Characterization of Intertidal Vegetation on European Coasts Using Multi-Scale Remote Sensing in Response to Natural and Anthropogenic Pressures

Simon Oiry

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Abstract

To Be Written

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# Preface

This PhD work was carried out at Nantes University between 2022 and 2024, within the “Remote Sensing, Benthic Ecology and Ecotoxicology” (RSBE²) team of the Institute of Marine Substances and Organisms (ISOMer). This thesis was funded by the Ministry of Research and Higher Education and supervised by the doctoral school “Plant, Animal, Food, Sea, Environment” (VAAME).

## Scientific papers

* Barillé, L., Paterson, I. L. R., **Oiry, S.**, Aris, A., Cook-Cottier, E. J., & Nurdin, N. (2025). Variability of *Kappaphycus alvarezii* cultivation in South-Sulawesi (Indonesia) related to the monsoon shift: Water quality, growth and colour quantification. *Aquaculture Reports*, 40, 102557. https://doi.org/10.1016/j.aqrep.2024.102557
* **Oiry, S.**, Davies, B. F. R., Sousa, A. I., Rosa, P., Zoffoli, M. L., Brunier, G., Gernez, P., & Barillé, L. (2024). Discriminating Seagrasses from Green Macroalgae in European Intertidal Areas Using High-Resolution Multispectral Drone Imagery. *Remote Sensing*, *16*(23), 4383. https://doi.org/10.3390/rs16234383
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* Davies, B. F. R., Gernez, P., Geraud, A., **Oiry, S.**, Rosa, P., Zoffoli, M. L., & Barillé, L. (2023). Multi- and hyperspectral classification of soft-bottom intertidal vegetation using a spectral library for coastal biodiversity remote sensing. *Remote Sensing of Environment*, 290, 113554. https://doi.org/10.1016/j.rse.2023.113554
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## Presentations to International Conferences

* Effect of Marine and Atmospheric Heatwaves on Reflectance and Pigment Composition of Intertidal *Zostera noltei* (February 2025); BioSpace25 - Biodiversity insight from Space, Frascati, Italy; Oral presentation
* Discriminating Seagrasses From Green Macroalgae in European Intertidal Areas using High Resolution Multispectral Drone Imagery (17 - 21 June 2024); Word Seagrass Conference, Napoli, Italy; Poster
* Remote Sensing discrimination of seagrass and green macroalgae: hyperspectral library and drone-mounted multispectral camera (22 - 24 November 2023); EC-ESA Joint Earth System Science Initiative, Frascati, Italy; Poster
* Precision aquaculture drone mapping of the spatial distribution of *Kappaphycus alvarezii* biomass and carrageenan (August 2023); 8th European Phycological Congress, Brest, France ; Oral presentation
* Remote Sensing discrimination of seagrass and green macroalgae: hyperspectral library and drone-mounted multispectral camera (August 2023); 8th European Phycological Congress, Brest, France ; Poster
* Remote Sensing discrimination of seagrass and green macroalgae: hyperspectral library and drone-mounted multispectral camera (23 - 27 may 2022); Living Planet Symposium, Bonn, Germany ; Poster

# 1. Introduction & Overview

**1.1 xxxxx**

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 habitats in intertidal zones over mudflats 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 (Len J. McKenzie et al., 2020a), microphytobenthos are affected by the global decline of intertidal mudflats (N. J. Murray et al., 2019), and areas colonized by macroalgae may be reduced due to the expansion of wild oyster reefs (Le Bris et al., 2016).

These habitats provide vital ecological functions, including 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 a variety of flora and fauna species, providing feeding, breeding, and nursery grounds. Seagrass meadows also offer protection against coastal erosion through root stabilization and sediment trapping, which in turn limits water turbidity (**refs**). 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.

### 1.1.1 Coastal Environments – Ecological and Socio-Economic importance

Coastal environments represent a complex and dynamic interface between terrestrial and marine ecosystems, characterized by exceptional biodiversity, diverse geomorphological structures, and significant socio-economic relevance. These regions span a continuum that includes saltmarshes, beaches, dunes, estuaries, deltas, tidal flats, wetlands, rocky shores, biogenic reefs and lagoons, each shaped by a combination of natural processes and anthropogenic influences (Laignel et al., 2023).

The coastal zone encompasses areas where terrestrial and marine domains intersect, including environments influenced by tidal flows, wave dynamics, and riverine inputs. This transition zone can extend from a few hundred meters inland to several kilometers offshore, depending on local topography and ecological gradients. It incorporates upper shores and dunes, intertidal zones, periodically submerged and exposed by tidal activity, as well as subtidal zones that remain submerged permanently ([Figure 1.1](#fig-CoastalHabitat); Laignel et al., 2023).

As one of the most dynamic and multifaceted regions on Earth, coastal environments host highly diverse and productive habitats. These include both natural ecosystems and managed systems that underpin key economic sectors and urban centers. The functionality of many coastal ecosystems is intrinsically linked to land-sea interactions, as observed in deltas and estuaries. These environments exhibit steep gradients in salinity—from freshwater to hypersaline—and energy levels, ranging from low-energy wetlands to high-energy, wave-dominated shorelines. On a broader scale, coastal regions encompass a spectrum of climatic zones, from tropical to polar, each characterized by unique biogeophysical processes and features. However, these areas are also exposed to a variety of land-based and marine hazards, including storms, tropical cyclones, storm surges, tsunamis, riverine flooding, shoreline erosion, sea-level rise(?) and biohazards such as algal blooms and pollutants.

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| Figure 1.1: Examples of the diversity of habitat found in coastal environment. **A**: Upper shore and dunal vegetation of Pen Bron, France, on the 15th of May 2023. **B**: Rocky shore of the Galician coastaline. Picture took at Baiona, Spain on the 1st of September 2023. **C**: Tidal flat of the Guadlquivir river, Spain. Picture took near of Trebujena, Spain on the 22nd of March 2023. **D**: Submerged seagrass meadows in Greece. Picture took at Nauplie, Greece on the 29th of October 2023. |

Coastal ecosystems provide a range of ecosystem services that are fundamental to environmental sustainability and human well-being. These ecosystems function as natural barriers against storm surges and coastal flooding, thereby mitigating the impacts of such hazards on inland regions and safeguarding human lives and infrastructure. They support significant biodiversity, serving as critical habitats and breeding grounds for numerous species, including commercially valuable fish, shellfish, and other marine organisms that sustain global fisheries. Coastal vegetation, including mangroves, salt marshes, and seagrasses, plays a crucial role in carbon sequestration by capturing and storing atmospheric carbon dioxide, thus contributing to climate change mitigation.

Beyond their role in climate regulation, coastal ecosystems enhance water quality by filtering pollutants, sediments, and excess nutrients, thereby maintaining healthier marine and estuarine systems. These ecosystems are integral to nutrient cycling, ensuring the continued productivity of adjacent marine environments. Additionally, they provide substantial cultural, educational, and recreational opportunities, drawing global attention and fostering an intrinsic human connection to nature. This societal value contributes directly to local and regional economies through industries such as tourism, artisanal fishing, and related enterprises. Furthermore, coastal ecosystems supply essential natural resources, including seafood and plant-based materials, while supporting sustainable aquaculture practices that promote global food security and bolster local livelihoods. Collectively, these functions highlight the indispensable ecological and economic importance of coastal ecosystems.

Coastal areas are among the most significant regions for human habitation due to their strategic geographic position, resource availability, and economic opportunities. Currently, approximately 2 billion people reside within 50 kilometers of coastlines, with nearly 1 billion living within 10 kilometers. This represents nearly 15% of the global population occupying only 4% of the Earth’s inhabitable landmass. Projections indicate that coastal populations will continue to rise, potentially reaching 2.9 billion by 2100 under various socioeconomic scenarios. These areas offer critical resources such as seafood and freshwater, while their moderate climates often support agricultural activities and other forms of sustainable land use. Proximity to oceans and rivers enables robust trade, transportation, and industrial growth, positioning many coastal cities as pivotal economic hubs on a global scale. The ecological and cultural roles of coastal landscapes further contribute to their appeal, attracting populations for both settlement and economic activities.

**1.1.2 Human Activities in Coastal Areas and their Environmental Impacts**

Human utilization of coastal areas spans a range of economic and social activities that highlight both the benefits and challenges of these environments. [Coastal tourism](https://blue-economy-observatory.ec.europa.eu/eu-blue-economy-sectors/coastal-tourism_en) is a significant driver of economic growth, particularly in regions like the European Union (EU). In 2021, the EU’s coastal tourism sector generated approximately €49.9 billion in Gross Value Added (GVA) and employed around 1.9 million people. [Coastal fishing](https://www.reuters.com/business/environment/aquafarming-becomes-main-global-source-fish-un-food-agency-says-2024-06-07) and aquaculture are vital components of the global economy, providing employment to millions and contributing significantly to food security. In 2022, the combined global production of fisheries and aquaculture reached a record 223.2 million tonnes, with aquaculture alone producing an unprecedented 130.9 million tonnes. Notably, for the first time, aquaculture surpassed wild capture in aquatic animal production, accounting for 51% of the total. Additionally, [maritime shipping](https://maritime-union.org/how-much-trade-is-maritime/?utm_source=chatgpt.com) is the backbone of international trade, with approximately 80% of global trade by volume and over 70% by value transported via sea routes. This extensive reliance on maritime transport underscores the critical importance of coastal infrastructure, including ports and harbors, in facilitating the movement of goods worldwide. However, the intensive exploitation of coastal environments for human activities has led to significant ecological challenges.

For instance, marine shipping contributes about 3% of global greenhouse gas emissions, a figure projected to rise by up to 50% by mid-century if stringent measures are not implemented (Jasper Faber, 2021). Additionally, shipping activities lead to marine pollution, including oil spills, ballast water discharge and underwater noise and light affecting marine life. Oil spills remain a critical environmental concern due to their devastating and long-lasting impacts on marine ecosystems. These spills contaminate water, harm marine biodiversity, and disrupt food chains, often leading to severe economic losses in fisheries and tourism. In 2023, ten oil spills were recorded globally, releasing over 2,000 tons of oil into the environment, including one major spill exceeding 700 tons in Asia [@itopf\_statistics]. While historical trends show a reduction in large spills, from over 20 per year in the 1970s to about 1.3 per year in recent decades, incidents such as the spill occurred in December 2024 in the Kerch Strait, where 3,700 tons of oil were released, underscore the persistent and significant risks. Such events highlight the necessity for stringent preventive measures and rapid response mechanisms to mitigate the ongoing threat posed by oil spills to marine environments.

Ballast water discharge represents a significant vector for the introduction of invasive aquatic species into new environments. Approximately 40% of introductions of non-indigenous aquatic species have been linked to ballast water release. Underwater noise pollution from shipping activities poses a growing threat to marine life, particularly cetaceans such as whales and dolphins. Elevated noise levels can disrupt communication, navigation, and feeding behaviors, leading to increased stress and altered migration patterns. Chronic exposure to underwater noise can also result in physical harm and population-level impacts. One significant impact of fishing and aquaculture on coastal habitats is the degradation of critical ecosystems such as seagrass beds, coral reefs, and mangroves. Destructive fishing practices, including bottom trawling and the use of dynamite or cyanide, physically damage the seafloor and associated habitats, resulting in biodiversity loss and the disruption of ecological functions. The expansion of aquaculture operations often necessitates the conversion of coastal wetlands, particularly mangroves, into fish or shrimp ponds. This land-use change reduces the availability of essential nursery habitats for marine species and diminishes the ecosystem services provided by mangroves, such as carbon sequestration, shoreline stabilization, and water filtration. Additionally, aquaculture activities contribute to nutrient enrichment and pollution in adjacent waters through the release of uneaten feed, feces, and chemical additives, exacerbating eutrophication and altering benthic community structures. Another significant concern is the introduction of alien invasive species into the environment through aquaculture, which can disrupt local ecosystems and biodiversity. This issue was explored in Chapter 4. Coastal tourism exerts a profound influence on ecosystem integrity, often driving substantial environmental degradation through mechanisms such as habitat destruction, pollution, and resource overexploitation. The construction and expansion of tourist infrastructure frequently lead to the removal or fragmentation of critical habitats, including mangroves, seagrass meadows, and coral reefs, all of which play pivotal roles in maintaining biodiversity and safeguarding coastal resilience. Furthermore, the rapid influx of visitors generates significant volumes of waste and untreated sewage, contributing to water quality deterioration and eutrophication, which disrupt aquatic ecosystems and alter trophic dynamics. The elevated demand for limited resources, notably freshwater and seafood, exacerbates ecological stress, leading to overharvesting and resource depletion.