##### 1.2.2.1.4 A story of trade-off

Remote sensing involves inherent trade-offs between spatial, temporal and spectral resolutions, 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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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 spatial 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.

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.

Although this work builds upon many of the concepts introduced in the previous sections, one critical remote sensing technique warrants further discussion in this introduction. This technique, characterized by its adaptability and technical precision, provides essential insights and complements the methods already outlined. The next section will introduce drones, focusing on their application as a remote sensing tool and detailing the associated techniques and data analysis methods.

### 1.2.3 About Drones

#### 1.2.3.1 History

At the beginning of the 20th century, Julius Neubronner, a German apothecary, faced a logistical challenge in his professional practice. Neubronner regularly relied on carrier pigeons to deliver and retrieve small, urgent medical packages, such as medications or prescriptions, between his pharmacy and a sanatorium located several kilometers away. This method, though efficient for short distances, often left Neubronner curious about the exact routes taken by the pigeons and the environmental conditions they encountered during their flights. Motivated by both practical concerns and a spirit of innovation, Neubronner sought a way to monitor and document the journeys of his pigeons. He developed a lightweight, auto-triggering camera that could be strapped to the pigeons’ chests ([Figure 1.10](#fig-pigeons) Top). The camera was designed to automatically take photographs at regular intervals during the birds’ flights. It had two lenses and a pneumatic system; it was activated by inflating the left chamber and as the air slowly escaped from the capillary at the bottom, the piston moved back triggering the exposure. Neubronner ensured that the camera was light enough not to impede the pigeons’ ability to fly (Simic Milas et al., 2018).

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| Figure 1.10: One of Neubronner’s pigeons (Top), around 1910 equipped with a camera. Bottom shows a picture took during a pigeon’s flight. |

The resulting aerial photographs offered a novel perspective, capturing bird’s-eye views of landscapes, towns, and natural features ([Figure 1.10](#fig-pigeons) Bottom). These images not only satisfied Neubronner’s initial curiosity about the pigeons’ routes but also demonstrated the broader potential of aerial photography for cartography, reconnaissance, and environmental observation. His innovative work garnered widespread attention, paving the way for further developments in remote sensing and aerial imaging. Neubronner’s experiments illustrated the practical applications of aerial imaging at a time when such perspectives were almost entirely unavailable, highlighting his contributions to both science and art.

Julius Neubronner’s early vision exemplifies how innovative thinking can overcome barriers in data collection. For many years, the practical limitations of remote sensing technologies, particularly regarding spatial and temporal resolution or the high costs and delays in data acquisition, constrained their applicability in various fields. However, innovations like drones have significantly addressed these challenges. Much like Neubronner’s pigeons, modern drones are not only accessible and affordable but also offer users the freedom to determine when and where to deploy them, providing unparalleled control over spatial and temporal data collection. Neubronner’s ingenuity in developing lightweight aerial cameras for pigeons paved the way for these advancements, demonstrating the enduring impact of pioneering solutions in expanding the potential applications of remote sensing.

Modern drone history has its roots in military applications, where the need for unmanned surveillance and targeted operations drove the initial technological advancements. Early drone systems, such as the use of radio-controlled aircraft in World War II, laid the foundation for what would become an essential tool in both civilian and military contexts. The transition to civilian applications gained momentum in the late 20th century, particularly with the advent of lightweight materials, improved battery technologies, and advances in GPS and remote sensing capabilities. Today, drones are integral to various industries, from precision agriculture and infrastructure inspection to environmental monitoring and emergency response. This evolution reflects the growing accessibility and versatility of drone technology, making it a transformative element in modern data acquisition and analysis.

#### 1.2.3.2 General presentation

Drones, also known as Unmanned Aerial Vehicles (UAVs), are aircraft systems operated without a human pilot onboard. They are often embedded with GPS and can be remotely controlled or fly autonomously through software-controlled flight plans. These devices have become indispensable tools in modern remote sensing, offering high accuracy, on-demand data acquisition, and the ability to access previously unreachable locations. The growing use of drones in various fields, from environmental monitoring to urban planning, underscores their versatility and importance.

Drones, while not inherently functional on their own, become highly effective tools when integrated with various sensors. These include hyperspectral sensors (Suomalainen et al., 2021), multispectral sensors (Nurdin et al., 2023; Román et al., 2023), RGB cameras (Sweet et al., 2022), thermal cameras (Speth et al., 2022), LiDAR systems (Krček et al., 2020; Lee et al., 2023), as well as gas and chemical sensors.

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| Figure 1.11: Schematic representation of image overlapping of a drone |

#### 1.2.3.3 Data hacquisition

A key parameter in drone-based image acquisition is the overlap between images (Figure 1.11). This is categorized as front overlap (FO), which refers to the overlap between consecutive images along the same flight path, and side overlap (SO), which pertains to the overlap between images from adjacent flight paths. Ensuring sufficient overlap is essential for accurate reconstruction of orthomosaics through photogrammetric processes. Typically, 80% front overlap and 70% side overlap are considered optimal to achieve reliable results. The mathematical definitions of FO and SO are as follows:

and

where:

: Flight altitude above the ground (m) : Camera focal length (mm) : Sensor dimension (height) in the flight direction (mm) : Sensor dimension (width) perpendicular to the flight direction (mm) : Ground speed of the drone (m.s-1) : Time interval between consecutive photos (s) : Distance between two adjacent flight lines (meters)

These equations show that for a given sensor (e.g., for known , , , and ), the only parameters that can be adjusted to ensure sufficient overlap are the flight speed or the altitude of flights. If the user chooses to set (directly linked to the spatial resolution of the final product), then will be automatically fixed by the system. The higher the flight altitude, the higher the flight speed, or conversely, if the user chooses to set (directly linked to the total time of the mission), then the altitude will be locked by the system, resulting in a higher corresponding to a higher flight height.

The area that can be covered by a drone during a mission grows exponentially as the flight height increases. However, the maximum flight height drones can technically reach is not inherently limited but strictly regulated by law. In Europe, for instance, the maximum permitted flight height is 120 m. This restriction can be a limiting factor for certain applications, particularly when the area to be covered exceeds several square kilometers. For instance, the largest intertidal meadow in France is located in the Bassin d’Arcachon and covers an area of nearly 40 km² (Cognat et al., 2018). Using a Micasense RedEdge-MX DUAL multispectral sensor mounted on a drone flying at 120 m altitude at 10 m.s⁻¹, this area would take approximately 44 hours of flight time to cover entirely. The total time required to map this entire area at low tide could be further extended when accounting for constraints such as daylight hours, tide levels, battery recharging, potential weather-related delays, and the need for the operator to frequently reposition due to regulatory restrictions that limit the drone’s distance to 1 km from the telepilot.

#### 1.2.3.4 Data processing

Satellite products produced by space agencies are often provided to users after extensive preprocessing steps, including orthorectification, precise georeferencing and radiometric calibration. Similarly, these preprocessing steps are crucial for utilizing drone-acquired data effectively. Nowadays, user-friendly software such as Agisoft Metashape and Pix4D enables users to perform these essential steps efficiently, making advanced data processing accessible even to non-expert users. Steps to obtain an orthoimage from a bunch of single images will be described in more detail.

##### 1.2.3.4.1 image pre-processing

The first step is to correct each individual image acquired by the drone from optical distortion that occurred during its acquisition. Photogrammetric software typically addresses lens distortion and vignetting through a combination of camera calibration and radiometric adjustments. During calibration, the software refines intrinsic parameters such as focal length, principal point offsets, and radial/tangential distortion coefficients (called k1, k2, k3, p1, p2) by matching features across overlapping images in a bundle adjustment process. Some camera manufacturers provide sensor-specific metadata, including correction factors, which can further enhance calibration accuracy. Vignetting, which manifests as reduced brightness near the image edges, is often corrected via additional vignetting coefficients or automated radiometric calibration routines that normalize illumination across the photo. These corrections are essential for ensuring both geometric precision in the 3D reconstruction and radiometric consistency in the final orthomosaic.

##### 1.2.3.4.2 Initial Image Alignment / Aerial Triangulation

Once corrected, each image can be aligned. During the initial image alignment phase, the photogrammetry software relies on Structure from Motion (SfM) algorithms to identify unique tie points in overlapping images and triangulate their 3D positions. These tie points are then matched across the dataset, and a bundle adjustment is performed to optimize camera parameters (position, orientation, and intrinsic calibration). Often referred to as aerial triangulation, this step produces a sparse point cloud that underpins all subsequent stages. Its accuracy is critical, as it defines the precision of the final 2D and 3D outputs.

##### 1.2.3.4.3 Dense Point Cloud Generation

Building upon the camera geometry established by SfM, the software uses Multi-View Stereo (MVS) techniques to compute dense depth maps for each overlapping image pair. These depth maps are merged to create a dense point cloud containing millions—or even billions—of points, capturing high-resolution details of the scene’s geometry. Although computationally intensive, this phase lays the groundwork for generating accurate surface models and textured 3D representations later in the workflow.

##### 1.2.3.4.4 Digital Surface Model (DSM) / Digital Terrain Model (DTM)

From the dense point cloud, a Digital Surface Model (DSM) is derived by capturing the highest elevation values within each pixel or grid cell, thereby representing above-ground features like buildings and vegetation. Alternatively, a Digital Terrain Model (DTM) can be produced by classifying and removing non-ground points to approximate the bare-earth surface. Both models are typically exported as raster files and used in various analytical applications, such as hydrological modeling, viewshed analysis, and volume calculations. Their accuracy depends on the quality of the dense cloud and effective point classification techniques.

##### 1.2.3.4.5 Orthorectification and Orthomosaic Creation

During orthorectification, the software projects each image onto the DSM or DTM to correct for camera tilt and terrain distortions, ensuring consistent spatial alignment. Afterwards, overlapping images are seamlessly blended—often balancing color and brightness variations—to form a georeferenced orthomosaic. This final 2D product is dimensionally accurate and vital for cartographic and analytic tasks, offering a reliable visual representation of the surveyed area.

##### 1.2.3.4.6 Optional steps

Following the creation of a dense point cloud ([Section 1.2.3.4.3](#sec-DPC)), photogrammetric software can convert the millions of data points into a continuous 3D surface known as a mesh. This process involves triangulating the points to form a polygonal framework that captures the shape and features of the surveyed scene. Once the mesh is generated, the software projects the original imagery onto the surface to create a photorealistic texture. This textured 3D model provides an immersive visualization, enabling more detailed analysis of structures, terrain, and other elements than would be possible through a 2D map alone.

Another optional step, depending on the dataset, is the radiometric calibration of the data. However, this step becomes mandatory for multispectral and hyperspectral datasets, as it ensures the accuracy and usability of radiometric information by compensating for sensor-specific biases and environmental conditions during data acquisition.

### 1.2.4 Remote Sensing applied to Coastal monitoring

Coastal environments represent highly dynamic and sensitive ecosystems shaped by complex interactions between natural processes and human activities. Remote sensing technologies are crucial for monitoring these regions, providing detailed data on shoreline erosion, habitat degradation, sediment dynamics, and water quality. 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).

# 6. General conclusions and future perspectives

This doctoral research successfully addressed its principal objectives, which were to: (1) demonstrate the effectiveness of remote sensing for mapping intertidal habitats, (2) develop advanced methodologies for accurate vegetation classification and ecosystem monitoring, and (3) to investigate the capacity of remote sensing to mmap ecosystem under biotic and abiotic pressures. This work underscore the potential of remote sensing technologies in addressing ecological challenges in intertidal zones, including the impacts of climate change, anthropogenic pressures, and habitat fragmentation. By demonstrating improved accuracy in habitat classification, from seagrass discrimination to invasive species mapping, this work highlights the critical role of multispectral and hyperspectral data in supporting biodiversity conservation and ecosystem resilience. The integration of ground-based, drone, and satellite observations proved pivotal in bridging spatial and temporal gaps, enabling a more comprehensive understanding of ecosystem dynamics. This concluding section reviews the key scientific advancements made through the application of remote sensing to intertidal ecosystems, the challenges encountered, and future research directions.

## 6.1 Macrophytes discriminations and associated challenges.

This work has demonstrated the capability of multispectral remote sensing when combined with sophisticated machine-learning techniques to differentiate between various types of intertidal vegetation, even among plants with similar pigment compositions. This capability was initially validated theoretically using a hyperspectral library degraded to the spectral resolution of several sensors. It was subsequently confirmed using a multispectral camera mounted on a drone. The distinction was particularly challenging between green macrophytes, such as seagrass and green macroalgae, which share similar pigment compositions and, consequently, spectral signatures. However, the slight variations in the spectral signatures of intertidal green macrophytes enabling this discrimination arise from differences in the proportions in which these pigments are present in each type of vegetation

Pigment concentrations are not static over time following phenological cycles and impacted by stress conditions or may not be uniform within a species due to phenotypic variability, limiting the application of the method developed here to certain conditions. Despite this limitation, a key strength of the method lies in its development across a wide geographical range, open-source and use-case-driven design. The Drone Intertidal Sediment Classification of Vegetation (DISCOV) algorithm was developed to be dynamic and adaptable over time. The algorithm has been detailed in a scientific journal, with its complete code and training/validation dataset shared openly on GitHub (Oiry et al., 2024a). This flexibility proved invaluable when applying the algorithm to a different use case: mapping the invasive *Gracilaria vermiculophylla*.

Interestingly, DISCOV v1.0 exhibited poor performance in identifying this red algae, despite its distinct and unique spectral signature attributed to the presence of phycocyanin and phycoerythrin. The algorithm’s underperformance was traced to the lack of enough samples of this class in the original training dataset, causing confusion with other classes when encountering this specific spectral signature during prediction. This issue was promptly addressed by updating the model’s training dataset to include more red algae samples. The updated model outperformed the original version on the new dataset while maintaining nearly the same accuracy on the original dataset. Including a more diverse training dataset improved DISCOV’s performance across broader ecological contexts. Expanding the geographic and temporal range of data collection has been shown to enhance algorithm robustness and adaptability. By incorporating spectral data from multiple seasons and regions, the algorithm could better account for temporal variations in pigment concentrations and environmental factors, ensuring more reliable predictions across diverse conditions.

## 6.2 Drone and Satellite Interactions

UAVs provide high spatial resolution imagery, which is essential for capturing fine-scale heterogeneity, enabling the observation of subtle spatial patterns within habitats, and validating data derived from lower-resolution satellite imagery. High-resolution multispectral drones, when paired with classifier models, facilitate precise habitat mapping by identifying variations that may not be apparent otherwise. Furthermore, these drones produce large training datasets that are critical for enhancing the accuracy of machine learning models based on deep-learning architectures in satellite-based remote sensing. By integrating UAV-derived observations with field-specific data, detailed assessments can be achieved, which are particularly relevant for complex environments such as intertidal zones.

Satellites, such as Sentinel-2, complement UAVs by offering broad spatial coverage and consistent temporal monitoring, facilitating the assessment of seasonal and inter-annual changes. This enables systematic analysis of long-term trends and spatial dynamics across expansive geographic areas and quantifying large surfaces. While drones excel in localized, high-resolution observations, satellites provide scalable and cost-effective solutions for monitoring intertidal ecosystems at regional and global scales. This integration ensures that monitoring programs benefit from detailed localized insights while maintaining broader ecological context.

The combination of these technologies allows to leverage their respective strengths. For instance, UAV-acquired habitat data significantly enhance and validate satellite-based classifications, as demonstrated in the Intertidal classifier of Emerged xxxx (ICE CREAMS) model (Davies et al., 2024a, 2024b), where UAV data were used to train and validate seagrass habitat classifications across Europe [Figure 6.1](#fig-WorkflowBede) with xxx % of global accuracy. This hybrid methodology achieves a balance between local accuracy and scalability, reducing the costs associated with large-scale monitoring while preserving the depth of localized observations necessary for comprehensive assessments.

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| Figure 6.1: Workflow showing process for neural network classification model building and seagrass cover (%) from this classification, with example images showing process from Sentinel-2 Data to Habitat Classification to Seagrass Cover. From Davies et al. (2024a). |

This integration of drone and satellite technologies enhances the ability to monitor, analyze, and manage intertidal ecosystems effectively. By combining detailed precision with extensive coverage, these technologies address scientific and environmental challenges efficiently. They improve modeling accuracy, inform evidence-based conservation strategies, and provide critical tools for adaptive management in the context of environmental change.

## 6.3 Seagrass and Invasive species interactions

The interaction between seagrasses following heatwave events and the rapid growth capacity of *Gracilaria vermiculophylla* presents a complex dynamic shaped by environmental stressors, competition, and ecological resilience. These interactions are crucial for understanding the evolving structure and function of intertidal ecosystems under climate change.

Seagrasses, such as *Zostera noltei*, are integral to coastal ecosystems, offering essential services including sediment stabilization, carbon sequestration, and habitat provision. However, their health and resilience are highly vulnerable to environmental stressors, particularly marine and atmospheric heatwaves. These events induce physiological stress that manifests as leaf browning, chlorophyll degradation, and reduced photosynthetic efficiency. Observations reveal extensive browning and decreased seagrass coverage in intertidal zones subjected to prolonged high temperatures. The reduction in seagrass cover weakens its competitive edge, particularly in areas where other stressors, such as eutrophication or sediment disruption, are present.

Invasive species such as *Gracilaria vermiculophylla* exploit ecological disturbances to establish dominance. This red macroalga exhibits remarkable adaptability to varied environmental conditions, including fluctuations in temperature, salinity, and nutrient availability. Post-heatwave environments might provide ideal conditions for *G. vermiculophylla*. The degradation of seagrass meadows leads to increased light availability and free space making them more susceptible to biological invasions. Dense mats of *G. vermiculophylla* form on soft-bottom sediments, where they can rapidly proliferate and monopolize space and resources. These mats can physically and chemically inhibit the recovery of seagrasses by reducing light penetration and altering sediment composition.

The competitive interplay between seagrasses and *G. vermiculophylla* is exacerbated in the aftermath of heatwaves. Seagrasses’ physiological stress limits their ability to recover quickly, creating a temporal window for *G. vermiculophylla* to expand. Furthermore, anthropogenic factors such as nutrient enrichment from agricultural runoff amplify this dynamic by promoting algal growth and suppressing seagrass resilience. The ecological consequences of *G. vermiculophylla* proliferation are multifaceted. While the alga can provide habitat and stabilize sediments, its dominance often disrupts existing trophic interactions and reduces biodiversity. Areas previously dominated by seagrasses may experience shifts in community composition, favoring species adapted to algal habitats. Additionally, the physical characteristics of dense algal mats can alter sediment dynamics and hydrology, further entrenching *G. vermiculophylla*’s presence.

Addressing the interaction between heatwave-stressed seagrass habitats and invasive species such as *G. vermiculophylla* requires integrated monitoring and management approaches. Remote sensing technologies, including multispectral and hyperspectral imaging, provide powerful tools for tracking changes in vegetation health and distribution. Monitoring metrics such as the SHSI developed in Chapter 5 enable early detection of thermal stress, allowing for timely interventions. Management strategies should focus on mitigating stressors that exacerbate competitive dynamics. Reducing nutrient inputs to coastal waters can limit the proliferation of *G. vermiculophylla* and other opportunistic species. Physical removal of algal mats, combined with restoration efforts to enhance seagrass resilience, can help reestablish ecological balance. Additionally, incorporating predictive models to assess the impacts of future heatwave scenarios can guide proactive conservation measures.

The possible interactions between seagrasses and invasive species after extreme events might imply a complex interplay of environmental stressors, competition, and ecosystem resilience. Understanding these dynamics might be critical for preserving the ecological integrity of intertidal zones. By leveraging advanced monitoring techniques and implementing targeted management interventions, it is possible to mitigate the adverse effects of invasive species and climate-induced stress, thereby supporting the long-term sustainability of these vital coastal ecosystems.