# 6. General conclusions and future perspectives

This doctoral research successfully addressed its principal objectives, which were to (1) demonstrate the effectiveness of RS for mapping soft-bottom intertidal vegetation at a multispectral resolution, (2) develop machine-learning algorithms for accurate vegetation classification and ecosystem monitoring, and (3) apply the methodology to map invasive species and analyse the effect of heatwaves on seagrass. This work underscores the potential of RS 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 IAS mapping, this work highlights the critical role of multispectral and hyperspectral data in obtaining explicit spatial distribution maps of the main classes of intertidal vegetation. Integrating ground-based, drone, and satellite observations proved pivotal in bridging spatial and temporal gaps, enabling a more comprehensive understanding of ecosystem structure and dynamics. This concluding section reviews the key scientific advancements made through the application of RS to intertidal ecosystems, the challenges encountered, and future research directions.

## 6.1 Macrophytes discrimination and associated challenges.

This work has demonstrated the capability of multispectral RS 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, slight variations in the spectral signatures of intertidal green macrophytes enable this discrimination to arise from differences in the proportions in which these pigments are present in each vegetation type. Pigment concentrations and ratios are not static over time following phenological cycles, are 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. The classification method was developed across a wide geographical range, with the initial objective of discriminating among green macrophytes. The Drone Intertidal Substrate Classification of Vegetation (DISCOV) machine-learning algorithm was designed to be dynamic and adaptable, allowing continuous evolution over time. The algorithm is open-source, with its complete code and training/validation dataset shared on GitHub (<https://github.com/SigOiry/>; Oiry et al., 2024). This flexibility proved invaluable when adapting the algorithm to specifically target a species from a different class of intertidal vegetation: the invasive rhodophyte *Gracilaria vermiculophylla*.

Interestingly, DISCOV v1.0 exhibited poor performance in identifying this red macroalgae, 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, 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 ML models based on deep-learning architectures in satellite-based RS. Integrating UAV-derived observations and field-specific data, is particularly relevant for developing machine -learning workflow in complex environments such as intertidal zones.

Satellites, such as Sentinel-2, complement UAVs by offering broad spatial coverage and consistent temporal monitoring, facilitating seasonal and inter-annual changes assessment. 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.

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

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 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). This hybrid methodology balances local accuracy and scalability, reducing the costs associated with large-scale monitoring while preserving the depth of localized observations necessary for comprehensive assessments.

Integrating drone and satellite technologies enhances the ability to monitor, analyse, and manage intertidal ecosystems effectively. By combining detailed precision with extensive coverage, these technologies address scientific and environmental challenges efficiently. They improve modelling 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 HW 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 MHWs and AHWs. 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.

IAS 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* or other IAS to expand. 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 HW 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 algae 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, favouring 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 seagrasses habitats and IAS such as *G. vermiculophylla* requires integrated monitoring and management approaches. RS 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 HW scenarios can guide proactive conservation measures.

The possible interactions between seagrasses and IAS after extreme events might imply the 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 IAS and climate-induced stress, thereby supporting the long-term sustainability of these vital coastal ecosystems.

dominated intertidal seagrass meadows. Remote Sensing of Environment 251, 112020.