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Project Report

Cave Monitoring Network and Long-Term Ecological Research in Portugal

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Abstract

This document describes the Portuguese Cave Monitoring Network (CaveNet), a scientific infrastructure established within the framework of the EcoSub Chair. CaveNet provides an integrated framework for the quantitative monitoring of caves in Portugal, encompassing data collection, validation, processing and storage. The document presents the architecture and objectives of the infrastructure, highlights its scientific and ecological relevance and characterises the sites selected for Long-Term Ecological Research in Portuguese caves (LTER-Grutas). These sites host monitoring stations whose long-term environmental and ecological data are integrated into CaveNet.

The document further discusses the advantages of an integrated cave monitoring network and its direct applicability to the assessment and reporting of the conservation status of habitat type 8310 - Caves not open to the public - under the Natura 2000 framework, as well as to the implementation of the Nature Restoration Regulation. In addition, CaveNet has significant socio-economic value, particularly in supporting the assessment and management of occupational risks associated with exposure to environmental hazards during underground work.

In the longer term, the infrastructure will enable innovative research on carbon fluxes across the atmosphere–soil–subsoil–groundwater continuum, subsurface radioactivity emissions and the implications of subterranean processes for ecosystem services. These

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research and monitoring activities are aligned with the United Nations Sustainable Development Goals and the One Health approach.

At a global scale, CaveNet provides a unique platform for investigating the complex ecological interactions occurring at the surface–subterranean interface. By integrating standardised, long-term observations across multiple cave systems, the network will contribute to a better understanding of subterranean ecosystems, their environmental dynamics and their responses to natural and anthropogenic pressures. It will also provide a robust scientific basis for conservation, environmental assessment, risk management and the sustainable management of subterranean environments.

Keywords

Caves, cave habitats, cave monitoring, karst, LTER, speleology, subterranean ecosystems

Introduction

The study, exploration and protection of caves, which are abundant in karst systems, depend on continuous inventory, study and monitoring work. Systematic monitoring is essential for safeguarding the natural and cultural heritage of caves, ensuring the safety of visitors, explorers and workers and generating long-term datasets of high value for scientific research and education (Gillieson et al. 2022).

Caves are associated with karst aquifer systems that support substantial groundwater resources (Saccò et al. 2025), some of which are used directly for human consumption and are home to a higher proportion of endemic species per habitat in Portugal (Reboleira 2025, Reboleira 2026). Long-term environmental monitoring is essential for detecting temporal patterns and quantifying ecosystem responses to emerging pressures, including climate change, which may increasingly affect subterranean ecosystems of transnational strategic importance (Medina et al. 2023). In the context of increasingly frequent extreme environmental events and growing demands for evidence-based environmental management, the availability of accurate, standardised and timely information is critical for the effective conservation and management of cave ecosystems and their associated natural resources (Novas et al. 2017, Weigand et al. 2022, Fišer et al. 2026).

To address this need, the Chair in Sustainability of Subterranean Ecosystems – Loulé (https://catedraecosub.rd.ciencias.ulisboa.pt), hereafter referred to as the EcoSub Chair, initiated a project to establish and support the implementation of an integrated system for environmental data acquisition, transmission, processing and integration within a national cave monitoring network. This initiative led to the development of the Portuguese Cave Monitoring Network (CaveNet; www.cavenet.pt), a scientific infrastructure designed to support the quantitative and long-term monitoring of cave environments. CaveNet

integrates the processes of data collection, validation, processing and storage, providing a standardised framework for the management and analysis of monitoring data.

The information generated through CaveNet is integrated into the georeferenced database of caves in mainland Portugal, providing technical and scientific support for ecological assessment, natural resource management and land-use planning. At the European level, the infrastructure supports the assessment and reporting of cave-related habitat types under the Natura 2000 network, including habitat type 8310 (Caves not open to the public) and habitat type 8330 (Submerged or partially submerged sea caves) (EUR-Lex 1992). By integrating spatial information with standardised, long-term environmental observations, CaveNet facilitates the retrieval and analysis of data required to support the assessment and reporting of habitat condition and conservation status within the Natura 2000 framework (Agency 2026).

In addition to integrating existing cave-related information, the CaveNet infrastructure incorporates three long-term monitoring stations, equipped with the "CaveBox" system described by Reboleira et al. (2026). Together, these sites constitute the "LTER-Grutas", a remote environmental monitoring network dedicated to the long-term observation of cave ecosystems in Portugal. Each CaveBox comprises a suite of automated sensors and probes that continuously record environmental parameters relevant to characterising local environmental dynamics and detecting broader environmental change, both within the cave and at its surface. Each unit is connected to a surface-based communication system that enables remote access to monitoring data and integrates measurements from an external weather station, thereby allowing subterranean conditions to be evaluated in relation to surface environmental variables.

The three monitoring stations are distributed across two major karst regions of Portugal: one in the Algarve karst massif, at Vale Telheiro Cave in southern Portugal and two in the Estremenho karst massif, at the Algar do Pena Cave Interpretation Centre and the Mira de Aire cave system in central Portugal. The network has been designed to accommodate additional monitoring sites that meet the ecological and methodological standards established for participation in international Long-Term Ecological Research (LTER) networks (Zacharias et al. 2026).

Continuous monitoring of a broad suite of ecological and environmental parameters began in 2024 through the project “Barrocal-Cave – Conservation, monitoring and restoration assessment of the world-class cave biodiversity hotspot in Portugal”, funded by the Belmiro de Azevedo–FCT Prize (ref. 2023.10009.PRIZE), with support from the Municipality of Loulé. CaveNet was subsequently established in 2026 to provide an integrated national framework for the monitoring and assessment of subterranean habitats, with particular relevance to habitat type 8310 (Caves not open to the public) under the Natura 2000 network.

By combining standardised field observations, automated long-term monitoring, data validation, processing and geospatial integration, CaveNet provides a coordinated evidence base for the assessment of subterranean ecosystems. The infrastructure has

applications in biodiversity conservation, nature restoration, surface land-use planning and environmental decision-making, while also providing data of potential relevance to disciplines including geology and environmental health. In particular, environmental measurements generated by the network can contribute to the identification and assessment of environmental conditions relevant to occupational exposure and health risks associated with underground work. This study describes the architecture, objectives and operation of the Portuguese Cave Monitoring Network (CaveNet), with particular emphasis on the LTER-Grutas monitoring component. It further discusses the scientific and ecological relevance of the infrastructure, its potential applications in environmental assessment and conservation and its contribution to the development of a long-term observation framework for subterranean ecosystems.

Long-Term Ecological Research in caves of continental Portugal

What are Caves?

Caves are natural cavities in the subsoil with permanent darkness, large enough for a human being to fit inside and they are public domain according to Article 84 of the Constitution of the Portuguese Republic (Reboleira 2025).

The caves of Portugal have crucial ecological relevance, harbouring > 150 specialised and endemic species of the country. There are more than 1000 cave sites registered in the Cave Monitoring Network of the Chair EcoSub (Fig. 1). Most are in the continental territory, with registered cave entrances in the archipelagoes of the Azores, Madeira and Selvagens (Reboleira et al. 2011).

Caves have total darkness and great environmental stability, little thermal amplitude, higher CO_2 and Radon and lower O_2 levels than the surface and low organic matter content (White et al. 2019). Caves are the exclusive habitat of highly specialised terrestrial organisms, adapted to a subterranean lifestyle and whose entire life cycle is underground – troglobionts (Troglobionts of Portugal: Reboleira (2026)). Caves are also shelters of national importance for bat species (Rainho 2013) and refuges for rare surface species at certain times of the year, providing ideal conditions for nurseries, egg-laying and the development of juveniles of some species, including protection from predators and thermal extremes (Reboleira 2025).

Caves are wetlands and habitats for aquatic species with their entire life cycle in groundwater – stygobionts (Stygobionts of Portugal: Reboleira et al. (2013)). Since 2026, the monitoring of these species has been imposed on Member States by the European Union in the consolidated document of the Water Framework Directive (EUR-Lex 2026). Groundwater ecosystems are fundamental for the purification and maintenance of groundwater quality, being responsible for recycling organic matter and pollution that seeps deep underground (Castaño-Sánchez et al. 2020). Therefore, they are essential for mitigating the effects of global climate change. From a holistic perspective, their role is fundamental for all ecosystems dependent on groundwater, such as rivers, lakes,

temporary ponds and, obviously, for all surface habitats, since they all depend on plants that feed on groundwater (Saccò et al. 2024).

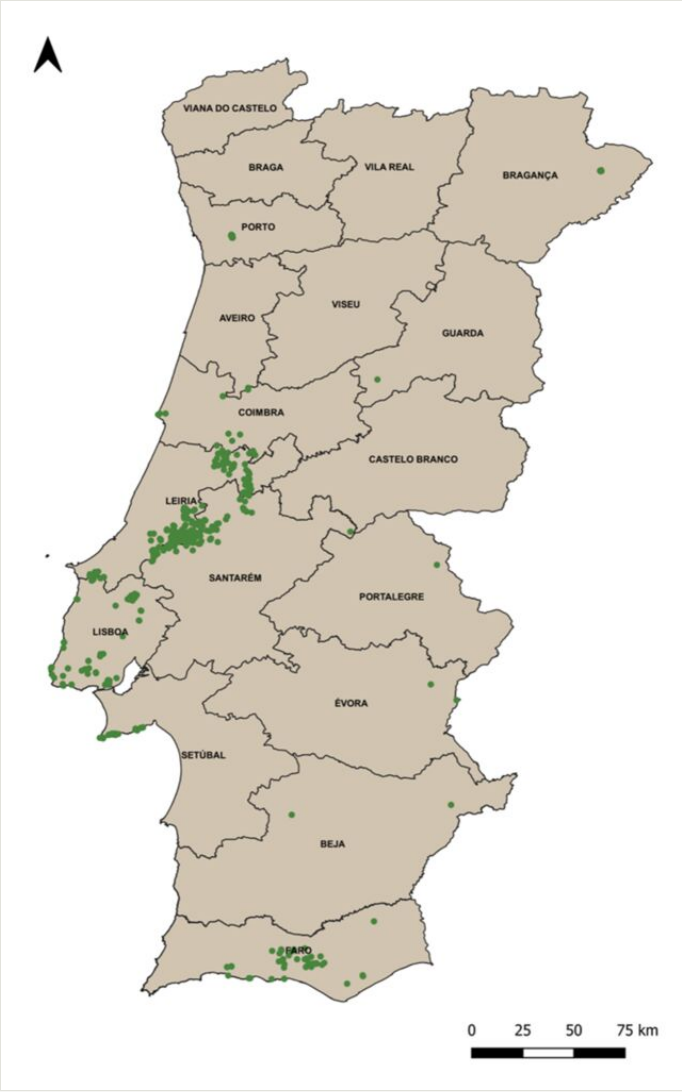

Figure 1.

Caves of continental Portugal.

Why Caves?

The "LTER-Grutas" (www.ltergrutas.pt) comprises three caves – Gruta do Vale Telheiro, Algar do Pena, and Grutas de Mira de Aire – which share the environmental characteristics of caves, e.g., absence of light and thermal stability. These sites are distributed in different areas of the country and in regions with different climates and

types of disturbance, which allow a comprehensive view of subterranean ecosystems in space, time and along a gradient of anthropogenic disturbance.

Objectives

The LTER-Grutas has the following main objectives:

- Monitoring subterranean biodiversity and its spatiotemporal variability;
- Characterising Carbon, Oxygen, and Radon flows between caves and the surface;
- Assessing the effects of climate change on temperature, humidity, and air circulation in caves;
- Characterising hydrological flows between the surface and the subterranean system;
- Studying the dynamics of carbon and biogeochemical cycles in ecosystems in the atmosphere-soil-subsoil-groundwater continuum;
- Distinguishing national priority habitats, aligned with the EU Natura 2000 strategy;
- Evaluating the potential for planetary analogues for space exploration and astrobiology;
- Understanding the impacts of human activities, such as changes in land use, groundwater extraction and tourism pressure on cave habitats;
- Developing ecological indicators to support the conservation and restoration of subterranean ecosystems.

All the objectives of LTER-Grutas converge on providing a solid scientific base to provide information for the European and national ecological conservation and restoration strategy targets. Crucial for complying with the Habitats Directive (EUR-Lex 1992), EU Soil Strategy in 2030 (EUR-Lex 2021), General Union Environment Action Programme to 2030 (EUR-Lex 2022), and Nature Restoration Regulation (EUR-Lex 2024). Additionally, at the national level, with the National Strategy for Nature Conservation and Biodiversity 2030 (República 2018), essential in point 4.5 of the strategy “deepen the integrated and coordinated application of policies for the management of water quality and quantity and the promotion and management of ecosystems, species and habitats dependent on waterbodies (surface and groundwater), as well as the maintenance and recovery of ecosystem services associated with the supply of water in quantity and quality for domestic and industrial consumption, soil conservation and the maintenance of biodiversity (...) and essential options for achieving the relevant management objectives of protected areas and the Natura 2000 Network”, for "The implementation of the aforementioned measures contributes to the fulfilment of the objective, identified in the strategic matrix, 3.5 - To guarantee the sustainable use of resources in inland waters and river systems".

LTER-Grutas is also a fundamental tool in two priority areas for complying with legislation protecting workers against risks related to carcinogenic or mutagenic agents' exposure, such as Radon, during work (República 2020). It provides solid scientific information for the National Radon Plan (República 2022), which establishes a set of actions aimed at

minimising exposure to this gas and reducing the incidence of associated lung cancers. Furthermore, it generates the necessary knowledge for compliance with EU Council Directive (EUR-Lex 2013), which lays down basic safety standards relating to protection against the hazards resulting from exposure to ionising radiation.

Environmental Monitoring

LTER-Grutas includes a network of automatic sensors that continuously record environmental parameters and transmit it in real time. The CaveBox continuously measures:

- Temperature of the atmosphere and soil, in the cave and at the surface;
- Relative humidity of the atmosphere and soil, in the cave and at the surface;
- Concentration of carbon dioxide (CO_2), oxygen (O_2) and radon (^{222}Rn) in the cave atmosphere;
- Atmospheric pressure at the surface and in the cave;
- Precipitation at the surface;
- Intensity of dripping water in the cave;
- Direction and intensity of wind at the surface;
- Direction and intensity of air displacement at the interface between the cave and the surface;
- Seismic movements inside the cave;
- Intensity of solar radiation at the surface.

In addition to this remote data acquisition process, there is the basic characterisation of each site and biological monitoring (Reboleira 2012), which focuses on different ecological groups, namely: troglobionts, stygobionts and microorganisms.

The use of standardised methods allows for the comparison of long-term time series and the assessment of population trends, as well as the health of subterranean ecosystems in the context of One Health, where caves act as critical environments for bats' reservoir and interface for zoonosis spillover (Festa et al. 2025). All of this is essential for evaluating the conservation status of endemic species in Portugal, as well as updating their status on the Red Lists of the International Union for Conservation of Nature (IUCN) and now also on the Green Lists for evaluating restoration.

The data obtained will contribute to understand functioning and spatiotemporal dynamics of subterranean ecosystems, as well as their connection to surface climatic conditions, thereby opening a window into the complex ecological study of the surface-subterranean interface.

Scientific relevance

LTER-Grutas constitutes a strategic infrastructure for various areas of knowledge and management of the national territory, allowing:

- Understanding the effects of global changes integrated into the atmosphere-soil-subsoil-subterranean continuum;
- Developing conservation and ecological restoration programmes, based on scientific evidence;
- Supporting sustainable management policies for caves and karst areas;
- Validating indicators for monitoring Ecological Restoration, considering the vertical dimension of the territory;
- Promoting transdisciplinary research in the areas of biology, ecology, medicine, education, geology, geophysics, hydrology, and conservation.

Socio-economic value

Caves have unique scientific and educational value, serving as a natural laboratory for biology, geology, history, archaeology and anthropology, attracting cutting-edge scientific research and academic training (White et al. 2019). Caves are tourist attractions, generating direct revenue through entrance tickets, guided tours and speleotourism activities and boosting local economies by stimulating commerce, restaurants and lodging in their territories, creating direct and indirect jobs and helping to avoid depopulation (Gillieson et al. 2022).

In addition, caves have an important role in the cultural identity associated with traditions and legends (e.g., "Mouras Encantadas") (Oliveira 1898), the historical and spiritual uses by local communities (Veiga 1982), and its unique natural heritage composed of endemic species, which reinforce the human sense of belonging and Portuguese intangible heritage. The economic importance of caves is also intrinsically linked to groundwater resources. These are essential for water supply, for domestic, agricultural and industrial use in karst areas, as well as for all ecosystems dependent on groundwater, such as springs, rivers, lakes, temporary ponds and, consequently to all plants (Castaño-Sánchez et al. 2020). It is worth noting that Portugal has the largest karst aquifer in the Iberian Peninsula, the Estremenho massif (de Figueiredo et al. 2024). All of this makes the conservation and sustainable use of caves a strategic investment, capable of reconciling environmental protection with lasting economic and social benefits.

Innovation

The most innovative aspects of LTER-Grutas, beyond remote data acquisition, is the integrated ecological approach to the atmosphere-soil-subsoil-groundwater continuum, which allows for the analysis of how ecological processes on the surface influence the functioning of subterranean ecosystems and vice versa.

In the long term, collected data will provide valuable information for studying carbon flux in the atmosphere-soil-subsoil-groundwater-atmosphere continuum, water and nutrient cycling in karst, deep development of plant roots, hydrological connectivity, radioactivity emission from the subsurface, biodiversity dynamics of endemic specialised species (troglobionts, stygobionts, microorganisms) and the implications for ecosystem services,

aligned with the United Nations Sustainable Development Goals and the One Health approach.

This integrated approach contributes new information with immediate application in the management and conservation of karst landscapes and in the context of the ongoing National Ecological Restoration Plan (República 2024).

LTER Gruta do Vale Telheiro

The LTER Gruta do Vale Telheiro is a world-class hotspot of subterranean biodiversity, in the Municipality of Loulé, in the Algarve, Portugal. It is one of the few places worldwide and the only one in Portugal, with this classification (Pennisi 2016). It constitutes a scientific infrastructure dedicated to the long-term ecological monitoring of subterranean ecosystems in an Atlantic karst environment with Mediterranean influence (Fig. 2). It is part of the Local Natural Monument of Gruta do Vale Telheiro (República 2026a) – the first protected area of troglobitic fauna in Portugal – and a geosite of the UNESCO Algarvensis Global Geopark. It is located in the heart of the Barrocal, a critical area of sensitivity and vulnerability for national water resilience and in the Barrocal Special Conservation Zone (República 2026b), an ecosystem of high importance for the conservation of subterranean biodiversity. This station integrates multidisciplinary approaches that allow us to understand the ecological, hydrological and climatic dynamics of caves over time.

Figure 2.

Surface of Vale Telheiro Cave with the Long-Term Environmental Monitoring Station installed in July 2026, in Loulé, Portugal.

The Vale Telheiro Cave harbours a diverse community of subterranean organisms, including > 20 endemic troglobionts and a wide diversity of microorganisms, adapted to the extreme conditions of lack of light, high humidity and reduced availability of energy resources (Reboleira 2025, Reboleira 2026, Reboleira et al. 2026). Continuous monitoring of these organisms allows understanding the assessment of changes in the composition and abundance of communities, as well as the identification of responses to environmental changes induced by natural and anthropogenic factors. This particular site opens a window to the knowledge of shallower subterranean ecosystems.

The LTER Gruta do Vale Telheiro was created with the support of the Barrocal-Cave project, funded by the Belmiro de Azevedo-FCT Award 2023, and the Chair in Sustainability of Subterranean Ecosystems – Loulé. Its environmental monitoring has been ongoing since 2008. According to the regulations of the Local Natural Monument (República 2026c), visitation is conditional on scientific activities.

The sustainability of the LTER Gruta do Vale Telheiro is formalised in a protocol with the Loulé Municipality, which owns the land where the cave is located and is responsible for managing the protected area (Local Natural Monument) in which it is situated.

LTER Gruta do Algar do Pena

The LTER Gruta do Algar do Pena is located in the homonymous Interpretation Centre in Alcanede, Santarém, Portugal. It is an interpretive infrastructure, dedicated to the long-term monitoring of the deep karst environment and allows some limited public visitation (Popova 2022). In the heart of the Serras de Aire e Candeeiros Natural Park (PNSAC), Pena is habitat for endemic species of the Estremenho massif (Reboleira et al. 2011). This station includes an underground laboratory (Fig. 3), with a stable temperature of ~ 14°C, which allows the development of experimental research with subterranean organisms' endemic to the Estremenho massif, providing unique opportunities for understanding the ontogeny, life cycles and ecophysiology of subterranean species.

The Algar do Pena Cave is home to a diverse community of subterranean organisms, including endemic troglobites and microorganisms, adapted to the extreme conditions of the deep subterranean habitat (Reboleira et al. 2011, Reboleira and Eusébio 2021, Popova 2022, Reboleira et al. 2022, Reboleira and Eusébio 2023, Alves and Reboleira 2024). There is also an endemic species exclusive to this cave, the millipede *Cylindroiulus villumi* (Reboleira and Enghoff 2018).

The cave allows easy access to the deeper underground ecosystems via stairs and an elevator. The cave is closed and the entry is made through the building. Public visitation is regulated by the Institute for Nature Conservation and Forests (ICNF), through the PNSAC, requires prior authorisation and has a defined carrying capacity per visit, with a maximum of 13 visitors (Popova 2022).

The Alcanede Secondary School, through its Science Club, developed collaboration in the infrastructure, actively participating in the monitoring of cave-dwelling species in

Algar do Pena Cave. The project entitled "Citizens & Science" also led to the organisation of the first Congress “Cientistas de Palmo e Meio”, which brought together > 500 national elementary school students in Alcanede in 2019, with its second event taking place in 2025, thus positioning this place prominently in the cave environmental education of younger generations at the national level.

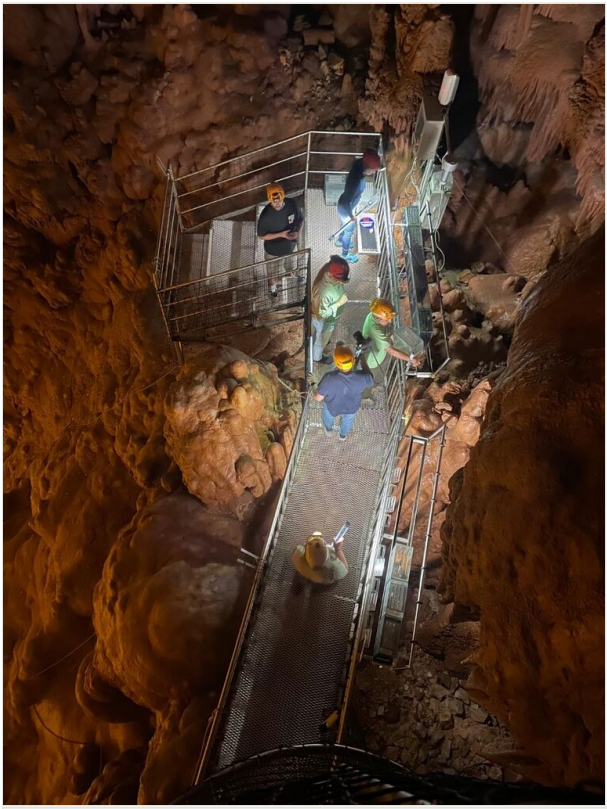

Figure 3.

Subterranean Laboratory in the Algar do Pena Cave in June 2026, Serras de Aire e Candeeiros Natural Park, Portugal.

The sustainability of the LTER Gruta do Algar do Pena is formalised in a protocol with the Institute for Nature Conservation and Forests, the entity that owns and manages the infrastructure where the cave is located.

LTER Grutas de Mira de Aire

LTER Mira de Aire Cave is located in the Moinhos Velhos-Contenda Cave system, commercially concessioned under the name Grutas de Mira de Aire, Municipality of Porto de Mós, Portugal. It constitutes the largest infrastructure dedicated to cave tourism in Portugal and allows public visitation of >300,000 visitors per year.

It is located in the town of Mira de Aire and the vast non-tourist extension of the cave, which extends to the Municipality of Alcanena, is inhabited by troglobionts (terrestrial) and stygobiont (aquatic) species, endemic to the Estremenho karst massif (Reboleira 2007, Reboleira and Eusébio 2021, Reboleira et al. 2022, Alves 2024, Alves and Reboleira 2024). This station houses a subterranean laboratory, with a stable temperature of ~ 18°C, which allows experimental research with subterranean organisms endemic to the Estremenho massif and has access to electricity and internet inside the cave.

This station allows the *in situ* study of the impacts of anthropogenic activities on the cave habitat, while also serving as a point of excellence for cave environmental education. It allows recording of visitation rates, length of stay and assessment of its impacts in the cave environment. It also includes a "House of Knowledge", an infrastructure at the surface of the cave, dedicated to disseminating cave science in the area, created following the celebration of Ecology Day in 2021 (Fig. 4).

Figure 4.

Tourist section of the Mira de Aire Cave, Serras de Aire e Candeeiros Natural Park, Mira de Aire, Portugal. Study visit during the celebration of Ecology Day 2021.

The sustainability of the LTER Grutas de Mira de Aire is formalised by protocol with the company Grutas de Mira de Aire, SA and the Institute for Nature Conservation and Forests, respectively the owner of the concession where the cave is located and the national authority responsible for managing the protected area where it is located, the Serras de Aire e Candeeiros Natural Park.

This station contributes to ensuring a balance between human presence and the conservation of the speleological, ecological and scientific natural values of the site.

Advantages of the National Integrated Cave Monitoring Network

The Portuguese Cave Monitoring Network (CaveNet) integrates the data from LTER-Grutas, working on a spatial and temporal scale with the capacity to produce continuous time series and capture dynamics of subterranean ecosystems that are impossible to detect in the short term. It guarantees open access to cave data in real time, in their respective websites, ensuring the archiving, calibration and public data sharing, under FAIR principles for scientific data. Long-Term data availability is ensured due to its online and physical storage at the infrastructure partners and local and national authorities, such as municipalities, Natural Protected Areas and the Institute for Nature Conservation and Forests.

The creation of the multidisciplinary Portuguese cave monitoring network, which unites biotic, abiotic, hydrological, climatic, geological and geographic data on a single platform, has the clear advantage of allowing the anticipation of collapse or flood risks and can also provide aid support civil protection in underground search and rescue situations. Under a public health point of view, it allows the establishment of thresholds to protect workers against risks related to exposure to toxic, carcinogenic or mutagenic agents during work, due to the continuous monitoring of harmful levels of gases, O_2, CO_2 and ^{222} Radon, which, in caves, are considerably far from the levels considered safe.

It has an immediate social and strategic national impact, with the active involvement of local populations, companies, policy-makers and stakeholders in the co-creation of cutting-edge scientific knowledge with a direct impact on understanding and mitigating global changes. CaveNet stands out in adding the vertical dimension of the national natural territory to ecological monitoring. It provides a main instrument for incorporating the subterranean environment data to support conservation and land-use management decisions in karst areas of Portugal. Moreover, it is fundamental for strengthening scientific research on a largely unknown natural heritage, some of them included in UNESCO sites, such as the Algarvensis and Oeste Global Geoparks and the Arrábida Biosphere Reserve.

Its international relevance stands out in allowing direct alignment with the objectives of the Long-Term Ecosystem Research in Europe network of the European Strategic Forum for Research Infrastructures, integrating, for the first time, the cave habitat typology, whose standard ecological monitoring is currently lacking.

Future perspectives

The integration of LTER-Grutas into national and international long-term ecological research networks will allow for the comparison of Mediterranean subterranean and karst systems with others on a global scale. The combination of continuous environmental monitoring, biological inventories, molecular techniques (eDNA and metabarcoding) (Saccò et al. 2025) and computational modelling will contribute to improving the understanding of the resilience of subterranean ecosystems and to supporting conservation and ecological restoration strategies, based on scientific evidence. It will allow understanding the dynamics of subterranean emissions of greenhouse gases, such as CO_2, in the atmosphere-soil-subterranean continuum, which causes global warming, essential for calculating global carbon budgets.

The Portuguese Cave Monitoring Network (CaveNet) infrastructure, integrating the Long-Term Ecological Research in Portugal (LTER-Grutas), represents a natural laboratory of excellence for ecological and climatic studies, reinforcing the country's role in international research on subterranean biodiversity, climate change and the sustainability of subterranean and karst ecosystems.

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Conflicts of interest

The authors have declared that no competing interests exist.

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