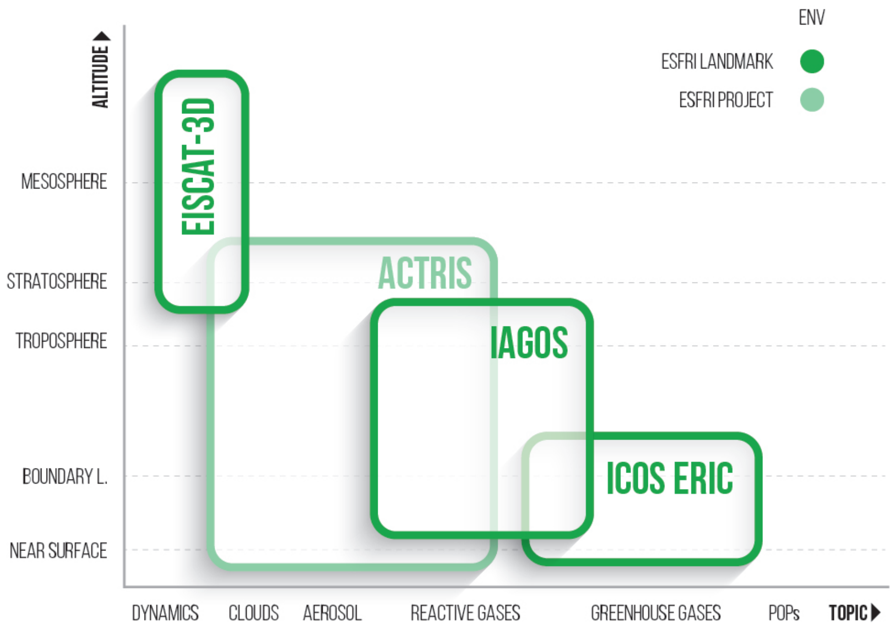

FIGURE 1.
Schematic overview of the ESFRI RI landscape for the atmosphere sub-domain

tion, services, tools and reference methodologies that are used and applied by a very wide community also outside Europe.

An assessment of the user community conducted in 2018 in the framework of the cluster of environmental Research Infrastructures (ENVRI) provided more than 3.000 users and more than 25.000 user requests per year for the Atmosphere Domain RIs. Areas of data use include fundamental research on atmospheric processes, climatological studies on the long-term evolution of the atmosphere and trends of key species, validation of Earth System Models, assimilation of data for numerical weather prediction, validation of satellite products and development of new measurement technologies.

One major user of Atmosphere RIs data products and services is COPERNICUS Atmosphere Monitoring service (CAMS)[13]. The **ESFRI Project ACTRIS**, and the **ESFRI Landmarks IAGOS** and **ICOS ERIC** data are used by CAMS, for example, for Near-Real Time Model Validation, Monitoring Air Quality in Europe and for providing forecast of air quality in Europe for European cities, also shown daily on EURONEWS.

GAPS, CHALLENGES AND FUTURE NEEDS

In response to the status of the existing RIs, specific gaps and challenges have been identified. It is important to study not just components of the atmospheric system but observe as many of those components synergistically as possible to fully understand processes and linkages. A synergistic approach must include the use of *in situ* ground based observations, together with columnar and vertical profile, aircraft and satellite observations and models to study and understand atmospheric composition and processes. Long-term data records for atmospheric parameters, which are relevant for both air quality and climate research, are inadequate at the moment and the geographical coverage by atmospheric observing infrastructures in the Mediterranean including North Africa and Eastern Europe is incomplete. Understanding the atmospheric composition changes and processes is a global issue, and the relevance for Europe is not limited to observations performed on sites located in European regions; there is a responsibility of Europe to explore where further atmospheric observations could be supported, in Africa to start with. Moreover, harmonised measurements on larger geographical scale are crucial and strong international cooperation is needed. A better integration of existing programs and projects in the atmospheric area will help to build and sustain the European component of GEOSS.

Interconnections with other domains – i.e. Health – need to be better explored. Air pollution is a major environmental risk to health. Short-lived atmospheric compounds have recognized adverse health effects at concentrations typically found across Europe and potentially lead to more than 400.000 premature deaths annually in the EU28. In particular, the effect on children's health should be better explored and in this context the role of atmosphere RIs to foster scientific cooperation in this field is of primary importance.

13.
COPERNICUS Atmosphere Monitoring service (CAMS)
https://atmosphere.copernicus.eu/

HYDROSPHERE

Water is essential for human life and nature and plays a critical role in most natural processes. Water covers about 70% of the Earth's surface and over 97% of it is in oceans, and most of the remaining freshwater is in the form of ice.

Water is of huge global geopolitical importance and is central to all the key, current environmental issues: climate change, biodiversity, natural hazards, pollution, ecosystem services, and desertification.

Most water on Earth, including that present in lakes, rivers, deltas/estuaries, lagoons, etc., is part of the hydrological cycle and is inter-linked with the atmosphere, cryosphere, soils, sediments and the rest of the geosphere, as well as with the entire biosphere. Water must therefore be seen and studied in a holistic way.

Climate change, land use and abuse, economic activities such as energy production, industry, agriculture and tourism, urban development and demographic change mostly impact negatively on the status of water and as a result, the ecological and chemical status of EU waters, from mountain springs to coastal zones, is threatened. In addition, more parts of the EU are at risk of water scarcity. Water ecosystems – on whose services our societies depend – become more exposed to extreme events such as floods and droughts. It is essential to better address these challenges on the basis of improved scientific understanding of all relevant processes so as to preserve our resource base and increase its resilience for life, nature, society and to protect human health in the changing climate.

FRESHWATER:
ICE, GROUNDWATER, LAKES, RIVERS, ESTUARIES

A holistic view on the water cycle requires integrated, interdisciplinary and trans-sectorial approaches that provide solutions to managing water-related societal risks. Environmental monitoring agencies across Europe continuously collect vast amount of data on freshwater. Linking this routine sampling with high-resolution data from freshwater supersites and remote sensing data would benefit society directly as well as by supporting research in the area. Some research facilities have collected data on snow, ice and freshwater and complementary environmental and ecological information for more than a century. These long time series have been instrumental in understanding the coupling between the water cycle, the changing climate and ecosystems. It is of vital importance to ensure that the long-time series are continued. Experimental facilities for studying complex water-related phenomena – e.g. physical modifications of estuaries, behaviour of substances and energy in mesocosms, etc. – allow physical models to underpin better systemic understanding, often in conjunction with mathematical models.

II CURRENT STATUS

Much of the current science is done relying on access to existing water bodies, i.e. without specific and dedicated large-scale Research Infrastructures. The **ESFRI Project DANUBIUS-RI** (International Centre for Advanced Studies on River-Sea Systems), supporting interdisciplinary research in river-sea systems, is the only physical pan-European Research Infrastructure devoted to support also research on transitional zones between coastal marine and freshwater areas, together with the **ESFRI Landmark LifeWatch ERIC** (e-Infrastructure for Biodiversity and Ecosystem Research) as the only e-RI, which extends its area of interest also to the whole freshwater environments. There are European networks of basins for hydrological monitoring and research, such as the European Network of Hydrological Observatories (ENOHA). The HYDRALAB+ network supports the use of environmental hydraulic facilities. The **ESFRI Project AnaEE** (Infrastructure for Analysis and Experimentation on Ecosystems, H&F) also offers access to experimental facilities in freshwater environments.

▸ GAPS, CHALLENGES AND FUTURE NEEDS

Europe needs a dense, highly instrumented super-sites network of freshwater monitoring, as well as simulation and experimental platforms. Lake, river and ground water monitoring and experimental super-sites should serve as calibration, validation and development services for remote sensing applications as well as for ecosystem and for ecosystem service modelling. For the comprehensive analysis of the changes in the aquatic ecosystems an integrated basin approach is necessary to understand the impact of different drivers and to find measures for sustainable water resources management. The **ESFRI Project DANUBIUS-RI**, with its structure consisting of the four Nodes (Observation/Measurements – Analysis – Modelling – Impact), is aiming to bridge the before mentioned gaps, at a basin-wide, river-to-sea approach.

The Water JPI Strategic Research and Innovation Agenda[14] and the WssTP Strategic Innovation and Research Agenda[15] provide frameworks for collaborative research and innovation efforts. The Water JPI intends to increasingly play a role in facilitating the use of relevant RIs, whereas for example WssTP advocates the use of "real life living labs" where innovative solutions can be tested hence facilitating the scaling up of solutions.

14. Water JPI, 2016
http://www.waterjpi.eu/images/documents/SRIA%202.0.pdf

15. WssTP, 2017
http://wsstp.eu/wp-content/uploads/sites/102/2017/01/WssTP-SIRA_online.pdf

MARINE:
FROM COAST TO DEEP OCEANS AND ICE CAPS

Shelf seas and the world-embracing ocean form a group of dynamic complex systems with a strong interplay of physical, chemical and biological phenomena at multiple spatial and temporal scales. Due to inaccessibility, even their *static* features – e.g. ocean bathymetry – are poorly known. Seas and oceans provide food, energy, and many other resources on which mankind depends. The oceans have a fundamental influence on our climate. Society is increasingly concerned about global change and its regional impacts. Sea level is rising at an accelerating rate, the Arctic sea ice cover is shrinking as high latitude areas are warming rapidly, and storminess is forecast to increase. Since 1955, over 90% of the excess heat trapped by greenhouse gases has been stored in the oceans[16]. The oceans are affected by the increased amount of CO2 in the atmosphere leading to ocean acidification which poses threats for many species. Changes in the thermal structure of water masses are likely to influence currents and stratification. The effects of climate change add to other stresses, such as pollution, in particular [micro]-plastics, and overfishing that are already threatening the biodiversity and health of the seas and oceans.

Last but not least, sources of geo-hazards such as slide prone slopes, active tectonic structures and volcanoes to mention some, lay in marine environment at various depth and distance from the coasts. Wherever they are adjacent to populated regions, to economically developed areas or sites of strategic relevance, they represent threats for the socio-economic fabrics and wellness. Marine observatories provide an essential integration to land-based RIs for a broader vision in the comprehension of the natural phenomena.

Ocean observation is currently a key component of the EU Strategy for Marine and Maritime Research and has become a high priority on the worldwide environmental political agenda.

16. IPCC (2013) WG1 AR5
http://www.ipcc.ch/report/ar5/wg1/

CURRENT STATUS

Marine RIs consist of up to 800 – increasingly networked – distributed facilities in Europe, serving various domains such as ocean – seafloor, subseafloor and water layers above – and coastal sea monitoring, marine biology research, blue biotechnology innovation, research in aquaculture and ocean engineering. Their observation and data management components form the foundation for a European Ocean Observing System (EOOS), providing the platforms and services to deliver environmental data, information and ultimately knowledge. Marine RIs, including e-RIs, are as diverse as: research vessels[17] and their underwater vehicles for sea access and deep sea exploration/sampling; voluntary vessels for surface and sub-surface monitoring; fixed and mobile, autonomous, including drifting, *in situ* observing systems for seawater column and seabed observation and monitoring; satellites for remote sensing for sea-surface monitoring; marine data centres; land-based facilities for ocean engineering, such as deep wave basins, water circulation canals, sensors tests and calibration laboratories; and experimental facilities for biology and ecosystem studies and for marine genomics, biodiversity, blue biotechnology, aquaculture, mesocosms; virtual research experimental facilities for biodiversity and ecosystem studies integrating data resources from the physical infrastructures and observation systems. Marine research stations, of which there is a high density around Europe, often provide a combination of services to marine researchers.

Key RIs for water-related research are fostered in ESFRI, as reported in **Figure 2**, while there are also other EU projects and initiatives supporting networks that are directly relevant for research.

17. UNESCO (2017), Global Ocean Science Report—The current status of ocean science around the world, L. Valdés et al. (eds), UNESCO Publishing, Paris
https://en.unesco.org/gosr

- River-sea interaction, freshwater, water-ice: the **ESFRI Project DANUBIUS-RI**, the **ESFRI Landmark LifeWatch ERIC** – as e-RI, HYDRALAB+, AQUACOSM (mesocosms).

- Open ocean mobile platforms: the **ESFRI Landmark EURO-ARGO ERIC** (European contribution to the international Argo Programme), EuMarineRobots.

- Open ocean fixed point observatories: the **ESFRI Landmark EMSO ERIC** (European Multidisciplinary Seafloor and water-column Observatory).

- Research vessels and underwater vehicles: ARICE, EUROFLEETS.

- Coastal/shelf seas observatories: JERICO-NEXT.

- Data storage and standards, access: EMODnet and linked Copernicus Marine Service (CMEMS) for operational oceanographic services; EuroGOOS, SeaDataNet/SeaDataCloud.

- Marine biology, *omics* and bio-informatics: the **ESFRI Landmark ELIXIR** (A distributed infrastructure for life-science information, H&F), the **ESFRI Landmark EMBRC ERIC** (European Marine Biological Resource Centre, H&F), the **ESFRI Landmark LifeWatch ERIC** – as e-RI – and the **ESFRI Project AnaEE** (H&F).

- Carbon cycle: the **ESFRI Landmark ICOS ERIC** and the **ESFRI Landmark LifeWatch ERIC**, as e-RI.

GAPS, CHALLENGES AND FUTURE NEEDS

Taking into account recent efforts to define research priorities and infrastructure needs, such as European Marine Board position paper, JPI Oceans SRIA agenda, SEAS-ERA reports, a gap analysis has been performed by the marine community to identify gaps and weaknesses of the present understanding of how the ocean functions and our observing system. Marine regions in open seas are under-sampled, thus additional observatory nodes, together with an acceleration of technological developments, are required – e.g. deeper measurements from Argo floats, Biogeochemical Argo floats and from SMART Cables[18]. The UNESCO Intergovernmental Oceanographic Commission (IOC) is preparing the UN Decade of Ocean Science for Sustainable Development (2021-2030) to improve the scientific knowledge base, in view of humanity's increasing reliance on ecosystem goods and services from the ocean. The current global knowledge base is very weak – e.g. IOC estimates that 99% of habitable marine areas lack basic biodiversity knowledge for their management[19]. However, efforts are on-going to employ newly developed sensors and samplers that can be mounted on observing autonomous platforms – buoys, glider, profiler etc. – or vessels and ships seizing opportunities for more automated sampling and analysis for biochemical and biological parameters. The use of opportunistic sampling needs to be further expanded, e.g. sensors could be further deployed on commercial ships operated by the private and public sector (analogue to **ESFRI Landmark ICOS ERIC**).

Beyond the development of existing or planned individual Research Infrastructures and networks, a more holistic approach is needed for the observing components which are serving many different communities, including but not limited to the scientific community. The observation component is the first crucial part of the system which needs standardisation and interoperability effort to ultimately allow us to better know and understand the functioning of marine ecosystems. Other components will require more sophisticated models. From the perspective of a user of scientific information for utilisation in policy, a large gap is the frequent absence of science-based assessment criteria to evaluate the impact of human activities on environmental status[20] and ecosystem services, indicating a strong need to understand better the multiple cause-effect chains in the marine environmental realm as a contribution to sustainable use of marine and maritime resources.

Economic constraints impose a flexible and multi-use approach, innovation towards cost-effective observing strategies, and prioritisation among possibly conflicting needs. Efforts towards an integrated and sustained EOOS are ongoing with discussions among the community on a specific strategy, implementation plan and sustainable budget. EOOS should build on the wealth of existing RIs capabilities and multi-platform assets already operational across European waters. EOOS would integrate marine observations from the coast to the open ocean and from surface to deep sea; promote multi-stakeholder partnerships for funding observing systems and sharing of data and align with global efforts within a robust framework. The EOOS should also be smart, resilient and adaptable, driven by scientific excellence, stakeholder needs and technological innovation, to fill the need for cross-disciplinary research and multi-stakeholder engagement.

18. ITU/WMO/UNESCO IOC Joint Task Force https://www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx

19. IOC, 2018. The United Nations Decade of Ocean Science for Sustainable Development (2021-2030) http://unesdoc.unesco.org/images/0026/002619/261962e.pdf

20. Identified gaps on MSFD assessment elements. PERSEUS Project. ISBN 978-960-9798-01-3. Laroche S. et al., 2013. https://bit.ly/2uppYmC

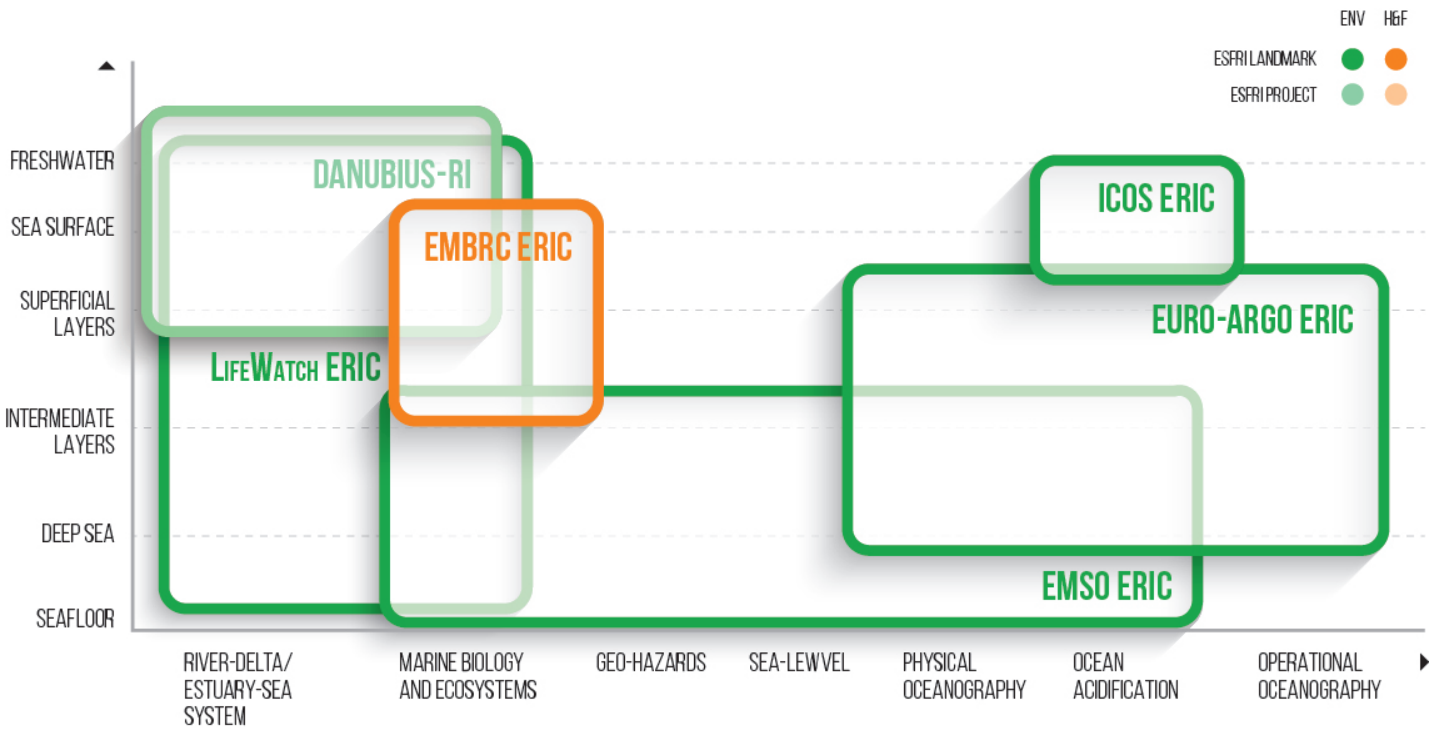

FIGURE 2.
Simplified diagram of the observation capabilities of ESFRI Landmarks and Projects respect to the hydrosphere components (Y axis) and to the environmental processes therein (X axis).

BIOSPHERE: BIODIVERSITY AND ECOSYSTEMS

Biodiversity research integrates the study of the diversity and variability of Life on Earth – namely terrestrial, marine and freshwater ecosystems, and including diversity at genetic, species and ecosystems. Ecosystem functions refer to the structural components of the ecosystems – e.g. water, soil, atmosphere and biota – and how they interact with each other, within ecosystems and across them, and how they interact with societal activities.

A better understanding of the interconnections, including quantitative relations, between biodiversity and ecosystem services will allow a better response to *Grand Challenges*, namely those included in the Sustainable Development Goals.

Biodiversity plays a central role in ecosystem functioning and provision of ecosystem services and is thus linked to key *Societal Challenges* such as a secure and safe supply of food and water and other natural resources, human health, energy as well as climate regulation and pollination. The biodiversity and ecosystem research is highly complex not only because of necessary multi-spatial and multi-temporal approaches, but also because associated time scales can range from microseconds up to millennia. Therefore, biodiversity and ecosystem research requires a multi- and interdisciplinary integrated approach.

Over the past 50 years or more, ecosystems have changed dramatically due to human pressure. Ecosystems have been affected by soil exploitation, land-use change – for example formation of large monocultures, over-exploitation of natural resources, habitat destruction and contamination. Furthermore, invasive species has resulted in biodiversity loss and disruption of natural communities. As a result, in Europe, a several species are threatened with extinction. For instance, it is estimated that 15% of all mammals are threatened with extinction, 13% of all birds, 37% of all fishes, 19% of all reptiles and 23% of all amphibians. These impacts affect the structure and functioning of ecosystems and consequently their sustainability.

The land-use change which causes habitat destruction and the alien invasive species are the most serious threats to biodiversity, the loss of which is recognised to cause decrease of ecosystem services by affecting ecosystem functioning and stability. The effective strategies to control invasive species include the early detection, regular monitoring of the growth of invasive alien species populations, and prediction of future spread. Research Infrastructures could be instrumental to develop these strategies, providing facilities to mobilize, access and analyse data of citizen science, remote sensing, and develop species distribution modelling for current and future distributions.

In order to protect biodiversity, it is important to also understand the societal drivers, such as demographic, economic, socio-political, cultural and religious, and scientific and technological changes (Millennium Ecosystem Assessment, 2005) as well as their impact on the ecosystems – habitat change, invasive alien species, and overexploitation of species – and thereby indirectly identify reasons for biodiversity loss.

Ecosystem integrity is indispensable to reach the UN Sustainable Development Goals (SDGs)[21]. Goal 15 directly refers to terrestrial ecosystems: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. Furthermore, standardised observations from the terrestrial ecosystem and biodiversity domain comprise essential climate variables (ECVs) and essential biodiversity variables (EBVs) and thus provide knowledge towards the UN Conventions on Climate Change (UNFCCC)[22] and Biological Diversity (CBD)[23].

Long-term observations and monitoring as well as long-term research programs are indispensable for the interpretation of ongoing ecosystem changes, including those responsible for biodiversity loss and erosion.

21. UN Sustainable Development Goals (SDGs) https://www.un.org/sustainabledevelopment/sustainable-development-goals/

22. UN Convention on Climate Change (UNFCCC) https://unfccc.int/

23. UN Convention on Biological Diversity (CBD) https://www.cbd.int/

II CURRENT STATUS

The European landscape for terrestrial ecosystem and biodiversity RIs covers the complexity of the research agenda (see **Figure 3**). The ESFRI RIs are built on or closely connected to EU-funded projects such as Integrating Activities (IA).

- Observatories and Monitoring Facilities: the **ESFRI Landmark ICOS ERIC**, the **ESFRI Projects DANUBIUS-RI** and **eLTER** (Integrated European Long-Term Ecosystem, critical zone and socio-ecological system Research Infrastructure), the IA InterAct (ongoing), InGOS (until 2015), and SIOS (Svalbard Integrated Arctic Earth Observing System) (Integrating all observations, terrestrial, marine and atmosphere at Svalbard).

- Facilities for *in situ* and in vivo experimentation: The **ESFRI Project AnaEE** (H&F), the IA AQUACOSM.

- Biological collections, Data infrastructures and reference data: the **ESFRI Project DiSSCo** (Distributed System of Scientific Collections), the **ESFRI Landmark ELIXIR** (H&F), and the **ESFRI Project MIRRI** (Microbial Resource Research Infrastructure, H&F), the IAs SYNTHESYS (until 2017).

- e-Infrastructures for analysis and modelling: the **ESFRI Landmark LifeWatch ERIC**, and the IA IS-ENES (ongoing).

The size of the researcher community served by these RIs might be estimated using as proxy the number of researchers engaged with national and international ecological associations, which raises up to 10.000 in Europe and 40.000 worldwide and additional researchers from climate and GHG communities. Other direct users include officers of regional, national and European environmental agencies responsible for national inventories and nature conservation, local and national administration, and environmental NGOs supporting decision making and policy implementation.

The paradigm shift in terrestrial ecological research from searching for a unifying ecosystem theory to tackling specific *Grand Challenges* (and in addition a shift from

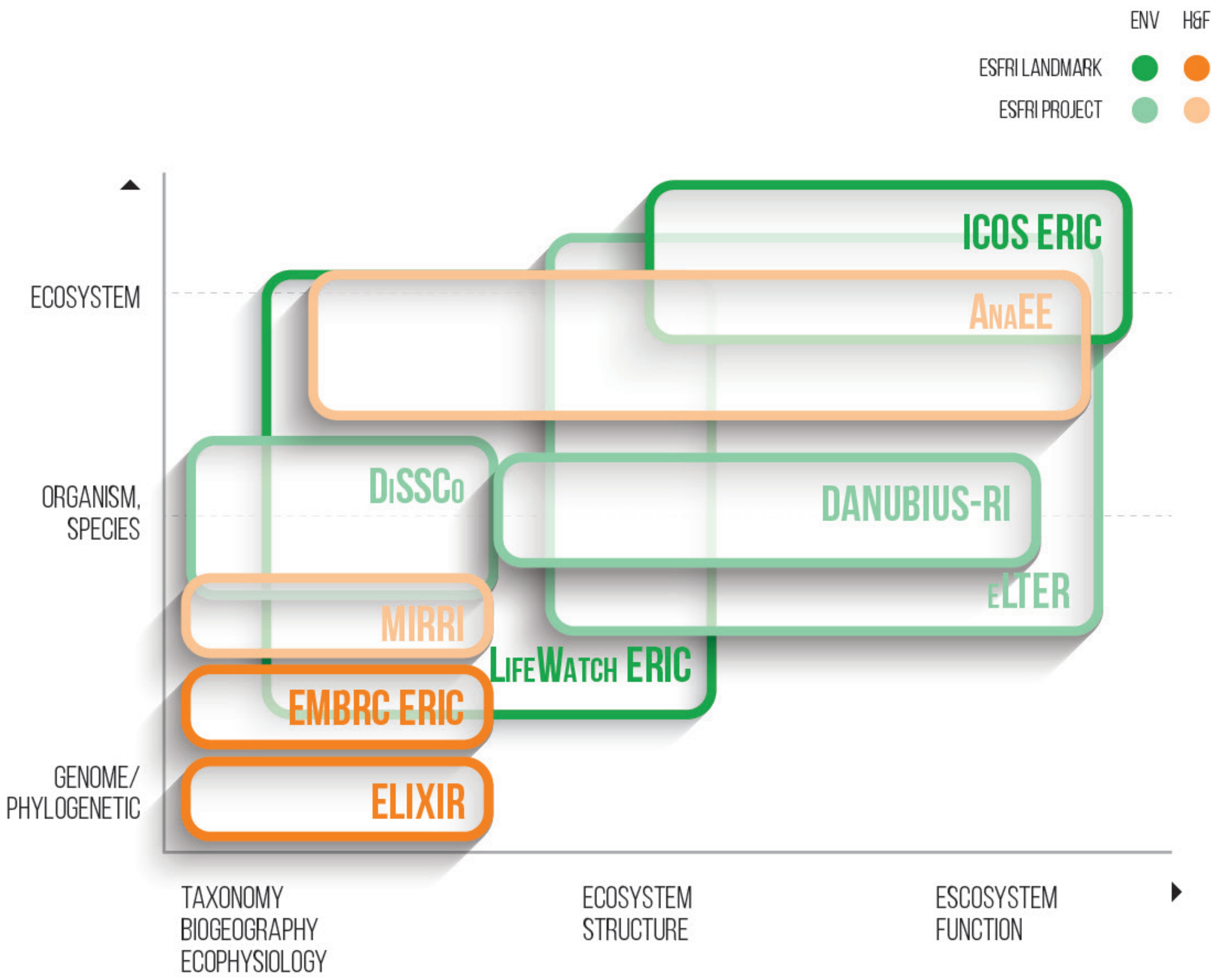

FIGURE 3.
Schematic landscape of biodiversity and ecosystem ESFRI Research Infrastructures.

ecosystem conservation to preservation of ecosystem services) is mirrored by all Research Infrastructures in the domain but differs in the degree of being conducted in the basic concept of individual RIs. With the strongest relation to the approach of ecological integrity, the **ESFRI Project eLTER** is tackling a broad spectrum of ecological challenges, however the theoretical base is starting from understanding ecosystems. The **ESFRI Project AnaEE** (H&F), providing experiments instead of observations, and with stronger focus on agriculture and food security, is starting a bit more specific from a defined set of ecological and societal challenges and has a more anthropocentric objective in the preservation of ecosystem services, food security as well as specific contributions to bioeconomy.

In contrast to the **ESFRI Projects eLTER** and **AnaEE** (H&F) with their basis in the ecological integrity approach or in a broad spectrum of related *Grand Challenges*, the **ESFRI Landmark ICOS ERIC** is following a cross-domain approach that aims to understand the carbon cycle and to provide necessary information on the land-ecosystem exchange of CO_2, CH_4 and N_2O with the atmosphere. The **ESFRI Landmark LifeWatch ERIC** has, similar to ICOS, a cross-domain approach and a focus on the *Grand Challenges* of preserving biological diversity and of protecting ecosystem health. The **ESFRI Landmark LifeWatch ERIC** is an e-Infrastructure without own observations and enables knowledge-based solutions to environmental managers by providing access to a multitude of sets of data, services and tools. Specific issues related with biodiversity research, the role of biodiversity in ecosystem functioning and conservation are addressed by the construction and operation of Virtual Research Environments (Virtual Laboratories & Decision-support Applications) where integrated models at the meso- or higher scales are executed.

The digitalisation of biological collections and the connection to genomics is a game changer in the biodiversity research aiming to close the taxonomic gap which still is a major limitation to biodiversity knowledge. Of the 8 million species that are estimated to exist, only 1.8 million are currently scientifically described. For some biological groups – insects, nematodes, and micro-organisms – only 10% of the species are known, and many species become extinct without being discovered. Many parameters in taxonomy need specialized human efforts. The overall ensemble of RIs in the terrestrial ecosystem and biodiversity field covers comprehensively the scales from molecules to continents and responds to a wide range of environmental challenges.

GAPS, CHALLENGES AND FUTURE NEEDS

The *Grand Challenges* related to biodiversity, ecosystems and biodiversity are highly inter-related. Land-use change is usually accelerating both loss of biodiversity and climate change by release of CO2 and by creating agricultural monocultures or land degradation.

Firstly, urged by the biodiversity loss, the taxonomic gap needs to be overcome, in order to discover and describe the ¾ of the biodiversity still to be known. Rapid advances in genetic sequencing and ICT, including big data analysis of genetic sequences, and mass digitization can be integrated to provide more automated systems with respect to genomics, species and ecosystem analysis.

Other challenges are the invasive species which can affect native species and habitats, alter the ecosystem primary productivity and thus the carbon sequestration. Consequently, the RIs need to better integrate their data life cycles and to seek common geographical coverage of their observing infrastructures by co-location and a mutual strategy to fill geographical gaps. Observations and experiments need further scientific integration. Modelling can be a powerful tool for the conjunction of organismic and process-oriented approaches as well as multiple challenges perspectives in ecosystem analysis. However, most existing ecosystem models represent only facets and require further development.

Monitoring biodiversity and ecosystems changes requires also the development and implementation of the Essential Biodiversity Variables[24] as ecological data products underpinned on data and metadata standards, data quality and data preservation would ensure the needed interoperable resources to perform ecological studies and assessments.

The manifold connections to other fields, particularly Health & Food, but also Social Sciences and Energy are obvious. Agriculture and Bioenergy directly affect ecosystem integrity which itself is an important factor for human health, but also for food production. Environmental literacy and behaviour are important interfaces to Social Sciences.

24. Pereira, H.M. et al., 2013. Essential Biodiversity Variables. Science 339, 277–278
https://doi.org/10.1126/science.1229931

GEOSPHERE: FROM THE SURFACE TO THE INTERIOR OF THE EARTH, FROM GEOHAZARDS TO GEORESOURCES

The solid Earth science is concerned with the internal structure and dynamics of planet Earth and with surface processes. Solid Earth science deals with multiscale physical and chemical processes, from microseconds to billions of years and from nanometres to thousands of kilometres.

Geology, natural hazards, natural resources and environmental processes, in general, do not respect national boundaries, therefore seamless, trans-national integration of measurements and calibrated data is crucial to enable research and societal applications.

Progress in Solid Earth science relies on integrating multidisciplinary data acquired through long-term monitoring, new observing systems, and high-level taxonomy data products. The understanding of environmental changes requires unravelling complex and intertwined processes. Solid Earth science contributes to systemic and highly cross-disciplinary investigations, representing an essential component of the investigation of the Earth system. The ash and gas dispersion during a volcanic eruption is a key example of the multidisciplinary observations required to monitor a natural phenomenon and its underlying processes – e.g. seismic activity, ground deformations, magma rheology – and of the cross-disciplinary implications for meteorology, atmospheric sciences, marine sciences, and the life sciences.

In addition to enable fundamental scientific advancement in understanding planet Earth, RIs in the solid Earth domain provide a crucial contribution to two areas of high societal relevance: geo-hazards and geo-resources. In particular, they:

- enable assessing and mitigating the risks caused by natural hazards, such as earthquakes, volcanic eruptions, tsunamis and landslides;

- make available monitoring infrastructures, experimental facilities and expertise for optimising exploration and exploitation of geo-resources and monitoring of natural resources, including geo-energy resources (i.e. geothermal energy, conventional oil and gas, shale gas), underground storage (carbon, gas, nuclear waste), raw materials, minerals and rare earth elements, and for estimating and mitigating the risk of anthropogenic hazards, such as earthquakes possibly induced by the extraction of geo-energy resources;

- provide the monitoring and research background for a correct use of the underground, taking into account considerations of RIs, long-term environmental sustainability and economic viability.

CURRENT STATUS

The solid Earth domain is represented in ESFRI by a single Research Infrastructure, the **ESFRI Landmark EPOS** (European Plate Observing System). The large community of RI operators and users chose to establish an all-encompassing RI framework, including all the different RI classes covering seismology, near-fault observatories, geodetic data and products, volcano observations, satellite data, geomagnetic observations, anthropogenic hazards, geological information and modelling, multi-scale laboratories, and geo-energy test-beds for low-carbon energy. As a result, the **ESFRI Landmark EPOS** integrates several hundreds of individual RIs, distributed in all countries of the Euro-Mediterranean region, with the aim to obtain an efficient and comprehensive multidisciplinary research platform for the Earth sciences in Europe based on novel e-infrastructure concepts for interoperability and provisions of distributed data through Integrated Core Services (ICS) and Thematic Core Services (TCS). In order to enable the required access to inter-disciplinary observations, the **ESFRI Landmark EPOS** established strategic and synergetic alliances and specific TCSs with existing data- and service-providers, such as ESA for the satellite data , the EuroGeoSurveys for the geological data and interpretations, INTERMAGNET for magnetic data and EUREF for reference GNSS data and products.

In addition to the **ESFRI Landmark EPOS**, other geosciences RIs and projects are operated globally or in fields currently not formally included in the EPOS RI framework; on-going work is conducted to ensure the required coordination and integration (**Figure 4**). These include:

- the continental- and ocean-drilling RI and programs (ICDP and IODP/ECORD);

- the collections of exploration data (oil and gas, minerals);

- the underground laboratory facilities established for research on geological waste repositories, now federated by the new initiative EUROL;

- European ERANET programs covering mineral and energy resources, ERA-min[25], coordinating research and development in Europe in the field of mineral prospecting, coordinating and integrating national infrastructures, data management and technical development to support the joint European research efforts with the aim to contribute to European mineral security; ACT, to advance carbon technologies towards the establishment of a carbon-free society; GEOTHERMICA, for the advancement of geothermal and petrothermal technologies for electricity and energy generation and storage;

- Research Infrastructures projects, for access to data, services and infrastructures in seismology and earthquake engineering

25. ERA-min http://www.era-min-eu.org/

SERA; for access to observatories and Research Infrastructures for volcanology EUROVOLC;

▪ supersites EC projects in GEO, MEDSUV and FUTUREVOLC (Volcano observatories), MARSITE (Near Fault Observatories);

▪ international organization involved in coordinating national RIs and monitoring networks in seismology and seismic risk, ORFEUS (seismological data) and EMSC (seismological products), key contributor to EPOS;

▪ research projects on seismic hazard, early warning and risk assessment – SHARE, SAFER, REAKT, MATRIX, STREST;

▪ e-science Virtual Environment Projects, including VERCE, EUDAT, ENVRI and ENVRI+ (with a strong EPOS participation).

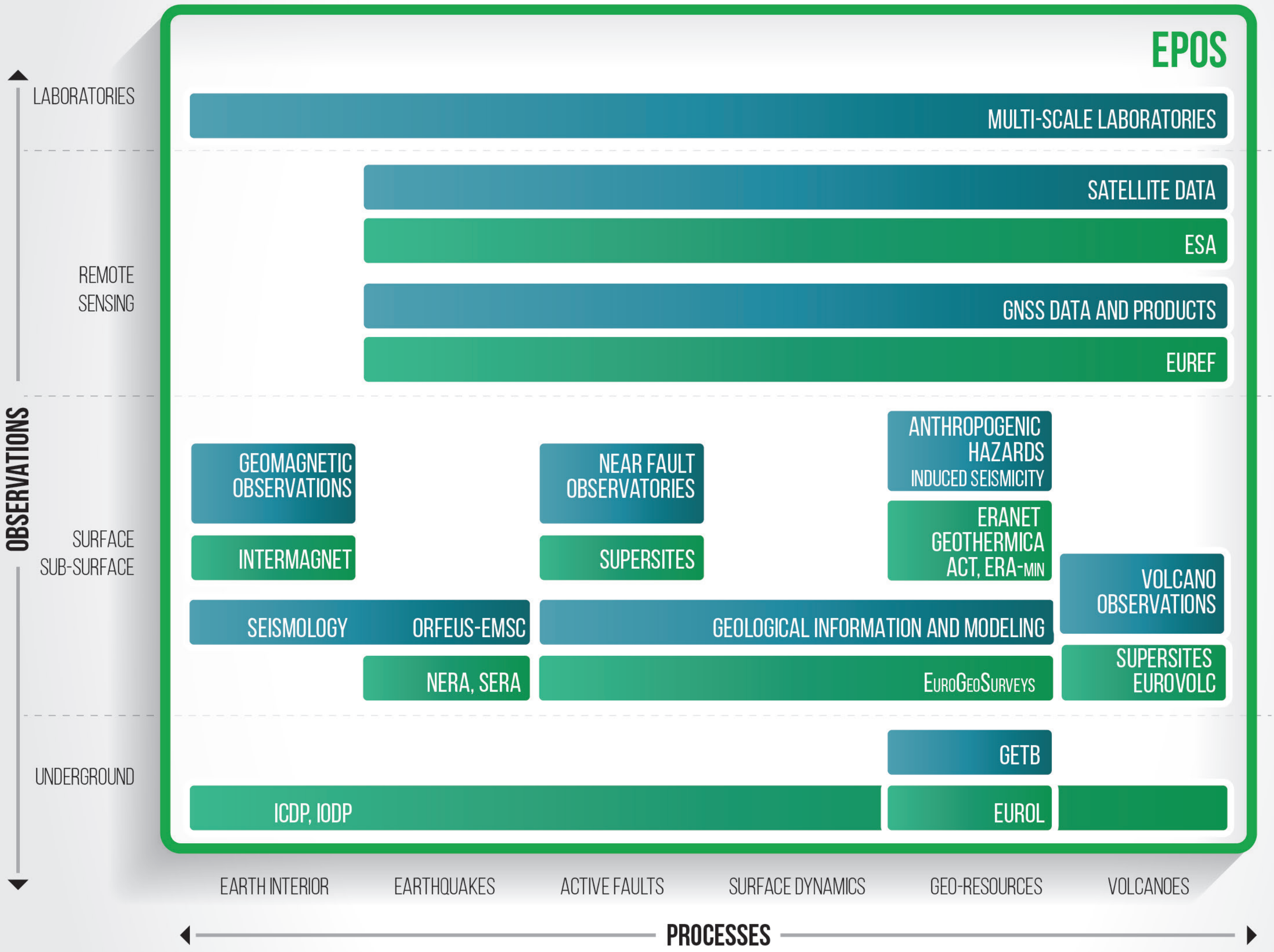

FIGURE 4.
Landscape of solid Earth science platforms and key application areas for the geosphere domain. Blue boxes identify the EPOS Thematic Core Services (TCS). Green boxes refer to other geosciences RIs and projects operated globally or in fields currently not formally included in the EPOS RI framework. (GETB=TCS Geo-Energy Test Beds for low carbon energy).

GAPS, CHALLENGES AND FUTURE NEEDS

In the future, integration and cooperation in the Geosphere domain needs to concentrate on a few strategic priorities.

The interactions and collaborations between industrial stakeholders and the public sector – such as the European geological surveys – needs to be strengthened. This also involves the accountability of data and data providers as well as the adoption of effective interaction strategies in which the role of scientists is clear. This is mandatory to face ethic issues in communicating science and geo-hazards to society.

Europe uses about 20% of the world's primary metal supply, but produces far less than this (3-8%); the situation is worse for *critical metals* and rare earth elements; new RIs and data are urgent in the fields of geo-resources and mining, in order to achieve meaningful targets of energy and mineral security in Europe; the involvement of laboratories – rock deformation labs, deep underground labs, geophysical exploration data, technologies for environmentally friendly mining, analytical facilities for geochemistry and mineral resources, and modelling facilities are key required ingredients.

There is also a need for RIs to enable member states to fulfil the requirements for scientific research and technological development for safe management of high and medium grade nuclear waste in accordance with international and European legislation – e.g. Directive on the Management of Radioactive Waste and Spent Fuel, 2011.

Ocean and continental drilling equipment and programmes need to be intensified, this to increase geographical coverage in critical areas; this requires to collect observations on the solid Earth from oceanic regions, including dense ocean-bottom geophysical and seismic monitoring and floating devices.

Finally, the **ESFRI Landmark EPOS** will be completed and it could serve as a European platform for fostering integration and coordination of all observing and surveillance systems and their services at European scale and for increasing global coordination in solid-Earth observing systems, in cooperation with IASPEI, FDSN, IAVCEI, WOVO, GEO and other international programs and organizations.

VISION AND PERSPECTIVES

The medium to long-term vision (2020-2040) for environmental Research Infrastructures is based on the objective to better facilitate and enable researchers to work in a more integrated manner towards universal understanding of our planet and its behaviour, and to tackle environmental challenges. It is important to study not just individual domains of our planet, but to observe as many of those domains synergistically. This should result in the evolution of a seamless holistic understanding of the Earth's system. Three interdependent resources, that of technological capital, cultural capital and human capital are needed to develop and achieve that vision: *technological resources* which entails the building of monitoring/observational, computational and storage platforms and networks; cultural resources entailing open access to data – requiring rules, licenses and citation agreements on metadata and data; and *human capital* requiring *data scientists* as well as *discipline scientists*.

A federated approach should help to reduce overlaps, to maximise synergies and benefits, and to coordinate Research Infrastructures in order to optimize observing systems ranging from *in situ* and remote sensing data measurement and collection, to data analysis in the laboratory. Concrete actions towards this direction have started already within the ENVRIPLUS (Environmental Research Infrastructures Providing Shared Solutions for Science and Society) project, the cluster of ENV RIs, built around ESFRI roadmap and associated leading e-infrastructures and Integrating Activities, and RIs from other domains as Health & Food for fostering cross-disciplinarity.

ENVRI has proven to be an excellent tool to coordinate Environmental RIs regarding everything from Management, Access policy, Data handling etc. It is of imperative importance that this initiative is continuing.