Project acronym	TERRA FORMA
Titre du projet en français	Concevoir et tester l'observatoire intelligent des territoires à l'heure de l'Anthropocène
Project title in English	Designing and testing a smart observatory of socio-ecological systems in the Anthropocene
Project manager	Laurent Longuevergne
Conventionned funding	9 603 000 €
Leading institution	CNRS
Institution managing the fundings	CNRS DR17 – Bretagne et Payse de la Loire
Axe / *Axis*	☐ Axe 1 : numérique ✘ Axe 2 : générique
Beginning of project **End of project** **End of set-up phase**	01/05/2021 30/08/2029 30/08/2029
Champ(s) scientifique(s) du projet / *Scientific field(s) of the project*	☐ Sciences de la Matière et de l'Energie ✘ Sciences du Système Terre-Univers-Environnement ☐ Sciences de la Vie et de la Santé ☐ Sciences du Numérique et Mathématiques ☐ Sciences Sociales et Humanités
Ce projet est-il la suite, pour tout ou partie, d'un (ou plusieurs) projet financé dans le cadre du PIA ?	☐ Non ✘ Oui : EQUIPEX CRITEX : Équipement innovant pour l'exploration spatiale et temporelle de la zone critique à l'échelle du bassin versant
Ce projet est-il partie prenante ou associé à un projet PIA ou France 2030 ?	☐ Non ✘ Oui : PIA3 GAIA DATA, PEPR FairCarbon, PEPR VDBI

List of partner institutions (as of 30/06/2025)

Nom de l'établissement d'enseignement supérieur / *Name of academic institution*	**Statut / *Legal status***
IPGP	EPSCP
Mines Paristech	EPSCP
Université Aix-Marseille	EPSCP
Université Bretagne Occidentale	EPSCP
Université Clermont-Auvergne	EPSCP
Université de Franche Comté	EPSCP
Université Grenoble-Alpes	EPSCP
Université de Montpellier	EPSCP
Université d'Orléans	EPSCP
Université de Reims	EPST
Université de Rennes	EPSCP
Université Savoie-Mont-Blanc	EPSCP
Université de Toulon	EPSCP
Université Toulouse Paul Sabatier	EPSCP
Nom de l'organisme de recherche / *Name of research organisation*	**Statut / *Legal status***
CNRS	EPST
INRAE	EPST
IRD	EPST
Autres partenaires / *Other partners*	**Secteur(s) d'activité / *Field of activity***
Extralab	Water quality control, analysis and services

Sommaire / Table of contents

SUMMARY (SUBMITTED VERSION)

The Anthropocene, a new geological period when human actions are altering the habitability of the Earth for all forms of life, raises new challenges in terms of knowledge integration that fragmented approaches cannot overtake. Due to complex interactions between humans and geo-ecosystems (territoires in French, i.e. socio-ecological systems in a wide sense, SES), we need to develop a "whole system" approach at the relevant scale for place-based research and action. Understanding the variability of SES involves (1) a large number of variables of diverse nature and (2) a high spatial and temporal acquisition frequency to identify hotspots and hot moments, as well as to better understand ordinary SES. To address these challenges, TERRA FORMA will design and test in-situ observatories offering a new multi-messenger vision, coupling sensor viewpoints on human, biotic and abiotic dynamics. This project builds on pioneering and mature technological advances (optical sensors, 3D printing, IoT, AI) to design and probe a scalable network of smart sensors. WP2 consists in developing a new generation of smart, connected, low-cost, low-impact and socially appropriated environmental sensors, adapted to field conditions, sometimes remote and technically challenging, dedicated to capture the behavior, metabolism and trajectory of SES emerging from states and fluxes of liquid, gas and solid matter, as well as biota. WP3 involves the development of a scalable communication infrastructure embedding energy harvesting, with computing power for inline processing of data generated by heterogeneous sensors and feeding databases in quasi-real time. WP4 consists in building a toolbox to ensure the appropriation of the scientific equipment by actors from the development phase. Testing the observatories will require a co-deployment effort on 3 pilot sites representative of different types of SES (mountain, plain, coastal zones) (WP5). The exploitation phase (WP6) consists in the co-deployment over 12 further sites representative of the main types of CZ and SES in France and abroad along socio-ecological gradients. WP1 (project coordination) is led by an interdisciplinary team of scholars and includes transversal axes (data management, industrialization, AI) to manage risks and accelerate implementation. TERRA FORMA observatories are focal points of convergence between scientific communities and societal stakeholders. Implementation will offer services to respond to both basic science questions and use-inspired demands of stakeholders about the environmental impact of practices, the functioning of SES and ecosystem services. Indeed, these pioneering observatories meet the challenge of a leap forward in studying internal processes and trajectories of SES with unequaled levels of accuracy and integration. These new technologies will contribute to shed light on "essential variables" for SES and evaluate the descriptive and predictive potential of models over a wide range of contexts. TERRA FORMA gathers scientists, in an interdisciplinary effort at the crossroad of Earth, environmental, technological, computer and social sciences and is based on two RIs: the Zones Ateliers and Critical Zone observatories that combine both living and abiotic dimensions. Both are sharing sites, developing complementary approaches, combining ecology and Earth science approaches, including soil depth and long-term geological dimensions, as well as society. The observatories will reinforce existing in-situ experimental platforms and international collaboration, through the participation in the European and international LT(S)ER networks, technological and industrial platforms, as well as the Earth Observation community. The communication infrastructure will favor such collaborations through structured, interoperable and open databases. The homogenization, completion and banking of the resulting datasets will pave the way towards big data approaches in environmental sciences.

1 PROJECT DESCRIPTION

1.1 SCIENTIFIC AND TECHNOLOGICAL DESCRIPTION OF WHAT WAS ACHIEVED (FROM START OF THE PROJECT TO 30/06/2025)

AMBITION OF THE PROJECT. TERRA FORMA (TF) is a national eight-year project (2021-2029) aimed at developing an observation platform designed to capture multi-variable interactions between abiotic elements, biota and humans, which define the habitability conditions of our place of living (socio-ecosystems, SES). TF aims to establish a **new value chain, from sensors to in-situ acquired data**, in order to promote data sharing based on open science principles. The platform is designed to support the **development of systemic approaches** and to fuel place-based research conducted on the observatories of the OZCAR and RZA research infrastructures (RIs). It is composed of a set of modular components that, when custom-assembled, form a **network of next-generation frugal sensors, orchestrated by a plug-and-play communication infrastructure**, contributing to data and knowledge production for academic research and beyond. The project also seeks to foster instrumental agility to **facilitate on-site operations within a coherent national architecture**.

INSTRUMENTATION IN THE HEART OF INTERDISCPLINARITY AND SOVEREIGNITY CHALLENGES. In France, the communities working on SES remain fragmented into several research institutions and universities, and most of the time contributes with discplinary approaches. TF marks a decisive shift by collectively redefining shared scientific needs, synergy among different expertises , bringing harmonized practices at national scale, therefore, reclaiming control over the community's trajectory. This ambition have brought forth challenges we initially underestimated. In response, we have developed **shared tools and created spaces for dialogue**, which are the result of compromise and the search for common ground between differing perspectives. TF also integrates an ambition of **instrumental sovereignty**, with a priority on reducing field operational constraints through technical innovation and minimizing reliance on (diminishing) technical human resources.

TF AS A STARTER PACK FOR SUSTAINABLE TERRITORIAL TRANSITIONS. By focusing the discussion on actual needs to answer critical new scientific questions, **technical tools become a meeting point** to foster interdiscplinarity and support TRL advancement through specification, adaptation and on-site valorization. TF contributes to a broader research strategy by supporting the development of systemic approaches needed to address societal challenges, as expected from the scientific community brought together by the OZCAR and RZA RIs[1], and in the context of building the European eLTER RI. By embedding the development of next-generation sensors and the design of data/digital infrastructure services within a research perspective involving territorial stakeholders, TF also aims to directly **engage a diverse range of non-academic actors**. The project is fostering new alliances with community-based research groups to **bridge the gap between a techno-scientific program and a broader socio-ecological initiative** for territorial innovation.

TF CORE SERVICES. Today, TF is structured as a platform offering five core services, primarily for the benefit of the national RIs OZCAR and RZA, and more broadly for environmental observatories (EU perspectives). These services respond directly to identified needs expressed in national foresight exercises and major research programs (e.g., PEPR initiatives). The ownership of these services are

[1] OZCAR and RZA RIs are listed on the national research infrastructure roadmap as key instruments for long-term environmental observation.

expected to be taken by institutions (therefore, blending in existing RIs), and animated by scientific and technical communities (such as the recent Enrivonmental Sensor Professional Network (RTCE) :

- **eRECA** (REssourcerie de CApteurs pour l'Environnement Numérique), a catalog of existing hardware and software solutions for environmental sensors, serving as a meeting tool between developers and thematic experts. It supports agility to answer thematic needs and valorize engineering work.
- **RIPOSTE** (Réseau d'Instruments Partagés pour l'Observation au Service des TErritoires, ou du Système TErre), a shared instrument pool, integrating instruments and expertise, facilitating collaborations between developers and site managers/stakeholders to acquire original data using a systemic approach (essential variables, high spatial and temporal resolution).
- **LNS-PULSE** (Plateforme Unifiée LoRaWAN pour Services Étendus), a national LoRaWAN server managing data transfer, ensuring their convergence towards a national cloud. The strategy is to build a « eduroam » network for in-situ sensors, by providing pre-programmed gateways, limiting required on-site technical expertise.
- **CEBO** (Cloud Environnemental au Bénéfice des Observatoires), a national server, receiving, decrypting data fluxes, then enriching data following an Open Protocol standard (SensorThings). This server, in charge of managing « hot » data might become a convergence point between TF and DATA TERRA RI in charge of Earth Data management.
- **SAPS[2] platform,** a community platform to support the emergence of citizen metrology in participatory science initiatives and provide an environment for data visualization and analysis. The ambition is to engage local communities and stakeholders in environmental data production and interpretation, connect them to a scientific and/or reglementary refecence (i.e. Make citizen and scientific data intercomparable), and ensure traceability of the data.

TF CORE DEVELOPMENTS. Initially, **25 research products were planned in the sensor portfolio** (WP2). Three levels of instrument development were pursued, reflecting varying levels of maturity and updated strategic orientation.

First, 13 instruments (52%) have reached a stage where they could be considered as duplicable in 2 years (generally at TRL6 in 2025). Documentation is being finalised, and duplication strategies are being consolidated to meet high-priority needs. These instruments will be promoted via eRECA, RIPOSTE, and through implementation on pilot and complementary sites. Two main examples : (1) a multiparameter probe (Fig. 1) measuring standard variables in aquatic ecosystems, developed in open science and duplicable in fablab. Material cost is lower than 500€, for observation capabilities of probes 20 times more expensive ; (2) a miniaturized hyperspectral camera (<1Kg) dedicated to continuous monitoring of vegetal cover and water color, including an embedded control software designed for non-expert users and limited cost (15 k€).

Second, 8 instruments (32%) will reach the demonstrator stage in 2 years (generally TRL5 in 2025). These developments are currently undergoing final documentation, with efforts to encourage further project proposals and identify viable duplication pathways. Their value is being enhanced through integration into eRECA, RIPOSTE, and deployment on pilot sites. As an example : an entomoscope with on-board AI to limit latency on data analysis. Note that the development period has been extended beyond the initial phase of 2024 to reach maturity for promising tools. As an example : observation of microbial biomass with in-situ ATP measurements with a microfluidic chip.

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[2] « Science Avec et Pour la Société », standing for Science with and for society

Finally, a set of 4 Proofs of Concept (16% of the portfolio) were discontinued after initial development and following a renegotiation of the project roadmap, which may lead to a reduced overall envelope. These will nonetheless be valorised through inclusion in the eRECA. As an example : Biomove[3], a miniaturized and low energy probe to observe the physical coordination of animals.

Figure 1 : Developed sensors in-situ during plateform deployement on Guidel pilot site (06/2025). From left to right and top to bottom : multiparameter probe, 3 depths soil moisture, water conductivity and temperature measurement system, tracesence passive sampler, transparent Greenhouse Gas Flux Chamber

Ensuring near real-time transmission of data from field-deployed sensors to servers (WP3) emerged as a major challenge for TF—and a potential game changer for observatory operations. In response, what was initially planned as a single demonstrator has evolved into a more ambitious, dual-service architecture: LNS-PULSE and CEBO, two complementary services now positioned as core components of the project's data infrastructure. The developments relies on the latest Internet of Things (IoT) technologies and related innovations. We have designed (1) « nodes » to allow connection of any sensor on a IoT/3G network. Then, we developed and tested an in situ communication infrastructure, based on technologies such as LoRaWAN and satellite IoT; (2) a central, grid-powered, multi-protocol platform, providing first-level data processing; (3) a federated set of platforms, supporting cloud-based data flow management, including data lakes for collection, pre-processing, publication, and distribution.

The social infrastructure dimension of TF (WP4) remains a strategic pillar, aiming to bridge social dynamics with the project's technical and scientific infrastructure. This integration is essential to enhance the societal relevance of the project and to foster active engagement toward more resilient

[3] The translation of the TERRA FORMA website in english is ongoing

and sustainable living environments. In addition to the ongoing SAPS platform (see services), the project leverages boundary objects—notably the Gaiagraphie, a renewed representation of sites that highlights depth–surface interactions and facilitates dialogue both across disciplines and between researchers and stakeholders. One exploratory initiative investigates how technology can support the reconnection between young people and nature, rooted in an interdisciplinary research framework. Lastly, the project places strong emphasis on student involvement and training activities, helping to build capacity and ensure long-term impact.

QUALITY-DRIVEN APPROACH TO DEVELOP. Best development practices have been progressively adapted, harmonised, and implemented as part of an ongoing effort to support quality assurance and facilitate technology transfer. To structure this approach, a first step focused on a technical specifications document, ensures consistent oversight of the instrument catalogue, promoting standardisation and operational reliability. The second, centred on project review, facilitates the phased involvement of external stakeholders, thereby encouraging collaboration and knowledge exchange beyond the core research teams. A third step, currently underway, addresses the qualification of in-situ sensors, marking a further step toward deployment readiness. In parallel, two feasibility studies have been conducted to assess technology transfer opportunities—one exploring partnerships with the private sector, and the other engaging with the third sector of research (ex. Fablab), thus broadening the reach and societal impact of the project's innovations.

LAUNCH OF THE IN-SITU DEPLOYMENT PHASE. The first large-scale deployment of various technical tools for continuous monitoring took place in June 2025 at the Guidel pilot site. We initiated procedural documentation to support replication on additional sites. A technical coordinator will be recruited to guide this new phase and prepare dissemination to 10 more sites in 2027. In December 2024, we launched a call for expressions of interest to extend the deployment of TF platforms more broadly—on OZCAR and RZA RI sites, as well as beyond. We received 22 applications, currently under review. This deployment can support (1) long-term monitoring, e.g. Sites applying for inclusion in the eLTER research infrastructure or (2) experimental initiatives. For example, an intensive field campaign took place in June 2023 at the Frasne peatland site, involving 15 research laboratories. The campaign tested TF sensors for monitoring CO_2 and CH_4 fluxes and concentrations across the groundwater–soil–atmosphere continuum. It included high-resolution greenhouse gas mapping via drone, groundwater gas measurements, and targeted sampling to inform the design of the dissolved organic matter probe. These developments contribute directly to research on the spatial variability of CO_2 and CH_4 fluxes, their transfers and balances, emissions to the atmosphere, and the metabolic pathways underlying methanogenesis and methanotrophy.

TF implemented developments remain fully aligned with the original vision, with a few adjustments linked to the compromise between an extended development phase and effective in-situ deployment. The focus on integrated observation site – sensor – data strategies has been maintained, and the project's outcomes exceed initial expectations in terms of instrumental maturity, service structuring, and interdisciplinary impact. Main pitfall

1.2 SCIENTIFIC, TECHNOLOGICAL DESCRIPTION OF WHAT WAS PLANNED AND NOT ACHIEVED

Despite significant progress, several scientific and technological actions planned in the initial roadmap could not be fully completed within the expected timeframe, or were stopped. The reasons are multiple and concern both structural limitations and unforeseen external constraints.

The delays in technological developements and project lead were mainly due to

- Insufficient human resources dedicated to R&D tasks. Several teams had to secure co-funding to carry out the developments properly ;
- Staff turnover within technical and administrative teams, making it difficult to maintain continuity and long-term commitment on sensitive components ;
- Delays in recruitment, especially in strategic profiles such as computer scientists or embedded systems engineers, where public research institutions face competition from the private sector ;
- Changes in WP leadership, which required reorganisation and redefinition of certain priorities ;
- Delays in the procurement of key components, due to global supply chain tensions (e.g., microcontrollers and low-power communication chips), which affected prototyping phase.
- Technical barriers, such as unanticipated integration issues (e.g. Multi-parameter probe)

Partial or complete interruption of some developments were caused by:

- Scientific dead-ends that emerged during the PoC or early testing phases, leading to a strategic decision to halt (e.g. In-situ $^{13}CO_2$ isotope in water)
- Technical barriers, such as unanticipated compatibilities and integration issues
- Partnerships issues, e.g. a team withdrawal in charge of prototype testing (e.g. BioMove sensor)

Overall, these difficulties underline the need for agility and iterative design in instrumentation projects, and several lessons learned are being incorporated into the second half of the project. As example, in-situ testing was found to provide valuable feedback to restart new development cycles. As a consequence, pilot site deployment was advanced ahead of schedule, despite the non-finalisation of certain components, in order to meet demonstration objectives, attract co-funding and maintain user engagement.

1.3 Initial Gantt chart from 01/01/2021 to 30/06/2025

1.4 Gantt chart from 01/01/2021 to 30/06/2025 as achieved

A single (instead of 3) Gantt chart (Fig. 2) is proposed to favour the indentification of (1) evolution with respect to initial plans and (2) to show continuity and coherence with second phase of the project. Modifications and delays are indicated with symbols, showing project flexibility and responsiveness.

The red vertical line indicates the current period (Mid-Term), showing that the project is entering a new critical phase of implementation (WP5) and dissemination (WP6) across pilot and complementary sites. Some tasks, such as sensor development (WP2) and communication systems (WP3), are pursued continuously throughout the project to allow versioning and adaptation based on new emerging opportunities (ideas with on-site development, technology, ...).

Initially developed as demonstrators, several services (e.g., RIPOSTE, PULSE, CEBA) have matured into robust operational tools, forming a lasting legacy of the TF project for national RIs.

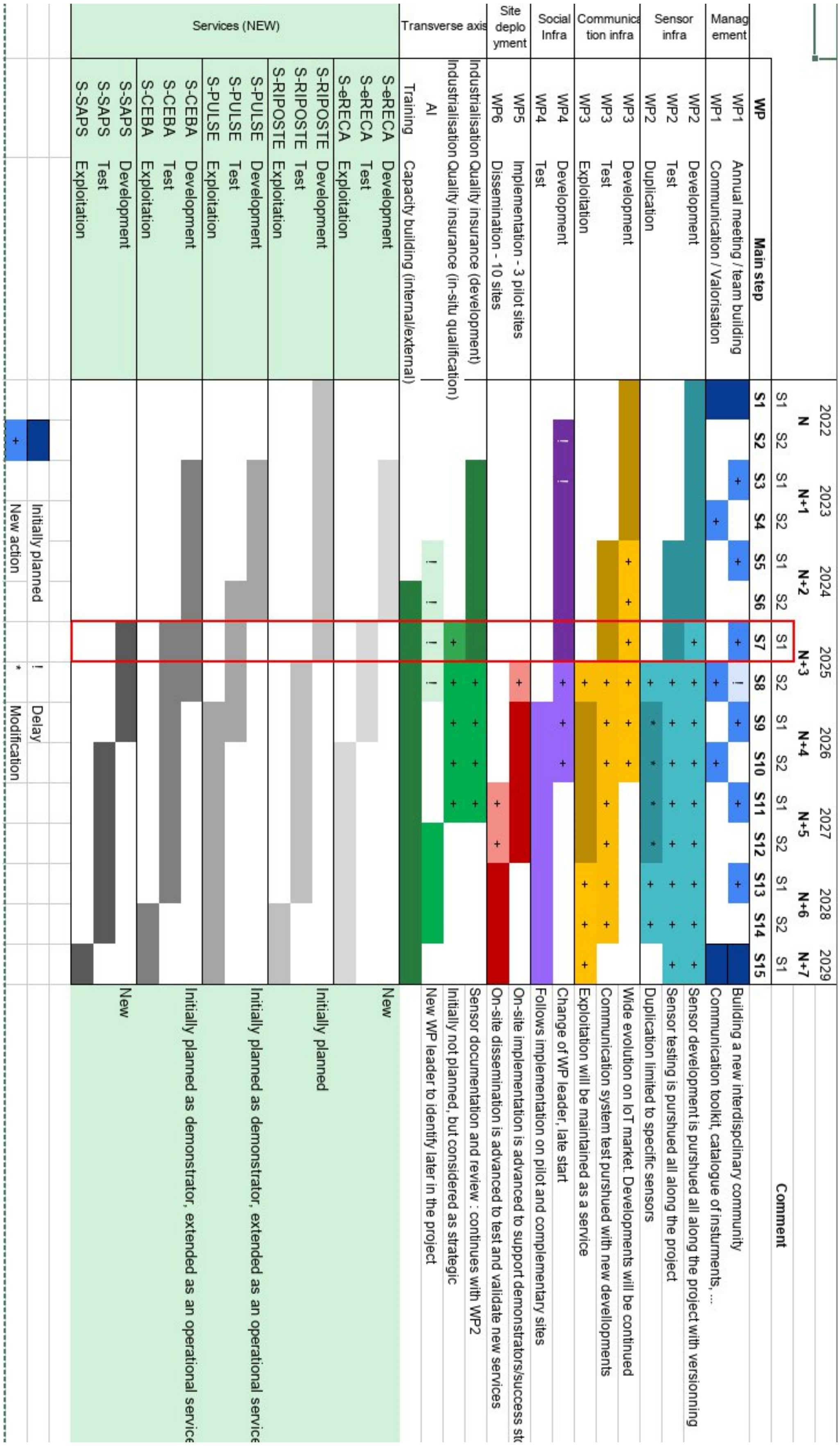

Figure 2 : Gantt chart of TF project

2 Organisation and strategy

2.1 Governance and administration

Figure 3 : simplified organigram of TF project

TF Coordination is set as a balance between OZCAR and RZA RIs and the different institutions within partners. Everyday operations are in charge of a bureau composed of the PI, Laurent Longuevergne from OZCAR community, the co-PI, Arnaud Elger from RZA community, and Virginie Girard, the project manager. The bureau ensures clear reporting and effective communication across all work packages. It is responsible for coordinating and organizing the actions defined in the project roadmap. Finally, forward-looking efforts are central to anticipate future needs and sustain long-term impact. The governance is compound of 4 instances (Fig. 3) :

- An **EXECUTIVE BOARD**, meeting monthly, composed of the bureau - composed of the PI, the co-PI, and the project manager, WP leaders, transversal axis (cross-cutting area) leaders and persons in charge of services. A key objective is to drive deliverables toward full operational implementation of services, demonstrating their relevance and added value.
- A **SUPERVISORY BOARD** gathering representative of all project 19 partners, meeting twice a year, with participation of ANR.
- A consultative **SCIENTIFIC COMMITTEE** composed of 5 key international researchers representing a different point of view (WP2/3, WP4, WP5). A single meeting has been planned in 2023.
- A consultative **STAKEHOLDER COMMITTEE** bringing together operators in the field of environment and energy, companies, associations, and SMEs, in charge to advise and enhance opportunities to co-construction and co-fund complementary developments locally or at national scale in line with local road maps. Annual meeting.

AN ADMINISTRATIVE CHANGE occurred early in the project with the withdrawal of INERIS as a partner. To address the evolving needs of the project on the SAPS service, we are now considering the integration of new partners (MNHN). In addition, the co-PI was replaced; however, he remains actively involved in the transversal axis « training ». TF has also been strengthened by the involvement of Daniel Gilbert, representative of the RZA RI, who brings valuable expertise in ecology and collaborative research approaches.

BOOSTING SITE STRUCTURATION THROUGH A NATIONAL EQUIPMENT STRATEGY : The deployment of TF equipment is contributing to the long-term structuring of the sites involved, reinforcing their strategic position locally (in a context of autonomous universities), and within national research infrastructures. Beyond the immediate technical gains, the project is shaping a broader vision for instrumentation and observation that resonates with institutional foresight exercises conducted by CNRS institutes (INSU, INEE, INP). This momentum is reflected in the CNRS's 2024–2028 strategic objectives and performance contract, which highlights two key themes aligned with TF's core approach: instrumentation and transitioning societies. The document emphasizes the importance of technical tools to foster data sharing and research collaboration, managing the balance between data flow and information relevance, and pursuing material and energy sobriety wherever possible. Innovating differently in TF means placing these principles of frugality and sustainability at the heart of our developments.

These observatories, with their diversity of climates, topographies, anthropogenic footprints, and technical capacities, are becoming strategic tools for understanding socio-ecosystems and co-producing actionable knowledge. TF aims to reinforce this role by providing shared tools and services to enhance data acquisition strategies (targeting essential variables), support operations, develop sentinel systems and early warning tools, and foster citizen science.

2.2 Realisation and scientific production

Most of teams involved in TF are about to evolve from development to deployment phase in 2025. Therefore, a limited number of 16 scientific productions have been published, most of them in instrumental journals and/or in thematic journal focusing on the evaluation of the new tools. We also aknowledge that a foundation paper in a high impact journal on systemic approaches and the value of a dedicated observation platform is still lacking.

- Grilli, R., DelSontro, T., Garnier, J., Jacob, F., & Némery, J. (2023). A Novel High-Resolution In Situ Tool for Studying Carbon Biogeochemical Processes in Aquatic Systems: The Lake Aiguebelette Case Study. Journal of Geophysical Research: Biogeosciences, 128(12), e2022JG007200. https://doi.org/10.1029/2022JG007200
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- Miquel, J., Latorre, L., & Chamaillé-Jammes, S. (2023). Energy-efficient audio processing at the edge for biologging applications. Journal of Low Power Electronics and Applications, 13(2), 30. https://doi.org/10.3390/jlpea13020030
- Sanchez, R. et al., 2023, Development of a Frugal, In Situ Sensor Implementing a Ratiometric Method for Continuous Monitoring of Turbidity in Natural Waters, Sensors, https://doi.org/10.3390/s23041897
- Wohleber, A., Blouzon, C., Witwicky, J., Ginot, P., Jourdain, N. C. and Grilli, R., « A membrane inlet laser spectrometer for in-situ measurement of triple water isotopologues », Limnology and Oceanography : Methods. doi :10.1002/lom3.10660 https://doi.org/10.1002/lom3.10660
- Nord, G., Safdar, S., Hasanyar, M., Eze, K. O., Biron, R., Freche, G., ... & Esteves, M. (2025). Streamflow monitoring at high temporal resolution based on non-contact instruments and manually surveyed bathymetry in a river prone to bathymetric shifts. Water Resources Research, 61(4), e2024WR037536. https://doi.org/10.1029/2024WR037536
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- Boitier V., Cao K.B.K., Estibals B., Raimbault V., Cauchoix M., Druilhe J.L. & Elger A. (2024). Solar Power Supply for Sensor Applications in the Field: A Guide for Environmental Scientists. In Solar (Vol. 4, No. 4, pp. 674-693). MDPI. https://doi.org/10.3390/solar4040032
- Hyperspectral Gousset, S., Legout, C., Choler, P., Barnola, S., Longuevergne, L., & Voisin, D. (2025, May). Development and testing of a hyperspectral camera network to monitor plant canopies and sediment transport dynamics. In ARPHA Conference Abstracts (Vol. 8, p. e152517). Pensoft Publishers. https://doi.org/10.3897/aca.8.e152517
- Pons, M. N., Brunello, D., Grissom, J., & McKenna, A. (2025, May). A low-cost dissolved organic matter probe for aquatic ecosystems. In ARPHA Conference Abstracts (Vol. 8, p. e151418). Pensoft Publishers. https://doi.org/10.3897/aca.8.e151418

- Raimbault, V., & Olvera, R. S. (2025, May). Openprobe: a frugal multiparameter probe for marine and continental waters monitoring. In ARPHA Conference Abstracts (Vol. 8, p. e151405). Pensoft Publishers. https://doi.org/10.3897/aca.8.e151405
- What a peaty contribution to global warming! An interdisciplinary study of atmospheric and hydrologic carbon fluxes in a temperate peatland in the Jura Mountains, eastern France https://doi.org/10.3897/aca.8.e155498

In terms of indicators, the overall advancement rate is 36%, including in the original plans for TF project, but ranges from 100% (Gaiagraphy), larger than 65% (multiparameter probe, CO2/CH4 drone mapping, GES gaz chambers, deep CO2/O2 probe, soil moisture probe, e-cagging), to POC which have been halted.

2.3 CONTRIBUTION TO INTERNATIONAL INNOVATION AND ATTRACTIVITY

Although the usage rate of instruments within the TERRA FORMA project is currently not a meaningful indicator—due to limited use of some purchased equipment and the ongoing delivery and integration of others—the project is already contributing significantly to international innovation dynamics.

At the European level, TF actively engages with key research infrastructures and communities. A recent milestone was the inaugural eLTER RI conference , held in Finland, where TF was represented. Two sessions were dedicated to "Technical innovation for whole-system observations," highlighting a shared vision among the six session chairs and invited experts. A common perspective emerged: instrumentation plays a decisive role in enabling us to understand and influence the future. Addressing today's complex socio-ecological challenges requires us to observe differently—redefining what is feasible, rethinking our methods and infrastructures to meet evolving needs with a site-based point of view. This involves developing and deploying innovative, in-situ monitoring systems capable of capturing the dynamic interactions between human societies, ecosystems, and abiotic environments across multiple spatial and temporal scales. TF's contribution aligns with this vision by promoting the co-development, qualification, and field application of novel sensor systems, therefore, a « topic center » focusing on innovation as a service have also emerged, co-lead by France (TERRA FORMA) and Danemark. TF embraces both low-tech and high-tech approaches, prioritizing solutions that are cost-effective, modular, adaptive, and easy to deploy. This orientation supports broad replication across diverse socio-ecological contexts and encourages international collaboration around emerging standards and shared infrastructure.

3 MANAGEMENT DU PROJET / MANAGEMENT FRAMEWORK

3.1 HUMAN RESSOURCES

The financial regulations governing PIA3 projects do not allow allocating more than 10% of the budget to human resources. As a result, these resources have been concentrated on strategic positions. Given TF's strong development ambitions, a significant share of the human resource effort has been supported through co-funding obtained from external competitive calls. To date, these co-funding mechanisms amount to 10 M€, primarily dedicated to recruitment, though not exclusively.

Directly funded by TERRA FORMA

2022-2028	IR project management	CDD	CNRS
2022-2023	IE, communication	CDD	CNRS
2026-2027	IE, informatics (CEBO service)	CDD	CNRS
2026-2029	IR, technical coordinator (WP5, WP6)	CDD	CNRS

Investment of partners (investment > 15%)

2021-2022	Ewan Negre IR (WP2.3c) (66%)	CDD	CNRS

2022	Maxime Rubeo-Lisa IE (WP3, communication node) (66%)	CDD	CNRS
2022	Martin Foin IE (WP2.1) (80%)	CDD	CNRS
2022-	Julien Moureau IE (eRECA, WP3) (70%)	Perm	CNRS
2022-2026	Elodie Godhino IR (eRECA) (15%)	Perm	CNRS
2022-2026	Karim Bernadet IR (eRECA) (15%)	Perm	CNRS
2022-	Sylvain Pasquet IR (RIPOSTE) (25%)	Perm	CNRS
2023-2030	Jérémy Mezhoud IR (CEBO, WP3, LNS-PULSE) (15%)	CDD	CNRS
2023-2025	Samuel Barnola IR (WP2.1) (50%)	CDD	CNRS
2023-2025	Julien Sudre IE (WP3) (70%)	CDD	CNRS
2024	Marie Bureau IR (WP3, CEBO) (50%)	CDD	CNRS
2024-2025	Matthieu Nicolas IE (WP3 Fog computing) (50%)	CDD	INRIA

PhD

2019-2023	Ivan Osorio	WP2.7b: dev passive sampler (30%) Thesis	UR
2020-2023	Melissa Garry	WP2.7b: relation O2/microbial div. (10%) Thesis	UR
2021-	Josselin Simion	WP2.8 : communicant loggers (20%)	UTLS
2021-	Nourelhouda FODIL	WP5.2 : e-cagging (25%)	U Havre
2021-2024	Jonathan Miquel	WP2.6a: low energy electro and software Thesis	
2022-2025	Raul Sanchez	WP2.2a : multi-parameter probe dev. Thesis	UTLS
2022-2025	Isalyne Blondet	WP2.4a: Tracesense probe dev.	UTLS
2022-2025	Margot Bremaud	WP2.7ab: subsurface microbial exosystems (10%)	UR
2023-2026	Marie-Léa Pouliquen	WP4 : connexion human-nature (100%)	UR
2023-2026	Eva Agranier	WP2.7c : lab on a chp (30%)	UTLS
2023-2026	Edgar Rémy	WP2.8a : integration of automated IA data (15%)	UTLN
2024-2027	Olivia Brunet	WP4 : connexion human-nature (100%)	UTLS
2024-2027	Stéphane Chavin	WP2.8a : bioaccoustics (15%)	UTLN

Post-docs

2022-2025	Olivier Bochet	WP2.7 dissolved gases and lab on chip (50%)	UR
2023-2024	Alexandra Arènes	WP4 Gaiagraphy (100%)	IPGP

4 Future of EquipEx+

4.1 Gantt chart and SWOT analysis from 01/07/2025 to the end of the project

Please see the Gantt chart from 01/01/2021 to 30/06/2025, which integrates planned chart for 2025-2029. The project is now entering a new phase that shifts the focus from prototyping to operational deployment and consolidation. This transition acts as a "crash test" for the developments carried out so far, confronting them with real-world constraints and the diversity of use cases emerging from interdisciplinary collaboration. **Ensuring a high quality of service becomes a central challenge**, particularly as the tools and infrastructures are increasingly shared across disciplines and user communities. To support this, significant effort is being invested in the documentation, standardisation, and packaging of the developed services, in order to facilitate their deployment and reproducibility across different sites and contexts. This phase also strengthens the project's integration with national research infrastructures (RIs) and strategic programs, reinforcing its anchoring within the broader French scientific and technical landscape.

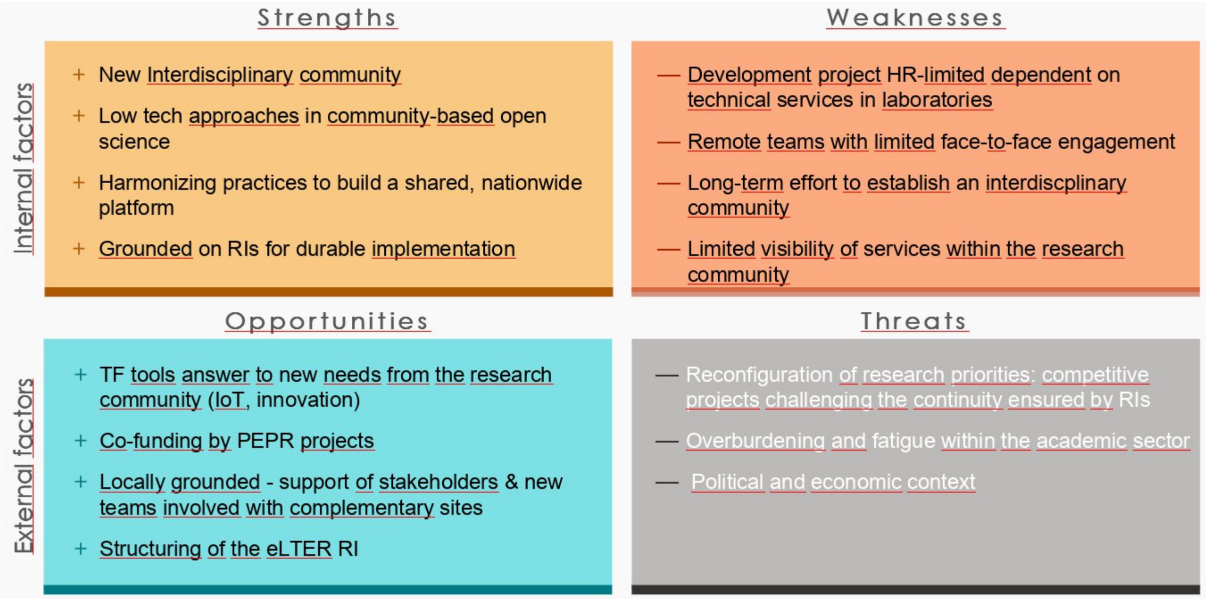
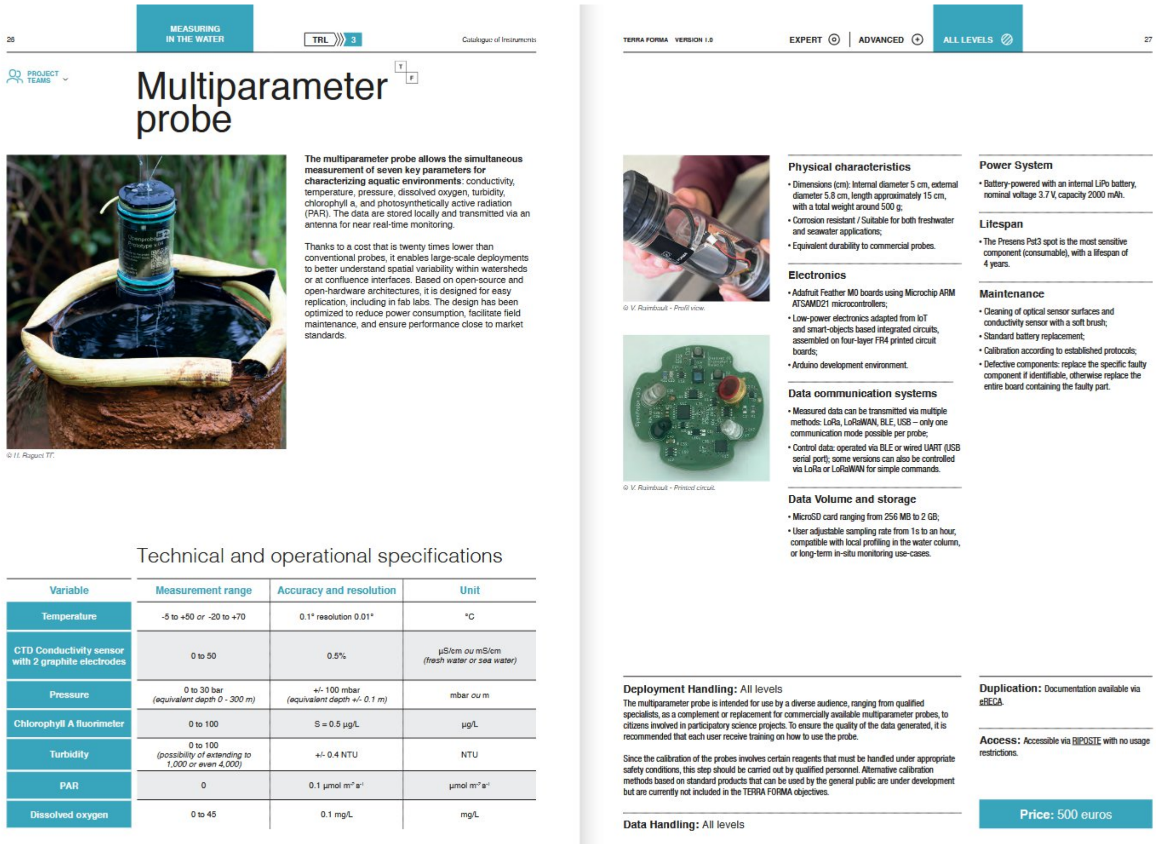


Figure 4 : SWOT for TF project

TF builds on strong assets (Fig. 4): an emerging interdisciplinary community, the use of low-tech and community-based open science approaches, and the harmonization of practices across sites to establish a shared, nationwide platform. These elements provide a solid foundation for long-term integration within research infrastructures (RIs). However, limited eligibility for funding of human resources (HR) makes the project heavily reliant on technical staff in laboratories and success to competitive calls. Moreover, TF's teams are often geographically dispersed, making sustained face-to-face engagement difficult and slowing the consolidation of an interdisciplinary research culture. The remedial actions consisted of (1) holding annual—not merely biannual—project meetings, and (2) organizing more technical in-person meetings. Despite recent efforts in communication — such as the publication of a first "instrument catalogue" (Fig. 5), a Canal-U space where we document all developments/concepts on videos and a LinkedIn account — the visibility of TF tools and services within the research community remains limited. Continued communication in interdisciplinary contexts and a stronger alignment between tool development and scientific use cases are needed to boost integration. In that sense, new collaborations—like the one established with the PEPR FairCarbon project, funding two PhDs on the qualification of TF sensors to assess carbon fluxes along the land-sea continuum—illustrate how TF tools can be mobilized for scientific impact. Yet, the pressure from site managers to meet immediate operational needs may divert attention away from medium-term development objectives.

Externally, TF benefits from promising opportunities: its tools are well-aligned with emerging needs from the research community (e.g. IoT, innovation), receive support through PEPR projects, and are embedded in locally anchored dynamics, with complementary sites and strong stakeholder engagement. Furthermore, the structuring of the eLTER RI offers prospects for broader integration. At the same time, several threats loom. Political and economic uncertainties, reconfiguration of research priorities, and increasing competition between initiatives risk fragmenting scientific efforts. The trend toward large, competitive projects often launched independently of existing RIs undermines the role of infrastructures, which are essential for scientific continuity and long-term observation. Overburdened research teams may adopt more inward-looking strategies, reducing inter-institutional cooperation at a time when coordinated, system-based approaches are most needed to address socio-environmental transitions.



26 MEASURING IN THE WATER TRL 3 Catalogue of Instruments

PROJECT TEAMS

Multiparameter probe

The multiparameter probe allows the simultaneous measurement of seven key parameters for characterizing aquatic environments: conductivity, temperature, pressure, dissolved oxygen, turbidity, chlorophyll a, and photosynthetically active radiation (PAR). The data are stored locally and transmitted via an antenna for near real-time monitoring.

Thanks to a cost that is twenty times lower than conventional probes, it enables large-scale deployments to better understand spatial variability within watersheds or at confluence interfaces. Based on open-source and open-hardware architectures, it is designed for easy replication, including in fab labs. The design has been optimized to reduce power consumption, facilitate field maintenance, and ensure performance close to market standards.

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Technical and operational specifications

Variable	Measurement range	Accuracy and resolution	Unit
Temperature	-5 to +50 *or* -20 to +70	0.1° resolution 0.01°	°C
CTD Conductivity sensor with 2 graphite electrodes	0 to 50	0.5%	µS/cm *ou* mS/cm *(fresh water or sea water)*
Pressure	0 to 30 bar *(equivalent depth 0 - 300 m)*	+/- 100 mbar *(equivalent depth +/- 0.1 m)*	mbar *ou* m
Chlorophyll A fluorimeter	0 to 100	S = 0.5 µg/L	µg/L
Turbidity	0 to 100 *(possibility of extending to 1,000 or even 4,000)*	+/- 0.4 NTU	NTU
PAR	0	0.1 $\mu mol\ m^{-2}\ s^{-1}$	$\mu mol\ m^{-2}\ s^{-1}$
Dissolved oxygen	0 to 45	0.1 mg/L	mg/L

TERRA FORMA VERSION 1.0 EXPERT | ADVANCED | ALL LEVELS 27

© V. Raimbault - Profil view.

© V. Raimbault - Printed circuit.

Physical characteristics
- Dimensions (cm): Internal diameter 5 cm, external diameter 5.8 cm, length approximately 15 cm, with a total weight around 500 g;
- Corrosion resistant / Suitable for both freshwater and seawater applications;
- Equivalent durability to commercial probes.

Electronics
- Adafruit Feather M0 boards using Microchip ARM ATSAMD21 microcontrollers;
- Low-power electronics adapted from IoT and smart-objects based integrated circuits, assembled on four-layer FR4 printed circuit boards;
- Arduino development environment.

Data communication systems
- Measured data can be transmitted via multiple methods: LoRa, LoRaWAN, BLE, USB – only one communication mode possible per probe;
- Control data: operated via BLE or wired UART (USB serial port); some versions can also be controlled via LoRa or LoRaWAN for simple commands.

Data Volume and storage
- MicroSD card ranging from 256 MB to 2 GB;
- User adjustable sampling rate from 1s to an hour, compatible with local profiling in the water column, or long-term in-situ monitoring use-cases.

Power System
- Battery-powered with an internal LiPo battery, nominal voltage 3.7 V, capacity 2000 mAh.

Lifespan
- The Presens Pst3 spot is the most sensitive component (consumable), with a lifespan of 4 years.

Maintenance
- Cleaning of optical sensor surfaces and conductivity sensor with a soft brush;
- Standard battery replacement;
- Calibration according to established protocols;
- Defective components: replace the specific faulty component if identifiable, otherwise replace the entire board containing the faulty part.

Deployment Handling: All levels
The multiparameter probe is intended for use by a diverse audience, ranging from qualified specialists, as a complement or replacement for commercially available multiparameter probes, to citizens involved in participatory science projects. To ensure the quality of the data generated, it is recommended that each user receive training on how to use the probe.

Since the calibration of the probes involves certain reagents that must be handled under appropriate safety conditions, this step should be carried out by qualified personnel. Alternative calibration methods based on standard products that can be used by the general public are under development but are currently not included in the TERRA FORMA objectives.

Data Handling: All levels

Duplication: Documentation available via eRECA.

Access: Accessible via RIPOSTE with no usage restrictions.

Price: 500 euros

Figure 5 : extract of the first version of the catalogue of instruments (in english, see later) for the multi-parameter probe. The catalogue is designed to communicate broadly on TF developments and will continue to grow until 2029 (the end of the project) with new devices and regular updates. This catalogue is the result of a documentation and description effort, based on the Technical Specification Sheets produced as part of the quality assurance process, and on eRECA's resource center for harmonized instrument descriptions. The catalogue covers descriptive, technical, deployment, and maintenance aspects, with the aim of ensuring broad accessibility — from experts to non-experts.

4.2 Current economic model and future economic model beyond closure

The economic model of TERRA FORMA is a central concern, particularly as the project transitions from development to the delivery of operational services. In line with open science principles and research infrastructure policies, our long-term objective is to offer cost-free access for academic users. For partnership-based research involving non-academic actors (e.g., public authorities, private stakeholders), a user contribution model will be defined according to collaboration types and access conditions.

A core ambition of the project is to transform field practices through technological innovation and standardisation, reducing the need for in-situ technical support. While this lowers recurring costs at the local level, it requires centralised maintenance capabilities and a robust technical backbone to ensure long-term efficiency and adaptability across diverse field conditions.

Access to services will be governed by quality assurance mechanisms. Instead of restricting access, we define "entry costs" in terms of compliance with documentation and metadata standards. For example, datasets will only be standardised if sensor developers and observation sites provide adequate contextual and technical information. Pilot site deployments and dissemination across complementary sites will be key to validating and optimising service delivery before the project ends.

Services are being co-developed with target user communities, with the aim that they be adopted and operated by institutions hosting national research infrastructures. These institutions are best placed to ensure long-term sustainability by aligning services with their core missions and funding. Additionally, several services are expected to be offered at the European level through eLTER RI Topic Centres, which are anticipated to benefit from dedicated five-year funding—a major opportunity for securing future resources.

While no major reinvestments are needed in the short term, targeted upgrades may be required 5–7 years after project completion, particularly for sensor fleets and IT infrastructure. These needs will be periodically reassessed based on service uptake, technological progress, and institutional priorities.

4.3 Place in the ecosystem

TERRA FORMA’s alignment with current national priorities is also visible in its proactive integration with PIA4 projects, which are reshaping the French research landscape. Many of these projects are rooted in socio-ecosystem contexts and include an "equipment" component where data acquisition tools are critical, but where dedicated instrumentation is often underdeveloped or lacking. TF offers synergies at four levels: (1) methodological innovation, including participatory science and evolving field practices; (2) instrumentation, through co-development or appropriation of sensors; (3) site-level collaboration, via co-investment on strategic observatories ; and (4) the progressive development of interoperable services tailored to target research communities. Current agreement and partnerships existe with PEPR FairCarboN, Sustainable city and smart building, more interactions are built with PEPR OneWater, FORESTT, Solubiod, Transform, and national program on biodiversity.

As services mature, the consortium itself is expected to evolve. Building and deploying tools for broad academic and societal use requires expanding the partnership base to include actors specialising in participatory science, collaborative research and technology transfer. The current TF call for expressions of interest (AMI) to select complementary sites opens a new phase of expansion, oriented towards co-construction with high-profile field partners—such as national nature reserves, UNESCO biosphere reserves, or regional natural parks. This territorial anchoring serves dual objectives: addressing real-world needs and reinforcing our positioning within future State-Region Planning Contracts (CPER), particularly under the research, ecological transition, and innovation components.

At the international level, TERRA FORMA is beginning to establish its role within the European infrastructure eLTER. Participation in the first eLTER RI conference and joint leadership of sessions on instrumental innovation have fostered promising connections with key actors. These exchanges point to the emergence of new forms of European coordination, both within and beyond the eLTER framework.

5 Recommandations du jury / Committee recommandations

The recommendations issued by the international selection jury have served as a key reference throughout the development and strategic orientation of TERRA FORMA. Many of the project's strengths highlighted by the jury have been reinforced and translated into operational outcomes. The **systemic and interdisciplinary ambition** remains central to the project's identity, shaping both the design of technological solutions and the integration of social and environmental dimensions. The **socio-economic component (WP4)** has become a structuring pillar, particularly through the SAPS platform service, development of participatory methodologies with third sector of researche (FABLAB) and documentation of boundary objects (such as the Gaiagraphie). These tools reinforce the societal relevance of TERRA FORMA in addressing contemporary socio-environmental transitions. On the technological side, WPs 2 and 3 have enabled the emergence of a **unique instrumentation platform** at the European level, aligned with global ambitions for whole-system observation. This infrastructure **capitalises on the complementarities between national RIs** (OZCAR and RZA) and mobilises a wide network of research laboratories. **Continuity over the long term** is now a core action with the identification and development of services.

Several of the jury's key questions and recommendations have been progressively addressed. The engagement of non-academic partners has been structured along multiple lines. On the technological side, the project has adapted quality assurance standards to provide proper documentation of instrument development, enabling potential partnership-based interactions—though the open-science orientation and limited market niche of TF reduce the scope for large-scale outsourcing. Institutional engagement has also been supported by the establishment of a COMOP committee, ensuring continuous dialogue with regional authorities and public policy actors. Furthermore, the open call for complementary sites (AMI) offers opportunities to forge new partnerships, particularly with emblematic territories such as national parks and UNESCO biosphere reserves, thereby strengthening TF's territorial anchoring and strategic positioning.

The project has also actively engaged with national data infrastructures, notably through strengthened collaboration with the PIA3 GAIA DATA and the eIR DATA TERRA. Therefore, we need to ensure that CEBO service is labellised by DATA TERRA. TF takes the responsibility to provide enriched hot data in an interoperable standard on a national or local servers, which that the data generated by TERRA FORMA can be harvested and contributes effectively to national and European-level scientific commons, while reinforcing the long-term visibility and reusability of site-based observations.