Monitoring the marine invasive alien species *Gracilaria vermiculophylla* with remote sensing

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Abstract

To be Written

[[1]](#footnote-1)

# 1. Title proposition

* Remote Sensing of *Gracilaria vermiculophylla* in the site of its First European Observation
* Monitoring the marine invasive alien species *Gracilaria vermiculophylla* using unmanned aerial vehicles
* Remote Sensing of *Gracilaria vermiculophylla*: Mapping its Distribution at the Site of its First European Description
* Mapping the Spread of the Invasive Species *Gracilaria vermiculophylla* using Remote Sensing at the Site of its Initial Description in Europe
* Quantifying *Gracilaria vermiculophylla* Spatial and Temporal Distribution Through Remote Sensing at its First Recorded European Site

# 2. Introduction

The introduction of Non-Indigenous Species (NIS) in terrestrial, freshwater, and marine ecosystems is one of the major threats to biodiversity worldwide. In particular, the proliferation and rapid spread of Invasive Alien Species (IAS) can radically change the structure and functioning of marine ecosystems, , requiring effective inventorying and monitoring programs (Massé et al., 2023). In Europe, 874 NIS have been introduced to the marine environment so far (i.e. until 2020) and it is expected that the rate of biological invasions will continue to increase in the coming years (Zenetos et al., 2022). Macroalgae represent more than 40 % of the NIS introduced to Europe waters, with many species native to the Temperate Northern Pacific (Williams and Smith, 2007). Amongst all invasive macroalgae, *Gracilaria vermiculophylla* (Papenfuss, 1967) (original name *Gracilariopsis vermiculophylla* (OHMI, 1956); also known as *Agarophyton vermiculophyllum* (Gurgel et al., 2018)), has spread extensively from its native distribution range in Japan and Korea (Terada and Yamamoto, 2002) across temperate estuaries in North America, Europe, and other regions, facilitated by aquaculture and maritime activities (Krueger-Hadfield et al., 2017; Rueness, 2005; Weinberger et al., 2008). In regions like the Baltic Sea and the eastern United States, it can affect native fucoid macroalgae and seagrasses negatively (Firth et al., 2024; Thomsen et al., 2013; Van Katwijk, 2003). It can also alter sediment composition (Nyberg et al., 2009), and disrupts trophic interactions (Ginneken et al., 2018). However, *G. vermiculophylla* can create new habitats for invertebrates and juvenile fish in a soft-bottom environment (Davoult et al., 2017) and, more generally, can positively enhance ecosystem processes (Ramus et al., 2017). The negative and positive effects of this species (Thomsen et al. 2019), which now dominate some coastal ecosystems, underscore the importance of monitoring and managing its population, particularly as climate change and anthropogenic pressures continue to facilitate biological invasions.

*G. vermiculophylla* success as an invader stems from its tolerance to a wide range of environmental conditions, including temperature (Sotka et al., 2018), nutrient variability (Abreu et al., 2011) and salinity (Weinberger et al., 2008). Its growth capacity at low salinities (Nyberg, 2007; Rueness, 2005) explains its presence in the brackish waters of the Baltic Sea (Weinberger et al., 2008) but also in the mesohaline sheltered part of estuaries of the Atlantic coast of Europe **(Surget et al., 2017)**. It is also present in confined areas of lagoons characterized by low hydrodynamism (Abreu et al., 2011; Sfriso et al., 2012). In Europe, it was first observed in 1996 in the Belon estuary (France) and later in many other estuaries on the Brittany coast of France (Rueness, 2005). It can be found on hard substrates such as invertebrate’s tubes and shells providing a substratum (Thomsen et al., 2007) or attached to pebbles and rocks (Terada and Yamamoto, 2002) but the largest populations are colonizing soft-bottom sediment and particularly estuarine intertidal mudflats **(Surget et al., 2017)**. In this habitat, extensive dark red mats are observed at low tide, covering vast areas that have largely been unquantified in most studies. Therefore, *G. vermiculophylla* can establish populations in soft-bottom sediment habitats, previously devoid of macroalgae (Ramus et al., 2017). These mats are usually monospecific, with the alga thalli partially buried in the mud (Rueness, 2005; Surget, 2017). Intertidal mats can, however, be temporarily overgrown by ephemeral green macroalgae (Weinberger et al., 2008). In the European estuaries where *G. vermiculophylla* was first documented, large monospecific mats were reported to be confined to the upper intertidal zones (Rueness, 2005); however, their spatial distribution relative to the mudflat topography and elevation had not been quantitatively assessed. In coastal lagoons of the East Atlantic coast, Besterman et al. (2021) have shown that the mudflat topography was a significant predictor of its abundance. In fact, *G. vermiculophylla* has never been mapped using remote sensing techniques, and existing descriptions of its distribution lack spatially explicit mapping (Abreu et al., 2011; Sfriso et al., 2012; Thomsen et al., 2007; Weinberger et al., 2008).

Remote sensing has revolutionized our ability to monitor and manage coastal ecosystems, offering efficient and scalable methods for detecting environmental changes in intertidal vegetation across a wide range of spatio-temporal scales (Calleja et al., 2017; Davies et al., 2024a, 2024b; Valle et al., 2015; Zoffoli et al., 2021). Among remote-sensing technologies, drone-based imagery has recently emerged as a particularly promising tool for studying the spatial distribution of intertidal primary producers such as benthic microalgae (Román et al., 2024, 2021), seagrass (Chand and Bollard, 2021; Duffy et al., 2018; Román et al., 2021) and macroalgae (Diruit et al., 2022; Peidro-Devesa et al., 2024). While it lacks the temporal consistency of satellite missions, drone remote sensing makes it possible to acquire at extremely high spatial resolution (i.e. cm-scale), rapidly target specific areas of interest, and provide observations in overcast conditions. In particular, the potential of drone remote sensing for monitoring the surface area occupied by IAS has been demonstrated (Roca et al., 2022). Drone-based photogrammetry also makes it possible to characterize the distribution of intertidal vegetation together with mudflat geomorphology, thus improving our understanding of primary producers patterning (Brunier et al., 2022; Douglas et al., 2024).

This study applied a drone-based remote sensing approach to map *G. vermiculophylla* spatial distribution at a very high spatial resolution in intertidal estuaries of the European Atlantic coast. We developed a neural network classification model of intertidal vegetation specifically trained with pixels of *G. vermiculophylla*. An *in situ* data validation dataset was obtained from French and Spanish sites to estimate the classification accuracy. LIDAR data were concurrently acquired to map the intertidal elevation accurately. A Generalized Additive Model (GAM) was used to examine the relationship between the seaweed spatial distribution and spatial metrics quantifying the mudflat topography. We expected the presence of *G. vermiculophylla* in mudflats to be associated with a specific height range as well as being more closely related to flat areas of the intertidal zone. In the Belon estuary (South Brittany, France) where it was first observed in Europe, a time series, starting from 1952, of RGB images was analysed to describe the temporal changes of its distribution over the last seventy years.

# 3. Materiel & Methods

## 3.1 Study sites

Field campaigns were conducted at three study sites in France and Spain. At each site, two locations were investigated [Figure 1](#fig-location_sites). The Aven & Belon Estuaries in South Brittany, France ([Figure 1](#fig-location_sites) A & C), are dynamic ria-type systems hosting diverse habitats, including tidal flats and subtidal zones with coarse, marine-origin sediments (Castaing and Guilcher, 1995; Michel et al., 2021). These habitats support key benthic species such as *Scrobicularia plana*, *Cerastoderma edule*, and *Tellina tenuis*, which play essential roles in sediment bioturbation and nutrient cycling (Blanchet et al., 2014; Tankoua et al., 2011). These estuaries serve as a nursery for juvenile fish and a feeding ground for migratory birds, with their ecological productivity driven by a mix of euryhaline and marine species adapted to salinity gradients (Blanchet et al., 2014). Oyster farming, particularly *Crassostrea gigas*, is a dominant activity, altering sediment dynamics and local biodiversity (Michel et al., 2021). Despite its ecological richness, the estuary faces pressures from nutrient loading and physical alterations (Tankoua et al., 2011).

The Saja-Besaya Estuary, situated along the Cantabrian Sea in northern Spain, is characterised by the confluence of the Saja and Besaya rivers near Torrelavega ([Figure 1](#fig-location_sites) C). The estuary, also known as San Martín de la Arena or Suances Estuary, has been subject to significant anthropogenic pressures, including industrial developments throughout the 20th century. These activities have led to contamination from mining, paper manufacturing, and carbonate discharges, classifying the estuary as highly polluted near its upper reaches (Ortega et al., 2005). This contamination impacted the water quality and biodiversity, with minimal aquatic life and sparse riverbank vegetation in its lower sections (Romero et al., 2008).

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| Figure 1: Location of the drone flights. A: Flights made in Aven Estuary, France; B: Flights made in Belon Estuary, France; C: Flights made in the Saja Estuary, Spain. Golden polygons represent intertidal areas. |

## 3.2 Remote sensing data acquisition and pre-processing

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| Figure 2: Gracilaria vermiculophylla in the Belon Estuary. A: Quadrat of 0.25 m² with a 100% cover of G. vermiculophylla; B: Single thallus showing cylindrical branches; C: Landscape view of mudflats covered by monospecific mats of G. vermiculophylla; D: Recording of the spectral signature of the algae using an ASD FieldSpec HandHeld 2 spectroradiometer. |

### 3.2.1 Hyperspectral measurements

At each location, hyperspectral reflectance signatures were recorded using an ASD FieldSpec HandHeld 2 spectroradiometer (Malvern Panalytical, Worcestershire, UK), which measures reflectance from 325 to 1075 nm with a spectral resolution of approximately 1 nm ([Figure 2](#fig-PictureFigure) D). Each spectrum was subsequently smoothed using a Savitzky–Golay filter (Savitzky and Golay, 1964) with a third-order polynomial and an 11-point window, selected to minimize noise while preserving salient spectral features. After this initial smoothing, the first and second derivatives were computed using a central difference approximation ([Equation 1](#eq-SecondDerivative)).

where is the reflectance at wavelength and is the uniform spectral sampling interval.

### 3.2.2 Drone data

A total of four drone flights were conducted across the three study sites. All flights were performed at an altitude of 120 m and a speed of 10 m·s⁻¹. Two flights were carried out in the Saja Estuary on June 25, 2024, covering areas of 20.4 hectares (Marisma de Cortiguera) and 8.4 hectares (Marisma de Cudón), respectively ([Figure 1](#fig-location_sites)). The other two flights took place in the Belon and Aven Estuaries on April 11, 2024, covering areas of 21.3 hectares and 26.7 hectares, respectively.

#### 3.2.2.1 Multispectral data

At each location, reflectance images with a resolution of 1.2 million pixels were captured using a DJI Matrice 300 quadcopter drone equipped with a Micasense RedEdge Dual MX multispectral camera. The camera recorded data across ten spectral bands, spanning from blue to near-infrared (NIR) wavelengths (444, 475, 531, 560, 650, 668, 705, 717, 740, and 840 nm) (). To ensure consistent lighting conditions, the drone’s flight trajectory was aligned to maintain a solar azimuth angle of 90 degrees. Image acquisition was carried out with an overlap of 70% between side-by-side images and 80% between successive images along the flight path. A downwelling light sensor (DLS2) was used to measure real-time irradiance, enabling the correction of reflectance values for variations in light intensity caused by cloud cover during the flight. The raw image data were subsequently calibrated to reflectance using a calibration panel with ~50% reflectivity, provided by the camera’s manufacturer. Images were processed using structure-from-motion photogrammetry software (Agisoft, 2019) to generate multispectral ortho-mosaics for each flight. The ortho-mosaicking workflow was consistent across all flights. Initially, key tie points were identified within each image and across overlapping images to create a sparse point cloud. This point cloud was refined by removing noisy points using a reprojection accuracy metric. Subsequently, a dense point cloud was generated using a structure-from-motion algorithm. A digital surface model (DSM) was then created through surface interpolation of the dense point cloud, which served as the basis for reconstructing the multispectral ortho-image (Nebel et al., 2020). The resolution of the multispectral ortho-mosaic obtained was 8 cm per pixel.

#### 3.2.2.2 LiDAR data

Using the Matrice 300 Series Dual Gimbal Connector, a DJI Zenmuse L1 LiDAR and RGB sensor was mounted on the drone alongside the multispectral camera. This setup enabled the simultaneous capture of LiDAR point clouds, high-resolution RGB images, and multispectral images collected by the MicaSense RedEdge Dual MX during the same flight. The same processing workflow as [Section 3.2.2.1](#sec-photo) was applied to process LiDAR RGB images, resulting in ortho-mosaic with a resolution of 2.5 cm per pixel. Since the mapping focused solely on surfaces without dense vegetation, the LiDAR measured only a single return. Operating in repetitive scanning mode with a sampling rate of 240 kHz, the system achieved a point density of 350 points per square meter. The LiDAR point cloud was extracted and converted into LAS format using DJI Terra software. The LAS point cloud was then imported into Agisoft Metashape (Agisoft, 2019) to generate a Digital Surface Model (DSM) with a resolution of 2.5 cm. From the DSM, the slope of each pixel based on a grid of 8 surrounding pixels was computed using the terrain function of the ‘terra’ package in R (Hijmans, 2024). The angle of the mudflat was categorized into three classes: Flat (angle < 10°), Intermediate (10° ≤ angle ≤ 40°), and Steep (angle > 40°).

## 3.3 Scene classification

We previously developed a neural network classification model for seagrass mapping using a multispectral drone (DISCOV; Oiry et al. (2024)). However, the algorithm had been marginally trained with a class of red macroalgae and was based on a workflow integrating different flight heights. In this study, we developed a new algorithm specifically designed for *G. vermiculophylla,* using a single flight height of 120 m, within a work-flow incorporating LIDAR data (Fig. X). A specific class of red macroalgae was trained with 427000 pixels in a neural network model. To validate the model, a Shiny app was developed, enabling independent users to photo-interpret snapshots of the ortho-mosaic from each drone flight (Chang et al., 2024; Simon, 2024). Users could click on various parts of the snapshots to indicate the type of vegetation they believed was present. Using this method, 3 independent users contributed to creating a validation dataset of 6755 pixels across 79 snapshots distributed among the four drone flights ([Section 7.2](#sec-AnnexeB)). The validation dataset was then simplified into two classes: the presence or absence of red macroalgae.

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| Figure 3: Schematic representation of the workflow. Parallelograms represent input or output data, rectangles represent Python processing algorithms, long rectangle represent instruments used and ovals represent study sites. Red shows Drone data; Orange shows the model training; Blue shows processing performed on the Digital Surface Model; Green shows the validation of the model; Purple shows the statistical analysis. |

## 3.4 Historical Presence of *Gracilaria vermiculophylla* in the Belon estuary

To assess the historical presence of *G. vermiculophylla* in the Belon Estuary, aerial imagery from flight campaigns was obtained via the IGN platform “Remonter Le Temps” (IGN, 2024). Nine images were selected between 1952 and 2012 from the IGN platform, and an additional one has been added for the year 2024 ([Section 7.3](#sec-AnnexeC)). Since most of the images retrieved from “Remonter Le Temps” were digitised versions of physical photographs, georeferencing was required.

For each date, polygons have been drawn around *G. vermiculophylla* patches by visual photo-interpretation. These polygons were used to calculate the total area of the mudflat covered by the

macroalgae within a common extent of 30 hectares in Pont de Guilly, located in the Belon Estuary, South Brittany, France.

# 4. Results

## 4.1 Historical records in the Belon estuary

A clear shift from bare sediment to vegetated mudflats has been observed over the past 70 years, corresponding to the colonisation of the Belon Estuary by *G. vermiculophylla* ([Figure 4](#fig-HistoricalMap)). In the 50s, the tidal flats showed no detectable presence of vegetation. In the 70s, some darkening of the sediment became discernible, but the first unambiguous presence of *G. vermiculophylla* was in 1982. During the subsequent decades, the spatial distribution increased and in 2024, a high-resolution mapping with a drone showed that monospecific mats of *G. vermiculophylla* exclusively colonised the mudflat.

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| Figure 4: RGB images of the Belon Estuary (Pont du Guilly) showing the colonisation of the mudflats by Gracilaria vermiculophylla between 1952 and 2024. |

The first detectable presence of *G. vermiculophylla* was observed after the introduction of the Pacific oyster *Crassostrea gigas* in the estuary in 1971/1972 (see vertical red dashed line in Figure 5). In the 70’s, its abundance was lower than 3%, but in the following two decades, the percent cover increased from 6.6% (2.0 ha) in 1982 to 14.7% (4.5 ha) in 1992 and nearly 30% (9.0 ha) by 1997. This increasing trend continued into the 21st century, peaking at 43.8% (13.3 ha) in 2012 and reaching a plateau of around 40 % in 2019 and 2024.

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| Figure 5: Trend of the Gracilaria vermiculophylla cover in the Belon Estuary (at Pont du Guilly). The red vertical line indicates the date of Crassostrea gigas introduction in South Brittany (Grizel and Heral, 1991), while the golden line represents the date of the first documented mention of Gracilaria vermiculophylla presence in Europe which was in the Belon Estuary (Rueness, 2005). |

## 4.2 Spectral description

The spectral signature of *G. vermiculophylla* was characterised by a reflectance pattern in the visible region of the spectrum shaped by the photosynthetic and accessory pigments common to all rhodophytes ([Figure 6](#fig-SpecDescri) A). This pattern was primarily driven by phycoerythrin and phycocyanin, which exhibited maximum absorption peaks at approximately 565 nm and 620 nm, respectively. An additional absorption feature around 495 nm was likely attributable to accessory carotenoid pigments. The most pronounced absorption peak occurred at 675 nm, corresponding to chlorophyll-a absorption. The second derivative analysis clearly highlighted the inflexion points corresponding to the main absorption peaks at 495, 565, 620, and 675 nm, allowing for more precise identification of the wavelength associated with these pigments ([Figure 6](#fig-SpecDescri) B).

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| Figure 6: Hyperspectral signature of Gracilaria vermiculophylla (A) and its second derivative (B). The black line represents the average spectra, while the shaded area indicates the standard deviation. Dashed lines mark the absorption maxima of Phycoerythrin, Phycocyanin, and Chlorophyll-a, shown in green, orange, and red, respectively. |

## 4.3 Spatial distribution

The classification map obtained from the neural network algorithm is shown for the Belon estuary ([Figure 7](#fig-Belon) A). Among the main classes of intertidal vegetation, the class of Rhodophyceae (red) was the dominant algal cover, forming extensive, continuous patches colonising mudflats. In contrast, Bacillariophyceae (orange) and Chlorophyceae (green) exhibited more localized distributions, typically restricted to smaller, fragmented patches. A few Phaeophyceae (brown) were confined to limited patches in the upper intertidal attached to rocks. In the Saja Estuary, the Rhodophycea were more evenly mixed with Chlorophyceae (Supplementary Fig. X). Across the study sites, the presence/absence of *G. vermiculophylla* was classified with a global accuracy of 91.1 %, a sensitivity of 96.5 % and a specificity of 71.5 %.

The elevation map showed that the main mats of Gracilaria were between 1 and 2 m above mean sea level (Figure 7 C). Algal presence was markedly elevation-driven, with lower intertidal zones closer to the tidal channel consistently exhibiting reduced macroalgal cover. Commentes la figure 7D

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| Figure 7: Classification of the main classes of intertidal vegetation with a neural network algorithm (A), RGB composition (B), elevation (C) and mudflat topography (D) of the Belon estuary site in Brittany, France. The total extent of this flight was 21 hectares with a resolution of 8 mm per pixel. Elevation corresponds to the height above mean sea level. |

Overall, the percent cover of *G. vermiculophylla* increased with elevation, as shown by the general relationship ([Figure 8](#fig-Gam_Slope), black line), which rises from approximately 16% at the lowest elevation to about 30% at the highest elevation. This indicates a consistent positive association between elevation and algal cover. When accounting for slope, the flatter the slope, the higher the percent cover of *G. vermiculophylla*. For flat slopes, the cover ranged from approximately 20% at the lowest elevation to nearly 38% at the highest elevation. In contrast, the increase was less pronounced for angled slopes, ranging from around 16% to 32%. The cover was the lowest on steep slopes, starting at about 15% and rising only slightly above 30% at the highest elevation ([Figure 8](#fig-Gam_Slope)). This demonstrates that slope modifies the relationship, with flatter slopes supporting a greater percent cover of the algae.

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| Figure 8: DISCOV Prediction (A), RGB composition (B) and Bathymetry (C) of the Bélon estuary site in Brttany, France. The total extent of this flight was 21 hectars with a resolution of 8 mm per pixel. Bathymetry is represented as the height above mean sea level. |

# 5. Discussion

## 5.1 Drone mapping *G. vermiculophylla* with machine learning

In this study, we produced the first spatial distribution maps of the invasive red alga *Gracilaria vermiculophylla* using a multispectral drone survey conducted at low tide in Atlantic estuaries representing varied environmental conditions. In southern Brittany, the species formed monospecific mats, while in the Cantabrian region of Spain, it was intermixed with other intertidal vegetation. Distinguishing among these vegetation types was a key prerequisite for the analysis.

To achieve this, we adapted the deep learning-based classification model DISCOV (Oiry et al., 2024), initially developed to discriminate seagrass from green macroalgae. Although the original model included Rhodophyceae as a class, this group constituted less than 3% of its training dataset. In contrast, the updated model presented here was trained on a dataset in which *G. vermiculophylla* covered 26 % of approximately one million pixels. This improved dataset allowed the model to achieve an accuracy of 91.1 %.

Rhodophytes possess unique phycobilin pigments, enabling their spectral distinction from other macroalgal groups (Douay et al., 2022; Mcilwaine et al., 2019; Olmedo-Masat et al., 2020). Even with the ten-band multispectral sensor used in our study, it remained feasible to discriminate the major classes of intertidal macrophytes (Davies et al., 2023; Oiry et al., 2024; Román et al., 2021). However, the model identifies *G. vermiculophylla* at the class level (Rhodophyceae) rather than at the species level. Although hyperspectral approaches may allow finer taxonomic resolution (Douay et al., 2022; Olmedo-Masat et al., 2020), it is unlikely that Gracilaria species can be precisely distinguished using standard multispectral sensors.

Ecological factors also aid in differentiating *G. vermiculophylla*. Unlike many other macroalgae that require hard substrates, *G. vermiculophylla* establishes itself on soft-bottom sediments. In fact, it is commonly found on mudflats, anchoring its thalli in the top 10 cm of mud (Surget, 2017), and inhabits the upper intertidal zone—an unusual trait for a Rhodophyte (Abreu et al., 2011; Davoult et al., 2017). By reliably detecting *G. vermiculophylla* in these soft-substrate, upper intertidal habitats, our method provides a framework for identifying environmental conditions that favor its spread, potentially offering managers early-warning indicators to control its expansion before it reaches nuisance levels. Thus, combining spectral data with sediment characteristics provides a strong indicator of *G. vermiculophylla* presence in European Atlantic estuaries, complementing the physical variables already used in species distribution modeling (Mendoza-Segura et al., 2023).

In addition, the scalability of drone-based surveying facilitates repeat mapping to detect temporal shifts in the distribution and abundance of *G. vermiculophylla.* Such continuous monitoring could capture seasonal patterns of colonization, allowing researchers and environmental managers to evaluate the effectiveness of mitigation measures, track long-term ecological impacts, and anticipate future shifts in habitat suitability under changing climate conditions.

## 5.2 *G. vermiculophylla* spatial distribution and mudflat topography

The spatial distribution of *Gracilaria vermiculophylla* across intertidal zones reveals a distinct relationship with mudflat topography, which significantly influences algal density and coverage. Our results show that higher elevations within the intertidal zone support greater densities of *G. vermiculophylla*. A pattern that aligns with findings by Thomsen et al. (2009), where elevated areas provided optimal conditions for algal survival.*Gracilaria vermiculophylla* demonstrates remarkable physiological plasticity, enabling it to tolerate a broad spectrum of environmental conditions, including temperature fluctuations (Sotka et al., 2018), nutrient variability (Abreu et al., 2011), and a wide range of salinities (Weinberger et al., 2008). Its capacity for sustained growth under low salinity conditions (Nyberg, 2007; Rueness, 2005) underpins its successful establishment and persistence within polyhaline and mesohaline estuarine environments. A strong constrain however for the implentation of the algae is the hydrodynamism. Unlike seagrasses, another type of marine plant that can also colonize soft sediment, which possess rhizomes that provide robust anchorage, *Gracilaria vermiculophylla* lacks such specialized structures. Its attachment to the substrate relies solely on its buried thalli, which embed into the upper layers of soft sediment. This mode of anchorage renders the alga particularly vulnerable to high hydrodynamic conditions, as it lacks the structural stability needed to withstand strong currents or wave action. To partially bury its thalli into the sediment, *Gracilaria vermiculophylla* requires areas with high sedimentation rates. These conditions are typically found in the upper regions of estuarine systems or in proximity to other macrophytes, such as *Sporobolus* spp. (commonly known as small cordgrass), which reduce current velocity and promote sediment deposition (Mudd et al., 2010). This observation aligns with the findings illustrated in [Figure 4](#fig-HistoricalMap), which show that one of the first areas colonized by *G. vermiculophylla* in 1992 in the Bélon estuary, France, was located near a salt marsh patch.  
As a result, *Gracilaria vermiculophylla* compensates for its vulnerability to hydrodynamic forces by forming dense mats, which enhance its stability and facilitate its persistence and proliferation in intertidal and estuarine environments with low to moderate hydrodynamic conditions (Surget, 2017).

The negative relationship between slope steepness and the density of *Gracilaria vermiculophylla* can be explained by the physical and ecological characteristics of steeper mudflat areas. Steeper slopes are typically associated with higher rates of water runoff during tidal exchanges, resulting in stronger hydrodynamic forces. These forces can lead to increased sediment erosion, reduced sedimentation, and less stable substrate conditions, which are unfavorable for *G. vermiculophylla* to anchor its thalli effectively (Besterman et al., 2021). Furthermore, steeper slopes may limit the retention of organic matter and nutrients, reducing the availability of essential resources needed for algal growth. In contrast, flatter areas within the intertidal zone are more likely to accumulate fine sediments and retain water for longer durations during low tides, creating a more stable and nutrient-rich environment conducive to *G. vermiculophylla* proliferation. Additionally, these conditions may favor the formation of dense algal mats, which further stabilize the sediment and promote growth.

## 5.3 Spatio-temporal monitoring of invasive macroalgae

Accurate, high-resolution maps of invasive or alien species are extremely scarce (Fourcade et al., 2014; Vilizzi et al., 2021), yet they enable in-depth evaluations of these species’ ecology, temporal dynamics, and niche behavior in relation to their environment. In this study, using individual flights over monospecific algal mats, we quantified how this invasive alga associates with local mudflat topography, demonstrating that its distribution is closely tied to specific topographical features, such as elevation and slope gradients. This relationship reveals how physical features of the mudflat can influence the extent and density of *Gracilaria vermiculophylla* mats. Understanding the drivers of the spatial distribution of the algae helps to anticipate the future development of this species and identify areas vulnerable to its invasion. Repeated monitoring of this type can further reveal phenological patterns, invasion dynamics, and local conspecific biological interactions—such as co-occurrence, displacement, or avoidance (Arim et al., 2006; Godoy et al., 2009).

Remote sensing using multispectral drone mapping can provide high-resolution, spatially explicit data, but it must be combined with repeated, in situ field measurements to maximize its potential (Chadwick et al., 2020; Zoffoli et al., 2023). As noted, temporal repetition makes it possible to assess dynamic processes, and integrating these mapping approaches with in situ analyses of local infauna, carbon cycling, riverine inputs, and sedimentology would yield valuable insights for local managers. Such an integrated approach could help determine how the invasive algae affects the local ecosystem and, more broadly, forecast its potential impact on other estuarine environments facing similar invasion events. This holistic approach can guide strategic interventions aimed at mitigating the alga’s spread, maintaining ecological balance, and protecting native biodiversity, ensuring that management efforts are informed by accurate, timely, and spatially explicit data.

Invasive species like *Gracilaria vermiculophylla* and *Rugulopteryx okamurae* can be identified using drones equipped with multispectral sensors, taking advantage of the characteristic reflectance of rhodophytes (Barillé et al., 2025; Nurdin et al., 2023). However, while RGB sensors on readily available commercial drones can be used to perform accurate scene classification, their effectiveness for mapping invasive species has not yet been demonstrated (Cheng et al., 2017; Kazakeviciute-Januskeviciene et al., 2020). These drones are easy to deploy, can cover large areas when flying at speeds of 15 m s-1 at an altitude of 120 m, and still maintain sufficient overlap between images to support photogrammetric reconstruction. Expanding these methodologies to RGB-based detection would significantly lower barriers to entry, allowing local stakeholders with limited resources to access valuable monitoring tools for early detection and rapid response. A promising avenue for operational applications lies in testing machine learning techniques for coastal habitat mapping using RGB imagery that do not rely on enhanced spectral resolution. Considering the low cost of RGB and multispectral commercial drones, coupled with ongoing advancements in machine learning, drone-based remote sensing has now matured into a practical tool for adoption by environmental authorities in coastal management. Integrating these technologies into routine monitoring protocols can enhance surveillance capabilities, improve understanding of invasive species dynamics, and ultimately contribute to more effective conservation and restoration strategies.

## 5.4 Timing of the Invasion of Gracilaria vermiculophylla in the Bélon Estuary

The invasive red alga *Gracilaria vermiculophylla* represents a significant example of delayed recognition and documentation in biological invasions. Historical aerial imagery and photo-interpretation analyses from the Bélon Estuary suggest the initial presence of this species in 1976 [Figure 4](#fig-HistoricalMap), preceding its first formal description in European waters in 1996 by two decades (Rueness, 2005). This lag highlights challenges associated with the detection, monitoring, and reporting of invasive species and their ecological impacts during early colonization.

The appearance of *G. vermiculophylla* in 1976 corresponds with the introduction of the Pacific oyster (Crassostrea gigas) into the estuary, a few years before, between 1971 and 1975, and a potential vector for algal dispersal through aquaculture activities (Grizel and Heral, 1991; Rueness, 2005). After initial establishment, the alga progressively occupied suitable habitats, consistent with theoretical invasion dynamics involving a lag phase followed by rapid spread (Arim et al., 2006). The establishment of *G. vermiculophylla* likely induced changes in sediment characteristics, trophic interactions, and habitat structure prior to formal recognition (BenDor and Metcalf, 2006). Such shifts are comparable to documented impacts in similar systems, yet remain difficult to quantify without early monitoring data.

The temporal gap between the first presence and documentation reflects limitations in early surveillance, potentially underestimating ecological and economic impacts during the initial colonization phase. Studies on invasion dynamics demonstrate that early detection is crucial for effective containment and management, particularly before an invasion reaches the exponential spread phase, which complicates control efforts (Arim et al., 2006; BenDor and Metcalf, 2006). In the Bélon Estuary, *G. vermiculophylla* appears to have thrived under ecological conditions favorable to its proliferation enabling the formation of dense mats in about 6 years (between 1976 and 1982; [Figure 4](#fig-HistoricalMap)). This undocumented growth likely contributed to substantial changes in the estuarine ecosystem.

Remote sensing technologies, including aerial imagery and drone-based multispectral imaging, are proving to be valuable tools for the early detection and monitoring of invasive species. Historical aerial imagery has provided valuable insights into long-term invasion patterns by enabling the retrospective identification of shifts in habitat characteristics. Modern drone-based systems enhance this capacity through high spatial and temporal resolution, enabling the rapid detection of invasive species at early stages of establishment. By capturing detailed data on the spatial distribution and habitat preferences of species such as *G. vermiculophylla*, remote sensing facilitates timely interventions, allowing stakeholders to take rapid measures to limit the invasion. Integrating these tools into routine monitoring programs offers a scalable and efficient means to track invasive species dynamics and inform targeted management strategies.

# 6. Conclusion

# 7. Annexes

## 7.1 Annexes A - Updated training dataset

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| Table 2: Class of the Neural Network model, with the number of training pixels used to train that class and the differences with the training dataset of DISCOV v1.0   | Name | Taxonomic Class | Training Pixels | Difference with DISCOV v1.0 | | --- | --- | --- | --- | | Benthic Diatoms | Bacillariophyceae | 62,436 | x13.95 | | Green macroalgae | Chlorophyta | 92,585 | x5.4 | | Seagrass | Magnoliopsida | 221,065 | - | | Brown macroalgae | Phaeophyta | 169,936 | - | | Red macroalgae | Rhodophyta | 268,637 | x46.55 | | Sediment | - | 117,956 | x1.24 | | Water | - | 91,614 | x1.09 | |

## 7.2 Annexes B - Validation dataset

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| Table 3: Presence and absence of red macroalgae for each drone flight   | Site | Absent | Present | Total | | --- | --- | --- | --- | | Marisma de Cortiguera | 1,531 | 483 | 2,014 | | Marisma de Cudón | 1,237 | 136 | 1,373 | | Notre-Dame De Tremor | 1,073 | 463 | 1,536 | | Pont de Guilly | 1,389 | 443 | 1,832 | | Total | 5,230 | 1,525 | 6,755 | |

## 7.3 Annexes C - List of historical images records

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| Table 4: Images used to assess the historical presence of Gracilaria vermiculophylla in the Belon esturay. Images from the IGN data source have been retrieved from the “Remonter Le Temps” plateform (IGN, 2024). Drone flight have been performed by the team using a Mavic 3 Entreprise.   | Date | Type | Data Source | Resolution (cm per Pixel) | | --- | --- | --- | --- | | 1952-04-26 | Black and White | IGN | 10 | | 1958-04-22 | Black and White | IGN | 90 | | 1976-07-? | Black and White | IGN | 4 | | 1978-08-22 | Black and White | IGN | 44 | | 1982-08-11 | Black and White | IGN | 44 | | 1992-05-17 | True Color | IGN | 70 | | 1997-04-11 | Black and White | IGN | 64 | | 2012-07-24 | True Color | IGN | 18 | | 2024-04-11 | True Color | Drone Flight | 3 | |

## 7.4 Annexes D - Maps of the Saja esturay, France

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| --- |
| Figure 9: DISCOV Prediction (A), RGB composition (B) and picture of the field campaign of the Saja esturay, Nothern Spain. The total extent of this flight was 20.4 hectars with a resolution of 8 mm per pixel. |

# 8. References

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