### 1.2.3 Remote Sensing applied to Coastal monitoring

High-resolution satellite imagery and drone-based platforms facilitate the detection of fine-scale changes in intertidal zones, mangroves, coral reefs, and other critical coastal habitats. These observations enable the quantification of spatial and temporal variations, informing evidence-based strategies for conservation and sustainable management.

Essential Biodiversity Variables (EBVs) and Essential Ocean Variables (EOVs) constitute a framework for systematically monitoring and understanding ecological and oceanographic changes. Based on the model of Essential Climate Variables (ECVs), EBVs provide a standardized set of biodiversity metrics to detect and analyze changes across spatial and temporal scales. These variables act as an interface between raw ecological data and the biodiversity indicators required for global reporting and policy-making. Similarly, EOVs focus on the biological and ecological characteristics of marine systems, emphasizing metrics such as plankton diversity and biomass, fish populations, and the spatial extent of habitats like coral reefs and seagrass meadows. By standardizing biodiversity and oceanic assessments, EBVs and EOVs enhance consistency and comparability across studies and regions (Muller-Karger et al., 2018).

These frameworks address the need for scalable and harmonized observations, aligning with international directives like the Water Framework Directive (WFD[, 2000](https://www.sciencedirect.com/science/article/pii/S1470160X21006981" \l "b0435)/60/EC) and the Marine Strategy Framework Directive (MSFD), which use habitat diversity as an indicator of aquatic health (Borja et al., 2013; Papathanasopoulou et al., 2019; Zoffoli et al., 2021a). Beyond enabling environmental monitoring, EBVs and EOVs provide a foundation for conservation strategies by addressing knowledge gaps and promoting coordinated action among stakeholders. However, evaluating the ecological status of a large number of water bodies using exclusively field observations turned out to be extremely challenging, and the status of many sites has still not been assessed ([Papathanasopoulou et al., 2019](https://www.sciencedirect.com/science/article/pii/S1470160X21006981" \l "b0305)).

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| Figure 1.10: Current capabilities of remotely sensed data for measuring Essential Biodiversity Variables (EBVs; Pereira et al. (2013a)). Adapted from F. E. Muller-Karger et al. (2018). |

Developments in remote sensing have further improved the applicability of EBVs and EOVs (Pereira et al., 2013a; Skidmore et al., 2015). Drone and satellite technologies enable large-scale, frequent observations of biodiversity and marine parameters, facilitating the detection of environmental changes. These technologies support tracking habitat extent, species distribution, and functional traits, incorporating these frameworks into conservation policies. The integration of EBVs and EOVs with RS tools advances ecological monitoring and decision-making at local, regional and global scales. However, past and current satellite missions lack optimal technical specifications (spatial, spectral, and temporal resolution) for full operational capability (Muller-Karger et al., 2018). For some habitats, multispectral resolution may be adequate under certain conditions (Zoffoli et al., 2020a), although risks of classification errors remain. For others, higher spectral resolution is necessary to distinguish taxonomically distinct groups of organisms (Fyfe, 2003; Launeau et al., 2018; Méléder et al., 2018). While satellite acquisitions are essential for covering large areas, heterogeneous habitats often require finer spatial resolutions, positioning drones as the most suitable observation tool. Drone-based studies can also serve as proof-of-concept techniques to refine and develop methodologies that are later applicable to satellite data.

## 1.3 Objectives and Overview

Discriminating between different types of intertidal vegetation using RS poses significant challenges due to overlapping spectral signature in the visible and near-infrared spectral regions caused by similar pigment compositions. This issue is particularly pronounced when comparing green macroalgae and seagrass. In addition to Chla, both green macroalgae and seagrass share the same accessory pigments such as chlorophyll-b and carotenoids. These shared pigments pronounce analogous reflectance patterns, making it difficult to differentiate between these vegetation types using conventional remote sensing techniques, especially in heterogenous habitats where these species often co exist. Despite these challenges, advances in spectral resolution and machine learning provide avenues for improved intertidal habitat mapping. The discrimination of vegetation type through remote sensing relies on differences in their spectral signatures, which might change under stress conditions. While the variability of spectral signatures in terrestrial plants has been well studied, to our knowledge, no studies have examined the variability of spectral signatures in marine vegetation under stress conditions.

**The principal objective** of this work was to demonstrate the effectiveness of remote sensing for mapping intertidal habitats and the environmental pressures they face, by developing advanced methodologies for accurate vegetation classification and ecosystem monitoring.

This goal was reached through specific objectives proposed as follow:

* To analyse the potential of multi- and hyperspectral RS data, for the discrimination among soft-bottom intertidal vegetation types, particularly between green macrophytes during low tide exposed conditions.
* To build an algorithm able to discriminate among the 5 most commun taxonomic classes of vegetation found on soft sediment intertidal substrates: seagrass, MPB, green, red, and brown macroalgae.
* Investigate the capacity of remote sensing to monitor coastal environments under abiotic factors, such as heatwaves events, and biotic pressures, such as biological invasions.

This document is organized in different chapters to respond to specific objectives. **Chapter 2** establishes the foundation by presenting a proof-of-concept study that demonstrates the feasibility of distinguising different types of vegetation using remote sensing. It demonstrates that this technique can effectively separate green macroalgae from seagrasses. By employing both multi- and hyperspectral datasets, the study identifies the number of spectral bands and specific wavelengths that maximize classification accuracy, showcasing the potential of remote sensing for detailed habitat mapping.

Building upon the proof of concept, **Chapter 3** focuses on the development of a robust algorithm called DISCOV v1.0, capable of automating the discrimination of green macrophytes in heterogeneous intertidal habitats. Utilizing high-resolution multispectral drone imagery and advanced machine learning techniques, this chapter addresses the spatial complexity of these environments. The algorithm’s validation across diverse geographic and ecological settings ensures its applicability beyond the initial study sites. This advancement underscores the critical role of cutting-edge remote sensing technologies in ecological monitoring.

In **Chapter 4**, the methodology evolves to include red macroalgae, specifically targeting the invasive species *Gracilaria vermiculophylla*. By updating the algorithm in its v2.0, this study extends its application to a different taxonomic group, demonstrating the flexibility and scalability of the approach. Additionally, this chapter integrates LiDAR-based topographical data to examine the relationship between habitat characteristics and macroalgal distribution. The insights gained from mapping and modeling the spatial dynamics of *G. vermiculophylla* provide valuable implications for managing invasive species and conserving native biodiversity.

**Chapter 5** examines the physiological impacts of environmental stressors, specifically marine and atmospheric heatwaves, on seagrass reflectance. Through controlled laboratory experiments and field validation, this chapter highlights the spectral responses of *Zostera noltei* under heatwave conditions. Well-established spectral indices such as the NDVI and GLI are employed, and a new index, the Seagrass Heat Shock Index (SHSI), is developed to specifically identify heatwave-impacted seagrasses. These indices provide metrics to detect and quantify stress-induced changes. These findings emphasize the role of remote sensing in assessing the resilience and vulnerability of intertidal ecosystems under climate change.

Finally, the **General conclusions and future perspectives** section will close the work, discussing about the broader implication of this work and suggesting future directions for research and application. This section will synthesize the key findings from each chapter, highlighting how the advancements in remote sensing methodologies contribute to improved habitat monitoring and management of intertidal ecosystems. It will also emphasize the potential for these approaches to be adapted to other coastal and marine environments, supporting biodiversity conservation and ecosystem resilience in the face of global environmental changes. Future perspectives will explore opportunities to further enhance remote sensing techniques, such as integrating additional data sources like satellite imagery, and advanced field validation methods. Additionally, potential applications for policy-making, ecosystem restoration, and long-term environmental monitoring will be discussed, emphasizing the critical role of technology in addressing ecological challenges and guiding sustainable coastal management practices.