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Rugulopteryx okamurae beachcast trends in Algiers beaches : Insights from Earth Observation

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Presented on 22/06/2026, before the jury composed of :

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Hoping that this work will be useful for future studies and will provide a modest contribution to further research and applications.

Souad Sid Ahmed

Table of contents

List of figures

List of tables

List of abreviations

AOI : Area of Interest

EASIN : European Alien Species Information Network

eDNA : environmental DNA

FAI : Floating Algae Index

GAM : Generalized Additive Model

GEE : Google Earth Engine

GISD: Global Invasive Species Database

GPS : Global Positionning System

IAS : Invasive Alien Species

IFAPA : Instituto Andaluz de Investigación y Formación Agraria, Pesquera, Alimentaria y de la Producción Ecológica

IPBES : Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

L2A : Level 2-A

MAP : Mediterranean Action Plan

MEER : Ministère de l'Environnement et des Énergies Renouvelable

NDMI : Normalized Difference Moisture Index

NDVI : Normalized Difference Vegetation Index

NDWI : Normalized Difference Water Index

NIR : Near Infra-Red

ODW : Optically Deep Water

RF : Random Forest

RGB : Red, Green, Blue

SAV : Submerged Aquatic Vegetation

S2A : Sentinel-2 A

S2B : Sentinel-2 B

S2C : Sentinel-2 C

SWIR : Short Wave Infra-Red

UAVs : Unmanned Aerial Vehicles

VNIR : Visible and Near Infra-Red

Units

°C : Degree Celcius

% : Percentage

cm : Centimeter

m : Meter

nm : Nanometer

µm : Micrometer

INTRODUCTION

Introduction

Biological invasions are a major driver of biodiversity loss and ecosystem change, particularly in marine environments where shipping, aquaculture, and trade facilitate the introduction of non-indigenous species beyond their native ranges. Owing to its intense maritime traffic and long history of species exchanges, the Mediterranean Sea has become one of the world's most invaded marine regions. Recent assessments indicate that the number of established non-indigenous species continues to increase, with new introductions reported every year across the basin (Zenetos et al., 2022)

Among the invasive macroalgae currently expanding in the Mediterranean, *Rugulopteryx okamurae* (E.Y. Dawson) I.K. Hwang, W.J. Lee & H.S. Kim has emerged as one of the most impactful species. Since its rapid expansion from the Strait of Gibraltar in 2015, the species has colonized large areas of the western Mediterranean, producing substantial quantities of biomass and altering coastal ecosystems (García-Gómez et al., 2020; Laamraoui et al., 2024). A particularly visible consequence of this invasion is the formation of extensive beachcasts, resulting from the accumulation of detached algal biomass along the shoreline. In several Mediterranean regions, these accumulations have affected beach use, tourism activities, and coastal management, generating significant environmental and economic concerns (García-Gómez et al., 2020).

The Algerian coastline extends over 2100 km along the southern Mediterranean Sea (MEER, 2023) and is increasingly exposed to marine biological invasions. A first national assessment identified 70 introduced marine species in Algerian waters, of which more than half were classified as true alien species, with macroalgae accounting for nearly 30% of all records (Grimes et al., 2018). Subsequent Mediterranean inventories have reported a continued increase in non-indigenous species throughout the region, highlighting the growing influence of biological invasions on Algerian marine ecosystems (Galanidi et al., 2023). In recent years, *R. okamurae* beachcasts have been observed on beaches in Algiers; however, their spatial extent, temporal evolution, and overall impact remain poorly documented.

Addressing this knowledge gap requires monitoring approaches capable of covering large coastal areas efficiently and repeatedly through time. While field surveys provide essential ecological information, their implementation along extensive coastlines is often costly and time-consuming. In this context, Remote sensing offers a valuable alternative for large-scale environmental monitoring. The Sentinel-2 mission provides freely available multispectral imagery with high spatial and temporal resolution, while cloud-computing platforms such as Google Earth Engine (GEE) enable the rapid processing and analysis of large satellite archives (Drusch et al., 2012; Gorelick et al., 2017). Recent studies have demonstrated the potential of combining satellite imagery and field observations to monitor the distribution of *R. okamurae* and other coastal macroalgae (Roca et al., 2022).

In this context, the present study aims to evaluate the potential of Sentinel-2 imagery and Google Earth Engine for detecting and monitoring *R. okamurae* beachcast accumulations along the Algiers beaches since 2023. By integrating satellite observations with field measurements, this study seeks to quantify the spatial distribution and temporal evolution of beachcasts, as well as assessing invasion trends. Ultimately, it provides the first assessment of *R. okamurae* beachcast dynamics in Algeria and highlights the potential of Earth Observation technologies for supporting invasive species monitoring and coastal management.

To address the objectives of this study, the thesis is organized into four chapters:

- **Chapter 1: Literature Review**

This chapter presents the scientific background of the study, focusing on marine biological invasions, *R. okamurae* biology and ecology, beachcast formation, and the use of Earth Observation for coastal monitoring.

- **Chapter 2: Material and Methods**

This chapter describes the study area, the field and satellite data used, and the methodology developed to detect and monitor *R. okamurae* beachcast using Sentinel-2 satellite imagery and Google Earth Engine.

- **Chapter 3: Results and Discussion**

This chapter presents the main findings of the study and discusses the spatial and temporal dynamics of *R. okamurae* beachcast along the Algiers beaches.

- **Chapter 4: Conclusion and Perspectives**

This chapter summarizes the main outcomes of the research, highlights its limitations, and suggests directions for future work.

Literature review

1. Literature Review

1.1 Marine Invasive Alien Species

Invasive Alien Species (IAS), as defined by the Convention on Biological Diversity (CDB, 2010) are organisms that humans have moved outside their natural habitats, which then harms local biodiversity. Global trade and travel have introduced over 37,000 alien species, of which around 3,500 become invasive, contributing to 60% of global plant and animal extinctions. . The economic impact of these species worldwide exceeded $423 billion in 2019, with costs having quadrupled every decade since 1970 (IPBES, 2023).

Marine invasions differ from terrestrial ones due to several general properties of the two systems: (i) marine systems are open, with global oceanic circulation patterns, pelagic larvae, and large-scale migrations, making them one of the most invaded systems on earth and a difficult ecosystem to study and control invasive species (Carr et al., 2003; Geburzi & McCarthy, 2018); (ii) marine systems exhibit less varability than terrestrial systems particularly in terms of temperature and currents (Steele et al., 2019); (iii) studies of invasions in terrestrial systems are more numerous than those concerning marine systems.

However, because of the increasing concern for marine biodiversity and marine resources, it is important to study the biological mechanisms and ecological impacts of invasive alien marine species, especially invasive macroalgae, due to their capacity to proliferate rapidly, outcompete native species, and alter the structure and functionning of coastal ecosystems (Li et al., 2023).

Many countries lack dedicated monitoring systems for marine IAS, and monitoring methodologies must be standardized and improved. In addition, the introduction pathways of numerous marine IAS remain uncertain. Eradication and control attempts have had limited effectiveness, highliting the need for improved biosecurity measure (Katsanevakis et al., 2023).

Despite these challenges, prevention is the most cost-efficient way to handle IAS. However, when prevention efforts fail, it is important to detect the invasion early stages to evaluate measures that prevent further expansion.

As an example, in the Mediterranean, Aglieri et al., (2023) used eDNA metabarcoding in fishing ports, combined with fishing fleet data, to detect IAS, showing that port waters provide effective rapid-assessment sites for monitoring invasive species and overall marine biodiversity.. The application of these rapid assessment techniques is particularly important, as ballast water is still the greatest vector for the spread of IAS (Kraus, 2023). The prevention strategy for this vector concentrates on the monitoring of ports to enable rapid detection of IAS as soon as they are introduced, thus allowing early warning systems to prevent their further spread into larger areas. When the ballast water contains suspected IAS, alternative preventive measures include the use of treated or drinking water for ballast or its disposal into specialized port reception facilities (Kraus, 2023).

1.2 Algal Invasions

Macroalgae invasions are the biggest threat to marine biodiversity and normal functioning of coastal ecosystems, representing more than 40% of IAS in the European Union (Schaffelke et al., 2006; Williams & Smith, 2007). Macroalgae represent the taxa with the greatest number of species potentially released through aquarium trade and frequetly introduced through aquaculture activities (Geburzi & McCarthy, 2018). However, humain vectors such as maritime transport and commercial transfers remain the main introduction pathway, particularly through shipping and hull fouling, which facilitate long-distance introductions, while habitat disturbances, eutrophication, and local biotic vectors facilitate the establishment and spread of invasive species such as Caulerpa cylindracea (Wonham et al., 2005; Hewitt et al., 2007; Mineur et al., 2008; I. C. Davidson et al., 2018; Hernández et al., 2024).

Ecological and economic risks such as loss of biodiversity, altered structure of benthic communities and negative impacts on the coastal ecosystem services are raised from the proliferation of invasive macroalgae (A. D. Davidson et al., 2015; Faria et al., 2022). Besides these threats, invasive macroalgae can exert positive effects on ecosystems establishing habitats and serving as secondary substrate to which sessile organisms can attach (Jones & Thornber, 2010). The impact of each marine invasive macroalgae must be examined separately and in the context of the specific environment (Thomsen et al., 2011).

1.3 Rugulopteryx okamurae

A. Biological and ecological background

Rugulopteryx okamurae (E.Y.Dawson) I.K.Hwang, W.J.Lee & H.S.Kim, 2009 transferred from *Dictyota okamurae*, is a brown macroalgae that belongs to the Dictyotales (Orchophyta) order. This species is indigenous to the western pacific ocean, particularly the coasts of China, Korea, and Japan (Hwang et al., 2009; Verlaque et al., 2009). The medulla consists of a single layer of large cuboidal cells, except at the margins where there are 2-4 layers of thick-walled cells; the apices are obtuse and slightly emarginate, and sporangia are borne on two stalk cellsfeatures that are distinctive. Confusion may occur with native Dictyota species, which have more or less rounded apices, a medulla that is never polystromatic at the margins and monostromatic in the central blade, and sporangia supported by a single stalk cell. Other taxonomic discrimination methods, beyond genetic identification, are also available. Fatty acid (FA) profiling, for example, provides a robust chemotaxonomic tool to distinguish *R. okamurae* from native Dictyota species (Guil-Guerrero et al., 2025). Nonetheless, genetic identification remains the most definitive and reliable method for differentiating closely related macroalgae, with chemical or morphological traits serving as complementary approaches (Vieira et al., 2025).

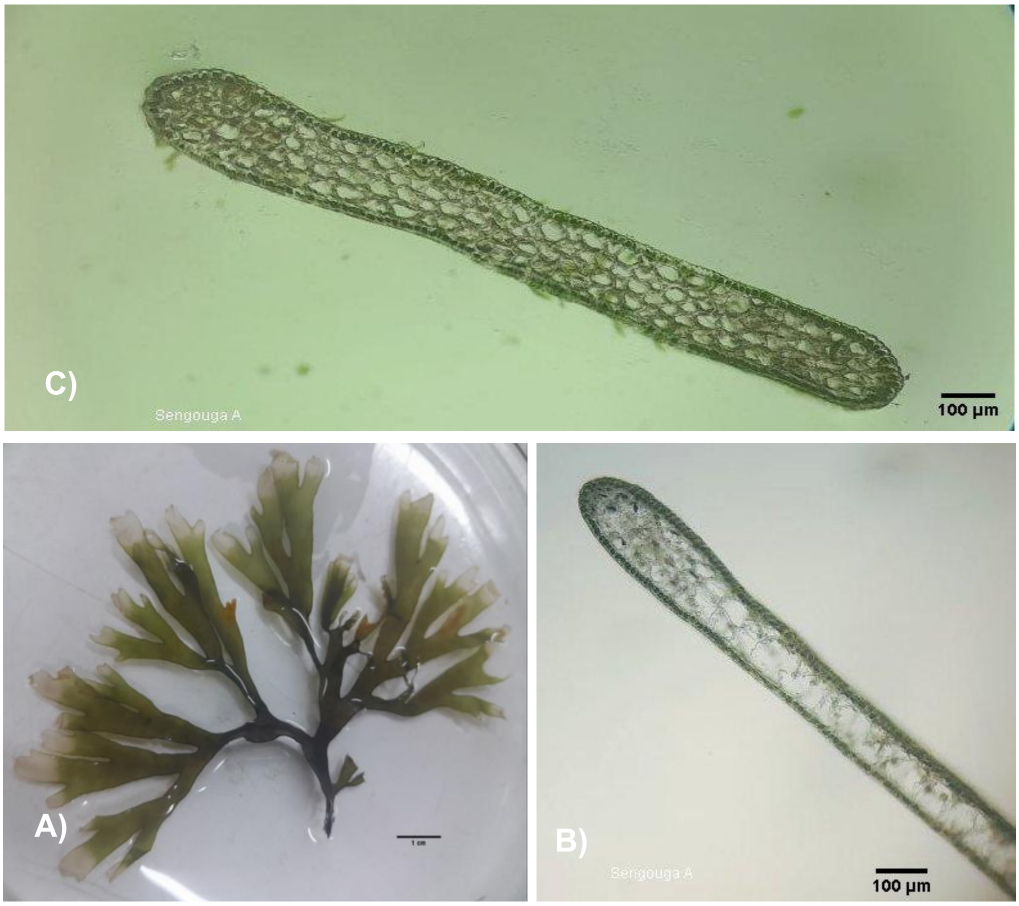


Figure 1. Morphology of R. okamurae. (a) Thallus habit showing dichotomous branching (scale bar = 1 cm). (B) Cross-section of the thallus showing a uni-layered medulla in the central region and a multi-layered medulla near the margin; (C) Cross-section of the basal part of the thallus showing –4 layers of thick-walled medullary cells.).

R. okamurae undergoes sexual and asexual reproduction and mainly spreads through vegetative propagation, through vegetative propagules, tetrasporangia, and monosporangia (Altamirano et al., 2016). In its natural habitat, this subtropical species exhibits optimal development and growth at seawater temperatures above 15 °C, thriving particularly under temperate conditions (Hwang et al., 2009). Additionally, it is also extremely tolerant to high salinity levels (Mercado et al., 2022), featuring the Mediterranean basin as a high favourability area for its establishment. Due to these favorable conditions, the rapid spread of the algae in the region has resulted in significant biomass production and invasive spread observed since 2015 (Mercado et al., 2022; Laamraoui et al., 2024)

According to (García-Gómez et al., 2020), *R. okamurae* can survive for long periods without being attached to the seabed. This ability improves its chances of spreading and colonising various surfaces. Besides rocky bottoms and artificial substrates, it has also been found growing on different coralligenous organisms and even epiphytising habitat-forming corals (Estévez et al., 2022). In terms of depth range, this species has been documented from the intertidal zone down to 50 meters in the rocky bottoms (Altamirano et al., 2016), while alive thalli has been found at more tan 800 meters' depth (Mateo-Ramírez et al., 2023). Althought the highest densities are typically found between 5 and 30m, the algae has spread widely across rocky bottoms in the subtidal zone (García-Gómez et al., 2021b).

B. Invasion

R. okamurae was first detected in European waters in 2002, in the coastal lagoon of Thau France, Mediterranean Sea (Verlaque et al., 2009; Ruitton et al., 2021) , Its introduction probably happened through the transportation of Japanese oysters *Crassostrea gigas* (Thunberg 1793) which were transported to Europe for mariculture purposes (Verlaque et al., 2009). With Korea and Japan acting as significant donor locations, the Thau Lagoon is widely recognized as a hotspot for the introduction of marine species into the Meditteranean Sea (Verlaque, 2001). As with other species introduced into the Thau Lagoon, the accidental introduction of *R. okamurae* most likely resulted from shortcomings in import decontamination methods and/or quarantine procedures (Verlaque et al., 2009). According to Vieira et al. (2025), *R. okamurae* exhibits six haplotypes, of which a single haplotype shared with Japan but absent in Korea accounts for all individuals introduced in the Mediterranean and Atlantic, indicating a Japanese origin.

Between 2015 and 2016, considerable amounts of *R. okamurae* biomass started washing up along both sides of the Strait of Gibraltar, highlighting the establishment of these IAS (Ocaña, Oscar et al., 2016). Because of its resemblance to native species under the genus Dictyota (mainly the species *Dictyta dichotoma*), it is probable that the alga existed in the area long before this event, remaining entirely undetected (Altamirano et al., 2017). It has since expanded to the Azores Archipelago (Faria et al.,2021), Madeira (Bernal-Ibáñez et al., 2022), the Canary Islands, which represent the species' new southern range border in the Northeast Atlantic (Bernal-Ibáñez et al., 2022), Morocco (Aamri et al., 2018), Italy (Bellissimo et al., 2024) and

Algeria (Bahbah et al., 2025) (Figure 2). *R. okamurae* was formerly absent from major global invasive species databases, but its status has shifted dramatically as a result of its fast spread and disastrous ecological and social repercussions. The species is now a top priority for worldwide surveillance, and the European Union has officially acknowledged it as the first macroalga to be designated as an Invasive Alien Species of Union Concern. As a result, it is now included in the European Alien Species Information Network (EASIN). Although it has not yet been incorporated into the Global Invasive Species Database (GISD), it is already well established in major invasive species monitoring systems, indicating its recognized invasive status. (*The European Banking Union*, 2015a; GISD, 2026).

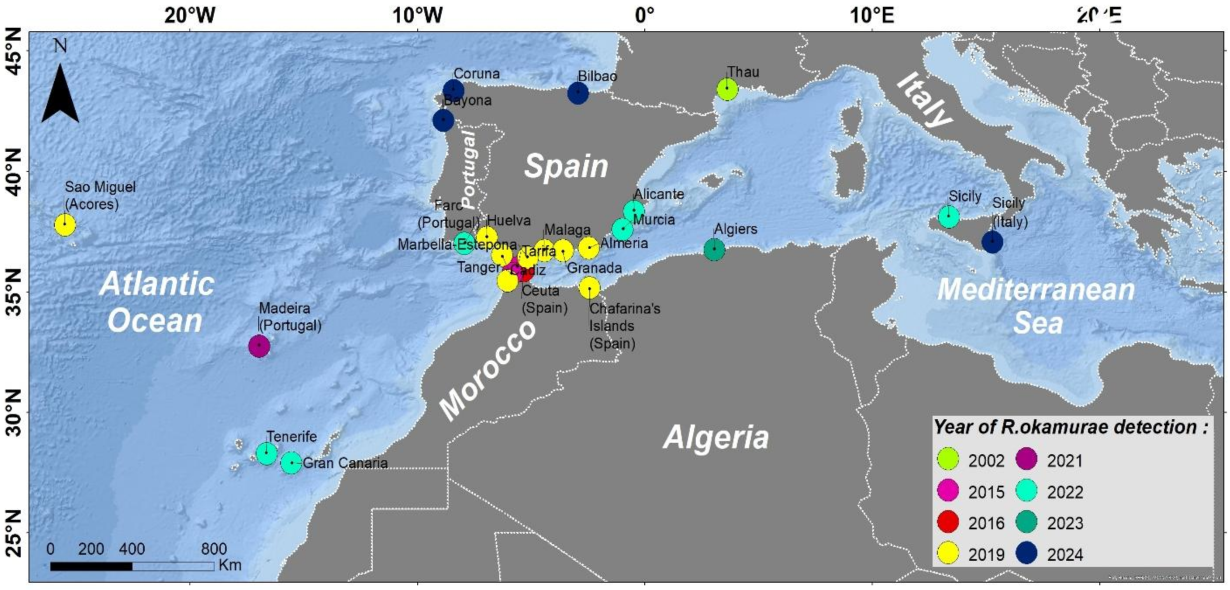


Figure 2. Map of the current distribution of R. okamurae in the Atlantic Ocean and Mediterranean Sea based on first detection years. Modified and updated for the Algerian coast from Laamraoui et al., (2024).

In Europe, invasive alien species, including invasive macroalgae, are mainly regulated under Regulation (EU) No 1143/2014, which focuses on prevention, early detection, eradication, and management of invasive species to protect biodiversity and marine ecosystems (*The European Banking Union*, 2015b). In Algeria, although no legislation specifically targets invasive species or macroalgae, broader environmental and coastal protection laws such as Law No. 03-10 on environmental protection and Law No. 02-02 on coastal management, play a role in conserving marine biodiversity and mitigating the impacts of IAS. Algeria is also part of the Barcelona Convention and the Mediterranean Action Plan (MAP), which support regional cooperation for monitoring and managing marine invasive species, including invasive macroalgae along the Mediterranean coast.

In 2023, *R. okamurae* was observed along the Algerian coastline, exhibiting a fast spread significantly reducing biodiversity and impacting the local economies, indicating a broad colonisation from shallow to deeper coastal waters (Bahbah et al., 2025).

R. okamurae has dominated shallow-water benthic ecosystems and significantly changed their structure and composition since its initial invasion, spreading over hundreds of kilometers of coastline (García-Gómez et al., 2020; Bernal-Ibáñez et al., 2022; Faria et al., 2022). The alga has not only colonized new territory, but it also appears to have greatly expanded its vertical distribution. Compared to the bathymetrical range of the invasive species in the Pacific, which does not extend beyond 15m, the species spreads up to 40m deep in the invaded areas (García-Gómez et al., 2020). Since its detection, the species can grow to depths of 50 meters (Altamirano et al., 2019).

C. Ecological and socio-economic impact

The displacement of local macroalgal species is an extremely serious effect of *R. okamurae*'s dominant occupation and competitive power, resulting in a homogenization of the seafloor. (García-Gómez et al., 2021). According to (Navarro-Barranco et al., 2019), the algas' habitat-forming capacities, which are similar to those of their native relatives, may have a differential impact on certain components of the ecosystem (e.g., epifauna), emphasising the importance of separately assessing the individual components of impacted ecosystems. However, not even sea urchins have been proved to exploit the alga as a food source for the long-term in the invaded environments, not contributing to its underwater biomass balance (Faria et al., 2022). A recent study from IFAPA showed that long-term consumption of the invasive macroalga *R. okamurae* affects negatively sea urchins (*Paracentrotus lividus*), showing weight loss, reduced reproductive capacity, and increased mortality. These results confirm that this invasive species is not effectively exploited as a food source by native organisms (Bernal-Ibáñez et al., 2025).

The accumulation of biomass caused by *R. okamurae* creates substantial social and economic issues, beached biomass accumulates along coastlines, generating management challenges and additional costs for coastal municipalities, while floating biomass in the water column significantly affects the fishing sector by entangling nets, reducing catch capacity, and damaging fishing gear (García-Gómez et al., 2021; Mogollón et al., 2024). Marine macrophyte biomass deposits, namely beachcasts, affect the recreational use of beaches and are costly to remove and relocate by local authorities (Altamirano et al., 2019).

1.4 Marine beachcast

The accumulations of macroalgal deposits are a natural aspect of sandy beach ecosystems, acting as important spatial subsidies supporting complex food webs and nutrient cycling. Natural beachcasts play a fundamental biogeochemical role in coastal ecosystems (Rodil et al., 2024). However, the sudden and huge spread of the non-indigenous brown algae *R. okamurae* has modified this natural process, changing beneficial organic inputs into dangerous environmental loads (El Madany et al., 2026). Unlike native macrophyte beachcasts, the dense biomass acculmulations of *R. okamurae* can harm coastal environments and disrupt the natural beach processes, while its degradation increases greenhouse gas emissions (Rodil et al., 2024).

As a result, the presence of *R. okamurae* on beaches represents a serious threat to coastal biodiveristy and local economies (Altamirano et al., 2019), highliting the need for effective management strategies.

Figure 3. R. okamurae beachcast in El Djamila beach, Ain Benian, Algiers, (19/04/2026)

Figure 4. R. okamurae beachcast in Tamentfoust beach, El Marsa , Algiers (18/02/2026)

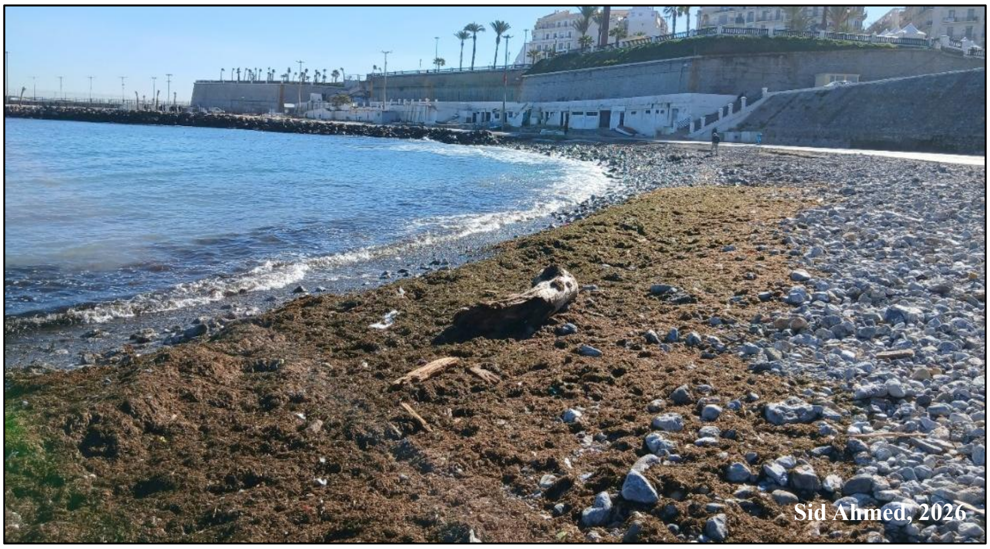


Figure 5. R. okamurae beachcast in El Kettani beach, Beb el Oued, Algiers (22/02/2026)

1.5 Remote Sensing for beachcasts monitoring

Remote sensing is a powerful, efficient and cost-effective method to track marine macrophytes on a recurrent and wide scale compared to *in situ* measurements, especially in large marine environments and difficult to access locations (Mannino et al., 2021), providing continuous, periodic information on their spatial distribution (Roca et al., 2022). There are several remote sensing techniques that can be used for monitoring beached and floating biomass of *R. okamurae* based on their distinct spectral signatures. Multispectral and hyperspectral sensors mounted on satellites such as Sentinel-2 MSI, Landsat-8 OLI or using Unmanned Aerial Vehicles (UAVs) (Roca et al., 2022) provide good resolution imagery that allows the tracking of the species distrubution and biomass changes over time (Mannino et al., 2021). Machine learning techniques such as Random Forest (RF) and Support Vector Machines (SVM) have also been adopted for handling the high-dimensional data required for an accurate management of invasive species (Villalobos Perna et al., 2023).

According to Roca et al. (2022), monitoring the *R. okamurae* invasion by using Sentinel-2 satellite imagery has been recognized as a synoptic and continuous source to map beachcasts and to assist management programs on a regional scale. With a spatial resolution of 10-meter for bands 2, 3, 4 and 8 and a revisit frequency of 2-3 days (Table 1), with 13 spectral bands spanning the VNIR, SWIR and atmospheric windows (Figure 6), it can detect and quantify beached *R. okamurae* with 80% accuracy (Roca et al. 2022). The use of GEE and similar cloud computing based platforms can simplify the tracking of beachcast by combining multitemporal satellite imagery and machine learning democratising the access to computational accessibility.

Table 1. Sentinel-2 bands Resolution

Sentinel-2 Bands	Central Wavelength (μm)	Resolution (m)
Band 1—Coastal aerosol	0.443	60
Band 2—Blue	0.490	10
Band 3—Green	0.560	10
Band 4—Red	0.665	10
Band 5—Vegetation Red Edge	0.705	20
Band 6—Vegetation Red Edge	0.740	20
Band 7—Vegetation Red Edge	0.783	20
Band 8—NIR	0.842	10
Band 8A—Vegetation Red Edge	0.865	20
Band 9—Water Vapour	0.945	60
Band 10—SWIR—Cirrus	1.375	60
Band 11—SWIR	1.610	20
Band 12—SWIR	2.190	20

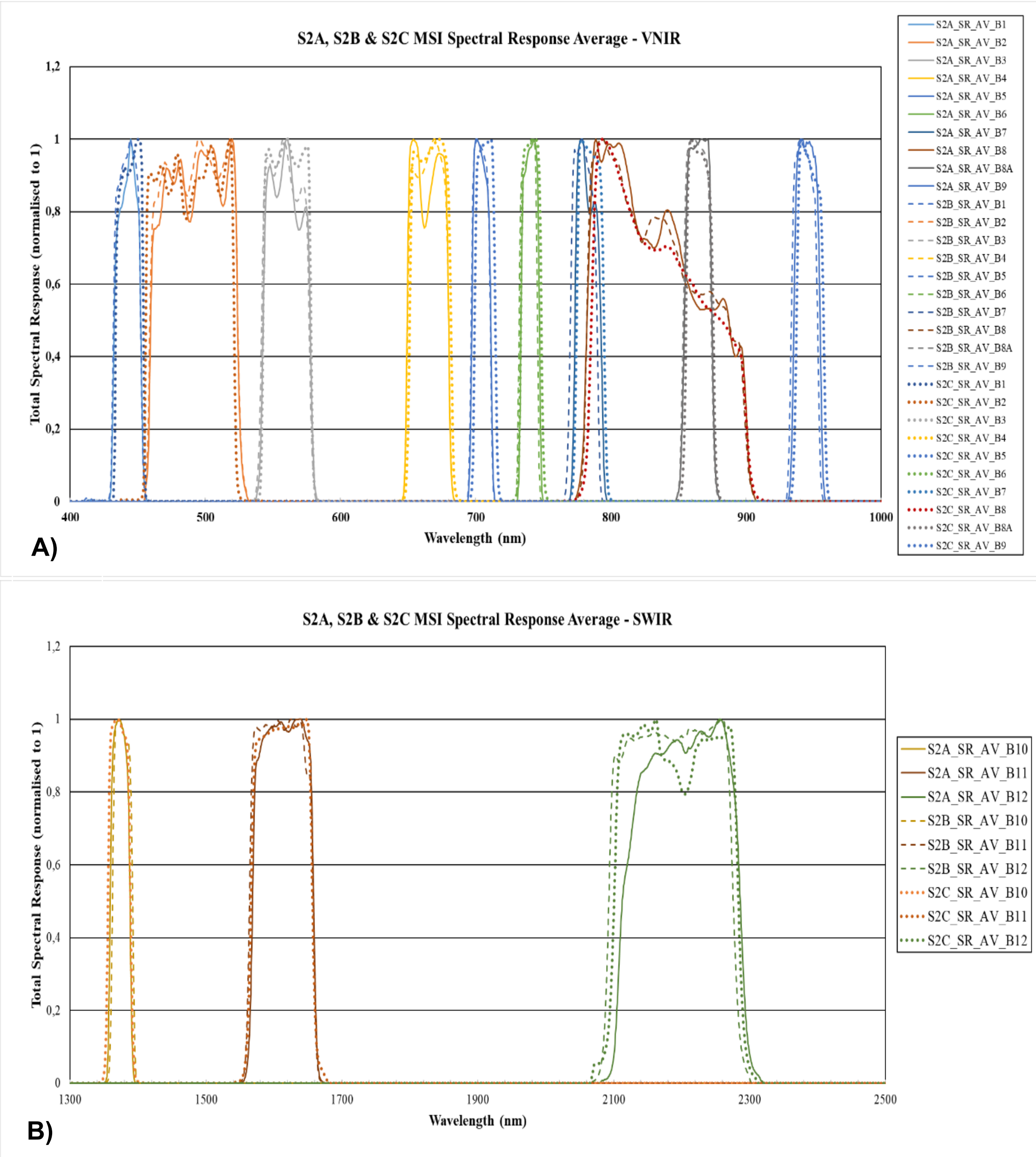


Figure 6. Sentinel-2 Spectral Response Functions. A)-S2A, S2B & S2C MSI spectral response average in the visible and NIR spectrum. B)-S2A, S2B & S2C MSI spectral response average in the SWIR spectrum, Source : COPE-GSEG-EOPG-TN-15-0007

Material and methods

2. Material and Methods

2.1 Study Area

Algiers, the capital of Algeria, is located on the southern shore of the Mediterranean Sea in the African continent. It is characterized by intense urbanization, a high population density, and a strong concentration of industrial, commercial, and port activities. Among the city is found Algiers bay, which extends from Cape Matifou (El Marsa) in the East to Cape Pointe Pescade (Rais Hamidou) westwards (Figure 7). Into this bay flows the Oued El Harrach river, which carries a significant load of urban and industrial pollution (Atroune & Boutaleb, Abdelhak, 2012). In addition, other important fluvial inputs include Oued El Hamiz and Oued Mazafran, which are also known to transport substantial urban, agricultural and industrial contaminants towards the coastal zone of Algiers (Zenati, B et al., 2018; Benhalima et al., 2022).

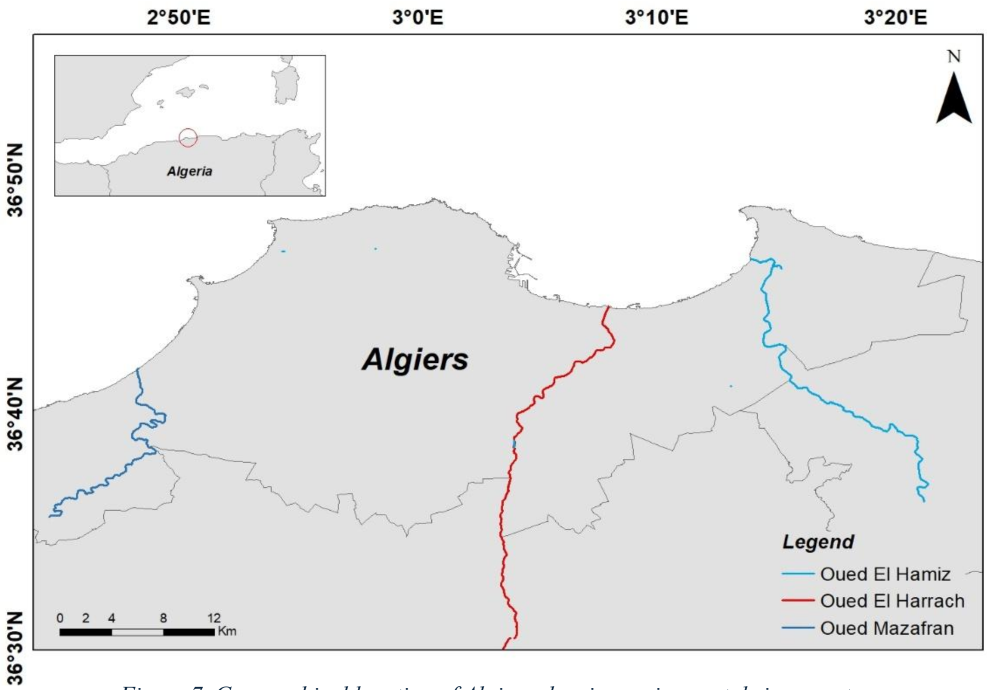


Figure 7. Geographical location of Algiers showing main coastal rivers systems

The Algiers' coastline includes a total of 85 sandy and rocky beaches. Among them, 70 beaches are officially authorized for swimming. In contrast, 9 beaches are prohibited for swimming due to several factors, including inaccessibility, poor bacteriological water quality, and ongoing construction works affecting these sites (EPIC HUPE/WA, 2024). Sandy beaches are generally composed of fine to medium sediment grain size, while rocky beaches are mainly associated with cliffs and consolidated substratum. Along the coast, the rocky areas are mainly found near the shoreline, especially around Bouzareah and Chenoua.

Based on the presence of beachcasts identified through both Copernicus Programme Browser Sentinel-2 satellite imagery and on-site surveys, six sites were selected to study *R. okamurae* beachacasts for validation purposes. These sites, distributed from east to west, included Tamentfoust, Les Ondines, El Kettani, Eden, El Djamila, and Sidi Fredj (Figure 8).

- **Tamentfoust beach** (36°48’22.44”N, 3°14’2.00”E), in the commune of El Marsa is located in the eastern part of Algiers, is characterized by a sheltered coastal zone with sandy substrate.A rocky reef platform, *Posidonia oceanica* and *Cymodocea nodosa* meadows are present in the seafloor of the area (Semroud et al., 1992; Soualili et al., 2008).
- **Les Ondines beach** (36°47'45.4"N 3°14'09.4"E), located in the commune of Bordj El Bahri on the eastern coast of Algiers, is a sandy beach situated in a highly urbanized area.
- **El Kettani beach** (36°47’35.38”N, 3°3’24.80”E) in the commune of Bab El Oued is characterized by an artificial and rocky coast, exposed to urban discharge.
- **Eden beach** (36°47’58.31”N, 3°2’57.44”E) in the commune of Bologhine, at the central part of Algiers coast and presents a sandy shoreline with the presence of rocks, exposed to urban discharge and wave action.
- **El Djamila beach** (36°47’57.91”N, 2°54’1.37”E) in the commune of Aïn Benian, in the western part of Algiers, and is situated near a fishing and recreational harbor, *P. oceanica* seagrass patches and rocky reef platforms are present in the seafloor of the area (Boumaza & Semroud, 2000).
- **Sidi Fredj (Thalassotherapie) beach** (36°45’56.0”N, 2°50’43.0”E), located in the commune of Staoueli in western Algiers, is characterized by a sandy shoreline bordered by rocky areas interspersed with sparse meadows of *P. oceanica* (Misraoui & Sengouga, 2011).

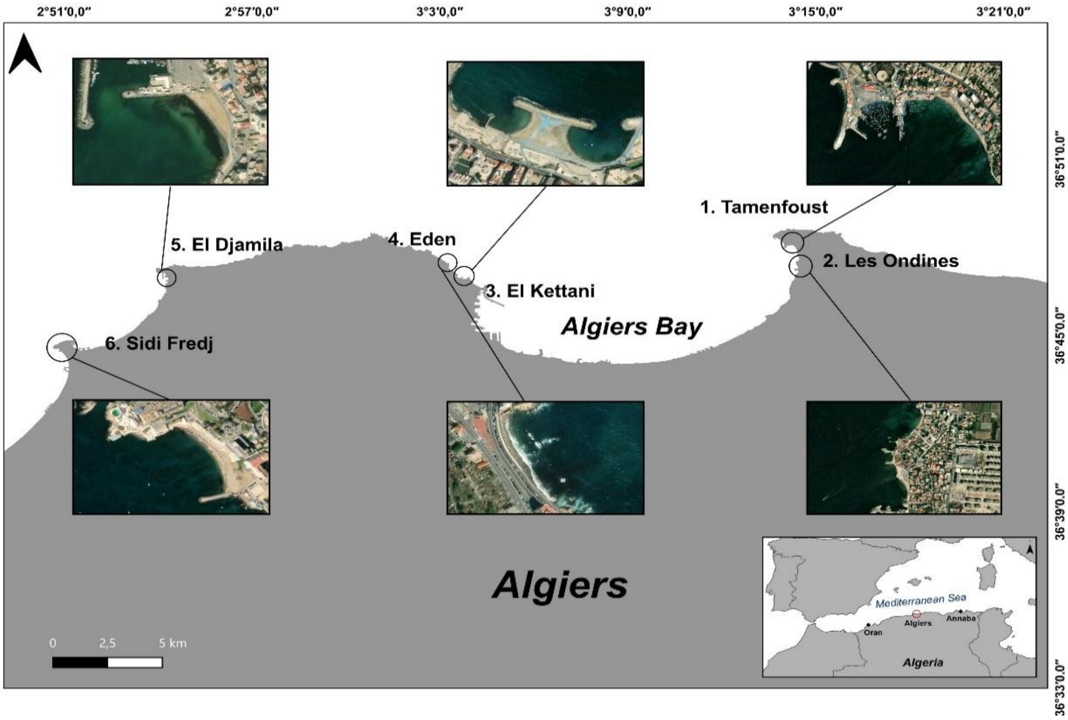


Figure 8. Location of the study sites

2.2 *In situ* sampling methodology

In situ samplig sites were selected along the Algiers' coastline by visually identifying beachcasts from Copernicus Browser Sentinel-2 satellite imagery, supplemented by on-site surveys. This biomass accumulations were then sampled either on the same day as the satellite overpass, when weather forecast reliability was very high, or on the following day, after ensuring a proper image acquisition matching the beachcast before each fieldwork campaign (Table 2). In order to get representative sites considering the spatial resolution of Sentinel-2, each sample was taken with at least 10 m distance between each quadrant. Percentage of the algae cover in each photoquadrant was visually observed and classified (0%, 25%, 50%, 75% or 100%). For biomass sampling, to make fieldwork more efficient, a stratified sampling method was used. When cover was 100% only 25% of each quadrant was harvested. When cover was below or equal to 75%, all the biomass within the quadrant was sampled.

Table 2. Dates of satellite image acquisition, field sampling, and number of quadrats collected at each study site

Satellite passage date	Satellite	Sampling date	Site	Number of Quadrats
17/02/2026	S2A	**18/02/2026**	Tamenfoust	6
22/02/2026	S2C	**22/02/2026**	El Kettani	3
22/02/2026	S2C	**22/02/2026**	Eden	6
18/04/2026	S2B	**19/04/2026**	El Djamila	8
21/05/2026	S2B	**21/05/2026**	Sidi Fredj	7
23/05/2026	S2C	**24/05/2026**	Les Ondines	10

Morphometric and geographical mesures were carried out in addition to biomass sampling. Ruler was used to measure the height of biomass within the quadrant. Pentadecameter was used to measure the distance of the accumulation from the shore and in width till the maximum sand length. GPS coordinates with a mean accuracy of 1m using both a Garmin GPS and GPS test mobile application on Samsung A16 phone, and photos were also registered. Sampled biomass were placed in plastic bags labeled and transported in an icebox with ice bags for further laboratory analysis to avoid further pigment photodegradation.

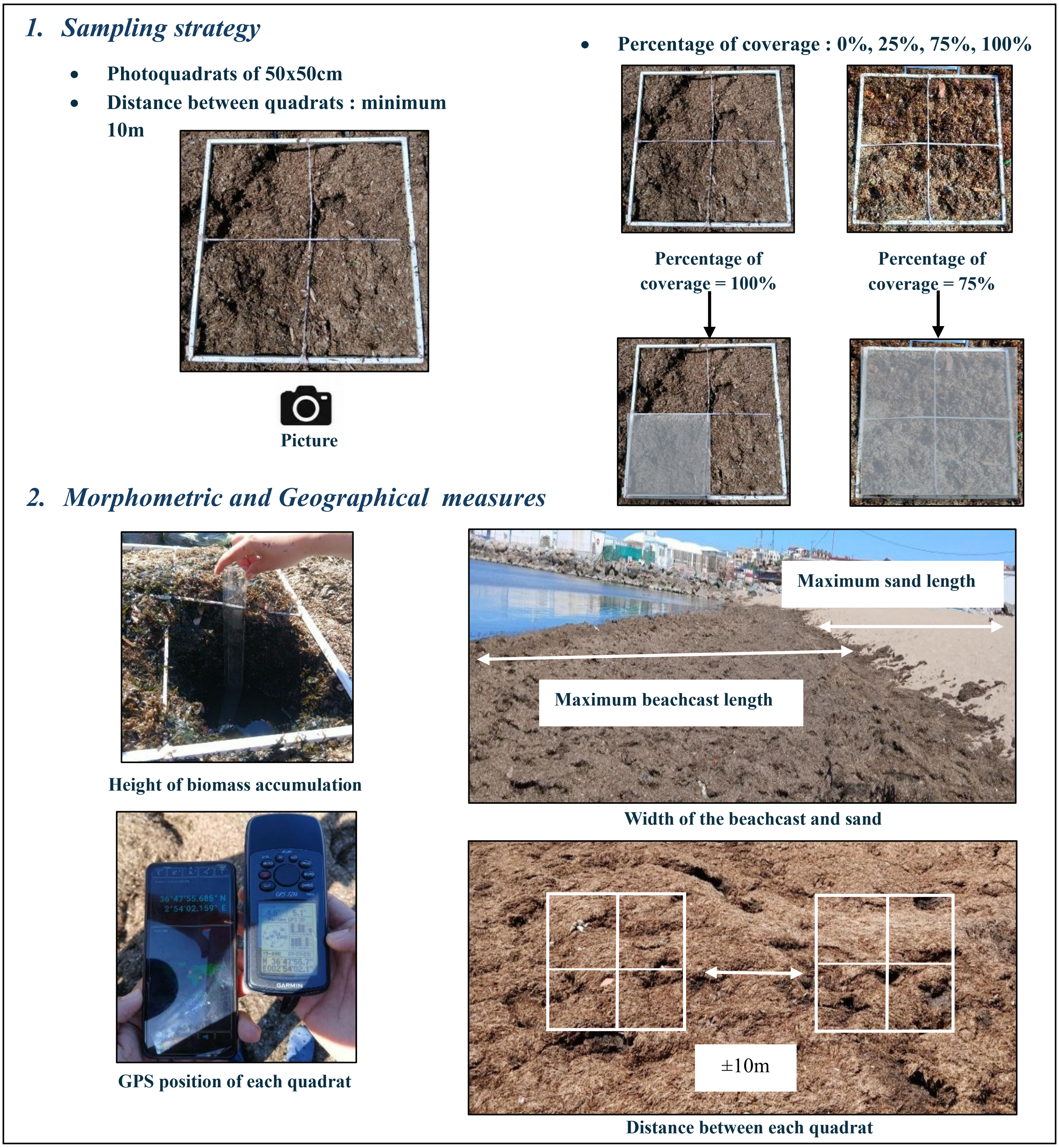


Figure 9. Methodology of field sampling of beachcast deposits.

2.3 Laboratory processing

Samples were processed immediately upon arrival at the laboratory or maintained in a refrigerator for analysis within 24 hours. For later analysis, samples were frozen and defrosted one day before processing. *R. okamurae* was then separated from the other macrolagal species, as well as seagrass leaves of *P. oceanica* and *Cymodocea nodosa*, and also any terrestrial debris. Once sorted, *R. okamurae* were wiped with absorbing paper to remove any surplus surface water, then placed into weighed and pre-labelled silver foil trays. For uniformity of drying, the thickness of biomass in each tray was restricted to approximately 2 cm. These were then placed in an oven at 60°C for at least 24 hours until their weights were constant. Finally, the total biomas per quadrat was calculated.

Figure 10. R. okamurae sample put in a plastic tray

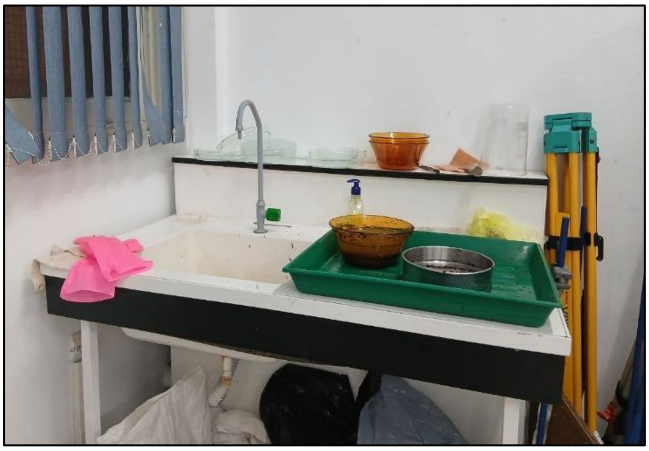


Figure 11. Washing the sample in a 5mm sieve

Figure 12. Separating R. okamurae from other macrophytes as well as terrestrial debrisin pre-labeled trays

Figure 13. Drying at 60°C for at least 24h Separating

Figure 14. Weighning the dry biomass

2.4 Satellite imagery processing and analysis

A. Spectral Separability

Sentinel-2 image annotation was carried out in Google Earth Engine (GEE) from January 2023 to December 2025. An Area of Interest (AOI) was first drawn manually along the Algiers coastline to delimit the study area and was used as the reference boundary for all image processing and analysis steps. Sentinel-2 L2A imagery, which consists of atmospherically corrected surface reflectance products, were then filtered according to the study period, the AOI, and a cloud cover threshold lower than 20%. After filtering, 345 images were selected, clipped to the AOI, and displayed in RGB composition. To improve the identification of coastal features, the NDVI and NDWI were calculated and used during the annotation process. Manual annotation was then performed by creating training points for the different classes (Table 3). The annotated data were then exported as a ee.FeatureCollection asset in GEE.

Table 3. Training features in GEE

	Training Feature Collection	**Related ids in GEE**
1	Beached biomass	At different degradation stages
2	Floating biomass	Floating biomass in water
3	Water	Optically shallow waters with sandy bottoms or bright bottoms
4	Wave foam	White wave foam
5	Emerged rocks	Rocks from cliffs or rocky beaches
6	Submerged rocks	SAV and underwater rocky substrates
7	ODW	Optically Deep Waters
8	Dry beach	Only dry sand
9	Wet beach	Only wet sand in low tide

* SAV (Submerged Aquatic Vegetation)

All training assets corresponding to the same year were grouped into a single ee.FeatureCollection, and the annotated polygons were converted into point data. The sampleRegions function was then used to extract pixel values from individual, date-specific satellite scenes at a spatial resolution of 10 m, all associated information, including class, date, image ID, and user was preserved. To facilitate processing and reduce memory usage, a random column was added to the dataset and the extracted points were divided into ten separate segments before export. Each segment was exported individually as an asset for each year and later used in R programming to extract and analyze the spectral reflectance values of the different classes.

Following the extraction of spectral information, the spectral signatures of each class were examined to verify the consistency and separability of the annotated data. A supervised Random Forest classification was then performed in GEE (ee.Classifier.smileRandomForest). The training points were first converted into numerical classes, and Sentinel-2 images were filtered again according to the study area, acquisition dates, and cloud cover conditions. Twelve spectral bands (B1–B12) were used as input variables for the classification. The RF classifier, trained with 100 decision trees, was applied to generate the classification maps. The classified outputs were displayed using a predefined color palette corresponding to each class. Finally, the classification accuracy was assessed using the independent validation set from *in situ* sampling by creating a confusion matrix and extracting accuracy metrics such as overall accuracy, user accuracy, producers' accuracy F1-score, Cohen's Kappa coefficient and the resulting graphs were exported.

B. Filtering imagery

An automated workflow was developed in GEE using the Python API within Google Colab to monitor the temporal evolution of *R. okamurae* along the Algiers beaches. The analysis was carried out using Sentinel-2 imagery time-series from January 2nd 2023 to May 25th 2026.

An 80 m buffer was first created using Algiers shoreline shapefile in order to include both the beach area and nearby potential floating biomass. To refine the study area and remove unwanted terrestrial features, a mean Sentinel-1 image from 2024 was integrated within the buffer area to generate a mask excluding vegetation, roads, buildings, and elevated surfaces. This step allowed the definition of a final AOI containing only beach and limited seawater surfaces.

Before building the Sentinel-2 Image Collection, images affected by clouds or excessive noise were filtered to improve data quality. Although a cloud cover threshold of less than 20% was applied during the spectral separability step, additional filtering was carried out to remove residual cloud contamination within the study area and ensure a higher-quality Image Collection. Instead of relying only on standard global cloud filters for the entire tile, a AOI cloud filtering approach was applied using the COPERNICUS/S2_CLOUD_PROBABILITY dataset (Roca et al., 2022b) The average cloud probability was calculated only within the AOI for each tile, and images exceeding 11% cloud cover were excluded. This approach helped preserve several usable coastal scenes that would otherwise have been removed by broader tile-scale cloud filtering.

For the classification process, all available Sentinel-2 L2A bands were used [‘B1’, ‘B2’, ‘B3’, ‘B4’, ‘B8’, ‘B11’, ‘B12’], except Band 10 which is not available in this product. In addition, four spectral indices were calculated for each image: **NDVI** was used to highlight *R.okamurae* beachcast, **NDWI** to distinguish water from land, **NDMI** to assess beachcast moisture, and **FAI** to detect the floating *R.okamurae* biomass, with the following equations:

$$NDVI = \frac{NIR-RED}{NIR+RED} \qquad (1)$$

$$NDWI = \frac{GREEN-NIR}{GREEN+NIR} \qquad (2)$$

$$NDMI = \frac{NIR+SWIR}{NIR-SWIR} \qquad (3)$$

$$FAI = R_{NIR} - R'_{NIR} \qquad (4)$$

$$R'_{NIR} = R_{Red} + (R_{SWIR} - R_{Red})\frac{\lambda_{NIR}-\lambda_{RED}}{\lambda_{SWIR}-\lambda_{RED}} \qquad (5)$$

These indices were added to the Image Collection composed of 258 images together with the spectral bands to improve the detection of floating and beached biomass.

A RF classifier composed of 100 decision trees was then trained using reference samples representing the nine classes. The classifier was subsequently applied to the complete Image Collection in order to identify the spatial distribution of *R. okamurae* throughout the study period. The processing and export of the classified images were automated using loops implemented in Python within Google Colab. Finally, the classified outputs were clipped to the study area and exported as Image Collection asset containing only the detected beached and floating macroalgae pixels.

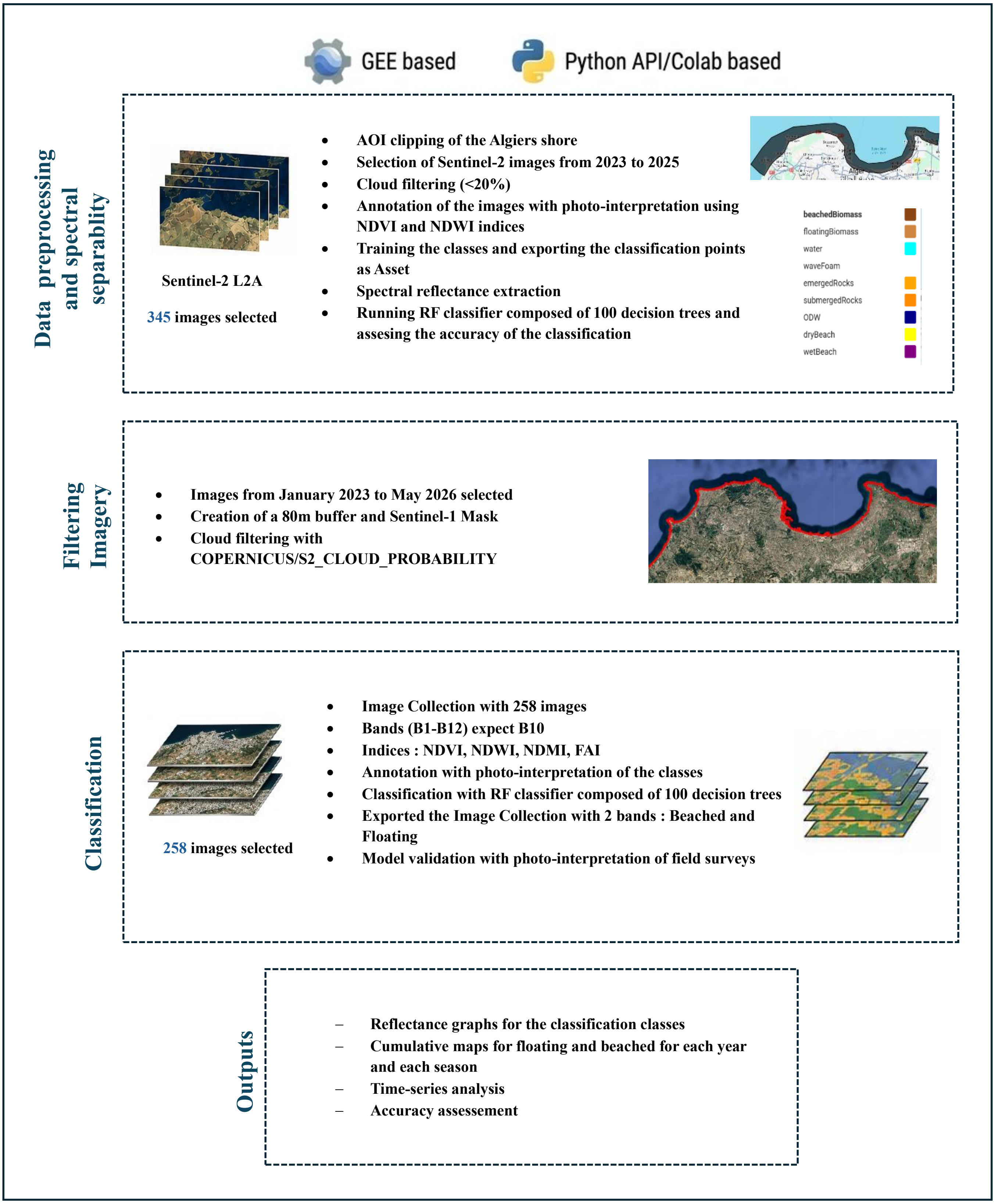


Figure 15. Satellite imagery processing and analysis workflow

C. Spatial and temporal analysis

To better understand the distribution of *R. okamurae* along Algiers beaches, cumulative maps were generated separately for floating biomass and beachcast accumulations across the time range. These maps were obtained by adding all recorded occurrences over the study period, making it possible to identify the most frequently affected sites by the presence of the species. To investigate whether its distribution varied over time, additional cumulative maps were produced for each year and for the four seasons (winter, spring, summer, and autumn). This approach allowed the identification of recurrent areas of accumulation as well as potential seasonal patterns.

Temporal changes in the occurrence of the species were also examined using time-series analyses. For each image date, the surface area occupied by floating and beached biomass was extracted from the classification results and plotted through time. These graphs provided an overview of the evolution of biomass occurrence during the study period and help identify periods of increased or reduced abundance.

Model validation was based on a presence-absence approach. Satellite images corresponding to field survey dates and sampling locations were carefully examined through photo-interpretation, and many pixels were manually annotated as floating, beached, or absence. The resulting observations were then compared with the model outputs to assess classification accuracy. Although information on biomass cover and biomass quantity was also collected, these results were not included in the validation process

Regarding the time-series evolution, both floating and beached biomass were evaluated using linear GAMs. Statistical modeling and visual trend estimations, including 95% confidence intervals to represent tracking uncertainty were also executed in Python utilizing the '*pygam*' and '*matplotlib*' libraries.

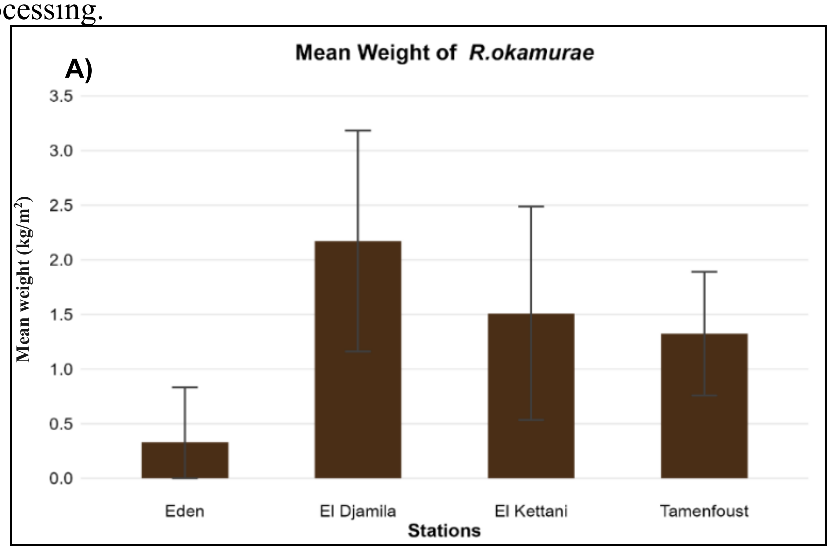
The accuracy assessment was performed by comparing the model outputs (Image Collection from 1st January 2023 to 25th May 2026) with validation data extracted from photo-interpretation of the fieldwork sites images. For each sampled pixel, the predicted class was matched with the corresponding ground truth class (beached, floating, or absence) using spatially aligned validation points. These paired observations were used to construct a confusion matrix, which summarises the number of correctly and incorrectly classified samples for each class. From this matrix, the overall accuracy was computed as the ratio of correctly classified pixels (sum of the diagonal elements) to the total number of validation samples. In addition, class-based performance metrics, including precision, Cohen's Kappa coefficient, recall, and F1-score, were derived to evaluate the model’s ability to correctly identify each individual class.

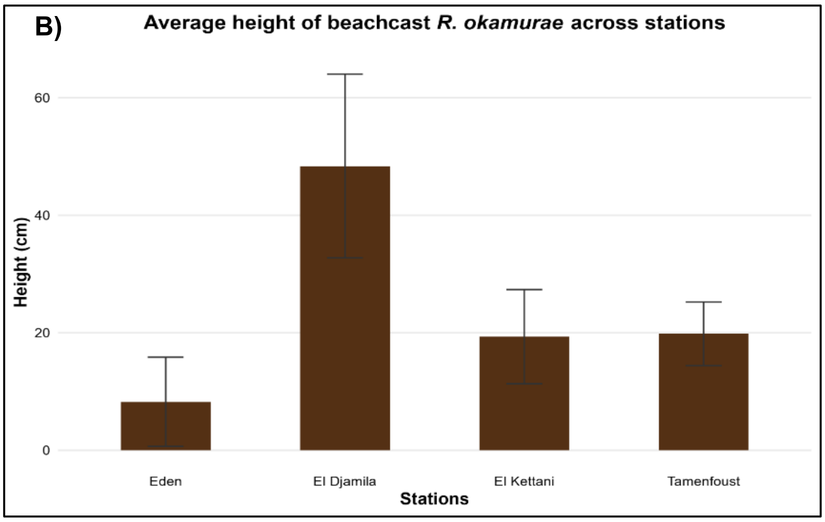
RESULTS AND DISCUSSION

3. Results and discussion

3.1 Beachcast biomass, height, and width

The stations of Tamentfoust, El Kettani, Eden, and El Djamila were selected for the analysis of the beachcast parameters measured *in situ* and in the laboratory. The Kruskal-Wallis test and ANOVA revealed significant differences among stations ($p < 0.05$) in beachcast biomass, height, and width (Figure 16). The highest values for all three parameters were recorded at El Djamila (2,42 kg/m^2 for biomass, 48.38 cm for height , and 12,04 m for width). In contrast, the lowest beachcast biomass 0,36 kg/m^2 and height 8,35 cm were observed at Eden, whereas the minimum beachcast width 3,75 m was recorded at Tamentfoust. These spatial variations may be related to local hydrodynamic conditions and the proximity of rocky platforms, which likely influence the development, the accumulation and persistence of *R. okamurae* beachcast. It should be noted that samples from Les Ondines and El Djamila have not been processed yet; therefore, the results presented here are preliminary and may be refined upon completion of the laboratory processing.





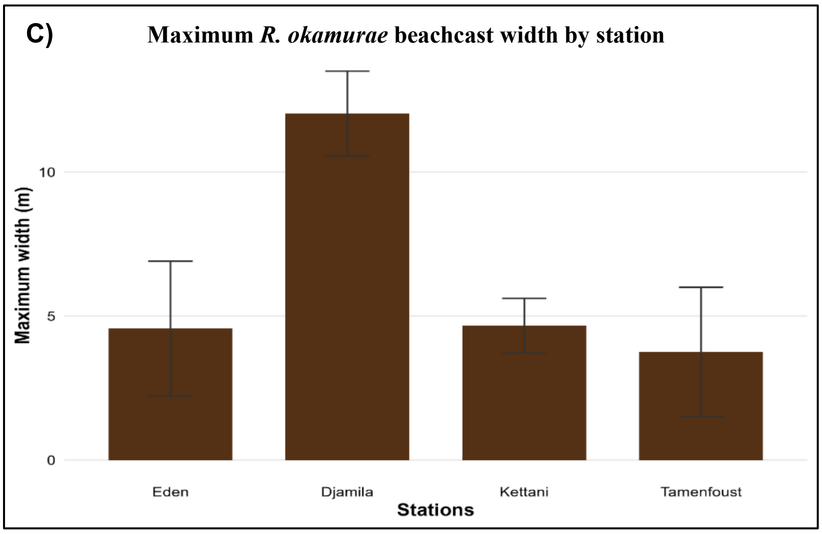


Figure 16. Mean beachcast biomass characteristics of R. okamurae across the sampled stations: A) mean weight (kg), B) average beachcast height (cm), C) maximum beachcast width (m). Error bars represent the standard deviation.

3.2 Spectral reflectance of training classes

The spectral reflectance signatures extracted from the training classes between 2023 and 2025 showed clear and consistent trends across the Sentinel-2 wavelength range (Figure 17). In 2023, beached biomass presented the highest reflectance values among all classes, which may be linked to a lower biomass and macrophyte mixture with other species at the beginning of the invasion. The reflectance increased gradually from the visible bands toward the NIR region and remained high in the SWIR bands, due to the 3D structure of the beachcast and the water content (Roca-Mora et al., 2026). A distinct peak around 705 nm was observed after the chlorophyll-a absorption in accordance to hyperspectral *in situ* data (Roca et al., 2022) characteristic of *R. okamurae*. The spectral profile of beached biomass was, however, relatively similar to that of dry beach for 2023. This similarity is likely due to the limited abundance of beached biomass during this period, resulting in mixed pixels containing both alga and sand. No floating biomass was identified in 2023, reflecting the very low abundance of the species during this period.

In 2024, beached biomass followed the same spectral pattern, with reflectance increasing from the visible bands to the NIR and SWIR regions. However, reflectance values were generally lower than those recorded in 2023. This difference may be explained by the greater abundance of *R. okamurae*, which allowed the selection of more representative pixels and reduced the spectral mixing with pure sand pixels. Unlike 2023, floating biomass was clearly present and displayed a spectral response similar to that of beached biomass. Nevertheless, its reflectance remained lower, especially in the NIR and SWIR bands, due to the absorption effect of seawater surrounding the alga.

The spectral signatures obtained in 2025 closely matched those observed in 2024 for both beached and floating biomass, suggesting that the spectral behavior of *R. okamurae* remained stable over the two years, showing the fast-spread behavior and establishing of the species in only one year time. This consistency justified the calculation of an average spectral profile for 2024 and 2025 years, which provides a representative signature of the species for the study area.

The RF classification achieved an overall accuracy of **87%** for the 2023-2025 period, indicating a good level of spectral separability between the training classes. This result demonstrates the ability of the model to reliably distinguish *R. okamurae* accumulations from other coastal features using the 345 selected Sentinel-2 images.

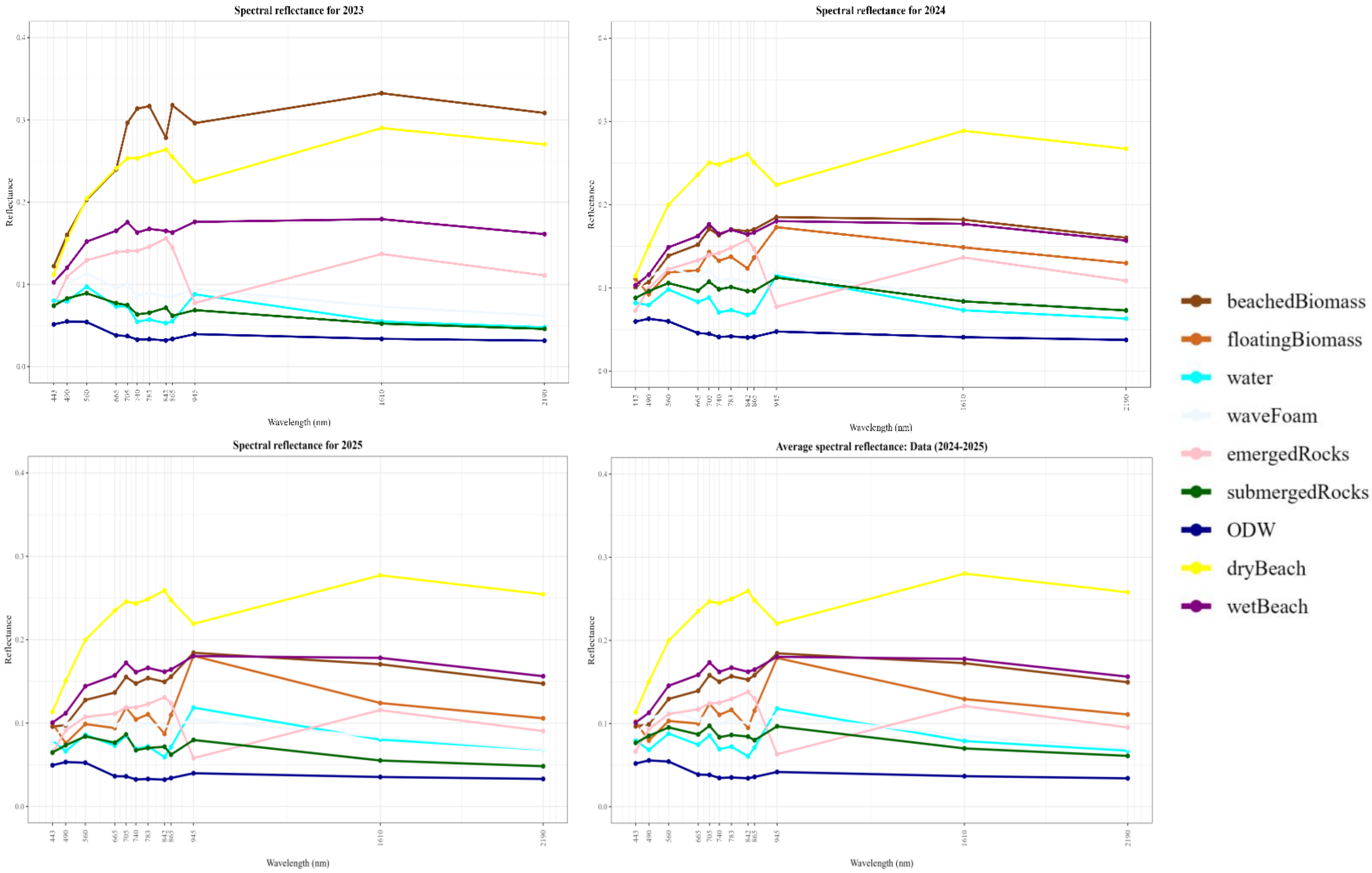


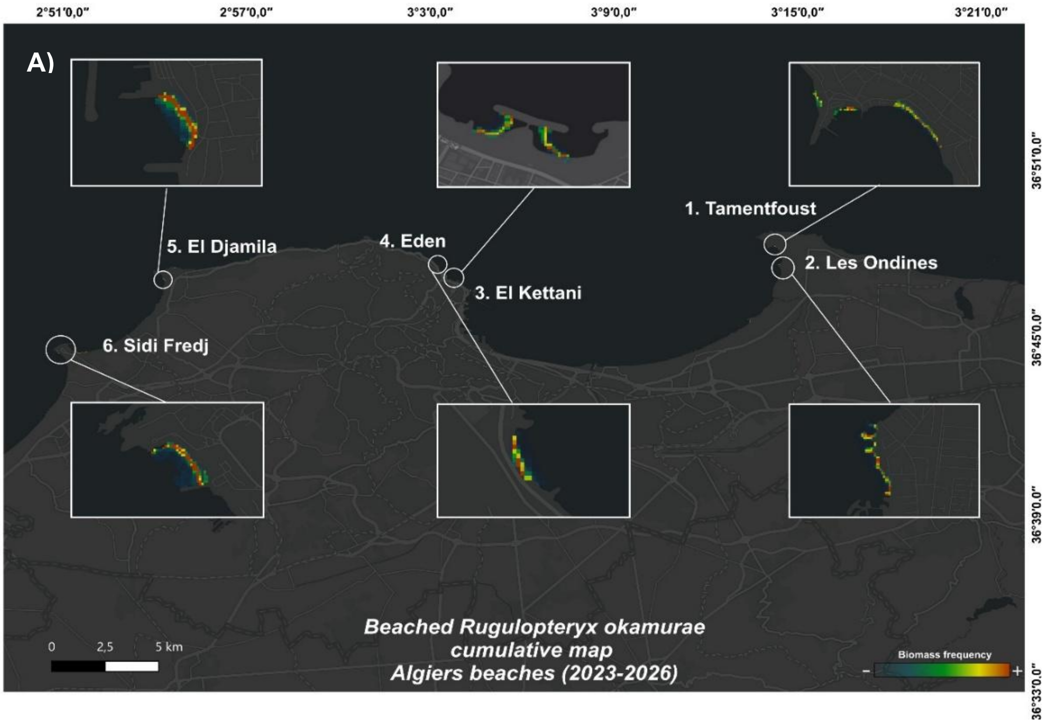
Figure 17. Spectral reflectance signatures of coastal classes and R. okamurae biomass (beached and floating) derived from Sentinel-2 imagery for 2023–2025 and the multi-year average (2024–2025)

3.3 Spatio-temporal distribution of *R. okamurae* biomass

A. Temporal impact of beached and floating *R. okamurae*

The spatial and temporal distribution of both beached and floating *R. okamurae* biomass along the 2023 and 2026 period reveal differences depending on the study site, season, and year, reflecting the influence of local environmental and hydrodynamic conditions on the accumulation of the species.

The cumulative maps of beached and floating *R. okamurae* (Figure 18) reveal that the species was present at all six study sites between 2023 and 2026, although the frequency and spatial extent of accumulations varied among beaches. In both cases, biomass was concentrated within specific shoreline and nearshore sectors rather than being evenly distributed across the sites, suggesting that local environmental factors, including coastal morphology, hydrodynamic conditions, the presence of rocky shore platforms, and *Posidonia oceanica* meadows, play an important role in controlling the transport, retention, and accumulation of the species. However, the persistence of these areas throughout the study period indicates that *R. okamurae* tends to repeatedly accumulate in the same locations, with floating biomass occurring in nearshore waters and potentially contributing to the beachcast deposits observed along adjacent beaches.



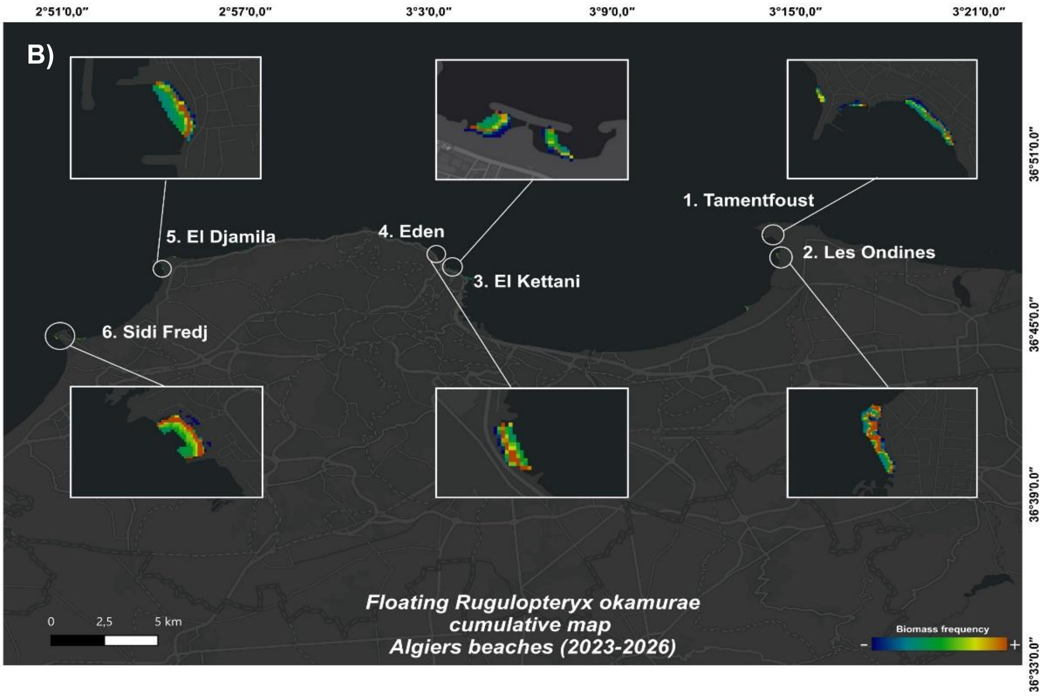


Figure 18. Cumulative impact of beached and floating R.okamurae biomass for the period (2023-2026). A)-Beached R. okamurae cumulative map, Algiers beaches (2023-2026). B)- Floating R. okamurae cumulative map, Algiers beaches (2023-2026)

The spatial distribution maps of beached *R. okamurae* biomass (Figure 19) reavel its presence at all selected beaches from 2023 to 2026, although its intensity varied among sites and years. In 2023, biomass accumulations were relatively moderate and mainly concentrated in localised sectors of the beaches, during 2024, the distribution pattern remained similar, with a slight increase in biomass frequency at several sites, particularly at El Djamila and Sidi Fredj beaches. However, 2025 showed the highest overall accumulation, characterized by a greater extent of high-frequency biomass deposits across most beaches, suggesting a period of intensified beachcast events, while in 2026, beachcast remained widespread but appeared more heterogeneous, with some beaches showing reduced accumulation compared to 2025 while others maintained relatively high biomass frequencies. However, this can be explained by the fact that 2026 was only considered from January to May 2026, while the field surveys were held from February 18th to May 24th, during which several adverse weather events occurred, and part of the biomass was also harvested by municipal services.

These variations are likely related to differences in hydrodynamic and meteorological conditions between years. Wave action, coastal currents, and prevailing winds can influence the detachment, transport, and accumulation of algal biomass along the shoreline. The recurrent accumulation observed at El Djamila and Sidi Fredj suggests that these beaches may function as preferential deposition areas, possibly due to their geomorphological characteristics and their exposure to dominant coastal circulation patterns, as well as the prescence of rocky shore platforms and *Posidonia oceanica* meadows. The pronounced increase in biomass observed in 2025 may reflect a greater abundance of *R. okamurae* in subtidal habitats, and favorable transport conditions, while the increase of the beachcast event continue in 2026. Nevertheless, the invasion dynamics of *R. okamurae* are more complex than these factors alone and are likely influenced by multiple interacting biological, environmental, and oceanographic processes.

The maps of floating *R.okamurae* biomass (Figure 20) show a clear spatial heterogeneity along the beaches between 2024 and 2026. Althought it was absent in 2023, the model classification detected the presence of some pixels during this period. In 2024 the biomass was very low, likely due to hydrodynamic conditions that limited its presence and movement in the area. In 2025 and 2026, an increase in floating biomass was observed, with a distribution mainly near the shoreline, which can be explained by the washed beachacast driven by wave action, or the alga detachment from the nearshone zone followed by its transport toward the shore.

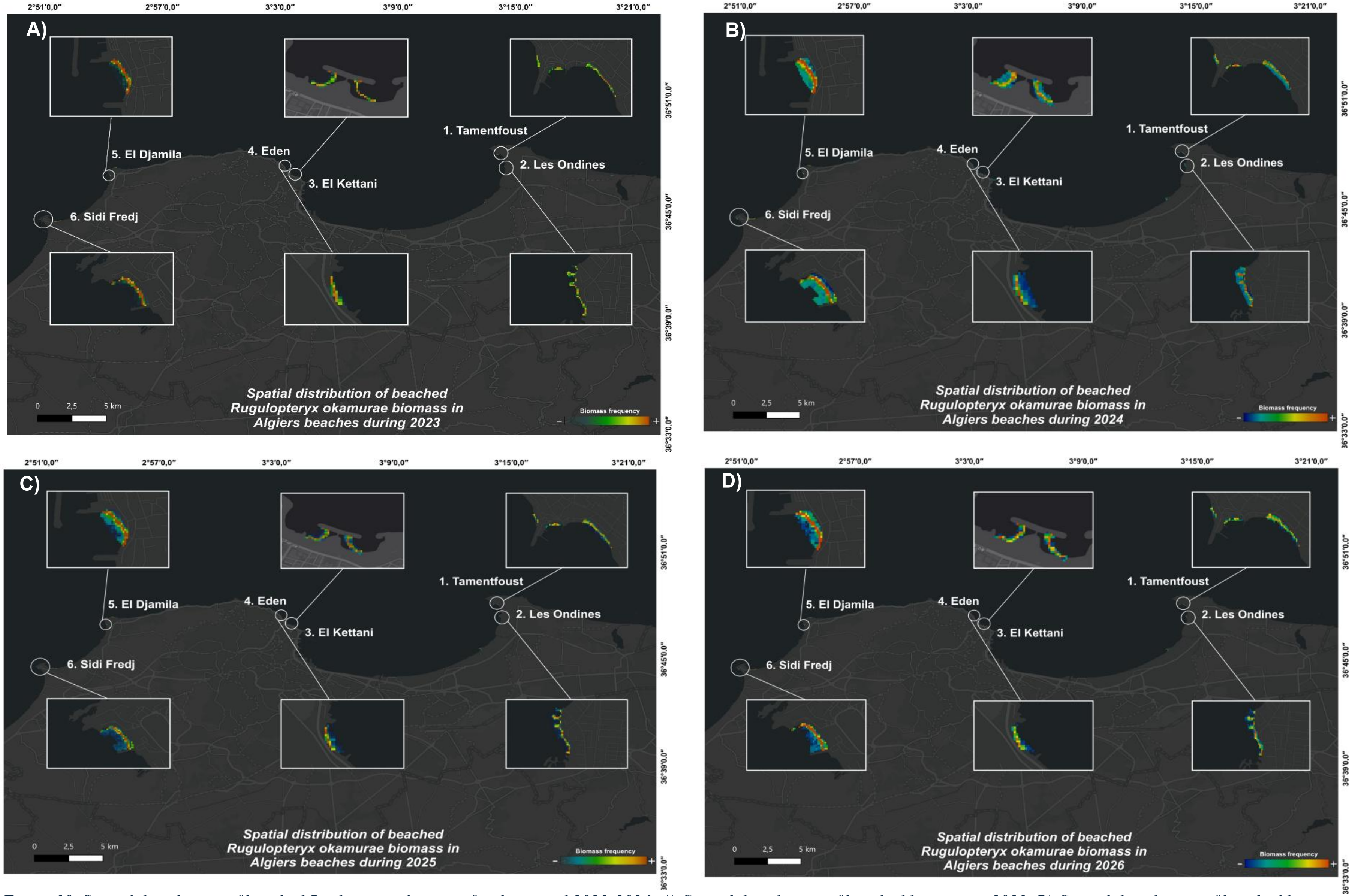


Figure 19. Spatial distribution of beached R. okamurae biomass for the period 2023-2026. A)-Spatial distribution of beached biomass in 2023, B)-Spatial distribution of beached biomass in 2024, C)-Spatial distribution of beached biomass in 2025, D)-Spatial distribution of beached biomass in 2026

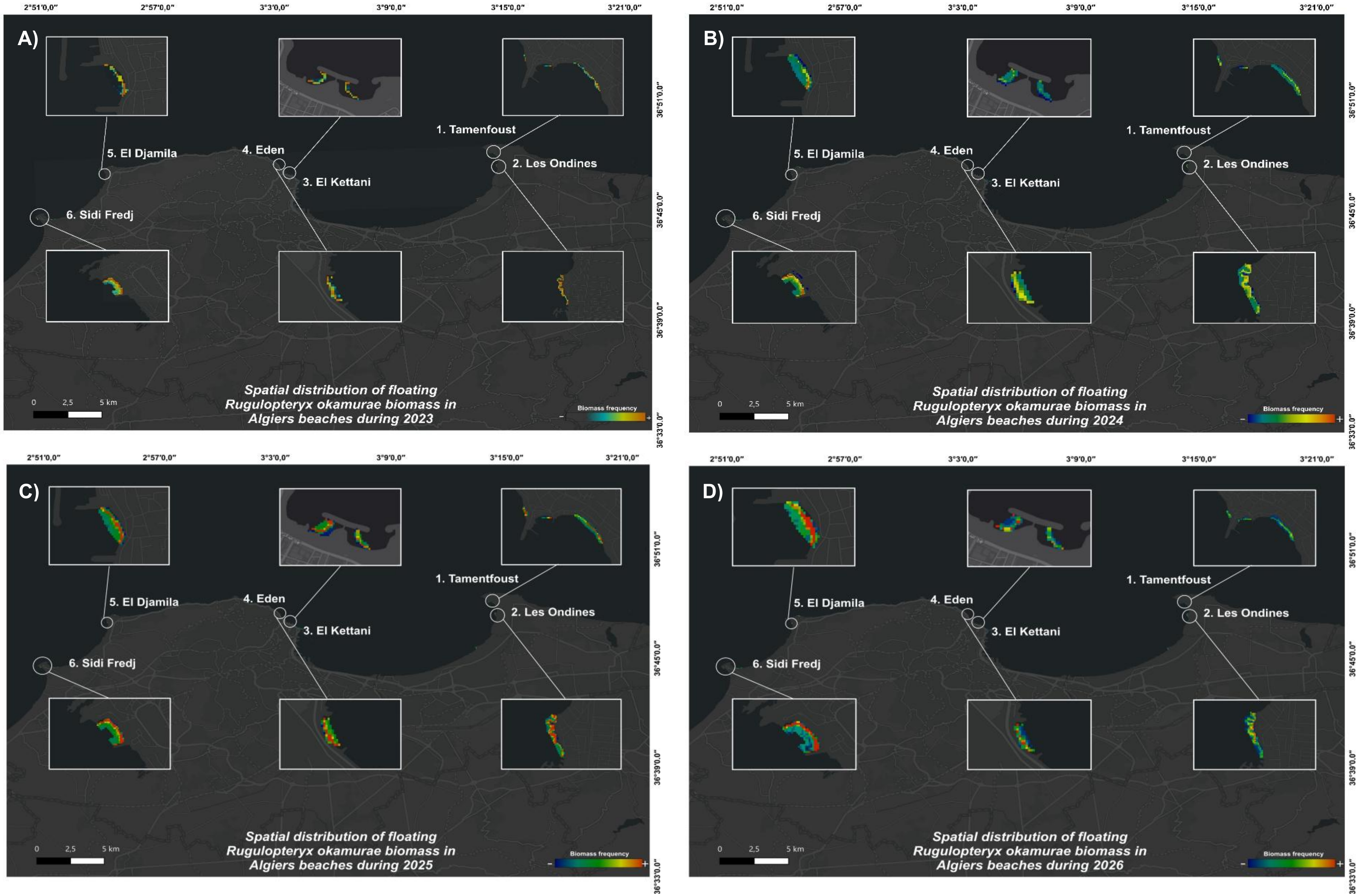


Figure 20. Spatial distribution of floating R. okamurae biomass for the period 2023-2026. A)-Spatial distribution of floating biomass in 2023, B)-Spatial distribution of floating biomass in 2024, C)-Spatial distribution of floating biomass in 2025, D)-Spatial distribution of floating biomass in 2026

B. Seasonal impact of beached and floating *R. okamurae*

The cumulative seasonal maps reveal clear spatial and temporal differences in the distribution of beached *R. okamurae* biomass along the Algiers coastline between 2023 and 2026. Biomass accumulation was concentrated within the six monitored beaches, but the frequency and extent of deposition varied among sites and seasons (Figure 21).

Across all seasons, El Djamila and Sidi Fredj showed the highest and most persistent biomass accumulation, with large areas displaying high occurrence frequencies. This pattern may be related to the orientation of these beaches and their exposure to prevailing currents and wave action, which can favor the transport and retention of detached algal material. In contrast, Les Ondines and El Kettani generally exhibited more localised accumulations, suggesting a lower capacity for long-term biomass retention.

Seasonal differences were also evident. During winter (Figure 21-A), biomass deposits were relatively widespread, particularly at El Djamila, Tamenfoust, and Sidi Fredj. This distribution may reflect the influence of stronger hydrodynamic conditions, which can increase the detachment and shoreward transport of algal fragments (Terradas-Fernández et al., 2023). In spring (Figure 21-B), the distribution remained similar, although biomass appeared more fragmented and concentrated in specific sectors of each beach.

Summer map (Figure 21-C) showed a reduction in the spatial extent of high-frequency accumulations at several sites. This decrease may be associated with calmer sea conditions and increased biomass removal through natural decomposition or beach-cleaning activities (Roca et al., 2022). In contrast, autumn (Figure 21-D) exhibited a renewed expansion of biomass accumulation, with several beaches displaying extensive areas of moderate to high occurrence frequencies. This seasonal increase may result from the combined effect of biomass production during warmer months and subsequent transport toward the shoreline (Haro et al., 2024).

Despite these seasonal fluctuations, the recurrent presence of biomass at the same locations highlights the existence of preferential accumulation zones along the coast. The persistence of these hotspots suggests that local coastal morphology and hydrodynamic processes play a key role in controlling the deposition of *R. okamurae* (Nadal et al., 2018; Haro et al., 2024). These findings indicate that some beaches are more vulnerable to recurrent strandings and may require more frequent monitoring and management efforts to mitigate the ecological and socio-economic impacts associated with this invasive species (Laamraoui et al., 2024).

Regarding floating *R. okamurae* biomass, the cumulative seasonal maps revealed marked spatial and seasonal variations along the Algiers beaches between 2023 and 2026. In general, floating biomass was detected at all study sites, although its frequency and spatial extent differed considerably among beaches and seasons (Figure 22).

The highest frequencies of floating biomass were consistently observed at El Djamila, Sidi Fredj, and, to a lesser extent, Les Ondines. These sites displayed extensive areas of recurrent biomass presence, indicating that they are important accumulation zones for drifting algal material. In contrast, Eden and El Kettani showed more restricted distributions, with biomass generally concentrated within smaller coastal sectors.

Seasonal patterns were particularly evident. During winter (Figure 22-A) and spring (Figure 22-B), floating biomass was present at most beaches but remained relatively moderate in extent and frequency. The distribution during these seasons was often fragmented, suggesting the influence of variable hydrodynamic conditions on the transport and dispersion of drifting algae (Terradas-Fernández et al., 2023; Figueroa et al., 2025). Summer (Figure 22-C) exhibited the most extensive and frequent floating biomass accumulations across the study area. Several beaches, especially El Djamila, Sidi Fredj, and Les Ondines, displayed large areas characterised by high occurrence frequencies, indicating increased persistence of floating mats during this period (Laamraoui et al., 2024; Figueroa et al., 2025).

In autumn (Figure 22-D), the spatial extent and frequency of floating biomass generally decreased compared to summer. Although floating algae remained present at all sites, the accumulations were less extensive and more localised. This reduction may be related to seasonal changes in wind patterns, wave activity, and biomass stranding processes, which can transfer part of the floating biomass to the shoreline (Haro et al., 2024).

The results suggest that floating *R. okamurae* biomass is not evenly distributed along Algiers beaches but tends to concentrate in specific coastal sectors. The occurrence of floating biomass at the same locations across seasons highlights the influence of local hydrodynamic conditions and coastal morphology on biomass transport and retention (Nadal et al., 2018).

The seasonal patterns observed for *R. okamurae* along Algiers beaches are comparable to those described for *Sargassum* beaching events in the tropical Atlantic. In winter and spring, stronger winds and higher wave energy tend to enhance dispersion and offshore transport, resulting in more fragmented biomass distribution along the coast, a behaviour also reported for *Sargassum* under high-energy conditions (Putman et al., 2018). In summer, calmer hydrodynamic conditions favour the persistence and nearshore accumulation of floating biomass, leading to higher and more continuous presence, consistent with satellite-based observations of increased *Sargassum* surface aggregation during stable oceanographic conditions (Wang & Hu, 2017). In autumn, changing wind regimes and increased wave activity can redistribute floating biomass and promote their partial stranding on beaches, a seasonal transition also described in studies linking wind forcing and ocean circulation to *Sargassum* beaching variability (Putman et al., 2018; Skliris et al., 2022). These similarities suggest that both systems are primarily driven by seasonal hydrodynamic conditions, which influences their spatial repartition and their accumulation patterns.

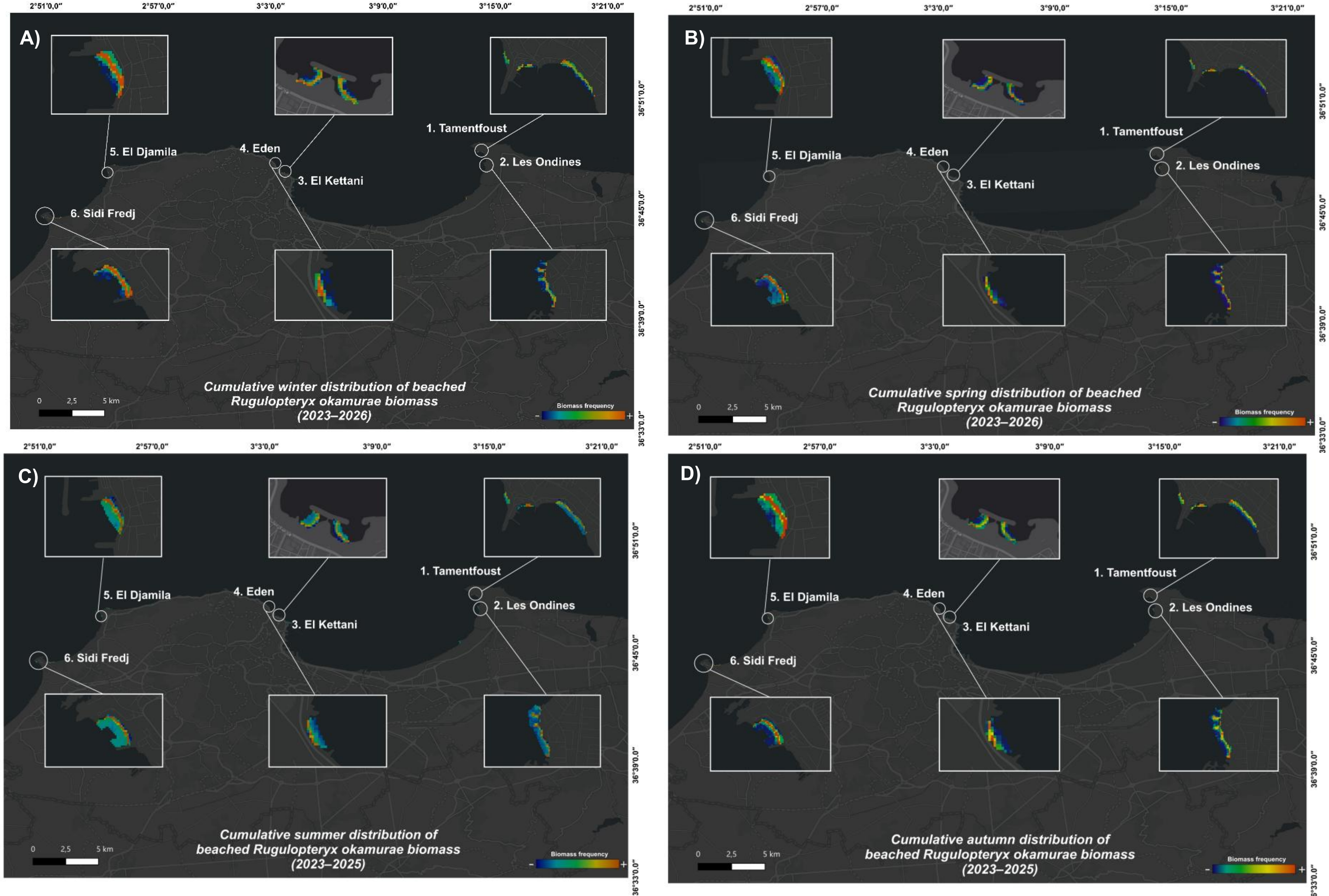


Figure 21. Seasonal distribution of beached R. okamurae biomass for the period 2023-2026. A)-Cumulative distribution in winter, B)-Cumulative distribution in spring, C)-Cumulative distribution in summer, C)-Cumulative distribution in autumn

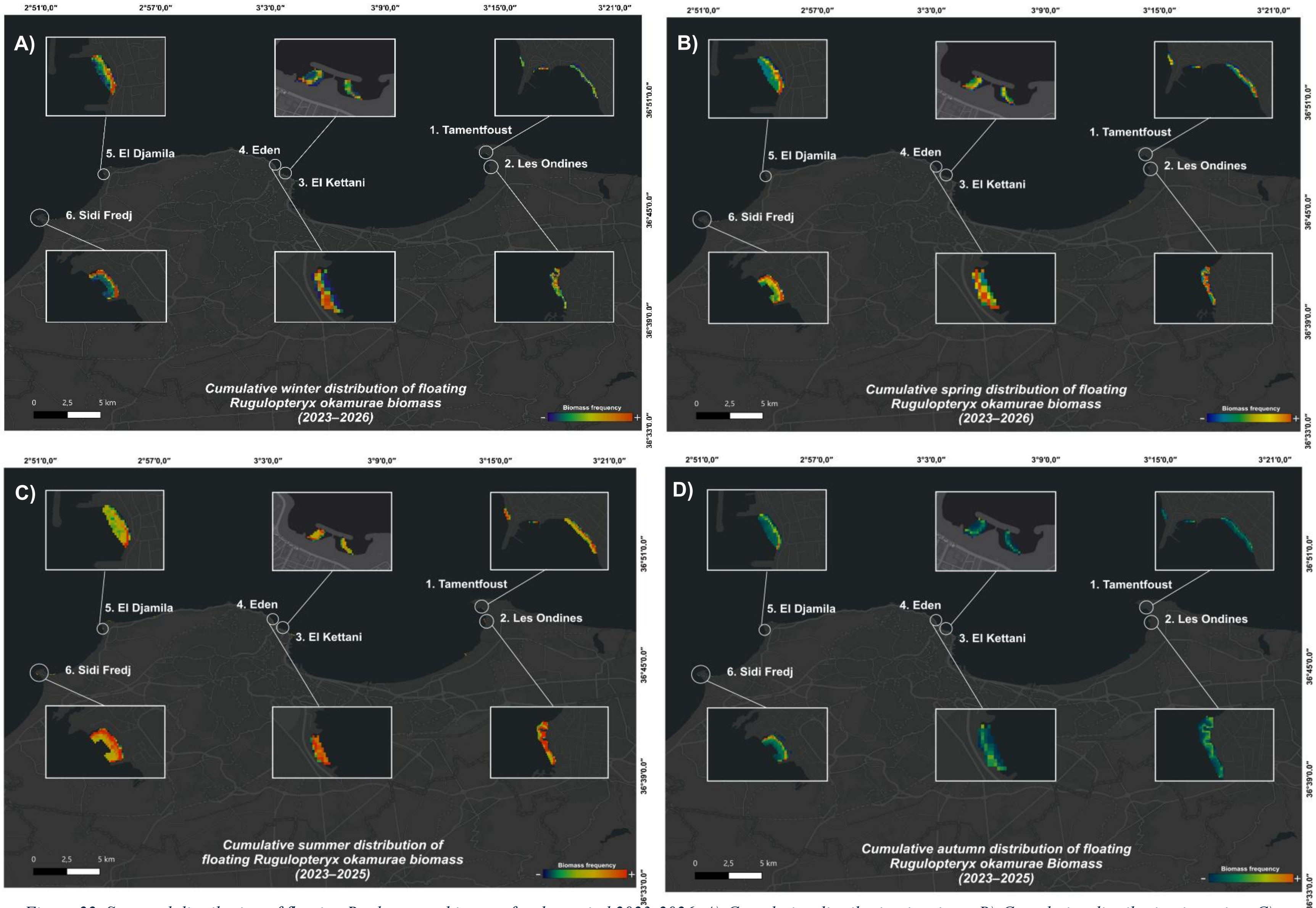


Figure 22. Seasonal distribution of floating R. okamurae biomass for the period 2023-2026. A)-Cumulative distribution in winter, B)-Cumulative distribution in spring, C)-Cumulative distribution in summer, C)-Cumulative distribution in autumn

C. Temporal Evolution

The time-series analysis (Figure 23) shows that both beached and floating *R. okamurae* biomass were present throughout the study period, although their abundance varied over time. Beached biomass generally remained between 0.02 and 0.06 km², with noticeable peaks occurring during mid-2024 and late 2025, where the smoothed trend reached values close to 0.06 km². After these peaks, biomass decreased before increasing again toward 2026. Floating biomass exhibited a similar temporal pattern but showed greater variability and more severe beaching events. The highest floating biomass levels were observed during mid-2024, mid-2025, and again in 2026, with some observations exceeding 0.10 km². The main similarity between the two trends suggests a strong connection between floating biomass and subsequent beachcast deposits. Therefore, periods of increased floating biomass were generally followed by higher amounts of beached biomass, indicating that floating algal accumulations may act as a source for biomass deposits, as detached biomass can be transported by coastal currents and accumulate along shorelines (Roca-Mora et al., 2026). Otherwise, these fluctuations are likely influenced by seasonal environmental conditions, including hydrodynamics which control the transport and accumulation of beached biomass along the beaches (García-Gómez et al., 2021b).

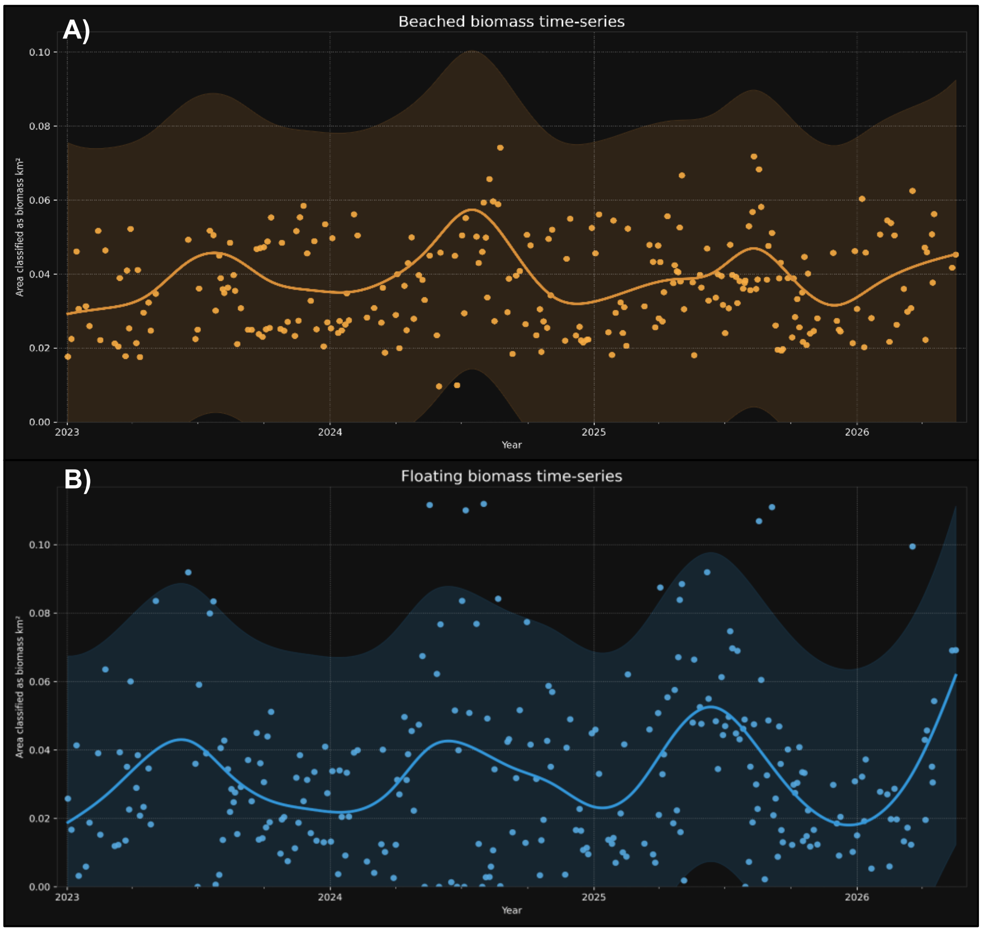


Figure 23. Beached and floating R. okamurae biomass time-series. A)-Beached biomass time-series, B)-Floating biomass time series

D. Assessement of the Accuracy of the model

The accuracy of the model was assessed by comparing the predicted classes with the independent validation data for beached, floating, and absence pixels. The results were summarized using a confusion matrix (Figure 24) standard classification metrics (Table 4), and algorithmic agreements (Table 5). The model achieved an overall accuracy of **70.25%**, meaning that around 70% of all validation pixels were correctly classified. The results show that the absence class is the most accurately detected, with a recall of 1.00, indicating that all absence pixels were correctly identified, although its precision (0.64) shows that some pixels were incorrectly labeled as absence. The beached class shows a good level of reliability when predicted (precision = 1.00), but a lower recall (0.43), meaning that many true beached pixels were not detected by the model. The floating class presents the lowest performance, with a recall of 0.14, indicating that most floating pixels were misclassified, despite a high precision when it is predicted. The classification shows a fair to moderate agreement with ground truth (Cohen's Kappa coefficient=0,4026), indicating that the model performs better than random assignment but still has room for improvement. These results indicate that the model performs well in detecting absence and is reasonably accurate for beached biomass, while floating biomass remains the most challenging class to identify, likely due to its spectral similarity with other conditions and the variability of coastal features.

However, the independent validation dataset was limited to only four satellite images with a total of 89 pixels for the three validation classes, corresponding to the available field surveys conducted during the study period. As only six field campaigns were completed constrained weather and limited time of the MSc, the number of validation images may not have been sufficient to fully assess the performance of the image collection, which consists of 258 images acquired between 2023 and 2026. In addition, Algiers' beaches are very narrow, which can make the detection of beached and floating biomass challenging even when the algae is present. Following this limitation, some beaches were not considered in this study due to their small size.

Consequently, the reported accuracy should be interpreted with caution, as a larger validation dataset would likely provide a more robust evaluation of the performance of the model. In addition, the spectral signature of beached biomass can change significantly during degradation stages and after prolonged exposure to the sun (Roca-Mora et al., 2026). These changes may alter its spectral characteristics and potentially leading to classification errors and a reduction in detection accuracy.

Table 4. Classification performance of the Random Forest model for detecting beached and floating R. okamurae biomass and absence, based on the validation dataset.

	precision	recall	f1-score	support
Beached	1.00	0.43	0.60	42
Floating	1.00	0.14	0.25	14
Absence	0.64	1.00	0.78	65
accuracy			0.70	121
macro avg	0.88	0.52	0.54	121
weighted avg	0.81	0.70	0.66	121

Table 5. Algorithmic agreement summary

Overall Accuracy (OA)	**70,25%**
Cohen's Kappa coefficient	**0,4026**

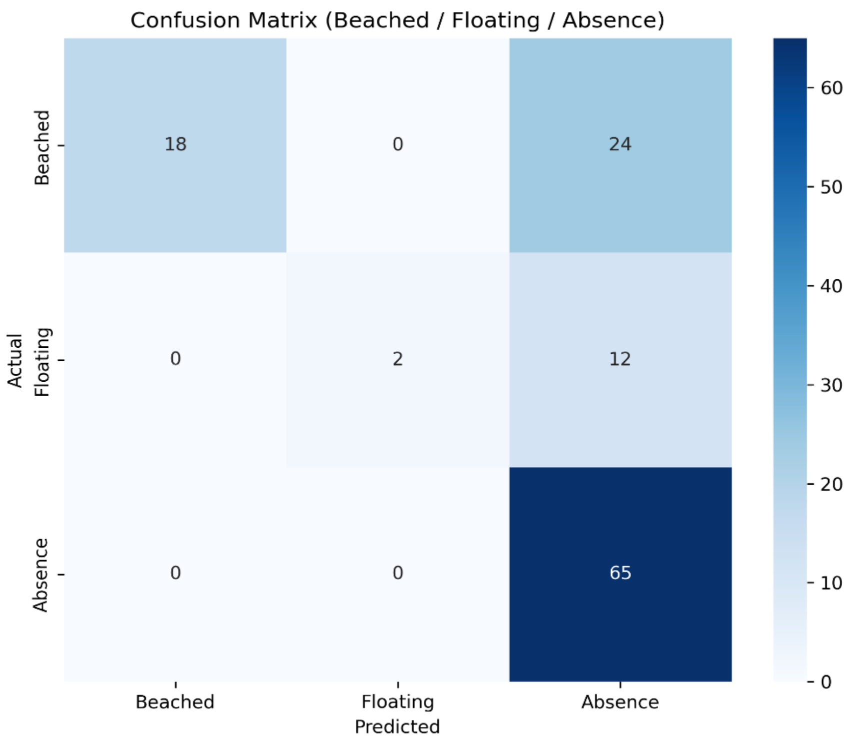


Figure 24. Confusion matrix of the Random Forest model showing the classification accuracy for beached and floating biomass and absence in the validation dataset

CONCLUSION AND PERSPECTIVES

4. Conclusion and Perspectives

This study represents the first assessment of beached and floating *R. okamurae* biomass along Algiers beaches using Sentinel-2 satellite imagery and Google Earth Engine. By combining field observations with remote sensing techniques, it was possible to monitor the spatial and temporal dynamics of this invasive macroalga between 2023 and 2026.

The results demonstrated that *R. okamurae* is now present along all monitored beaches, although its distribution varies according to location, season, and year. The highest and most persistent accumulations were observed at El Djamila and Sidi Fredj beaches, suggesting the existence of preferential deposition zones controlled by local hydrodynamic and geomorphological conditions. Seasonal analyses revealed that biomass accumulation occurs throughout the year, with noticeable fluctuations linked to environmental conditions and coastal transport processes. Beached biomass is abundant in winter and autumn, while floating biomass reaches it's peak during summer, regarding that periods of increased floating biomass were generally followed by beached biomass, suggesting that floating biomass acts as a source of beachcast episodes.

The spectral analysis confirmed that *R. okamurae* presents a distinctive reflectance signature that can be detected using Sentinel-2 imagery. The Random Forest classification achieved an overall accuracy of 87% during the training phase and 70.25% during independent validation, demonstrating the potential of Earth Observation techniques for monitoring beachcast accumulations at a regional scale. Although floating biomass remained more difficult to detect, the methodology successfully identified the main distribution patterns of the species previous to the biggest beachcast events.

To conclude, the study highlights the rapid expansion of *R. okamurae* in Algeria and confirms the usefulness of remote sensing as a cost-effective tool for invasive species monitoring. Therfore, the generated maps, time-series analyses and methodology provide valuable information for operational coastal management, as well as to contribute with a better understanding of the invasion dynamics of this species in the southern Mediterranean.

Several research perspectives emerge from this work, including the increase of the number of field surveys and validation campaigns would improve the robustness of the classification model and allow a more accurate assessment of detection performance. For this reason and due to the severity of the invasion, future studies should also include additional Algerian coastal regions to evaluate the invasion at a national scale, as well as an *in situ* repository of beachcasts from different species such as *P. oceanica*. This efforts are being jointly developed in the framework of the RugOBSS project.

REFERENCES

References

Aamri, F. E., Idhalla, M., & Tamsouri, M. N. (2018). *Occurrence of the invasive brown seaweed Rugulopteryx okamurae (E.Y.Dawson) I.K.Hwang, W.J.Lee & H.S.Kim (Dictyotales, Phaeophyta) in Morocco (Mediterranean Sea)*.

Aglieri, G., Quattrocchi, F., Mariani, S., Baillie, C., Spatafora, D., Di Franco, A., Turco, G., Tolone, M., Di Gerlando, R., & Milazzo, M. (2023). Fish eDNA detections in ports mirror fishing fleet activities and highlight the spread of non-indigenous species in the Mediterranean Sea. *Marine Pollution Bulletin*, *189*, 114792. https://doi.org/10.1016/j.marpolbul.2023.114792

Altamirano, De la Rosa, Martínez Gil, & Muñoz. (2017). *Prolifera en el Estrecho un alga nunca citada en nuestro litoral : De origen asiático, Rugulopteryx okamurae ocupa ya una gran extensión*.

Altamirano, Garreta, A. G., & Pérez-Lloréns, J. L. (2019). *Altamirano Jeschke, M., De la Rosa, J., Carmona, R., Zanolla, M. and Muñoz, A.-R. (2019) 'Macroalgas invasoras en las costas andaluzas', ALGAS, Boletín de la Sociedad Española de Ficología, 55e, pp. 10–13*.

Altamirano, M., De la Rosa, J., & Martínez-Medina, F. J. (2016). *Arribazones de la especie exótica Rugulopteryx okamurae (E.Y. Dawson) I.K. Hwang, W.J. Lee & H.S. Kim (Dictyotales, Ochrophyta) en el Estrecho de Gibraltar : Primera cita para el Atlántico y España*. (52), 20.

Atroune, F. & Boutaleb, Abdelhak. (2012). *LES MÉTAUX LOURDS DANS LES SÉDIMENTS SUPERFICIELS DE LA BAIE D'ALGER : INFLUENCE DE L'OUED EL HARRACH SUR LEUR DISTRIBUTION. 23*, 169-178.

Bahbah, L., Bilel, B., & Halima, S. (2025, mai 31). *Expansion of the Non-Indigenous Alga Rugulopteryx okamurae Along the Algerian Coast : Current Status and Ecological*

Implications. Séminaire National sur la Gestion des Espèces Exotiques Envahissantes (SNGEEE 2025): Défis et Solutions. https://www.researchgate.net/publication/392262611_Expansion_of_the_Non-Indigenous_Alga_Rugulopteryx_okamurae_Along_the_Algerian_Coast_Current_Status_and_Ecological_Implications

Bellissimo, G., Altamirano, M., Muñoz, A., De La Rosa, J., Hung, T. H., Rizzuto, G., Vizzini, S., & Tomasello, A. (2024). The invasive brown seaweed Rugulopteryx okamurae (Dictyotales, Ochrophyta) continues to expand : First record in Italy. *BioInvasions Records*, *13*(2), 385-401. https://doi.org/10.3391/bir.2024.13.2.08

Benhalima, M., Boulahdid, M., Guendouzi, Y., Radakovitch, O., Aroua, M., Fowler, S. W., Ambrosi, J.-P., & Angeletti, B. (2022). Occurrence, contamination level and ecological risk assessment of dissolved and particulate trace elements in rivers entering the southwestern Mediterranean Sea. *Marine Pollution Bulletin*, *180*, 113723. https://doi.org/10.1016/j.marpolbul.2022.113723

Bernal-Ibáñez, A., Castilla-Gavilán, M., Sumariva, E. G., & Hachero-Cruzado, I. (2025). Invasion context matters : Vulnerability of the sea urchin Paracentrotus lividus to ingestion of Rugulopteryx okamurae increases with invasion time. *Marine Pollution Bulletin*, *214*, 117826. https://doi.org/10.1016/j.marpolbul.2025.117826

Bernal-Ibáñez, A., Chebaane, S., Sempere-Valverde, J., Faria, J., Ramalhosa, P., Kaufmann, M., Florido, M., Albert-Fonseca, A., Canning-Clode, J., Gestoso, I., & Cacabelos, E. (2022). A worrying arrival : The first record of brown macroalga Rugulopteryx okamurae in Madeira Island and its invasive risk. *BioInvasions Records*, *11*(4), 912-924. https://doi.org/10.3391/bir.2022.11.4.10

Boumaza, S., Semroud, R., 2000. Surveillance de l'herbier à *Posidonia oceanica* d'El Djamila (Algérie), in Symposium on Marine Vegetation (Ajaccio, 3-4 Octobre 2000): p 111.

Carr, M. H., Neigel, J. E., Estes, J. A., Andelman, S., Warner, R. R., & Largier, J. L. (2003). COMPARING MARINE AND TERRESTRIAL ECOSYSTEMS : IMPLICATIONS FOR THE DESIGN OF COASTAL MARINE RESERVES. *Ecological Applications*, *13*(sp1), 90-107. https://doi.org/10.1890/1051-0761(2003)013%5B0090:CMATEI%5D2.0.CO;2

CDB. (2010). *What are Invasive Alien Species?* Secretariat of the Convention on Biological Diversity. https://www.cbd.int/invasive/WhatareIAS

Davidson, A. D., Campbell, M. L., Hewitt, C. L., & Schaffelke, B. (2015). Assessing the impacts of nonindigenous marine macroalgae : An update of current knowledge. *Botanica Marina*, *58*(2), 55-79. https://doi.org/10.1515/bot-2014-0079

Davidson, I. C., Scianni, C., Minton, M. S., & Ruiz, G. M. (2018). A history of ship specialization and consequences for marine invasions, management and policy. *Journal of Applied Ecology*, *55*(4), 1799-1811. https://doi.org/10.1111/1365-2664.13114

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., Meygret, A., Spoto, F., Sy, O., Marchese, F., & Bargellini, P. (2012). Sentinel-2 : ESA's Optical High-Resolution Mission for GMES Operational Services. *Remote Sensing of Environment, The Sentinel Missions - New Opportunities for Science*, *120*, 25-36. https://doi.org/10.1016/j.rse.2011.11.026

El Madany, M., Florido, M., Hassoun, M., El Aamri, F., & El Mtili, N. (2026). Massive strandings and local perception highlight the extent of Rugulopteryx okamurae invasion on the Moroccan coast. *Marine Environmental Research*, *213*, 107690. https://doi.org/10.1016/j.marenvres.2025.107690

EPIC HUPE/WA. (2024). *Rapport sur l'état et l'evolution des plages algéroise*. EPIC HUPE/WA.

Estévez, R., Palacios, M., Cervera, J., & González-Duarte, M. (2022). Expansion of the invasive alga Rugulopteryx okamurae (Dictyotaceae, Ochrophyta) in the Mediterranean Sea : First evidence as epiphyte of the cold-water coral Dendrophyllia ramea (Cnidaria: Scleractinia). *BioInvasions Records*, *11*(4), 925-936. https://doi.org/10.3391/bir.2022.11.4.11

European Commission, 1143/2014. (2015a). https://doi.org/10.5040/9781509909568

Faria, J., Prestes, A. C. L., Moreu, I., Cacabelos, E., & Martins, G. M. (2022). Dramatic changes in the structure of shallow-water marine benthic communities following the invasion by Rugulopteryx okamurae (Dictyotales, Ochrophyta) in Azores (NE Atlantic). *Marine Pollution Bulletin*, *175*, 113358. https://doi.org/10.1016/j.marpolbul.2022.113358

Faria, J., Prestes, A. C., Moreu, I., Martins, G. M., Neto, A. I., & Cacabelos, E. (s. d.). *Arrival and proliferation of the invasive seaweed Rugulopteryx okamurae in NE Atlantic islands*.

Figueroa, F. L., Vega, J., Flórez-Fernández, N., Mazón, J., Torres, M. D., Domínguez, H., & Pereira, L. (2025). Challenges and opportunities of the exotic invasive macroalga Rugulopteryx okamurae (Phaeophyceae, Heterokontophyta). *Journal of Applied Phycology*, *37*(1), 579-595. https://doi.org/10.1007/s10811-024-03404-w

Galanidi, M., Aissi, M., Ali, M., Bakalem, A., Bariche, M., Bartolo, A. G., Bazairi, H., Beqiraj, S., Bilecenoglu, M., Bitar, G., Bugeja, M., Carbonell, A., Castriota, L., Chalabi, A., Çinar, M. E., Dragičević, B., Dulčić, J., El-Haweet, A. E. A., Farrag, M. M. S., … Zenetos, A. (2023). Validated Inventories of Non-Indigenous Species (NIS) for the Mediterranean Sea as Tools for Regional Policy and Patterns of NIS Spread. *Diversity*, *15*(9), 962. https://doi.org/10.3390/d15090962

García-Gómez, J. C., Florido, M., Olaya-Ponzone, L., Sempere-Valverde, J., & Megina, C. (2021). The Invasive Macroalga Rugulopteryx okamurae : Substrata Plasticity and

Spatial Colonization Pressure on Resident Macroalgae. *Frontiers in Ecology and Evolution*, *9*, 631754. https://doi.org/10.3389/fevo.2021.631754

García-Gómez, J. C., Florido, M., Olaya-Ponzone, L., Sempere-Valverde, J., & Megina, C. (2021b). The Invasive Macroalga Rugulopteryx okamurae : Substrata Plasticity and Spatial Colonization Pressure on Resident Macroalgae. *Frontiers in Ecology and Evolution*, *9*, 631754. https://doi.org/10.3389/fevo.2021.631754

García-Gómez, J. C., Sempere-Valverde, J., González, A. R., Martínez-Chacón, M., Olaya-Ponzone, L., Sánchez-Moyano, E., Ostalé-Valriberas, E., & Megina, C. (2020). From exotic to invasive in record time : The extreme impact of Rugulopteryx okamurae (Dictyotales, Ochrophyta) in the strait of Gibraltar. *Science of The Total Environment*, *704*, 135408. https://doi.org/10.1016/j.scitotenv.2019.135408

Geburzi, J. C., & McCarthy, M. L. (2018). How Do They Do It? – Understanding the Success of Marine Invasive Species. In S. Jungblut, V. Liebich, & M. Bode (Éds.), *YOUMARES 8 – Oceans Across Boundaries : Learning from each other* (p. 109-124). Springer International Publishing. https://doi.org/10.1007/978-3-319-93284-2_8

GISD. (2026). *Global Invasive Species Database (2026). Species profile : Rugulopteryx okamurae. Available at : Http://www.iucngisd.org/gisd/ [Accessed : May, 2026].*

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine : Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment, Big Remotely Sensed Data: tools, applications and experiences*, *202*, 18-27. https://doi.org/10.1016/j.rse.2017.06.031

Grimes, S., Benabdi, M., Babali, N., Refes, W., Boudjelal-Kaidi, N., & Seridi, H. (2018). Biodiversity changes along the Algerian coast (Southwest Mediterranean basin) : From 1834 to 2017 : A first assessment of introduced species. *Mediterranean Marine Science*, *19*(1), 156-179. https://doi.org/10.12681/mms.13824

Guil-Guerrero, J. L., Carmona-Fernández, M., Chileh-Chelh, T., Belarbi, E.-H., Urrestarazu, M., Loeiro Cunha-Chiamolera, T. P., Ezzaitouni, M., Rincón-Cervera, M. Á., & Rodríguez-García, I. (2025). Fatty acid profiling in the invasive brown seaweed Rugulopterix okamurae : A usefulness taxonomical tool. *Continental Shelf Research*, *286*, 105412. https://doi.org/10.1016/j.csr.2025.105412

Haro, S., Morrison, L., Caballero, I., Figueroa, F. L., Korbee, N., Navarro, G., & Bermejo, R. (2024). Assessing Golden Tides from Space : Meteorological Drivers in the Accumulation of the Invasive Algae Rugulopteryx okamurae on Coasts. *Remote Sensing*, *16*(15), 2689. https://doi.org/10.3390/rs16152689

Hernández, S., D.-C. Martínez, B., & Olabarria, C. (2024). Predicting habitat suitability for alien macroalgae in relation to thermal niche occupancy. *Marine Pollution Bulletin*, *208*, 116953. https://doi.org/10.1016/j.marpolbul.2024.116953

Hewitt, C. L., Campbell, M. L., & Schaffelke, B. (2007). *Introductions of seaweeds : Accidental transfer pathways and mechanisms*. *50*(5-6), 326-337. https://doi.org/10.1515/BOT.2007.038

Hwang, I.-K., Lee, W. J., Kim, H.-S., & De Clerck, O. (2009). Taxonomic reappraisal of *Dilophus okamurae* (Dictyotales, Phaeophyta) from the western Pacific Ocean. *Phycologia*, *48*(1), 1-12. https://doi.org/10.2216/07-68.1

IPBES. (2023). *IPBES Invasive Alien Species Assessment : Full report*. Zenodo. https://doi.org/10.5281/zenodo.10127795

Jones, E., & Thornber, C. (2010). Effects of habitat-modifying invasive macroalgae on epiphytic algal communities. *Marine Ecology Progress Series*, *400*, 87-100. https://doi.org/10.3354/meps08391

Katsanevakis, S., Olenin, S., Puntila-Dodd, R., Rilov, G., Stæhr, P. A. U., Teixeira, H., Tsirintanis, K., Birchenough, S. N. R., Jakobsen, H. H., Knudsen, S. W., Lanzén, A., Mazaris, A. D., Piraino, S., & Tidbury, H. J. (2023). Marine invasive alien species in Europe : 9 years after the IAS Regulation. *Frontiers in Marine Science*, *10*, 1271755. https://doi.org/10.3389/fmars.2023.1271755

Kraus, R. (2023). Ballast Water Management in Ports : Monitoring, Early Warning and Response Measures to Prevent Biodiversity Loss and Risks to Human Health. *Journal of Marine Science and Engineering*, *11*(11), 2144. https://doi.org/10.3390/jmse11112144

Laamraoui, M. R., Mghili, B., Roca, M., Chaieb, O., Ostalé-Valriberas, E., Martín-Zorrillae, A., Sabino-Lorenzo, A., & Aarab, S. (2024). Rapid invasion and expansion of the invasive macroalgae Rugulopteryx okamurae in the Mediterranean and Atlantic : A 10-year review. *Marine Pollution Bulletin*, *209*, 117194. https://doi.org/10.1016/j.marpolbul.2024.117194

Li, H., Geng, Y., Shi, H., Wu, C., Yu, Z., Zhang, H., Chen, L., & Xing, R. (2023). Biological mechanisms of invasive algae and meta-analysis of ecological impacts on local communities of marine organisms. *Ecological Indicators*, *146*, 109763. https://doi.org/10.1016/j.ecolind.2022.109763

Mannino, A. M., Borfecchia, F., & Micheli, C. (2021). Tracking Marine Alien Macroalgae in the Mediterranean Sea : The Contribution of Citizen Science and Remote Sensing. *Journal of Marine Science and Engineering*, *9*(3), 288. https://doi.org/10.3390/jmse9030288

Mateo-Ramírez, Á., Iñiguez, C., Fernández-Salas, L. M., Sánchez-Leal, R. F., Farias, C., Bellanco, M. J., Gil, J., & Rueda, J. L. (2023). Healthy thalli of the invasive seaweed *Rugulopteryx okamurae* (Phaeophyceae) being massively dragged into deep-sea bottoms by the Mediterranean Outflow Water. *Phycologia*, *62*(2), 99-108. https://doi.org/10.1080/00318884.2023.2177057

MEER. (2023). https://www.me.gov.dz/fr/telechargements/

Mercado, J. M., Gómez-Jakobsen, F., Korbee, N., Aviles, A., Bonomi-Barufi, J., Muñoz, M., Reul, A., & Figueroa, F. L. (2022). Analyzing environmental factors that favor the growth of the invasive brown macroalga Rugulopteryx okamurae (Ochrophyta) : The probable role of the nutrient excess. *Marine Pollution Bulletin*, *174*, 113315. https://doi.org/10.1016/j.marpolbul.2021.113315

Mineur, F., Johnson, M. P., & Maggs, C. A. (2008). Macroalgal Introductions by Hull Fouling on Recreational Vessels : Seaweeds and Sailors. *Environmental Management*, *42*(4), 667-676. https://doi.org/10.1007/s00267-008-9185-4

Misraoui & Sengouga. (2011). *Caractérisation des herbiers à Posidonia oceanica (L.) Delile de la baie de Bou Ismaïl* [Mémoire de fin d'études]. École Nationale Supérieure des Sciences de la Mer et de l'Aménagement du Littoral (ENSSMAL).

Mogollón, S. L., Zilio, M. I., Buitrago, E. M., Caraballo, M. Á., & Yñiguez, R. (2024). Economic impact of Rugulopteryx okamurae (Dictyotales, Ochrophyta) along the Andalusian coastline : The case of Tarifa, Spain. *Wetlands Ecology and Management*, *32*(1), 19-32. https://doi.org/10.1007/s11273-023-09951-2

Nadal, I., Röhrs, J., Breivik, Ø., & Ådlandsvik, B. (2018). A predictive numerical tool for invasive species monitoring and management : Rugulopteryx okamurae as a case study. *Geoscientific Model Development*, *11*(4), 1405-1420. https://doi.org/10.5194/gmd-11-1405-2018

Navarro-Barranco, C., Muñoz-Gómez, B., Saiz, D., Ros, M., Guerra-García, J. M., Altamirano, M., Ostalé-Valriberas, E., & Moreira, J. (2019). Can invasive habitat-forming species play the same role as native ones ? The case of the exotic marine macroalga Rugulopteryx okamurae in the Strait of Gibraltar. *Biological Invasions*, *21*(11), 3319-3334. https://doi.org/10.1007/s10530-019-02049-y

Ocaña, Oscar, Afonso-Carrillo, Julio, Ballesteros, Enric, Sansón, Mercedes, & González, Yamile. (2016). *Massive proliferation of a dictyotalean species (Phaeophyceae, Ochrophyta) through the Strait of Gibraltar*. *28*, 165-170.

Putman, N. F., Goni, G. J., Gramer, L. J., Hu, C., Johns, E. M., Trinanes, J., & Wang, M. (2018). Simulating transport pathways of pelagic Sargassum from the Equatorial Atlantic into the Caribbean Sea. *Progress in Oceanography*, *165*, 205-214. https://doi.org/10.1016/j.pocean.2018.06.009

Roca, M., Dunbar, M. B., Román, A., Caballero, I., Zoffoli, M. L., Gernez, P., & Navarro, G. (2022). Monitoring the marine invasive alien species Rugulopteryx okamurae using unmanned aerial vehicles and satellites. *Frontiers in Marine Science*, *9*. https://doi.org/10.3389/fmars.2022.1004012

Roca, M., Navarro, G., García-Sanabria, J., & Caballero, I. (2022b). Monitoring Sand Spit Variability Using Sentinel-2 and Google Earth Engine in a Mediterranean Estuary. *Remote Sensing*, *14*(10), 2345. https://doi.org/10.3390/rs14102345

Roca-Mora, M., Davies, B. F. R., Gernez, P., Zoffoli, M. L., & Barillé, L. (2026). Beachcast degradation stages of Rugulopteryx okamurae and Zostera noltii : Towards a scalable remote-sensing monitoring platform. *Remote Sensing Applications: Society and Environment*, 102108. https://doi.org/10.1016/j.rsase.2026.102108

Rodil, I. F., Rodriguez, V. P., Bernal-Ibáñez, A., Pardiello, M., Soccio, F., & Gestoso, I. (2024). High contribution of an invasive macroalgae species to beach wrack CO2 emissions. *Journal of Environmental Management*, *367*, 122021. https://doi.org/10.1016/j.jenvman.2024.122021

Ruitton, S., Blanfuné, A., Boudouresque, C.-F., Guillemain, D., Michotey, V., Roblet, S., Thibault, D., Thibaut, T., & Verlaque, M. (2021). Rapid Spread of the Invasive Brown

Alga Rugulopteryx okamurae in a National Park in Provence (France, Mediterranean Sea). *Water*, *13*(16), 2306. https://doi.org/10.3390/w13162306

Schaffelke, B., Smith, J. E., & Hewitt, C. L. (2006). Introduced Macroalgae – a Growing Concern. *Journal of Applied Phycology*, *18*(3), 529-541. https://doi.org/10.1007/s10811-006-9074-2

Semroud, R., Verlaque, R., Crouzet, A., & Boudouresque, C. F. (1992). On a broad-leaved form of the seagrass *Posidonia oceanica* (Posidoniaceae) from Algiers (Algeria). *Aquatic Botany*, *43*(2), 181-198. https://doi.org/10.1016/0304-3770(92)90042-H

Skliris, N., Marsh, R., Appeaning Addo, K., & Oxenford, H. (2022). Physical drivers of pelagic sargassum bloom interannual variability in the Central West Atlantic over 2010–2020. *Ocean Dynamics*, *72*(6), 383-404. https://doi.org/10.1007/s10236-022-01511-1

Soualili, D., Dubois, P., Gosselin, P., Pernet, P., & Guillou, M. (2008). Assessment of seawater pollution by heavy metals in the neighbourhood of Algiers : Use of the sea urchin, Paracentrotus lividus, as a bioindicator. *ICES Journal of Marine Science*, *65*(2), 132-139. https://doi.org/10.1093/icesjms/fsm183

Steele, J. H., Brink, K. H., & Scott, B. E. (2019). Comparison of marine and terrestrial ecosystems : Suggestions of an evolutionary perspective influenced by environmental variation. *ICES Journal of Marine Science*, *76*(1), 50-59. https://doi.org/10.1093/icesjms/fsy149

Terradas-Fernández, M., Pena-Martín, C., Valverde-Urrea, M., Gran, A., Blanco-Murillo, F., Leyva, L., Abellán-Gallardo, E., Beresaluze, E., Izquierdo, A., Del Pilar-Ruso, Y., Aguilar, J., & Fernández-Torquemada, Y. (2023). An outbreak of the invasive macroalgae Rugulopteryx okamurae in Alicante Bay and its colonization on dead Posidonia oceanica matte. *Aquatic Botany*, *189*, 103706. https://doi.org/10.1016/j.aquabot.2023.103706

The European Banking Union : A Compendium. (2015b). Nomos Verlagsgesellschaft. https://doi.org/10.5040/9781509909568

Thomsen, M. S., Wernberg, T., Olden, J. D., Griffin, J. N., & Silliman, B. R. (2011). A framework to study the context-dependent impacts of marine invasions. *Journal of Experimental Marine Biology and Ecology*, *400*(1-2), 322-327. https://doi.org/10.1016/j.jembe.2011.02.033

Verlaque, M. (2001). Checklist of the macroalgae of Thau Lagoon (Hérault, France), a hot spot of marine species introduction in Europe. *Oceanologica Acta*, *24*(1), 29-49. https://doi.org/10.1016/S0399-1784(00)01127-0

Verlaque, M., Steen, F., & De Clerck, O. (2009). Rugulopteryx (Dictyotales, Phaeophyceae), a genus recently introduced to the Mediterranean. *Phycologia*, *48*(6), 536-542. https://doi.org/10.2216/08-103.1

Vieira, C., Kang, J. C., Daudinet, M., Akita, S., & Kim, M. S. (2025). Critical taxonomic revision of Korean Dictyoteae describing three new species and honoring Haenyeo culture. *Journal of Phycology*, *61*(2), 353-378. https://doi.org/10.1111/jpy.70010

Villalobos Perna, P., Di Febbraro, M., Carranza, M. L., Marzialetti, F., & Innangi, M. (2023). Remote Sensing and Invasive Plants in Coastal Ecosystems : What We Know So Far and Future Prospects. *Land*, *12*(2), 341. https://doi.org/10.3390/land12020341

Wang, M., & Hu, C. (2017). Predicting *Sargassum* blooms in the Caribbean Sea from MODIS observations. *Geophysical Research Letters*, *44*(7), 3265-3273. https://doi.org/10.1002/2017GL072932

Williams, S. L., & Smith, J. E. (2007). A Global Review of the Distribution, Taxonomy, and Impacts of Introduced Seaweeds. In *Annual Review of Ecology, Evolution, and Systematics* (Vol. 38, Numéro Volume 38, 2007, p. 327-359). Annual Reviews. https://doi.org/https://doi.org/10.1146/annurev.ecolsys.38.091206.095543

Wonham, M. J., Lewis, M. A., & MacIsaac, H. J. (2005). Minimizing invasion risk by reducing propagule pressure : A model for ballast-water exchange. *Frontiers in Ecology and the Environment*, *3*(9), 473-478. https://doi.org/10.1890/1540-9295(2005)003%5B0473:MIRBRP%5D2.0.CO;2

Zenati, B, Kourdali, S., Inal, A., Mesbaiah, F.-Z., Meknachi, A., & Belhouchet, N. (2018). *Caractérisation et dynamique de la charge polluante véhiculée par l'oued Mazafran sur le milieu côtier. Hippocampus, 4, 7-8.* https://doi.org/https://asjp.cerist.dz/en/article/207915

Zenetos, A., ALBANO, P. G., LÓPEZ GARCIA, E., STERN, N., TSIAMIS, K., & GALANIDI, M. (2022). Established non-indigenous species increased by 40% in 11 years in the Mediterranean Sea. *Mediterranean Marine Science*, *23*(1). https://doi.org/10.12681/mms.29106

Abstract

This thesis examines the invasion of *Rugulopteryx okamurae* along the beaches of Algiers using Sentinel-2 satellite imagery and the Google Earth Engine platform. The methodology is based on six field surveys and the analysis of 258 satellite images acquired between 2023 and 2026. The classification model achieved an overall accuracy of 70.25%. The results indicate a progressive expansion of the species, with the highest biomass accumulations observed at El Djamila and Sidi Fredj beaches. Seasonal dynamics revealed increased floating biomass during summer and higher beachcast accumulation in winter and autumn, emphasizing the role of hydrodynamic conditions in biomass distribution. This study provides the first large-scale assessment of *R. okamurae* dynamics in Algeria and highlights the effectiveness of remote sensing for monitoring invasive marine macroalgae and supporting coastal management.

Keywords: *Rugulopteryx okamurae*, invasive macroalgae, remote sensing, beachcast, Algerian coastline.

الملخص

تبحث هذه الأطروحة في غزو الطحلب *Rugulopteryx okamurae* على طول شواطئ الجزائر العاصمة باستخدام صور الأقمار الصناعية Sentinel-2 ومنصة Google Earth Engine. تعتمد المنهجية على ست حملات ميدانية بالإضافة إلى تحليل 258 صورة أقمار صناعية تم الحصول عليها بين عامي 2023 و2026. حقق نموذج التصنيف دقة إجمالية بلغت 70.25%. تشير النتائج إلى توسع تدريجي لهذا النوع، مع تسجيل أعلى تراكمات للكتلة الحيوية في شاطئي الجميلة وسيدي فرج. كما أظهرت الديناميكيات الموسمية زيادة في الكتلة الحيوية الطافية خلال فصل الصيف وارتفاعًا في التراكمات الشاطئية خلال فصلي الشتاء والخريف، مما يبرز دور الظروف الهيدروديناميكية في توزيع الكتلة الحيوية. تمثل هذه الدراسة أول تقييم واسع النطاق لديناميكية *R. okamurae* في الجزائر، وتؤكد فعالية الاستشعار عن بعد في مراقبة الطحالب البحرية الغازية ودعم إدارة المناطق الساحلية.

الكلمات المفتاحية : *Rugulopteryx okamurae*،الطحالب البحرية الغازية، الاستشعار عن بعد، التراكمات الشاطئية، الساحل الجزائري.

Résumé

Ce mémoire étudie l’invasion de *Rugulopteryx okamurae* le long des plages d’Alger à l’aide des images satellitaires Sentinel-2 et de la plateforme Google Earth Engine. La méthodologie repose sur six campagnes de terrain ainsi que sur l’analyse de 258 images satellitaires acquises entre 2023 et 2026. Le modèle de classification a atteint une précision globale de 70,25 %. Les résultats indiquent une expansion progressive de l’espèce, avec les accumulations de biomasse les plus élevées observées sur les plages d’El Djamila et de Sidi Fredj. Les dynamiques saisonnières ont révélé une augmentation de la biomasse flottante en été ainsi qu’une hausse des échouages en hiver et en automne, soulignant le rôle des conditions hydrodynamiques dans la répartition de la biomasse. Cette étude constitue la première évaluation à grande échelle de la dynamique de *R. okamurae* en Algérie et met en évidence l’efficacité de la télédétection pour le suivi des macroalgues marines invasives et la gestion des zones côtières.

Mots-clés : *Rugulopteryx okamurae*, macroalgue invasive, télédétection, échouage, littoral algérien.