MULTITEMPORAL SEAGRASS MAPPING AND MONITORING OF POSIDONIA MEADOWS AND BANQUETTES FOR BLUE CARBON CONSERVATION: THE POSEIDON PROJECT

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Abstract

In the framework of mapping underwater environments, Posidonia Oceanica (PO) is a fundamental indicator for environmental monitoring and related studies and analyses for climate change. The POSEIDON project aims to study, develop and test new methodologies to provide knowledge, as well as ultra-high-resolution (UHR) and beyond ultra-high-resolution (BUHR) mapping and monitoring data for the conservation of the PO and related meadows and banquettes in the Mediterranean area. The project is funded by the National Recovery and Resilience Plan and stems from the recommendation of international organizations (European Environmental Directives, Mediterranean PO Network, International Partnership for Blue Carbon, Intergovernmental Oceanographic Commission of UNESCO in the Save the Wave project). Starting from new integrated survey methods and legacy data, the PO, ichthyofauna and seagrass banquettes will be mapped to understand their evolution and extract indicators and useful trends. Furthermore, the produced information will be stored and shared in a webGIS and a dedicated app to prevent unexpected damages during sailing or other activities. POSEIDON will use imaging sensors (RGB and multi/hyperspectral cameras) to extract information. With specific lighting equipment for significant water depths, these sensors will be conducted (by scuba divers or Autonomous Underwater Vehicles) next to the object to acquire BUHR data. Finally, to monitor the fauna (fish, other species, invertebrates), terrestrial and underwater videogrammetry will be applied using mono and stereo-cameras with object detection algorithms.

1. Introduction

The ocean covers approximately 70% of Earth’s surface and provides the largest liveable space on our planet; nevertheless, only 29.4% of the global seafloor has been mapped up to 2023 (Seabed2030 project, 2023).

In this context, mapping the Posidonia Oceanica (PO) can constitute a significant step in understanding the marine habitat and conditions, aside from investigating the effects of climate change.

In particular, PO is a slow-growing marine seagrass endemic to the Mediterranean that benefits the ecosystem in terms of biodiversity and some fundamental environmental functions, such as carbon sequestration, nutrient cycling, erosion prevention, and tourism benefits. This seagrass is fundamental throughout its life cycle, both when it lives underwater and when it settles on the beaches at the end of its life cycle. In fact, when dead, phanerogam leaves accumulate on beaches in the form of banquettes, which is very important for the ecosystem, both in terms of biodiversity and to protect beaches from marine erosion.

Regarding the monitoring of PO and banquettes, on one side, an Italian-level PO health status monitoring methodology is defined by the Higher Institute for Environmental Protection and Research (ISPRA), on the other side, no monitoring is provided at the regulatory level for the banquettes.

In detail, ISPRA's methodology defines the sampling plan and the parameters to be analysed. It involves the collection of: i) some bundles by ripping them out of the prairie and ii) visually estimated parameters. Since snatching bundles is not healthy for the PO and visual estimates made in the field may not always be accurate, the POSEIDON project aims to support these monitoring steps. This overall goal will be pursued through *ultra-high-resolution* (UHR) and *beyond ultra-high-resolution* (BUHR) data collection and mapping which will enable the experienced operator to estimate the parameters a posteriori by achieving higher resolution (centimetre and sub-centimetre).

1.1 Objectives

The POSEIDON project (www.poseidon-pnrr.eu) encompasses four objectives, each addressing crucial environmental conservation and management aspects. Firstly, there will be a focus on bolstering the implementation of Environmental European Directives through the integration of novel digital techniques and methodologies. This objective involves aligning with the *European Integrated Maritime Policy* (IMP), which emphasizes a cohesive approach to maritime issues, fostering better coordination among various political sectors and stakeholders. Within this framework, activities like the *Maritime Spatial Planning* (MSP) emerge as pivotal actions carried out by the EU to address environmental concerns.

Moving on, another core objective revolves around enhancing the efficiency of seagrass monitoring for effective management and planning. Coastal marine ecosystems are intricately influenced by climate and human-induced changes, underscoring the need for robust monitoring strategies. Here, the POSEIDON project advocates for non-destructive, quantitative, georeferenced, detailed, and accurate monitoring techniques, recognizing seagrass meadows as critical indicators of water quality and overall seascape health.

Furthermore, the project aims to develop reproducible best practices within the Mediterranean basin, acknowledging the global significance of simulating marine environments to comprehend their sensitivities to climate change. Despite advancements in global sea modelling, a notable gap exists in delivering accurate local-scale information. Hence, the project proposes the development of a local sea model grounded in monitoring results and collaboration with stakeholders, paving the way for improved coastal planning and environmental assessment procedures.

Lastly, the POSEIDON project emphasizes disseminating awareness and knowledge regarding priority habitats and *Natura 2000* marine sites, particularly focusing on protecting PO meadows under the Habitat Directive 1992/43/EEC. Despite their designation as protected habitats, PO meadows face significant regression across the Mediterranean region due to climate change and human impacts. Thus, additional efforts to raise awareness about the importance of PO banquettes systems become paramount in safeguarding these vital ecosystems.

1.2 State-of-the-art

As mentioned above, seagrasses are the most important marine coastal ecosystems. They have a key role in ecosystem functioning and services, providing blue carbon sequestration and nutrient cycling, forming habitats, nursery grounds, sediment stabilization and trophic transfer to other habitats (Hemminga and Duarte, 2000). Several local anthropogenic stressors, such as sediments and nutrient inputs, physical disturbance, in combination with climate change effects (Marbà and Duarte, 2010; Smale et al., 2019) have put seagrasses under high pressure over the past decades (Waycott et al., 2009; Ceccherelli et al., 2018). In the Mediterranean Sea, PO is the most important seagrass for the variety and extension of its meadows. It performs many ecosystem services even when it is on the beach, where wrecks (dead leaves, broken rhizomes and leaf bundles) accumulate in banks, commonly known as banquettes (Rotini et al., 2020). Banquettes protect the beaches from erosion of swell and waves, particularly during the winter season (Fonseca and Cahalan, 1992), while the residual nutrient content of PO dead matte constitutes an important input of nitrogen and carbon. The PO presence is used as a biological indicator of water quality and health by Annex V of the *Water Framework Directive* (WFD, 2000/60/EC) (Montefalcone et al., 2009), where seagrasses are listed as biological quality elements to be used in assessing the ecological status of coastal water bodies (Foden and Brazier, 2007). Despite all these benefits, PO is increasingly at risk and sometimes in decline (Telesca et al., 2015), leading in the last two decades to increasing restoration efforts to compensate or mitigate PO loss and to enhance the associated ecosystem services (Pansini et al., 2022). Then, protected PO habitats need to be monitored for correct and prompt management: a replicable, complete, accurate, multitemporal and multiscale model able to describe the marine system formed by the PO banquettes in local areas is necessary, combining in a common spatial environment all the useful parameters, indicators and metrics. During the last decades, several techniques have supported seagrass mapping (Pasqualini et al., 2001), from Multibeam Echo-Sounding, Side Scan Sonar, Laser Imaging Detection and Ranging to panchromatic and multi-spectral data from satellites and Uncrewed Aerial Vehicles (Veettil et al., 2020). In this regard, multi/hyperspectral satellite sensors (i.e., Sentinel 2 MSI and PRISMA) have been successfully tested to monitor the stress level of PO (Borfecchia et al., 2021): time-series imagery exploits high-resolution data, while up-to-date sensors and techniques would allow to achieve even ultra-high resolution also for the time-series.

More recently, photogrammetry is also increasingly being used to monitor the state of PO and the outcome of restoration projects, to derive finer-scale measurements with respect to the other geomatics techniques (Rende et al., 2022). In particular, monitoring protocols with underwater photogrammetry entail the integration of GNSS–RTK positioning performed with a small boat, depth measurements and a diver-operated underwater propulsion vehicle for image collection. The Autonomous Underwater Vehicles (AUV) are thus crucial to build ultra-high resolution coverage maps (Burguera et al., 2017) and 3D models (Rende et al., 2015). Hyperspectral imaging has also been applied for habitat mapping (Foglini et al., 2019) and its classification, still its correlation with other indicators has not been considered yet, and machine learning techniques (He et al., 2022) are still in the initial research stages when dealing with the underwater environment.

Object-based image Analysis (OBIA) are, for example, employed to count transplanted PO fragments and estimate the bottom coverage. From the resulting digital maps, analyses and measures such as the mean height of transplanted fragments and variation of seabed vector ruggedness measure are derived. Aiming at the preliminary characterization of seagrass habitats exploiting OBIA methods, Rende et al. (2020) discussed the integration of underwater photogrammetric orthomosaics with acoustic bathymetric data and multispectral satellite images. These systems allowed to map of the distribution of PO meadows over Europe (Telesca et al. 2015), but integration with the banquettes and the contemporary analysis of the shallow invertebrates and ichthyofauna is still missing to ameliorate and consolidate a complete general framework. Furthermore, new sampling techniques should be developed relying on novel tools and monitoring methods that can substitute or assist the traditional ones.

1.3 Areas of study

The research will be conducted in several marine protected areas (MPAs) of Sardinia, an Italian island in the Mediterranean Sea (Figure 1). In particular, POSEIDON focuses on:

- the MPA *Capo Testa Punta Falcone*, which encompasses approximately 5,000 hectares of open sea, located in the far north of Sardinia;
- the MPA *Capo Carbonara* that encompasses roughly 14,360 hectares, in the south-east part of Sardinia;
- the MPA *Tavolara and Punta Coda Cavallo*, in the north-east of Sardinia;
- the port area of *Porto Torres*;
- the *Culuccia peninsula*, which is about 12 kilometres away from AMP *Capo Testa Punta Falcone*.

In particular, it is reported that both the Porto Torres study area and the MPA Capo Carbonara have some replanting areas of PO, which are crucial for the aims of the project. Finally, the Culuccia peninsula is chosen as the testbed.

2. Actions

POSEIDON is set to roll out a suite of innovative tools and methods aimed at the *ultra-high resolution* (UHR) mapping of maritime ecosystems, marking a significant stride toward

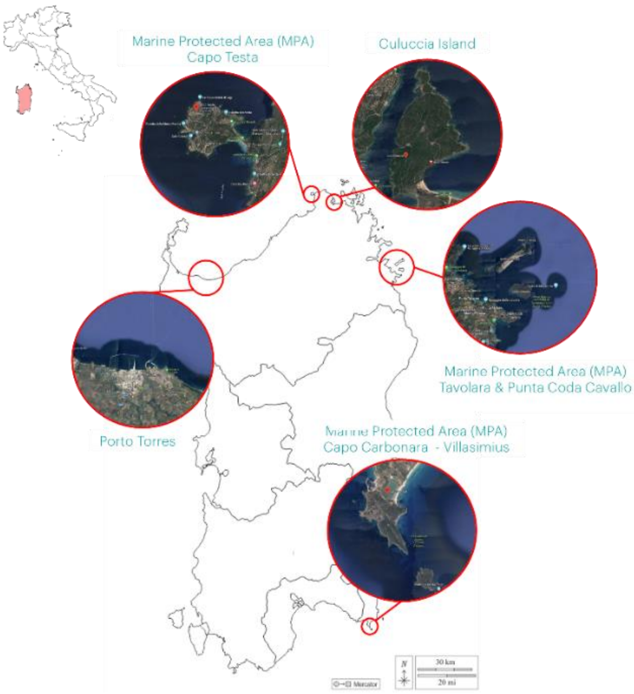

Figure 1. Location of case study areas.

supporting the implementation of the *European Integrated Maritime Policy*. This comprehensive digital approach entails the development of integrated tools capable of mapping and monitoring maritime ecosystems with unparalleled precision (a few centimetres in resolution and accuracy).

Such advancements will pave the way for a multitude of actions, including the delineation of spatial indicators for PO-beach systems and the design of a robust framework for multisensory data fusion. Through collaboration with various autonomous platforms such as drones, uncrewed surface vehicles (USVs), and autonomous underwater vehicles (AUVs), the project aims to capture comprehensive data on beaches and shallow seawater (ranging from 0 to 50 meters). Additionally, leveraging machine learning algorithms will facilitate the automatic extraction of UHR thematic maps, streamlining the process of data analysis and interpretation.

In parallel, efforts are underway to enhance the contents of multitemporal legacy images acquired through aerial and satellite platforms. Recognizing the imperative for long-term monitoring of PO-beach systems in compliance with the EU Habitats Directive (92/43/EEC), the project seeks to overcome the limitations from low to medium resolution imagery from past decades. This involves the development of novel methodologies, including the application of deep learning super-resolution algorithms, to augment the information content of legacy images. By enhancing the resolution and fidelity of historical data, POSEIDON aims to provide valuable insights into the long-term evolution of PO meadows and banquettes, thereby informing effective conservation strategies.

Furthermore, POSEIDON endeavours to establish a robust Spatial Data Infrastructure (SDI) to describe PO-beaches systems comprehensively. This initiative aims to facilitate seamless data management and sharing by designing an SDI capable of storing all acquisitions, processing, and analysis results generated by the project.

Through direct interaction with stakeholders, the SDI will ensure accessibility and usability, fostering collaboration and knowledge exchange among researchers and users alike. Embracing a user-friendly spatial information system, such as a webGIS solution, will further promote open data sharing and stimulate collaboration in the ongoing conservation efforts.

In pursuit of enhancing the efficiency of PO-beaches systems control, POSEIDON is embarking on a multifaceted exploration of descriptors aimed at monitoring the conservation status of seagrass meadows. This initiative involves delving into various descriptors encompassing morphological, biochemical, genetic, and synthetic aspects. By systematically assessing these descriptors, POSEIDON aims to develop a suite of indicators representing plant physiological stress and environmental disturbance across three biological levels: individual, population, and community.

At the individual level, emphasis is placed on scrutinizing plant morphology and biochemistry to glean insights into the health and vitality of seagrass meadows. Moving to the population level, the focus shifts to evaluating the leaf canopy structure and morphology as indicative of broader ecological health. Finally, at the community level, attention is directed towards assessing the associated flora and fauna, providing a holistic perspective on ecosystem dynamics.

To facilitate the measurement of these indicators, POSEIDON is exploring novel instruments and methods leveraging imaging sensors, including RGB and multi/hyperspectral cameras. These sensors, equipped with specific lighting apparatus for significant water depths, enable the acquisition of high-resolution data in near real-time. Whether deployed by scuba divers or AUVs, these imaging sensors facilitate the capture of detailed imagery crucial for monitoring fauna and other species. Furthermore, terrestrial, and underwater videogrammetry techniques will be employed, utilizing both mono and stereo-cameras equipped with object detection algorithms. This approach allows for the precise measurement of fauna populations and other descriptors, enabling the comparison of traditional measurements with imagery-derived data.

Through rigorous analysis, POSEIDON aims to identify potential correlations between radiometric information (reflectance) and indicators' values. Such correlations could pave the way for the adoption of more cost-effective, rapid, and efficient imaging solutions, thereby augmenting the efficacy of monitoring efforts.

Under the initiative outlined, POSEIDON is innovating a fresh model to portray the dynamics of the local PO-beach system. This ambitious effort involves conducting survey campaigns at various intervals, aligned with the evolving landscape of PO. Data collected from these surveys will be meticulously stored in the SDI and subjected to rigorous analysis to uncover temporal trends, spatial correlations, and other significant relationships.

Leveraging this wealth of information, POSEIDON aims to construct a conceptual ecological model (CEM) that serves as a comprehensive framework for understanding the intricate interactions shaping seagrass ecosystems within the study areas. Researchers will craft a visual narrative, accompanied by descriptions, to highlight key indicators for drivers, major ecological factors, key attributes, and ecosystem services. By elucidating these relationships, the CEM provides valuable insights into the dynamic interplay between physical and biotic parameters, ecosystem structure, and external drivers, guiding effective management strategies. Ultimately, the ecological factors and services encapsulated within the CEM will be integrated into the GIS and disseminated via webGIS platforms, ensuring accessibility and facilitating broader utilization of the model. Under the initiatives outlined, POSEIDON is embarking on the development of a comprehensive communication plan with the aim of raising awareness among sea users, including tourists and sailors, about the significance of the PO habitat and the EU *Natura 2000* sites. The overarching objective is to foster sustainable behaviour while enhancing understanding and effective management of PO-beaches systems.

Through targeted communication strategies, POSEIDON thus seeks to instil a sense of responsibility and stewardship towards these critical ecosystems.
In the meantime, the project will be actively involved in public dissemination efforts to ensure widespread awareness and engagement among stakeholders at local levels, including schools, representatives from institutions, the scientific community, environmental associations, and civil society.
In parallel, the development of a web-mobile platform, known as the POSEIDON Web App (PWA), will provide a user-friendly interface for accessing project information and resources. This innovative tool will be a hub for sharing POSEIDON-related updates and insights with a diverse audience, including citizens, tourists, policymakers, technicians, and experts, encouraging a culture of knowledge sharing and community engagement.

2.1 Methodology

The POSEIDON workflow follows several steps. PO mapping will be carried out at different scales, from satellite analysis to BUHR, taking into account also the PO health status: degraded, dead or restored (Figure 2).

2.1.1 Satellite scale: At the satellite scale, the goal, through multitemporal analysis of PO, is to assess its trend due to climate change. Specifically, the time window analyzed starts from 2000 to the present (2024). For each year, one acquisition is analyzed, this is because the growth of the plant is resulted very slow (Marbà et al., 1996), while the period chosen is summer, being the time when the leaves are longest (Bay, 1984). The satellites used are Landsat 7 (2000 to 2013), Landsat 8 (2013 to 2019) and PRISMA, hyperspectral satellite (2019 to present).

For the latter, the Water Colour Correction (WCC) of Lyzenga, was used where the variable effects of the water column are compensated by calculating the ratio between two spectral bands with assumed equal attenuation coefficients. As a result, the depth invariant index (DII) is calculated as follows:

$$DII = \ln(R_i) - \frac{k_i}{k_j}\ln(R_j) \tag{1}$$

where R_i and R_j are reflectance of band i and j, the ratio k_i/k_j represent attenuation coefficients between band i and j.

$$\frac{k_i}{k_j} = a + \sqrt{a^2 + 1} \tag{2}$$

where a is calculated like:

$$a = \frac{\sigma_{ii} - \sigma_{jj}}{2\sigma_{ij}} \tag{3}$$

where σ_{ii} and σ_{jj} represents the variance of band i and j, σ_{ij} represent the covariance between the bands. In conclusion, the ration between attenuation coefficients can be rewritten as:

$$\frac{k_i}{k_j} = \frac{\sigma_{ii} - \sigma_{jj}}{2\sigma_{ij}} + \sqrt{\left(\frac{\sigma_{ii} - \sigma_{jj}}{2\sigma_{ij}}\right)^2 + 1} \tag{4}$$

2.1.2 Ultra High Resolution (UHR): Several instruments are used for the UHR scale (Table 1). UAV drones are used for mapping banquettes.

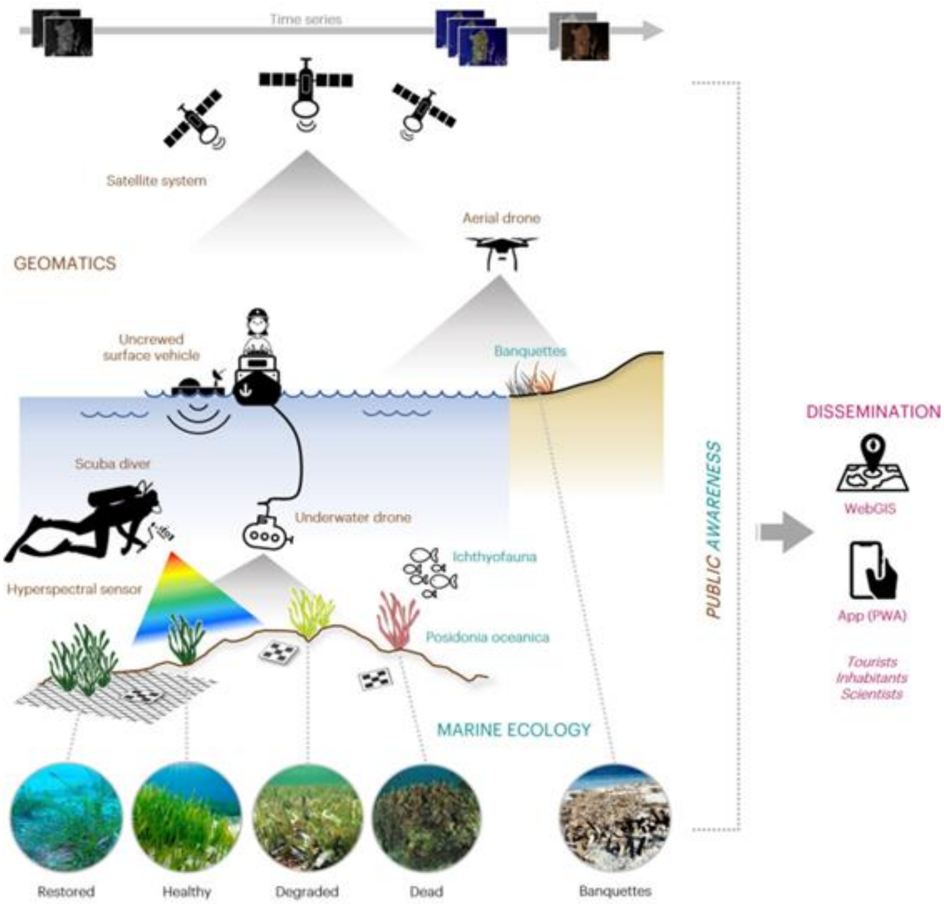

Figure 2. POSEIDON methodology.

As previously said, banquettes are very important both for the protection of beaches from erosion (Gómez et al., 2013) and because a particular well-structured community rich in endemic species is housed within it. POSEIDON tries to address the lack of monitoring regulation, and add innovation on this aspect, using photogrammetric techniques. Since banquettes are constantly changing, through drone mapping and three-dimensional reconstruction it will be possible to estimate their volume and health status. The latter will be investigated by also combining data such as wave motion, temperature and macro-invertebrates on the banquettes in terms of density, biodiversity, and richness.
The drones to be used are different, in particular the DJI Mavic 3M, Matrice 300 RTK, Matrice 350 RTK and DJI Mini 3 (Table 1). As for PO mapping at the UHR scale, the instruments are two, the BlueROV2 from BlueRobotics and an Unmanned Surface Vessel (USV) Manufacturer from MSHeli Srl.
The BlueRov2, with a maximum attainable depth of 100 meters, has an RGB camera with 1080p resolution and a 110-degree horizontal camera field. The main use of the ROV is to map the deepest areas of the PO meadow, between 30 to 40 meters (Vacchi et al., 2012).
Instead, the USV has a WASSP S3 survey multibeam echosounder that with a maximum resolution of 2 centimetres can track the seafloor. The maximum depth that can be reached by the instrument is 350 meters, while the minimum is 1 meter; in addition, the vessel is also georeferenced by a dual GNSS RTK system.

	Name and specifications
	**DJI Mavic 3M** GNSS RTK 5 sensors *RGB 4/3 17.3x13 mm* 20 Mpix, 5280×3956 Pixel size 3.3x3.3 µm Focal length 13 mm *Multispec 1/2.8", 6.058x 4.415mm* 5 MPix, 2592×1944 Pixel size 2.3x2.3 µm Bands: Verde (G): 560 ± 16 nm; Rosso (R): 650 ± 16 nm; Red Edge (RE): 730 ± 16 nm; Near-InfraRed (NIR): 860 nm ± 26 nm Weight 951 g **Maximum detectable depth < 5 m**
	**Unmanned Surface Vessel (USV)** POLITO design MSHeli Srl. Solid print GNSS RTK Multibeam WASSP S3 Transceiver type IP66 DRX-32 Coverage 120° with 224 beems Weight 40 kg **Maximum detectable depth 350 m**
	**BlueROV2 from BlueRobotics** Underwater GPS G2, Waterlinked Weight 11 kg **Maximum detectable depth 100 m**

Table 1. List of instruments used for UHR scale.

2.1.3 Beyond Ultra High Resolution (BUHR): if in the UHR scale it is possible to reach the centimetre scale, with the BUHR the goal is to to reach the sub-centimetre scale.
All instruments at these stages are used by qualified divers, who conduct the cameras at a distance in the range of tens of centimetres from the PO (Table 2).
The first instrument involved at this scale is the Rikola Hyperspectral Imager, with which we map the EO for the first time at the hyperspectral level. Through this tool, the goal is to refine and help ISPRA's monitoring steps.
The other tool is a portable underwater mobile mapping system consisting of a tubular frame with two handles. Two Sony ILX-LR1 cameras with a resolution of 61 MP are affixed to the frame. Two halogen lamps are also installed to be able to illuminate the full spectrum for the hyperspectral camera as well. A handheld device is installed that shows in real time, via photogrammetric reconstruction application (PIX4Dcatch), the acquisition path, allowing precise planning and adjustments.
(Menna et al, 2023) designed a low-cost, lightweight, and portable underwater mobile mapping prototype system called FROG. FROG is engineered on top of a vSLAM stereo-vision system, named GuPho developed by (Torresani et al., 2021) to provide real-time guidance to the underwater surveyor during the image capturing phase, ensuring a more reliable, and effective photogrammetric data acquisition and processing. Given its modular design, FROG can be installed on a micro ROV, and controlled remotely from the support vessel.

	Name and specifications	Weight
	**Rikola Hyperspectral Imager by Senop** Spectral range 500-900 nm 380 spectral channel Spectral resolution 1 nm Focal length 9 mm Pixel size 5.5x5.5 µm 1010x1010 pixels	720 g
	**Sony ILX-LR1** Industrial digital camera Sensor CMOS Exmor R Full Frame 35,7 x 23,8 mm 9504×6336 pixel (61 Mpix) Pixel size 3.8x3.8 µm Focal length 14-24 mm (Sigma)	243 g
	**FROG** 2 digital cameras with 1.3 MP global shutter cameras mounting fisheye lenses with parallel optical axes in normal configuration and baseline of about 250mm. Raspberry Pi4 microcomputer While a mobile phone is used for 3D visualization Max depth 100 m	5 Kg (neutral in water)

Table 2. List of instruments used for BUHR scale.

A further application of mapping at the BUHR scale is to aid and assist the fauna monitoring phase. Currently, measurement is done by a diver, who visually counts fish within a known area, called a transect, with measurements of 50m×4m. With the help of BUHR scale measurements, this count can be self-actualized through artificial intelligence.

3. Preliminary results

An initial test has been performed in the Capo Carbonara MPA related to the satellite scale and PO automatic mapping. RGB bands of Sentinel 2 acquired on 24-12-2023 were used, and the Lyzenga’s method was applied, choosing as bands the Blue and the Green one.
From the first results obtained (Figure 3), the PO on the bottom is clearly visible, particularly the upper limit, while the lower limit is not yet identifiable.

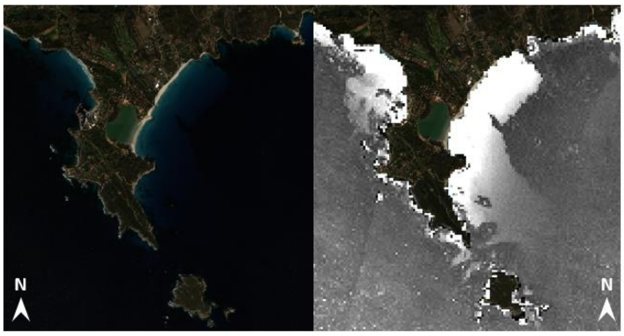

Figure 3. Comparison of uncorrected image (left) with corrected image (right) via WCC with band blue and green.

4. Conclusions

Three quarters of the planet Earth is water and 97.5% of it is salt water. On land we tend to look to the mountains and forests as biosphere reserves and CO_2 filters, but we forget to consider the oceans. Vast underwater Posidonia Oceanica seagrass meadows in the Mediterranean store more CO_2 than forests, and are particularly sensitive to greenhouse gas overload.
The POSEIDON research project is developed with a multi-disciplinary approach fusing geomatics, biology and ecology discipline. Potentially, the application of the POSEIDON methodology based on multi/hyperspectral, multiscale and multitemporal acquisitions can improve the knowledge of PO evolution, monitoring the health, the spatial distribution of seagrass and banquettes and the correlation with environmental parameters. Lastly, it will allow to define new methodologies, systems and solutions to acquire BUHR data, in addition to contribute to the worldwide goal of enhancing the underwater environments and habitats mapping.

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