Introduction

Marine coastal zones are among the most densely populated regions globally, serving as critical hubs for economic activity, transportation, and tourism. These areas support diverse ecosystems and provide essential resources. Additionally, they play a pivotal role in global trade and commerce while also offering cultural and recreational value. However, their popularity and utility make them highly vulnerable to environmental pressures such as pollution, habitat destruction, and climate change impacts like sea-level rise and coastal erosion. Effective management and sustainable practices are crucial to preserving their ecological integrity and ensuring long-term viability.

Marine vegetative habitats in intertidal zones that are exposed at low tide (such as seagrass meadows, microphytobenthos, and macroalgae) are significantly impacted by human activities. Seagrass meadows are under threat due to various anthropogenic activities (McKenzie et al., 2020), microphytobenthos are affected by the global decline of intertidal mudflats (Murray et al., 2019), and areas colonized by macroalgae may be reduced due to the expansion of wild oysters (Le Bris et al., 2016).

These habitats provide vital ecological functions, including coastal erosion protection through root stabilization and sediment trapping (refs), mitigation of eutrophication effects by absorbing excess nutrients and improving water quality (refs), atmospheric CO2 fixation, contributing to carbon sequestration and combating climate change (refs), serving as biodiversity hotspots that support unique flora and fauna, providing feeding, breeding, and nursery grounds for various species. Despite their ecological significance, intertidal zones, particularly mudflats, are challenging to access, and traditional field sampling methods are too time- and labor-intensive to allow repeated observations over large areas. This limitation underscores the need for advanced monitoring technologies to better assess and protect these habitats.

Intertidal habitats, at the interface between marine and terrestrial ecosystems, face significant pressures from both anthropogenic activities and natural forces affecting both realms. Human-induced threats include coastal development, pollution, overfishing, and habitat modification, which degrade these ecosystems and diminish the valuable ecosystem services they provide. Meanwhile, natural factors such as storms, sea-level rise, climatic extreme events and climate change exacerbate these pressures, altering the structure function, and resilience of intertidal habitats. Despite their ecological importance in supporting biodiversity, providing coastal protection, and contributing to nutrient cycling, intertidal habitats remain highly vulnerable. Addressing these challenges requires robust management practices, targeted conservation strategies, and ongoing monitoring to ensure their sustainability and resilience against future pressures.

Regulatory frameworks, such as the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD), emphasize the need for regular mapping of marine habitats to monitor ecological health. These directives utilize habitat diversity as a bioindicator of coastal and estuarine water quality (Borja et al., 2013; Zoffoli et al., 2021).

Satellite remote sensing has emerged as a promising tool for studying essential biodiversity variables in these habitats (Peirera et al., 2013; Skidmore et al., 2015). Remote sensing offers several advantages over in situ sampling: repeated monitoring over large-scale coverage, high-frequency data acquisition, enabling seasonal and phenological studies, reduced costs and logistical challenges compared to field surveys, reconstruction of past conditions when used long time-series.

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., 2020), although risks of classification errors remain. For others, higher spectral resolution is necessary to distinguish taxonomically distinct groups of organisms (Fyfe et al., 2003; Launeau et al., 2018; Méléder et al., 2018). Identification relies partly on the presence of visible absorption bands associated with photosynthetic and accessory pigments, which can be detected and quantified using high-performance liquid chromatography (Méléder et al., 2003, 2005; Bargain et al., 2013; Jesus et al., 2014).

OverviewDiscriminating between different types of intertidal vegetation using remote sensing poses significant challenges due to overlapping spectral signatures in the visible and near-infrared spectral regions caused by similar pigment compositions. This issue is particularly pronounced when comparing green macroalgae and seagrasses. In addition to chlorophyll-a, a pigment found in all vegetal cells, 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 heterogeneous habitats where these species often coexist. Despite these challenges, advances in spectral resolution and machine learning provide avenues for improved classification.

Chapter 2 establishes the foundation by presenting a proof-of-concept study that demonstrates the feasibility of distinguishing different types of intertidal 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 DISCOV 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.

Finally, Chapter 5 examines the physiological impacts of environmental stressors, specifically marine and atmospheric heatwaves, on seagrass reflectance. Through controlled laboratory experiments and field validations, 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.