# 1. Introduction

## 1.1 Coastal Environment

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 [@orth2006global, @walker1992seagrass, @valle2013comparing]. Effective management and sustainable practices are crucial to preserving their ecological integrity and ensuring long-term viability.

Marine vegetative habitats in intertidal zones, such as seagrass meadows, microphytobenthos, and macroalgal habitats, face significant hazards from both anthropogenic activities and natural forces. Human-induced threats include coastal development, pollution, overfishing, and habitat modification, which degrade these ecosystems. Seagrass meadows are threatened by various anthropogenic activities (Len J. McKenzie et al., 2020a), microphytobenthos are affected by the global decline of intertidal mudflats (Nicholas J. Murray et al., 2019a), and areas colonized by macroalgae may shrink due to the expansion of wild oyster reefs (Le Bris et al., 2016). Additionally, 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.

These habitats provide vital ecological functions, including coastal erosion protection through root stabilization and sediment trapping [@bos2007ecosystem, etc], mitigation of eutrophication effects by absorbing excess nutrients and improving water quality (**refs**), atmospheric CO2 fixation, contributing to carbon sequestration and combating climate change [@mcroy1977production, @krause2018sequestration, @saderne2019role], serving as biodiversity hotspots that support unique flora and fauna, providing feeding, breeding, and nursery grounds for various species [@unsworth2019seagrass, @sanabria2024unveiling].

Despite their ecological significance and ecosystem services they provide, intertidal habitats, particularly mudflats, remain highly vulnerable yet often overlooked. Tidal flats are challenging to access, and traditional field sampling methods are too time- and labor-intensive for repeated observations over large areas. Moreover, large variations across different temporal scales in these habitats require frequent monitoring, which is impractical through field surveys alone. This underscores the need for advanced monitoring technologies, effective management practices and targeted conservation strategies to ensure their sustainability and resilience against diverse and evolving pressures.

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

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 to 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, well-functioning 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.

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

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.

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 tons, with aquaculture alone producing an unprecedented 130.9 million tons. 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, 2023). 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 involves converting coastal wetlands into fish or shrimp ponds or constructing structures over mudflats. These activities usually conflict with ecosystem conservation, as both uses compete for limited space. Change of land-use into aquaculture facilities reduces the availability of essential nursery habitats for marine species and diminishes the ecosystem services provided by these natural habitats, 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.

### 1.1.3 Tidal flats

The intertidal zone refers to the coastal area between the high and low tide marks, characterized by periodic exposure and submersion due to tidal cycles. This dynamic zone forms the interface between terrestrial and marine ecosystems and is influenced by complex physical, chemical, and biological processes.

Tidal flats, a specific type of intertidal habitat, are defined as expanses of sand, rock, or mud that experience regular tidal inundation. These ecosystems are shaped by sediment deposition driven by tidal currents, wave action, and terrestrial runoff. As transitional ecosystems between terrestrial and marine environments, tidal flats face pressures from both domains. Additionally, they encounter unique threats, including coastal development (Arkema et al., 2013; Hassan et al., 2005), rising sea levels (Lovelock et al., 2017; Passeri et al., 2015), coastal erosion (Nicholls et al., 2007), decreased sediment input from rivers (Blum and Roberts, 2009), and the subsidence and compaction of coastal sediments (Minderhoud et al., 2020).

Globally, tidal flats are experiencing significant declines in extent due to both natural and anthropogenic factors. Murray et al. (2019a) using a satellite time series have shown that tidal flats have declined by approximately 16% from 1984 to 2016, representing a net loss of over 20,000 km² ([Figure 1.2](#fig-TidalFlats)).

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| Figure 1.2: The global trajectory of tidal flats extent, showing areas in which the development of consistent time-series data over 1984–2016 (orange) and 1999–2016 (orange and blue) was possible. b, Change in extent of tidal flats in 17.1% of the mapped area, 1984–2016 (linear regression, P = 0.00437). c, Change in extent of tidal flats in 61.3% of the mapped area, 1999–2016 (linear regression, P = 0.1794). Shading in b and c indicates the standard error of the linear model. From Murray et al. (2019a) |

Regions such as East Asia, the Middle East, and North America have shown the greatest losses. These declines mirror trends observed in other coastal ecosystems, such as mangroves and seagrasses. Despite these losses, some areas have exhibited resilience or even expansion, highlighting the dynamic interplay between sedimentary processes, sea-level rise, and human interventions (Murray et al., 2019a).

A potential solution to limit the disappearance of tidal flats is to protect the ecosystems they host. These ecosystems contribute significantly to nutrient cycling and sediment stabilization, enhancing the overall resilience of tidal flats. By maintaining these biotic communities, the ecological functions of tidal flats can be preserved, buffering them against threats such as erosion and rising sea levels.

#### 1.1.3.1 Bacillariophyceae, Euglenida and Cyanophyceae

Within estuarine biological communities, microphytobenthos (MPB) can contribute up to 50% of total primary production (N-Uptake, 1999). This assemblage comprises unicellular algae—particularly epipsammic diatoms (associated with sand grains) and epipelic diatoms (free and motile within muddy sediments, [Figure 1.3](#fig-MPBpictures) B)—as well as cyanobacteria and euglenids (MacIntyre et al., 1996). These organisms proliferate on sediment surfaces during low tide (Kelly et al., 2001), colonizing intertidal superficial sediments and forming biofilms ([Figure 1.3](#fig-MPBpictures) A) that can extend over several square kilometers (Benyoucef et al., 2014).

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| Figure 1.3: Picture of the sampling of microphytobenthos biofilm in the Guadalquivir river, on the 22nd of March 2023 (A) and a single diatoms cell (B), likely Navicula spp. took using a scanning transmission electron microscope by Alexandre Barnett. |

The MPB fulfills both structural and trophic functions within intertidal mudflats. Structurally, microphytobenthic biofilms decelerate sediment resuspension and enhance mudflat stability by mitigating erosive processes (Decho, 2000). Trophically, they serve as a food resource for deposit-feeding and suspension-feeding invertebrates (Miller et al., 1996). MPB forms the foundation of various food chains, being consumed at low tide by organisms ranging from gastropods (Savelli et al., 2018) to shorebirds (Drouet et al., 2015). Additionally, at high tide, tidal currents and waves can resuspend MPB, making it available in the water column for suspension feeders and facilitating the export of a portion of its biomass to adjacent ecosystems (De Jorge and Van Beusekom, 1995; Decottignies et al., 2007).

MPB’s role in sediment stabilization is further supported by its production of extracellular polymeric substances (EPS), which enhance sediment cohesion and reduce erosion. Moreover, it contributes to nutrient cycling within coastal ecosystems, influencing the availability of nutrients such as nitrogen and phosphorus, which are essential for primary production. The dynamic nature of MPB communities allows them to adapt to varying environmental conditions, making them integral to the resilience and functioning of coastal habitats.

#### 1.1.3.2 Chlorophyceae

Green macroalgae, belonging to the Class of Chlorophyceae, are a diverse group of multicellular photosynthetic organisms predominantly inhabiting marine environments, though some species are found in freshwater and terrestrial habitats ([Figure 3.2](#fig-vegetation) D). They are characterized by green pigmentation, resulting from the dominance of chlorophylls a and b, which play a crucial role in their photosynthetic processes (Cikoš et al., 2022).

Ecologically, green macroalgae are significant primary producers of coastal ecosystems. Species such as those in the genus *Ulva* are known for their rapid growth rates and are often indicators of nutrient-rich conditions (Liu et al., 2020). In addition to their ecological roles, green macroalgae have been utilized in various human applications. They are cultivated for food use in aquaculture and their potential in biofuel production and as bioindicators for monitoring environmental health is being actively researched (Moreira et al., 2022).

However, under conditions of eutrophication—excessive nutrient enrichment—green macroalgae can proliferate excessively, leading to algal blooms. These blooms can have detrimental effects on marine ecosystems, including hypoxia conditions (low oxygen levels) and competition with other important species (Schreyers et al., 2021a; Sun et al., 2022).

#### 1.1.3.3 Phaeophyceae

Brown macroalgae, classified under the class Phaeophyceae, are a diverse group of multicellular marine algae predominantly found in temperate and polar coastal regions ([Figure 3.2](#fig-vegetation) B). Their characteristic brown coloration arises from the presence of the pigment fucoxanthin, which masks the green color of chlorophylls a and c. This pigmentation is integral to their photosynthetic efficiency, particularly in low-light underwater environments (Cikoš et al., 2022).

Ecologically, brown macroalgae play a pivotal role in marine ecosystems. They form extensive underwater forests, commonly known as kelp forests, which provide habitat, food, and shelter for a multitude of marine organisms, thereby enhancing local biodiversity. These structures influence coastal oceanography by affecting water flow and light penetration. In intertidal areas, they often colonize rocky substrates, creating suitable habitat for various species like sea anemone, limpet and fishes (Eger et al., 2023).

In terms of human utilization, brown macroalgae have been harvested for centuries for various purposes. They are a source of alginates—polysaccharides extracted from their cell walls—widely used as gelling, thickening, and stabilizing agents in the food, pharmaceutical, and cosmetic industries, but as also the potential to be uses in Lithium-ion batteries production (Kovalenko et al., 2011). Additionally, certain species are consumed directly as food, particularly in East Asian cuisines, and are recognized for their nutritional value and health benefits.

Brown macroalgae also contribute to environmental management practices. Their ability to absorb and accumulate heavy metals makes them effective in bioremediation efforts to remove pollutants from marine environments (Davis et al., 2003). Furthermore, their potential in carbon sequestration positions them as valuable components in strategies aimed at mitigating climate change impacts.

However, brown macroalgae are susceptible to environmental changes. Factors such as ocean warming, pollution, and overfishing can lead to declines in their populations, which in turn affects the broader marine ecosystems they support (Manca et al., 2024). Conservation and sustainable management of these algae are therefore crucial to maintaining the health and productivity of coastal marine environments.

#### 1.1.3.4 Rhodophyceae

Red macroalgae, or Rhodophyta, constitute a diverse group of predominantly marine, multicellular algae characterized by their reddish pigmentation, which results from the presence of phycoerythrin and phycocyanin pigments ([Figure 3.2](#fig-vegetation) C). These pigments enable red algae to efficiently absorb blue and green wavelengths of light, facilitating photosynthesis at greater ocean depths compared to other algal groups (Cikoš et al., 2022).

Ecologically, red macroalgae play a vital role in marine environments. They contribute significantly to primary production and serve as foundational species in various marine habitats. Notably, coralline red algae, which secrete calcium carbonate, are instrumental in building and stabilizing coral reef structures, providing habitat complexity that supports diverse marine life (Cornwall et al., 2023).

In terms of human utilization, red macroalgae have been harvested for centuries for their nutritional and industrial value. Species such as *Porphyra* (known as nori in Japan and gim in Korea) and *Palmaria palmata* (dulse) are consumed as food, valued for their high protein content, essential vitamins, and minerals (Stévant et al., 2023; Wei et al., 2023). Additionally, red algae are a primary source of phycocolloids like agar and carrageenan, which are extensively used as gelling and stabilizing agents in the food, pharmaceutical, and cosmetic industries (Nurdin et al., 2023; Valderrama et al., 2013).

Red macroalgae also possess bioactive compounds with potential therapeutic applications. Research has identified various secondary metabolites in red algae that exhibit antimicrobial, anti-inflammatory, and anticancer properties, highlighting their potential in drug development and functional food ingredients (Ismail et al., 2020).

However, red macroalgae face challenges due to environmental changes. Factors such as climate change, pollution, and habitat destruction can adversely affect their populations and the ecosystems they support. Conservation efforts and sustainable harvesting practices are essential to preserve these ecologically and economically important organisms (Hanley et al., 2024).

#### 1.1.3.5 Magnoliopsida

Intertidal seagrass meadows, classified under the class Magnoliopsida, consist of flowering plants adapted to the unique challenges of periodic exposure and submersion in the intertidal zone. These meadows stabilize sediments via their root systems, which anchor substrates and mitigate erosion, thereby reducing sediment loss and maintaining substrate integrity (Davies et al., 2024a; Sousa et al., 2019; Zoffoli et al., 2023). Additionally, seagrass meadows provide essential ecosystem services, including acting as habitat, nurseries or feeding location for numerous species ([Figure 1.4](#fig-SeagrassHabitat)), many of which are commercially important (Moussa et al., 2020). Their structural complexity offers refuge from predators, supporting juvenile survival and biodiversity. These meadows play a significant role in global carbon sequestration, capturing and storing carbon at rates comparable to, or exceeding, terrestrial forests. Furthermore, they regulate nutrient cycles and improve water quality by trapping sediments and filtering pollutants, thus sustaining the health of adjacent marine environments (Los Santos et al., 2019a). By cycling nutrients and contributing organic matter through detritus production, intertidal seagrass meadows enhance the ecological productivity and resilience of tidal flats, underscoring their critical role in supporting both ecological functions and socio-economic benefits.

Seagrass meadows, like tidal flats, are undergoing significant declines on a global scale due to a variety of anthropogenic and natural stressors (Davies et al., 2024a). Despite their critical ecological roles, seagrass ecosystems remain comparatively underrepresented in scientific research within the broader scope of coastal ecosystems. As illustrated in [Figure 1.4](#fig-SeagrassHabitat) (e), the proportion of publications focusing on seagrasses in the context of coastal ecosystem studies is considerably lower than those dedicated to other key habitats such as coral reefs, mangroves, and salt marshes. This disparity highlights a critical research gap, underscoring the need for increased scientific attention to better understand and mitigate the factors contributing to the degradation of these vital ecosystems.

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| Figure 1.4: Seagrass meadows are beautiful habitats containing biodiverse faunal communities such as the following a the Spiny Seahorse (Hippocampus guttulatus) in the UK (source N Garrick-Maidment), b Dogfish (Scyliorhinus canicula) in the UK (source Frogfish Photography), c the Green Sea Turtle (Chelonia mydas) in the Dutch Antilles, d Flying Gurnard (Dactylopterus volitans) in Puerto Rico (source Luis R. Rodriguez) and e shows the proportion of publication each year dedicated to Coral reefs, Mangroves, Seagrasses and Salt marshes. Edited from R. K. Unsworth et al. (2019). |

## 1.2 Concepts of Remote sensing

Coastal environments represent highly dynamic and sensitive ecosystems shaped by complex interactions between natural processes and human activities. Remote sensing (RS) technologies are crucial for monitoring these regions, providing detailed data on shoreline erosion, habitat degradation, sediment dynamics, and water quality. This section reviews fundamental concepts and methodologies of RS applied to coastal environments.

RS defines the ability to retrieve information in a non-invasive way, without direct contact with the target. It relies on the propagation of signals, typically optical, acoustic, or microwave, between the target and the sensor. This technology has been applied in a wide variety of fields, ranging from medical imaging to detect stem cells, to the analysis of the structure of the primordial universe (Aghanim and Dole, 2020; Zhu et al., 2021). RS provides the basis to Earth observation (EO), where its methodologies facilitate large-scale and long-term data collection. Instruments on satellites, aircraft, and drones provide high-resolution imagery and measurements critical for monitoring environmental changes, mapping natural resources, and assessing land use patterns. These technologies enable systematic data collection over large areas and extended periods, supporting analyses such as deforestation, glacial melting, variations in ocean temperature, and changes in land use.

### 1.2.1 Active Remote Sensing. Example of LiDAR

Active remote sensing is a technique in which a sensor emits its own energy—typically in the form of electromagnetic radiation—toward a target and measures the energy reflected or backscattered from it. This method allows for the collection of data regardless of natural light conditions, enabling observations during both day and night and through various weather conditions.

The Light Detection and Ranging (LiDAR) sensor emit laser beams in the ultraviolet (UV), visible or infrared (IR) regions of the electromagnetic spectrum. By analyzing the return signal, they can estimate distances to objects or surfaces, detect optically active constituents in water bodies, and assess aerosols in the atmosphere (Dionisi et al., 2024; Jamet et al., 2019)

LiDAR works by emitting a beam of light and measuring the time it takes for the beam to return to the sensor. This process not only calculates distances but also captures the intensity of the returned signal. In many instances, multiple returns from a single pulse are measured, enabling the mapping of varying objects height within the same x and y coordinates. This capability allows the creation of precise, three-dimensional representations of the environment such as mapping the heights of trees in forests or measuring crop heights in agricultural fields [Figure 1.5](#fig-LIDAR). When ground height cannot be directly measured, LiDAR data can generate a digital surface model (DSM), which represents the uppermost layer of the environment. However, if multiple returns are recorded, it becomes possible to create both a DSM and a digital terrain model (DTM), which represents the ground surface, by differentiating between the surface and underlying layers. The difference between DSM and DTM can be used to assess living stock or biomass.

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| Figure 1.5: Diagram showing several signal-return for a single emited beams of a LIDAR system. adapted from |

Achieving accurate 3D measurements of a target using LiDAR technology requires a high level of precision in assessing each parameter of the system. The quality of the final output depends on careful calibration and execution at every stage of the process. One critical step is ensuring the precise timing of the laser beam’s return after it reflects off the target. This timing directly determines the distance calculations that form the basis of the 3D structure. Equally important is the accurate positioning of the LiDAR sensor, which is often mounted on a drone, aircraft, or satellite. The sensor’s x, y, and z coordinates must be continuously tracked with a high degree of precision. To achieve this, Real-Time Kinematic (RTK) positioning systems are commonly employed. These systems enhance the accuracy of the positioning data by providing real-time corrections to the sensor’s GPS coordinates, ensuring minimal error and maintaining the integrity of the spatial measurements. Without such stringent measures, the resulting LiDAR data is prone to errors that can lead to distorted and noisy representations of the mapped surface. These inaccuracies not only diminish the reliability of the data but also compromise its utility for detailed analysis and decision-making processes.

In coastal environment monitoring, LiDAR systems are classified based on their emitted wavelengths, which determine their performance and application. These systems are categorized into “topographic LiDAR” and “bathymetric LiDAR,” each suited to specific tasks in coastal studies. Topographic LiDAR operates in the near-infrared (NIR) spectrum (approximately 1000 nm) and is used to map terrestrial features, such as beach contours, vegetation density, rocky shore structures and man-made installations. Its ability to generate high-density point clouds stems from efficient operation at lower power. Unlike other types of LiDAR, NIR LiDAR requires less power, making it generally more affordable and compact. These attributes allow topographic LiDAR systems to be easily mounted on drone platforms, offering greater flexibility and accessibility for coastal monitoring. In contrast, bathymetric LiDAR, utilizing green (~532 nm) and red wavelengths, penetrates the water column to reveal submerged landscapes, including coral reefs, seagrass meadows, and shallow seabeds. Operating within the visible region of the electromagnetic spectrum, it is more susceptible to atmospheric scattering than NIR LiDAR, making it less suitable for terrestrial applications.

The Litto3D® product (SHOM, 2021) consists in high-resolution bathymetric and topographic maps in coastal areas, created using LiDAR technologies. During airborne missions, the system captures terrestrial and submerged terrain features with exceptional precision. The topographic LiDAR achieves spatial resolution of 1 m, with vertical accuracy up to 20 cm under optimal conditions, such as minimal atmospheric interference, stable flight paths, and favorable weather. The bathymetric LiDAR maps underwater landscapes to depths of approximately 70 m, depending on water transparency. This dual-mode capability is essential for modeling complex coastal environments, seamlessly integrating terrestrial and marine datasets. The airborne platform enables rapid data acquisition over large areas, overcoming challenges associated with ground-based or shipborne methods. The fusion methodology used by Litto3D® ensures the precise alignment of terrestrial and marine datasets, resolving inconsistencies in elevation data at land-water interfaces. The resulting unified dataset accurately represents coastal environments and support diverse scientific and practical applications such as coastal risk assessment and ecological studies. Distributed by the Service Hydrographique et Océanographique de la Marine (SHOM, 2024) and the Institut National de l’Information Géographique et Forestiere (IGN, 2024), this dataset is open-source but currently available only for selected coastal regions in France.

In this study, LiDAR data were utilized in **Chapter 4** using a drone-borne NIR LiDAR system. These data were employed to evaluate the elevation and slope of mudflats in French and Spanish estuaries and to map the spatial distribution of the invasive red macroalga *Gracilaria vermiculophylla*. In **Chapter 5**, the Litto3D product was used along with a water height dataset to assess the emersion time of seagrass meadows in Quiberon, France, during low tide. Since this thesis focuses on intertidal environment mapping, field campaigns were conducted during low tide to ensure optimal conditions for the effective use of NIR LiDAR providing unobstructed access to exposed intertidal zones.

### 1.2.2 Passive Remote Sensing

Passive remote sensing is a method of collecting data about the Earth’s surface or atmosphere by measuring naturally emitted or sunlight-reflected electromagnetic radiation without actively transmitting signals. This technique relies on energy sources external to the instrument, such as sunlight for optical and near-infrared sensors or Earth’s thermal emissions for thermal infrared sensors.

Passive remote sensing is widely utilized in spaceborne satellite missions and has played a pivotal role in programs developed by major space agencies, including the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). For instance, Sentinel-2 which provides ESA’s highest spatial resolution imagery, employs passive sensors. Data measured by these sensors have been applied to monitor land cover, vegetation dynamics and coastal and in land water environments.

As sunlight enters the Earth’s atmosphere, it interacts with various gases and particles altering its properties. These interactions include scattering, absorption, and refraction. Scattering occurs when atmospheric molecules and aerosols disperse light in different directions, with shorter wavelengths like blue light being more strongly affected. Absorption results from atmospheric constituents such as ozone, water vapor, and carbon dioxide, which absorb energy at specific wavelengths, reducing the intensity of the transmitted light that reaches the Earth’s surface. Refraction occurs as light changes direction and speed while passing through atmosphere layers with varying densities.

When sunlight reaches Earth’s surface, it exhibits several behaviors, depending on the surface properties and the angle of incidence. These behaviors include:

* Absorption: The light is absorbed by the surface, converting it into heat or another form of energy. This process varies based on the biogeochemical characteristics of the surface, with darker surfaces typically absorbing more light.
* Transmission: The light passes through the surface, entering a different medium, such as water or transparent materials. The extent of transmission depends on the material’s transparency and refractive index.
* Reflection: The light that is neither absorbed nor transmitted is redirected back in the opposite direction. The amount of reflection depends on the surface’s albedo, with bright surfaces like snow reflecting more light compared to darker surfaces such as forests.

Only reflected light can be detected by spaceborne sensors. The most used metric in passive remote sensing, to quantify electromagnetic radiation (EMR), is reflectance (). is typically measured as the ratio of upwelling radiance to downwelling radiance ([Equation 1.1](#eq-reflectance)). is defined as the radiant intensity per unit of projected area in a specified direction and is expressed in units of W.m-2.sr-1. , however, is dimensionless.

is defined for each wavelength as a value between 0 and 1. A value of 0 indicates that all light has been absorbed or transmitted by the target, while a value of 1 indicates that all light has been reflected.

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| Figure 1.6: Light pathways involved in remote sensing: illustrating the interaction of solar radiation with the atmosphere, vegetation, and water surfaces, highlighting processes such as scattering, absorption, and reflectance contributing to the top-of-atmosphere (TOA) radiance observed by a satellite sensor. |

at the Top of Atmosphere (TOA), i.e., the magnitude directly measured by spaceborne or airborne sensors, contains signals originating from both the atmosphere and the Earth’s surface. Therefore, to study targets located on the Earth’s surface, must undergo atmospheric correction processing to transform it into Bottom of Atmosphere (BOA) , which represents the intrinsic reflectance properties of the surface target. Precise is crucial for accurately analyzing surface characteristics and for applications like vegetation monitoring, water quality assessment, and land cover classification.

One of the most basic atmospheric correction methods is the “black pixel” method, which assumes that all the signal retrieved over optically deep waters originates entirely from the atmosphere. This information is then used to correct the reflectance across the entire scene. However, this method requires the presence of optically deep water targets within the scene and assumes uniform aerosol concentrations across the scene. Such assumption may be inaccurate, particularly for satellites with a wide field of view, such as MODIS, where a single image can cover a swath of 2,330 km. Limitations to this technique arise also when the target of study is a water body itself. These limitations highlight the need for more advanced correction techniques that account for spatial variability in atmospheric properties.

To address these challenges, sophisticated atmospheric correction algorithms tailored to specific sensors and study areas have been developed. These algorithms account for atmospheric scattering, absorption, and path radiance contributions by leveraging radiative transfer models, auxiliary atmospheric data, and sometimes *in situ* measurements. For example, data of the ESA constellation Sentinel-2 can be processed using Sen2Cor, a correction algorithm designed to produce by incorporating atmospheric parameters such as water vapor, aerosols, and ozone concentrations. Additionally, some atmospheric correction methods are customized for specific targets, for example, algorithms specifically designed for water bodies, such as POLYMER (Steinmetz et al., 2011) or ACOLITE (Vanhellemont and Ruddick, 2018).

provides information regarding light reflected by the target across various wavelengths. This phenomenon, referred to as the spectral signature, is a unique feature of each target type. Spectral signatures contain data about the physical and chemical properties of surfaces, forming the basis for RS applications. By analyzing spectral signatures, its possible to identify and classify surface types, as well as derive insights into environmental changes and land-use dynamics. For example, Chlorophyll-a (Chla), a pigment found in all vegetation cells, plays a key role in defining the spectral signature of plant life. Chla absorbs light in specific regions of the electromagnetic spectrum, particularly in the blue region around 440 nm and the red region near 675 nm. Consequently, healthy vegetation exhibits a spectral signature with low at 440 and 675 nm. Variations in physiological states and vegetations types result in different spectral patterns, enabling their differentiation and monitoring of ecological conditions over time ([Figure 1.7](#fig-Spectral_signature)).

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| Figure 1.7: The spectral signature of vegetation (green), Water (blue) and bare soil (red). Absorption features of Chlorophyll-a are indicated for the spectra of vegetation. |

Spectral indices are mathematical combinations of reflectance values at specific wavelengths, designed to maximize particular surface characteristics with simple processing. Vegetation indices, for example, leverage the distinct reflectance patterns of photosynthetic pigments. The Normalized Difference Vegetation Index (NDVI) is a widely used index based on the normalised difference between in the NIR and red. It is calculated as:

where is the reflectance in the infrared region arround 800 nm and is the reflectance in the red region around 665 nm.

NDVI values range from -1 to 1, with negative values indicating water and higher positive values corresponding to dense healthy vegetation. While NDVI serves as a proxy for vegetation biomass and photosynthetic activity, its interpretation can be complex in heterogeneous environments, such as areas with overlapping vegetation types or substrates. Some studies propose a simple classification of NDVI based on thresholds to differentiate between distinct types of habitats or vegetations (Méléder et al., 2003). While this simple first approximation can be useful for delimitating contrasting types of targets, establishing thresholds depends on specific sensor characteristics and this technique often fails in mapping vegetation types with similar pigment content or highly heterogeneous targets. More sophisticated techniques that utilize a greater amount of spectral information are required in such situations (Oiry and Barillé, 2021a)

can be used to identify key absorption features of chemical compounds of the traget, by applying derivative analysis to the spectral signature. The second derivative of the is utilized to enhance the detection of subtle pigment or mineral absorption features. By analyzing the second derivative, these small features are amplified, allowing for more precise identification of pigment presence and estimation of their concentrations. This approach is particularly effective for identifying accessory pigments that have weaker absorption features compared to Chla.

#### 1.2.2.1 Remote Sensing resolutions

##### 1.2.2.1.1 Spectral and Radiometric resolution

Detecting of pigment absorption features necessitates measuring light reflectance at fine spectral resolution. However, measuring detailed spectral signatures depends on the sensor’s characteristics. Spectral resolution is defined by three main components: the number of spectral bands, the bandwidth (Full Width at Half Maximum, FWHM), and the spectral sampling interval. Sensors with higher spectral resolution can distinguish closely spaced wavelengths within the electromagnetic spectrum, enabling precise characterization of spectral features ([Figure 1.8](#fig-Spectral_resolutions)).

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| Figure 1.8: Comparison of spectral resolution between multispectral (A) and hyperspectral (B) sensors in the solar radiance spectrum. Panel C illustrates the impact of spectral resolution on the same spectral signature of Gracilaria vermiculophylla. With hyperspectral resolution (red), absorption features of pigments such as phycocyanin and phycoerythrin are distinguishable, whereas these features are absent in the multispectral resolution provided by Sentinel-2 (green). D is showing exemple of different radiometric resolutions for the same band of a Sentinel-2 tile. One is coded in 12 bits (left) and the other is coded in 6 bits (right). |

Remote sensing sensors are generally classified into two categories based on their spectral resolution: multispectral and hyperspectral sensors. Multispectral sensors are characterized by a limited number of broad spectral bands, with a bandwidth generally exceeding 20 nm. Their spectral sampling interval is relatively large, resulting in a coarser spectral resolution that provides a broad overview of the spectral characteristics of a scene. In contrast, hyperspectral sensors are equipped with hundreds of narrow, contiguous spectral bands. These bands are separated by small spectral sampling intervals, often just a few nanometers, which results in a much finer spectral details. High spectral resolution capturing subtle variations in absorption features and spectral shapes allow distinguishing between targets with similar spectral characteristics, such as vegetation with similar pigment profile. Multispectral sensors, while less detailed, are efficient for general spectral analyses where fine discrimination is not required.

Another specification of sensors in the spectral discrimination is the radiometric resolution. It refers to precision at which the data are recorded by the sensor. It is defined by the number of discrete levels, or bits, used to represent the energy recorded for each pixel in an image. Higher radiometric resolution enables finer distinctions in brightness levels, which is particularly important for detecting subtle differences in reflectance and ensuring accurate analysis of surface features. For example, an 8-bit sensor can record 256 levels of intensity, while a 12-bit sensor can capture 4,096 levels, providing greater detail and dynamic range in the captured imagery ([Figure 1.8](#fig-Spectral_resolutions) D).

##### 1.2.2.1.2 Spatial resolution

Spatial resolution, defined as the smallest discernible detail a sensor can detect on Earth’s surface, is another fundamental characteristic of RS sensors. It is typically represented by the ground area covered by a single pixel in an image and is influenced by the sensor’s instantaneous field of view (IFOV), which determines the angle of view and, consequently, the ground area visible to the sensor. A smaller IFOV or lower sensor altitude results in finer spatial resolution, enabling the detection of smaller features. For the same IFOV, sensors mounted on satellites can cover larger areas compared to those on drone, albeit with reduced detail.

Spatial resolution can range widely depending on the research objective and sensor platform. For instance, moderate-resolution sensors like MODIS aboard Terra and Aqua capture data at spatial resolutions of 250 m, 500 m, and 1 km, making them suitable for large-scale environmental monitoring. In contrast, Sentinel-2 provides higher spatial resolutions, from 10 to 60 m depending on the spectral band, facilitating detailed observations for applications such as vegetation and land-use mapping. At the finer end, high-resolution sensors on platforms like Pleiades-Neo achieve sub-meter resolutions (e.g., 30 cm per pixel), ideal for precise Earth observations.

Unmanned Aerial Vehicles (UAVs), equipped with high-resolution cameras, offer even finer spatial resolutions, often down to a few cm, even mm, depending on flight altitude and sensor specifications. This ultra-high resolution is particularly advantageous for heterogeneous site mapping. Chapter 3 will show that an ultra-high spatial resolution can be valuable for machine learning model training. However, such high resolution requires increased data storage and processing capacity, illustrating the trade-off between detail and operational feasibility.

In scenarios involving mixed vegetation types or intricate landscape features, coarse-resolution sensors may fail to capture fine-scale heterogeneity, limiting the accuracy of ecological or land-use analyses. Conversely, high-resolution imagery excels in such contexts but demands significant computational resources. Selecting the appropriate spatial resolution depends on specific research objectives and the spatial scale of the phenomena under investigation, underscoring the necessity of aligning sensor capabilities with study requirements.

##### 1.2.2.1.3 Temporal Resolutions

Another key characteristic of remote sensing sensors is their temporal resolution, defined as the time interval between successive image acquisitions over the same study site. Temporal resolution is critical for monitoring dynamic environments, such as coastal ecosystems, where conditions can change rapidly due to tides, weather events, or human activity.

Temporal resolution varies significantly depending on the sensor’s design and mission. For example, the Sentinel-2 constellation, composed of two satellites, offers a temporal resolution of 5 days at the equator. This revisit time improves to approximately 3 days at higher latitudes, such as in France, due to the overlap in satellite paths. Such frequent revisits make Sentinel-2 an excellent choice for applications requiring consistent monitoring, such as vegetation health assessments, sediment transport studies, or vegetation phenology estimations. Certain missions, like Sentinel-3, achieve even shorter revisit times. Equipped with sensors designed for ocean and land monitoring, Sentinel-3 provides near-daily coverage, making it particularly suited for applications that require high temporal frequency, such as tracking phytoplankton blooms, which can appear and disappear within a few days, or surface temperature variations. This capability is crucial for capturing fast-evolving phenomena and ensuring timely data delivery for decision-making.

The temporal resolution of a satellite sensor may vary from hours to days, depending on whether the platform orbit is geostationary or sun-synchronous. Geostationary satellites provide continuous coverage over a fixed location, while sun-synchronous orbits follow sun illumination, allowing image acquisition at the same time of the day for a location. This consistency is particularly important for visible-infrared sensors, as it ensures usable images and maximizes the temporal resolution of the sensor by avoiding night-time acquisitions. On the other hand, airborne platforms exhibit more variable temporal resolutions, ranging from days to years, depending on mission planning.

Usually, temporal resolution is highly dependent on the spatial resolution of the sensor. Higher spatial resolution often corresponds to lower temporal resolution, although geostationary platforms and pointable sensors can be exceptions to this trend ([Figure 1.9](#fig-ResolutionSatellite)).

In contrast, some sensors are operated on-demand, with data acquisition triggered directly by the user. This is particularly characteristic of drones and specialized satellite missions like Pleiades or PRISMA. While these systems may lack consistent temporal archives for a given study site, they provide unmatched flexibility for high-resolution data collection. Such sensors are invaluable for addressing specific research objectives, including acquiring detailed imagery immediately after extreme weather events or capturing localized features with high spatial precision, complementing routine satellite-based monitoring programs.

#### 1.2.2.2 A story of trade off

Remote sensing involves inherent trade-offs between spatial resolution, temporal resolution, and coverage area, which influence the suitability of sensors for different applications ([Figure 1.9](#fig-ResolutionSatellite)). High spatial resolution sensors, capable of capturing fine-scale details, are essential for precise tasks like urban infrastructure mapping or site-specific ecological studies. In coastal environments, high-resolution sensors are invaluable for identifying small-scale features such as intertidal vegetation patterns, sediment deposition dynamics, or the mapping of coral reef health. However, these sensors typically have lower temporal resolution and smaller coverage areas, limiting their utility for monitoring dynamic or widespread phenomena, such as tracking algal bloom events across entire coastal regions.

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| Figure 1.9: Intersection of spectral resolutions (x-axis), temporal resolutions (y-axis), and spatial resolutions (circle size) of the main satellite sensors used to observe coastal areas. |

In contrast, sensors with coarser spatial resolution offer extensive coverage and higher revisit frequencies, making them ideal for tracking large-scale environmental changes. For coastal areas, these sensors can effectively monitor phenomena such as sea surface temperature variability, coastal erosion trends, and seasonal changes in primary productivity over larger geographic extents. For example, instruments like MODIS or VIIRS are well-suited for observing ocean color and Chla concentrations, which are critical for understanding broader ecosystem health in coastal zones.

Intermediate-resolution sensors provide a compromise, offering sufficient detail for regional studies while maintaining adequate temporal resolution for periodic monitoring. These are particularly useful for applications such as mapping coastal vegetation transitions, estuarine dynamics, and changes in sediment plumes from rivers into the ocean over time. Instruments like Sentinel-2 or Landsat provide this balance, making them key assets for monitoring coastal ecosystems at scales relevant to regional management.

The selection of an appropriate sensor depends on the specific requirements of the study, balancing the need for detail, frequency, and geographic extent. Coastal zone management, for instance, often benefits from using a combination of sensors to capture both fine-scale spatial patterns and broader temporal trends, ensuring comprehensive monitoring of these dynamic environments.