Research Article

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Proliferation of *Undaria pinnatifida* along the Atlantic coast of the Iberian Peninsula

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Abstract: The spread of non-indigenous species is a critical concern for marine ecosystems, particularly in regions with high biodiversity and economic reliance on coastal resources. This study investigates the distribution, abundance, and expansion of the invasive kelp *Undaria pinnatifida* along the Atlantic coast of the Iberian Peninsula. A comprehensive survey was conducted in 2024, covering 59 locations across Spain and Portugal. This dataset was complemented by biodiversity records from citizen science platforms. Historical records were also reviewed to assess changes in its distribution over time. Results indicate that *U. pinnatifida* has notably increased its presence in Portugal since its first record, now occurring at 16 sites (compared to only 2 in 2007), while remaining well-established in Galicia. However, the species co-occurs with native kelps and, at this stage, does not dominate the communities where it has established itself. Furthermore, it remains absent from southern Iberia and the Bay of Biscay. Hence, environmental conditions and biotic interactions might be shaping their distribution, which warrants further investigation. Given the ongoing environmental changes and human-mediated dispersal, continuous monitoring is essential to track future range shifts. This study also showcases how integrating citizen science data can enhance the spatial and temporal resolution of non-indigenous species monitoring.

Keywords: intertidal; invasion; seaweed; macroalgae; distribution

1 Introduction

Marine non-indigenous species (NIS) (Richardson et al. 2011) spread beyond their natural range, mainly transported by maritime traffic and marine aquaculture (Hewitt et al. 2007; Schaffelke et al. 2006). NIS are known as “invasive species” when they establish, spread, and proliferate without direct human assistance (according to Mack et al. 2000) or alter the environment (according to Simberloff et al. 2013). Invasive alien species have contributed solely or alongside other drivers to 60 % of recorded global extinctions, and are the only driver in 16 % of the documented global animal and plant extinctions (Roy et al. 2023) by outcompeting native taxa and leading to considerable negative economic impacts (Brondizio et al. 2019; Dudeque Zenni et al. 2021; McKnight et al. 2021).

Intertidal macroalgae play an important role in coastal ecosystems, acting as primary producers and providing habitat and nursery grounds for a wide variety of species, many of which are ecological and economically relevant (Steneck et al. 2002). Their canopies offer a buffer against the harsh physical conditions of the intertidal, helping to maintain ecological balance and support the resilience of coastal ecosystems (Mineur et al. 2015; Thomsen et al. 2012). Nevertheless, some invasive marine macroalgae can disrupt coastal ecosystems, driving ecological change (Çinar et al. 2014). For example, the alteration of competitive relationships within the recipient habitat, often manifested as space monopolization, leads to significant reductions in both the abundance and diversity of native macroalgae and

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associated fauna. Davidson et al. (2015) showed that, in numerous instances, areas affected by invasive species exhibited a marked decline in the richness and abundance of native macroalgal species compared to non-invaded areas. However, the impacts of invasive species are often species- and region-specific (Epstein and Smale 2017).

Undaria pinnatifida (Harvey) Suringar, commonly known as "Wakame", is a cold-temperate kelp native to the northwest Pacific Ocean (coastlines of Japan, Korea, Russia, and China) (Epstein and Smale 2017). *U. pinnatifida* is one of the 100 most invasive species in the world according to the Invasive Species Specialist Group list (Lowe et al. 2000). Nowadays, this kelp is present in nearly all temperate coastal marine ecoregions (Spalding et al. 2007), including the northeast Atlantic, southwest Atlantic, New Zealand, Australia, and the northeast Pacific (Heiser et al. 2014; James et al. 2015; Raffo et al. 2009; Thornber et al. 2004). Due to its photosynthetic adaptability and ability to grow, this species can extend its distribution into deeper subtidal habitats, enhancing its ecological impact across a broader range of marine environments (Desmond et al. 2019; Russell et al. 2008). It has been suggested that *U. pinnatifida* might act as a passenger rather than a driver of ecological change (sensu) (MacDougall and Turkington 2005), as it colonizes areas that have lost their natural canopy cover (South and Thomsen 2016). Hence, it typically establishes itself first on artificial substrata (Kaplanis et al. 2016) or on disturbed natural substrata with little competition. In a second phase, it often spreads to nearby natural rocky substrata, where the effects on native communities are region-specific, ranging from little impact (e.g., De Leij et al. 2017) to a substantial decrease in local diversity. For example, in Argentina, the presence of *Undaria* resulted in a decrease in native seaweed diversity and richness (Casas et al. 2004); in Italy, a decrease in the surface area of native seaweeds was observed following *Undaria*'s establishment (Curiel et al. 2002) and, in New Zealand, there was a reduction in the abundance of epifauna with the spread of *Undaria* (Suárez-Jiménez et al. 2017).

In the Northeast Atlantic, *U. pinnatifida* has its southern limit in central Portugal (Pereira et al. 2022) and its northern limit in the island of Sylt, Germany (Schiller et al. 2018). *U. pinnatifida* was first recorded in Europe in the Thau lagoon on the French Mediterranean coast in 1971, probably as the result of the import of oysters from Japan (Boudouresque et al. 1985; Floc'h et al. 1991). Then it was transferred for farming to northern France in 1983 and, in 1988, reproducing individuals were found growing on mussel lines outside the seaweed farm (Floc'h et al. 1991, 1996).

The species was first recorded in the Iberian Peninsula in Galicia in 1988, probably introduced via oysters imported there (Caamano et al. 1990). In Spain, *U. pinnatifida* has extended its distribution to various regions, including Asturias and Cantabria, as documented by Peteiro (2008), Pérez Ruzafa et al. (2002) and Salinas et al. (1996). Ugarte et al. (2006) provided a detailed review of its distribution, confirming its expansion in these regions.

In Portugal, *U. pinnatifida* was first recorded in 2007 by Araújo et al. (2009) at a marina in Póvoa de Varzim (northern Portugal) and in the Ría de Aveiro (central Portugal). Later, Veiga et al. (2014) reported the disappearance of the Aveiro population and documented a new one in Buarcos (central Portugal). More recently, Monteiro et al. (2022) documented the presence of *U. pinnatifida* at four new sites – two on artificial substrata and two on natural substrata. A study by Carreira-Flores et al. (2023) did not identify any additional locations in mainland Portugal.

The Atlantic coast of the Iberian Peninsula exhibits unique ecological conditions. The nutrient-rich waters and pronounced latitudinal thermal gradient driven by the cooling effect of the Canary upwelling system during summer create a biogeographical transition zone in northern Portugal (Fiuza 1983). This area serves as the southern range limit for various cold-temperate species and as a biogeographical poleward barrier for warmer-water species (Casado-Amezúa et al. 2019; Monteiro et al. 2022). Modelling efforts to predict the fate of the distribution of *U. pinnatifida* in the region give mixed results, ranging from the identification of favorable conditions for the expansion of *U. pinnatifida* (Báez et al. 2010), to a low or very low probability of establishment outside the Galician rías (Blanco et al. 2021). Nevertheless, recent distribution shifts in northern Portugal of both native and non-indigenous intertidal and subtidal seaweeds (de Azevedo et al. 2023; Monteiro et al. 2022), highlight the importance of closely tracking the expansion of non-native species and its potential impacts on coastal communities.

This paper describes the expansion of *U. pinnatifida* along the Atlantic coastlines of the Iberian Peninsula since its initial establishment. It also updates the presence and absence of this species based on recent survey data (summer 2024).

2 Materials and methods

2.1 Data collection

Fieldwork was conducted from February to November of 2024 to monitor the distribution and abundance of the kelp *U. pinnatifida* in the intertidal zone along the Atlantic coast

of the Iberian Peninsula, from the Strait of Gibraltar to the northeast Spanish border with France. Survey sites were selected to ensure broad geographical coverage, focusing on areas where kelp populations were previously known to occur (Figure 1).

At each site, a team of 2 people surveyed the rocky shore for 2 h during low tides employing an *ad-libitum* search focused on the low intertidal zone where *U. pinnatifida* is typically found. This method enhances the detection of rare species such as an invasive species at its early stages (Monteiro et al. 2022). Furthermore, the SACFOR abundance scale (Burrows et al. 2008; Hiscock 1981) was used to estimate the abundance of the *U. pinnatifida* populations, providing a standardized assessment for future comparisons. This scale grades abundances as 6: Superabundant (more than 90 % cover), 5: Abundant (60–90 % cover), 4: Common (widespread on the shore, 30–59 %), 3: Frequent (patches apparent, up to 30 % cover), 2: Occasional (3–20 individuals scattered) and 1: Rare (only 1 or 2 individuals). The scale was applied in each site, except for those records obtained from citizen science monitoring platforms. Only the locations where *U. pinnatifida* was found attached to the substratum were counted as confirmed presence, as specimens floating in the water or lying on the sand could have arrived through other means of transport and were, therefore, not considered established populations.

2.2 Citizen science platforms

We also mined two biodiversity monitoring programs, MINKA (https://minka-sdg.org/) and iNaturalist (https://www.inaturalist.org/) for records of *U. pinnatifida* in the Atlantic Iberian Peninsula. These platforms allow for the collection of observations from a wide range of contributors, helping to address potential geographical gaps in our dataset. Observations were limited to the geographical distribution within continental Portugal and the Atlantic coast of Spain, excluding any data beyond the borders of the study area (i.e., in the Atlantic coast of France or in the Mediterranean Sea). Both platforms employ a curator system to ensure the accuracy and reliability of records, hence only records with “research grade” were kept. Additionally, data from these platforms were carefully reviewed for accuracy. Only observations documented with pictures of the specimen visibly attached to the substratum were used for the analysis.

2.3 Historical distribution

To compare with the present survey, we conducted a comprehensive review of previous *U. pinnatifida* records along the intertidal Atlantic coast of the Iberian Peninsula, from the first record in 1988 to January 2025. We performed a

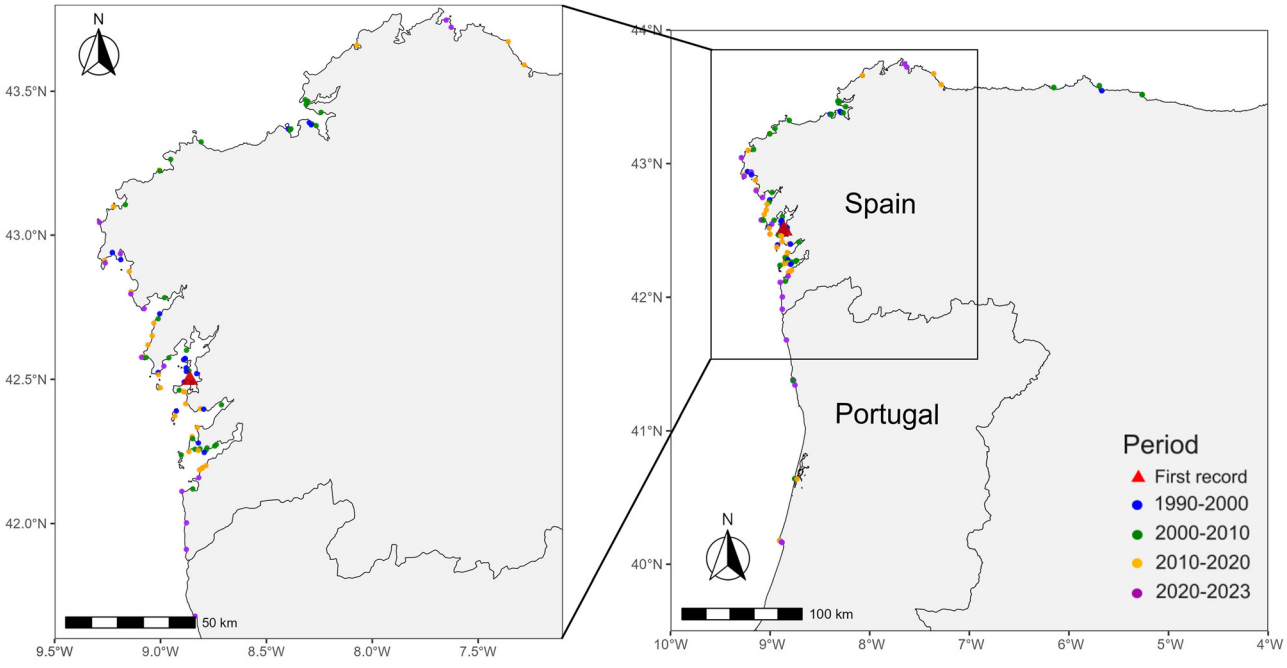

Figure 1: Distribution of *Undaria pinnatifida* before 2024. Red triangle represents the first record within the Atlantic coast of the Iberian Peninsula. Blue points represent presences between 1990 and 2000; green points between 2000 and 2010; yellow points between 2010 and 2020, and purple points between 2020 and 2023.

systematic literature search using popular scientific search engines, namely Web of Science (WoS) and Google Scholar with the keywords "*U. pinnatifida*", "Iberian Peninsula" and "Península Iberica" for Portuguese and Spanish references, as well as species distribution databases such as GBIF and WoRMS. Only studies that provided records of the species' geographical distribution – including location and year/date of observation – were included, while articles focused on other aspects, e.g. aquaculture, were excluded. We then carefully document the location and date of its first record at each site. In some cases, approximate locations were used due to a lack of precise geographic details in the literature.

2.4 Distribution and abundance – maps

Data analysis was conducted using R Statistical Software (R Development Core Team 2024). We generated distribution maps of the year 2024 and the temporal range from 1988 to 2023 to assess the expansion of *U. pinnatifida* using 'ggplot2' (Wickham 2016), 'sf' (Pebesma and Bivand 2023), 'ggrepel' (Slowikowski 2024), 'giscoR' (Hernangómez 2020) and 'rnaturalearth' (Massicotte and South 2023) R packages.

3 Results

3.1 Historical distribution

After compiling all available data on the presence of *U. pinnatifida* along the Atlantic coast of the Iberian Peninsula, our database showed that the species had been found in 108 locations, 94 in Spain and 14 in Portugal (Supplementary Table S1). To facilitate interpretation, data were divided into four distinct periods: (1) from the late 1980s to 2000, (2) from 2000 to 2010, (3) from 2010 to 2020, and (4) from 2020 to 2023 (Figure 1).

In the first period (1980s–2000), *U. pinnatifida* was found in 18 locations in Galicia and one site in Asturias, but there were no records in Portugal at that time. During the second period (2000–2010), it was found in 35 locations in Spain, and it was recorded for the first time in Portugal at 2 sites. By the third period (2010–2020), it had been observed in 27 locations in Galicia and 3 locations in central Portugal. Finally, prior to this study (2020–2023), *U. pinnatifida* was reported in 13 locations in Galicia and 9 locations in Portugal, expanding to the north.

To construct the historical distribution map (Figure 1), we used data from seven published references and seven citizen science observations. Of these references, Araújo et al. (2009) and Veiga et al. (2014) provided records exclusively for Portugal, while Blanco et al. (2021), Caamano et al. (1990), Carreira-Flores et al. (2023), Pérez Ruzafa et al. (2002), Peteiro (2008), Salinas et al. (1996) and Ugarte et al. (2006) contained data points only for Spain. Additionally, Pereira et al. (2022) included distribution records from both countries. Between 2010 and 2020, only one study in the Iberian Peninsula reported *Undaria*'s distribution.

3.2 Present survey (2024)

The survey carried out in 2024 covered a total of 60 sites, 35 in Spain and 25 in Portugal (Supplementary Table S2 and GBIF – https://doi.org/10.15468/sd2kdv). Of these, *U. pinnatifida* was found in a total of 31 locations, 15 in Spain and 16 in Portugal (Figure 2). During this survey *U. pinnatifida* was recorded in four new sites in Spain (Espasante, Punta Arroás, Praia das Cabanas, and A Guarda) and in six new sites in Portugal (Montedor, Viana do Castelo, Praia da Amorosa, Mindelo, Angeiras, and Praia do Homem do Leme). *U. pinnatifida* was not found in high abundances; it was recorded as rare in five sites (corresponding to an abundance level of 2) and observed as frequent at nine sites (corresponding to an abundance level of 3). All sites visited are urban shores, very close to human settlements. As reported in several other studies, we found *Undaria* near harbours, marinas and pontoons (3 sites) and often in natural rocky shores near man-made structures (10 sites). An overview of these shores can be found in Figure S1.

In total, 24 observations came from citizen science biodiversity platforms, MINKA and iNaturalist, contributed by 15 different observers, spanning from 2016 to 2024. We identified a geographic bias in the data, with most Portuguese observations concentrated in Buarcos and Aveiro, while fewer records were available from northern areas. In Spain, records were mainly localized within rías, with very few observations from the A Coruña area.

The current distribution limits of *U. pinnatifida* in the Iberian Peninsula are Buarcos (central Portugal, 40° 09′ 58.6″ N; 8° 53′ 08.0″ W) and Burela (Lugo, Spain, 43° 40′ 17.2″ N; 7° 21′ 28.9″ W) observed for the first time in 2013 and 2017, respectively. Several sites were surveyed south of Buarcos and east of Lugo, but no specimens were found (Figure 2).

Undaria pinnatifida was observed in the low intertidal zone, commonly alongside other kelp species such as *Saccorhiza polyschides* and *Laminaria* spp. (Figure 3). It frequently hosted epibionts such as the gastropods *Steromphala* spp. and *Patella pellucida*. Overall, individuals ranged in size from 0.5 m to approximately 1.5 m in length during its maximum size peak in early summer. Sporophytes of *U. pinnatifida* were recorded throughout the year, with the

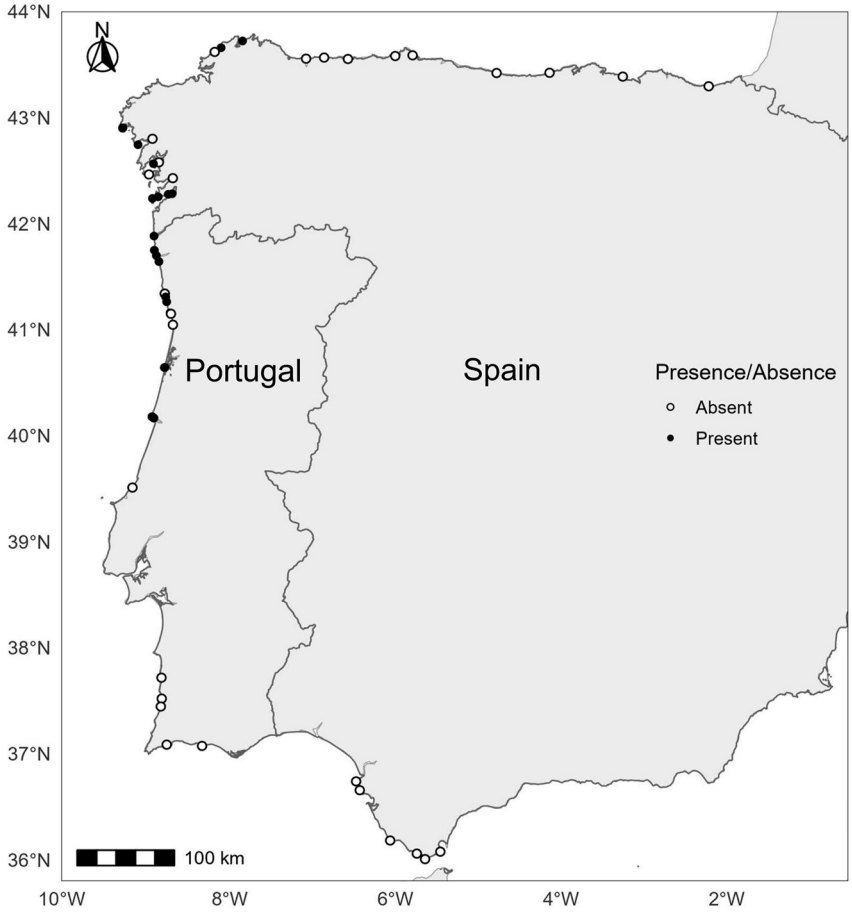

Figure 2: 2024 survey of *Undaria pinnatifida* in the Iberian Península. Black circles indicate presence, while white circles indicate absence.

largest specimens observed in spring, while by the end of summer, blade senescence was common.

4 Discussion

Our results indicate that *U. pinnatifida* has (i) proliferated along the Portuguese coast, increasing its distribution from 2 sites in 2007 to 16 sites in 2024, while (ii) persisting in Galicia, where it was first recorded in 1988 and it has been reported in 15 locations in the 2024 survey. The 2024 survey documented *Undaria* in 10 new sites across Portugal and Spain (out of 31 sites where *Undaria* was recorded and out of 60 sites surveyed). This pattern aligns with previous predictions that identified the northwest of the Iberian Peninsula as a suitable habitat for the species (Báez et al. 2010). However, its spread and establishment are not uniform throughout the Iberian Peninsula. Populations of *U. pinnatifida* in the Lower Rías were the first to establish in the Iberian Peninsula, and their abundances are higher there than in the Upper Rías and northern Portugal (this study; Pereira et al. 2022). In Portugal, although northern shores are geographically closer to the introduction site in Galicia (Ria de Arousa), *U. pinnatifida* was first established in Buarcos (central Portugal), located 255 km from the point of the first introduction in Ria de Arousa. It was only reported in northern Portugal (Póvoa de Varzim) in 2007.

The species was mainly observed co-occurring with native kelps, which supports the hypothesis that it may act as a passenger of ecological change, occupying newly available niches as conditions shift (De Leij et al. 2017). South et al. (2017) highlights that *U. pinnatifida*'s success as an invasive species is related to its ability to exploit disturbed habitats and to its effective dispersal mechanisms. Additionally, De Leij et al. (2017) emphasize that the establishment and persistence of *U. pinnatifida* in natural habitats are negatively correlated with the presence of native macroalgal canopies. Dense canopies of native kelp species in the Iberian Peninsula, such as *Saccorhiza polyschides* and *Laminaria* spp. (e.g. Boaventura et al. 2002; Casado-Amezúa et al. 2019), can limit the availability of light and space, restricting the colonization and growth of *U. pinnatifida* (De Leij et al. 2017; South et al. 2017). This apparent lower competitive ability might explain why *Undaria* does not dominate any of

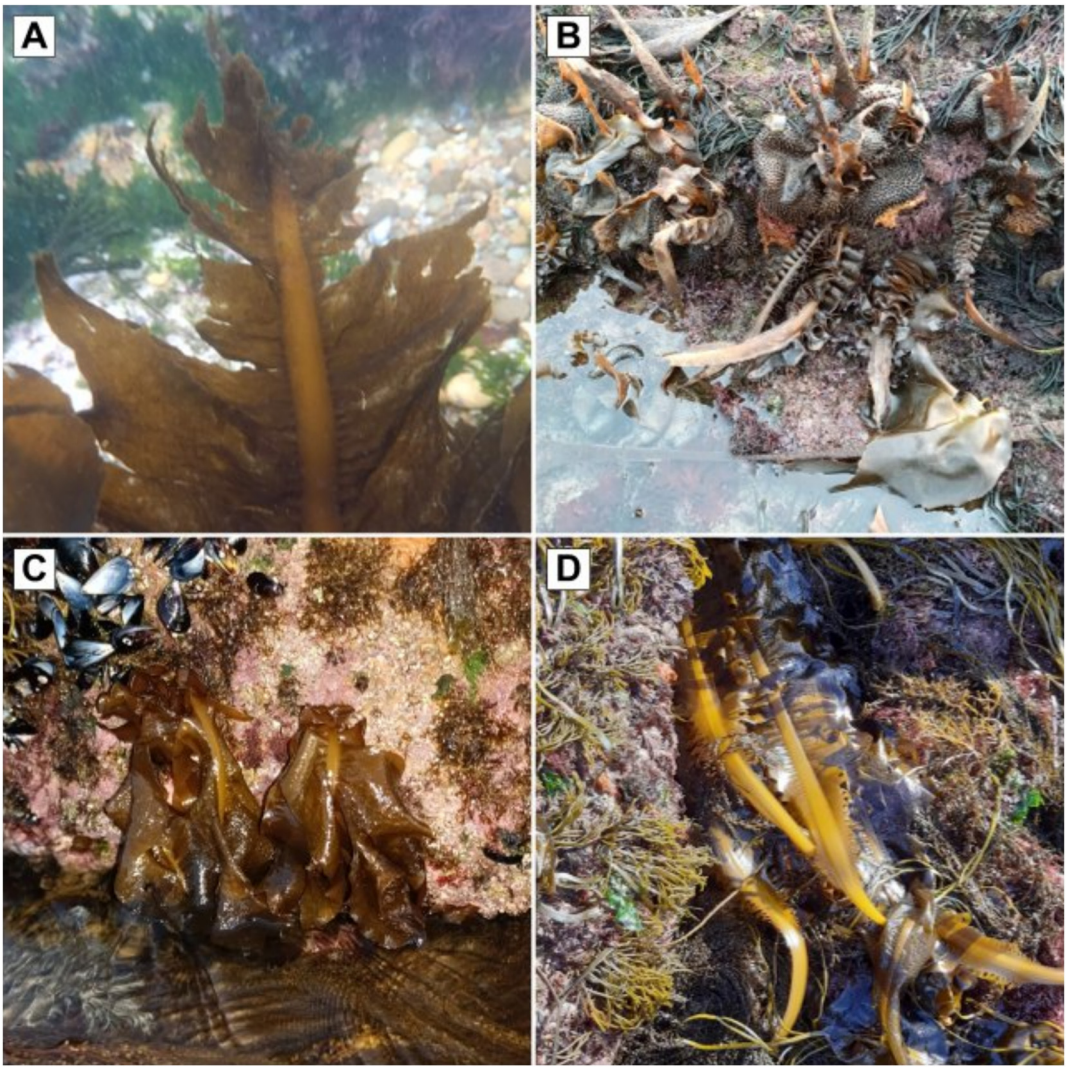

Figure 3: Specimens of *Undaria pinnatifida* found in: (A) Homem do Leme, Portugal (sourced from MINKA, ©juliana09); (B) Praia Norte, Viana do Castelo, Portugal (M. Humet); (C) Muros, Spain (A. Sinde-Mano); (D) Ilha de Arousa, Spain (sourced from iNaturalist, ©javsagg34).

the sites where it has established itself in NW Iberia and that it has spread slowly at its northeastern limit. Apart from competition, other local environmental factors, such as temperature and nutrient availability could be influencing or even determining some of this regional heterogeneity (Gao et al. 2013; Thornber et al. 2004). Although these factors may currently limit its expansion, *U. pinnatifida* has proven its ability to overcome such constraints (Russell et al. 2008) and today it comprises 70 % of the subtidal seaweed biomass in Otago, New Zealand (Jiménez et al. 2015). This highlights the importance of sustained monitoring efforts in newly invaded areas.

In Asturias, *U. pinnatifida* was not found in 2024, even though the species was previously reported there between 2002 and 2008. In Portugal, a population in the Ria de Aveiro was first reported in 2007, not observed in 2013, then reported again in 2019 from a citizen science platform, and then again in 2021 (Pereira et al. 2022). These fluctuations indicate that these populations are most likely poorly established and subjected to seasonal or annual fluctuations in abundance. Caution is warranted, though, as these results were not collected in a standardized, consistent way (different research teams and methods) and geographical and temporal gaps exist – ours is the first study to cover the Iberian Peninsula in the same year. For example, in Spain, there is a gap of eight years (2008–2016) where there is no data about the occurrence of *Undaria*, and there is more information about the distribution in Lower Rías than in Upper Rías.

Given that the species is at its warmer-edge limit in Europe, temperature might be playing a key role in the study area. We show that *U. pinnatifida* is neither in the south of

Portugal nor in the Bay of Biscay (northeast Spain). This is likely due to the specie's temperature requirements, as it is a temperate kelp with upper thermal limits of around 20 °C for year-round populations and 29 °C for annual (winter) populations (James et al. 2015). The south of Portugal and the Bay of Biscay experience higher summer temperatures than Galicia and northern Portugal (Lima et al. 2007; Ramos et al. 2016). At the same time, the colder, nutrient-rich waters surfaced by the NW Iberian upwelling appear to provide an optimal environment for *U. pinnatifida* to establish and persist (Gómez-Gesteira et al. 2008). Further studies should explore which life-cycle phases and temperature metrics limit its expansion in the Iberian Peninsula.

Like *U. pinnatifida*, several non-native species have also recently colonized and spread in northern Portugal and Spain, namely *Asparagopsis armata*, *Codium fragile* and various bryozoans (Ramos et al. 2020). Given this, along with the pressure of maritime traffic in the area (James and Shears 2016), *U. pinnatifida* is expected to continue expanding its distribution. Furthermore, considering the decline in native kelp communities observed at different sites (Arriaga et al. 2024; Pereira et al. 2022; Ramos et al. 2020), large *U. pinnatifida* populations will likely establish in the future. This calls for intensive spatial and temporal monitoring and early intervention by managing bodies since eradication measures are costly and often have proven unsuccessful elsewhere (e.g. Forrest and Blakemore 2006; Hewitt et al. 2005). Moreover, the impacts of *U. pinnatifida* populations on biodiversity and ecosystem functioning have not been assessed in this region; therefore, we cannot accurately determine its invasion status on the Iberian Peninsula. Field studies are urgently needed to address this outstanding question.

The integration of observations from citizen science biodiversity monitoring programs provided 24 extra observations, expanding the geographical coverage of our survey. It confirmed the continued presence of *U. pinnatifida* in previously documented locations not visited during our fieldwork. This highlights the valuable role of public participation in biodiversity and biogeography research, providing complementary data that can enhance monitoring efforts, especially for non-native species (Encarnação et al. 2021). Citizen science initiatives increase temporal and spatial resolution and contribute to early detection and long-term tracking of species distribution (Kelly et al. 2020).

Overall, our findings contribute to better understand the distribution range and temporal dynamics of a non-indigenous species along the Atlantic coast of the Iberian Peninsula. While *U. pinnatifida* remains restricted to the Galician rias and north Portugal, ongoing environmental changes and human-mediated dispersal may influence its future spread. Further research is needed on the interactions of *U. pinnatifida* with native macroalgal communities, as well as its physiological response to environmental fluctuations such as potential changes in the upwelling system. Additionally, by integrating field-based studies with citizen science initiatives, we can improve early detection and track long-term trends to help develop effective conservation and mitigation measures for non-indigenous species in the region.

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Data availability: The authors confirm that the data supporting the findings of this study are available within the article and its Supplementary material.

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