

DISCOV-Gracilaria Paper

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To be Written

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1 Introduction

Coastal ecosystems are among the most dynamic and productive environments on Earth, providing ecosystem services and supporting biodiversity (Barbier et al., 2011; Unsworth et al., 2022; Watanabe et al., 2018). These ecosystems, spanning mangroves, salt marshes, seagrass meadows, and rocky intertidal zones, play a pivotal role in carbon sequestration, nutrient cycling, and shoreline stabilization (Liquete et al., 2013; Mehvar et al., 2018). They also serve as habitats for numerous species, many of which are commercially or ecologically significant (De Valck et al., 2023; Seitz et al., 2014). Coastal areas are densely populated, with billions of people globally depending on their resources for livelihoods, fisheries, and tourism (Mukherjee et al., 2023; Small and Nicholls, 2003). However, coastal ecosystems face mounting pressures from human activities such as land reclamation, pollution, and overfishing, compounded by the impacts of climate change (Hall-Spencer and Harvey, 2019; Lu et al., 2018). Sea level rise, ocean acidification, and increasing storm intensity further exacerbate the vulnerability of these systems, threatening their resilience and the services they provide (He and Silliman, 2019).

One of the significant threats to coastal ecosystems is biological invasions by non-native species, which can disrupt native biodiversity and alter ecosystem functions (Capdevila et al., 2019; Krueger-Hadfield, 2018; Liu et al., 2020). *Gracilaria vermiculophylla*, an invasive red macroalga native to the northwest Pacific, exemplifies this issue. Over the last century, this species has spread extensively across temperate estuaries in North America, Europe, and other regions, facilitated by aquaculture and maritime activities (Krueger-Hadfield et al., 2017;

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Rueness, 2005; Weinberger et al., 2008). Its success as an invader stems from its tolerance to a wide range of environmental stressors, including temperature (Sotka et al., 2018), salinity (Weinberger et al., 2008), and nutrient variability (Abreu et al., 2011), as well as its ability to establish in soft sediment habitats traditionally devoid of macroalgae (Ramus et al., 2017). While *G. vermiculophylla* can provide some ecosystem services, such as habitat for invertebrates and juvenile fish, it often outcompetes native vegetation, alters sediment composition (Nyberg et al., 2009), and disrupts trophic interactions (Ginneken et al., 2018). In regions like the Baltic Sea and the eastern United States, it has been documented to negatively affect native fucoids and seagrasses (Thomsen et al., 2013; Van Katwijk, 2003). These impacts underscore the importance of monitoring and managing the spread of *G. vermiculophylla*, particularly as climate change and anthropogenic pressures continue to facilitate biological invasions.

Remote sensing has revolutionized our ability to monitor and manage ecosystems, offering efficient and scalable methods for detecting environmental changes over large areas (Davies et al., 2024a, 2024b; Zoffoli et al., 2021). Among these technologies, drone-based remote sensing has emerged as a particularly promising tool for studying coastal environments (Román et al., 2024, 2023). Equipped with high-resolution cameras and multispectral or hyperspectral sensors, drones can capture fine-scale spatial and spectral data, enabling researchers to identify and map vegetation, detect stress in plants, and monitor changes over time [Román et al. (2021) ; Oiry et al. 2024]. Unlike traditional satellite imagery, drones provide the flexibility to operate in overcast conditions, achieve higher spatial resolution, and target specific areas of interest. For invasive species like *G. vermiculophylla*, drones equipped with multispectral sensors can differentiate it from native vegetation based on its unique spectral reflectance characteristics (Davies et al. 2025). This capability not only enhances detection accuracy but also reduces the time and labor associated with traditional field surveys. As the cost of drone technology continues to decrease and advancements in machine learning facilitate data analysis, drone-based remote sensing is becoming increasingly accessible and impactful for ecological research and management.

In this study, we aim to harness the potential of drone-based multispectral remote sensing to map *Gracilaria vermiculophylla* in intertidal zones. Bla bla what are we going to do ? bla bla .

2 Materiel & Methods

2.1 Study sites

The Aven & Belon Estuary in South Brittany, France, is a dynamic ria-type system hosting diverse habitats, including sandy tidal flats and subtidal zones with coarse, marine-origin sediments Figure 1. 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). The estuary serves as a nursery

for juvenile fish and a feeding ground for migratory birds, with its 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, with bioindicators like *S. plana* used to monitor the impacts of salinity, sediment quality, and pollution (Tankoua et al., 2011).

The Ria d'Étel, located in Brittany, France, is a macrotidal estuary characterized by its unique hydrodynamics and biodiversity (Figure 1 B). Influenced predominantly by tidal regimes, the estuary exhibits high-energy zones with strong currents reaching up to 2.5 m/s, shaping both sediment deposition and ecological habitats (Portas et al., 2023). The estuary supports diverse benthic communities, with sedimentary organic matter originating from both terrestrial inputs and marine sources, contributing to nutrient cycling and benthic fluxes (Jeanneau et al., 2023). Vegetation gradients transition from halophytic plants in saline zones to freshwater species upstream, reflecting the estuary's salinity dynamics and ecological complexity (Cianfaglione, 2021). This estuary is also notable for its shellfish farming, with species like *Crassostrea gigas* cultivated extensively. The presence of filter-feeding organisms such as sponges (*Hymeniacidon perlevis*) enhances water quality by mitigating bacterial loads and promoting bioremediation (Gentric and Sauleau, 2024). However, the estuary faces environmental pressures, including nutrient enrichment from agricultural runoff and anthropogenic impacts on sedimentary processes.

The Saja-Besaya Estuary, situated along the Cantabrian Sea in northern Spain, is characterized by the confluence of the Saja and Besaya rivers near Torrelavega (Figure 1 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 impacts the estuarine ecosystem, including water quality and biodiversity, with minimal aquatic life and sparse riverbank vegetation in its lower sections (Romero et al., 2008).

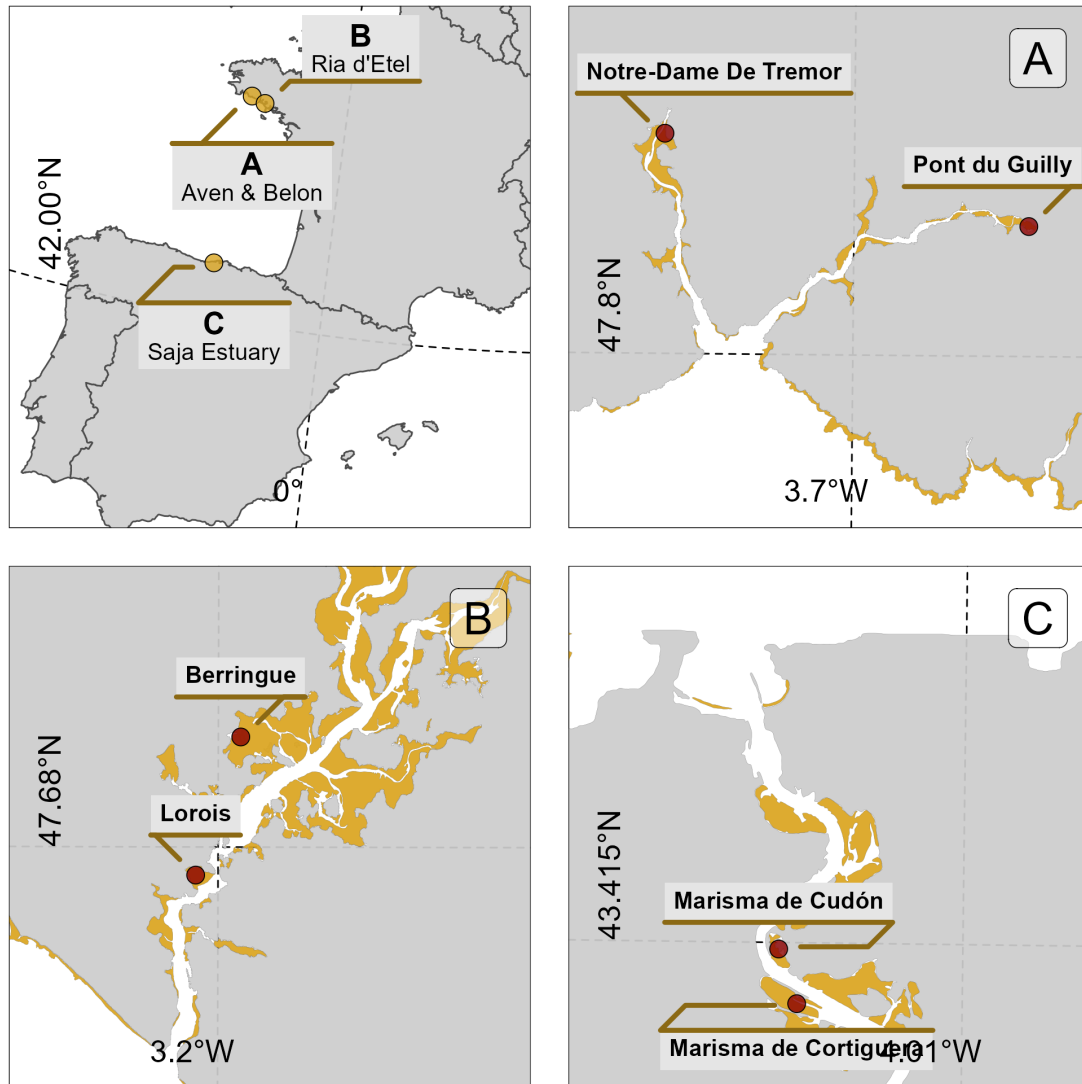


Figure 1: Location of the drone flights. A: Flights made in Aven & Belon Estuaries, France; B: Flights made in Etel Estuary, France; C: Flights made in Saja Estuaries, Spain. Golden polygons represent intertidal areas.

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