



SHALLOW-WATER MEDITERRANEAN MARINE BIODIVERSITY AND CLIMATE CHANGE: INSIGHTS FROM A MULTISOURCE DATABASE

A Thesis Submitted in Partial Fulfilment of the Requirements
for the Degree of Doctor of Philosophy in

EARTH SYSTEM AND ENVIRONMENT

Obtained in the framework of the Doctoral Programme of National Interest in Sustainable Development and Climate Change



by

Chiara Siddiolo

November, 2026



SHALLOW-WATER MEDITERRANEAN MARINE BIODIVERSITY AND CLIMATE CHANGE: INSIGHTS FROM A MULTISOURCE DATABASE

A Thesis Submitted in Partial Fulfilment of the Requirements
for the Degree of Doctor of Philosophy in

EARTH SYSTEM AND ENVIRONMENT

Obtained in the framework of the Doctoral Programme of National Interest in
Sustainable Development and Climate Change



by

Chiara Siddiolo

Supervisor: Prof. Antonietta Rosso
Co-supervisor: Prof. Renato Chemello

ABSTRACT

This research investigates the correlation between the spatial distribution of Mediterranean marine species - particularly benthic megafauna - and key environmental variables associated with climate change, such as rising sea temperatures, sea level fluctuations and the spreading of thermophilic and non-indigenous warm species following biological invasion events, with a specific focus on the Mediterranean Basin. The primary objective is to build comprehensive datasets including a wide selection of native and non-indigenous species (NIS), both invertebrates and vertebrates, and to analyze their distribution patterns in relation to environmental drivers across the Mediterranean basin, as well as their potential future distributions.

In pursuit of this goal, our data collection targeted approximately 30 representative marine species from different high-rank taxa, selected for their ecological relevance and varying responses to environmental stressors. The data were collected through a multisource approach, integrating peer-reviewed literature, direct field sampling, global biodiversity databases (e.g., GBIF, OBIS), Local Ecological Knowledge (LEK), Citizen Science (CS) and digital platforms including social media.

A multilingual Google Form was also developed and disseminated across Mediterranean countries to facilitate participatory data gathering on some of the chosen species (the coral *Oculina patagonica,* the bryozoan *Amathia verticillata,* the mollusk *Lamprohaminoea ovalis,* the crustacean *Ocypode cursor,* and the fish *Acanthurus monroviae, Fistularia petimba* and *Pterois miles*), including also species with limited formal records.

Species Distribution Models (SDMs) were employed to predict current and future distribution trends for two NIS crab species (*Callinectes sapidus* and *Portunus segnis*), and one Mediterranean reptile species (*Caretta caretta*), incorporating long-term environmental datasets and focusing on environmental variables most influenced by climate change, such as Sea Surface Temperature (SST), rising temperatures of the sand, precipitation, pH, Oxygen and Chlorophyll. These models highlight the complex interactions between species traits and environmental gradients, revealing patterns of expansion among NIS organisms and potential resilience or decline among native populations and their ecosystems, but also the spread of thermophilic species.

As part of the monitoring activities in the field, the analysis of stranded plastic debris led to the detection of living colonies of the NIS bryozoans *Microporella hastingsae* and *Microporella browni* along the Sicilian coastline, in areas far from their known ranges (in the Suez Canal, approaching the Mediterranean and Lebanon, respectively), suggesting a potential expansion in the Mediterranean, likely facilitated by passive rafting on floating plastics driven by

surface circulation, besides human-mediated diffusion, essentially by maritime transport.

The extension of distribution's ranges also involves the species *Caretta caretta*, expanding its nesting range in the Mediterranean according to rising temperatures and *Ocypode cursor*, following a similar pattern and colonizing northern beaches. A distribution clearly correlated with water temperature has also been highlighted for *Fenestrulina*, a bryozoan genus well diversified in the Mediterranean, currently apparently missing in the Levantine Sea where it was present at least with one species in the mid nineteenth century.

The study conducted for this PhD thesis, though strongly based on existing literature and field work for collecting new data, emphasizes the critical role of a multisource approach, which includes Citizen Science and LEK in enhancing biodiversity monitoring and bridging data gaps, especially in understudied regions.

ACKNOWLEDGEMENTS

This PhD thesis is the result of three intense years of work, learning, challenges, and personal growth, made possible thanks to the support of many people and institutions.

First and foremost, I would like to sincerely thank my Supervisor, Prof. Antonietta Rosso, for her constant guidance, scientific rigor, and encouragement throughout my doctoral journey. Her support and trust have been fundamental to the development of this work. I am also deeply grateful to my Co-supervisor, Prof. Renato Chemello, for his valuable advice, availability, and insightful suggestions, which greatly contributed to shaping this research.

I would like to acknowledge the University of Catania and the University of Pavia for providing the academic framework and resources necessary to carry out this PhD, as well as the Doctoral Programme in Sustainable Development and Climate Change, within which this work was developed.

My sincere thanks go to Prof. Claudia Lupi, coordinator of CU1, for her support and commitment, and to Prof. Mario Martina, current Rector of IUSS Pavia and former coordinator of the PhD programme, for his guidance and dedication to the programme.

A special thank you goes to Dr. Erik Olsen, my supervisor during the period abroad at the Institute of Marine Research (IMR) in Bergen, Norway, for welcoming me into his research environment and for the stimulating scientific discussions that greatly enriched my experience abroad.

I would like to thank all the co-authors of the published papers included in this thesis, whose collaboration and expertise were essential to this work. In particular, I am deeply grateful to Prof. Mario Lo Valvo and Dr. Carlo Pipitone for their valuable contributions, support, and scientific exchange.

I also wish to thank my research group, as well as all my colleagues of the PhD programme in Sustainable Development and Climate Change, who have been a constant presence throughout this journey and have become important points of reference, both professionally and personally. Special thanks to Momo, Khim,

Natalia, Ameer and Teresa: with them, these three years have been a continuous exchange of ideas, perspectives, and interests, but above all the construction of a truly special friendship.

My deepest thanks go to Giorgia, my partner, for supporting me through these years of commitment, sacrifices, travels, achievements, and difficulties, always with love, patience, understanding, and encouragement.

I am profoundly grateful to my family and to all my friends, who have been by my side throughout this journey. Finally, a heartfelt thank you to Lucilla and Paolo, who made my time in Norway intense, fun, unforgettable, and *very Italian*.

TABLE OF CONTENTS

LIST OF FIGURES XIII

LIST OF TABLES XV

GLOSSARY 1
REFERENCE LIST 3

1 INTRODUCTION 7

1.1. GLOBAL CONTEXT: THE MEDITERRANEAN AS AN EXAMPLE FOR STUDYING THE IMPACTS OF CLIMATE CHANGE ON BIODIVERSITY 7
1.2. DRIVERS OF CHANGE: THERMOPHILIA, NON-INDIGENOUS SPECIES (NIS) AND ENVIRONMENTAL STRESS 8
1.3. THE DATA GAP: THE NEED FOR A MULTI-SOURCE APPROACH FOR MORE ROBUST MAPPING 10
1.4. THESIS OBJECTIVES AND RESEARCH QUESTIONS 14
1.5. REFERENCE LIST 17

2. GENERAL METHODOLOGY AND CONSTRUCTION OF THE MULTISOURCE DATABASE 23

2.1. THE MULTISOURCE DATABASE 23
2.2. SELECTION OF BIOLOGICAL TARGETS: THERMOPHILIC SPECIES AND NON-INDIGENOUS SPECIES (NIS) 24
2.3. PARTICIPATORY DATA COLLECTION METHODOLOGY: LOCAL ECOLOGICAL KNOWLEDGE AND CITIZEN SCIENCE 27
2.4. SYNERGISTIC INTEGRATION OF DATA INFLOW 28
2.5. SPECIES DISTRIBUTION MODELS (SDMS) 34
2.6. METHODOLOGICAL LIMITATIONS 36
2.7. SUPPORTING SCIENTIFIC RESULTS 38
2.8. REFERENCE LIST 40

3. *MICROPORELLA HASTINGSAE* HARMELIN, OSTROVSKY, CÁCERES-CHAMIZO AND SANNER, 2011 (BRYOZOA, CHEILOSTOMATIDA): A

POSSIBLE NEW LESSEPSIAN SPECIES IN THE MEDITERRANEAN SEA? 46

3.1. ABSTRACT 46
3.2. INTRODUCTION 46
3.3. MATERIALS AND METHODS 48
3.4. RESULTS 48
3.5. DISCUSSION AND CONCLUSION 52
3.6. REFERENCE LIST 57

4 GOING WEST: THE SPREAD OF NON-INDIGENOUS *MICROPORELLA* (BRYOZOA) SPECIES ON DRIFT PLASTIC DEBRIS 64

4.1. ABSTRACT 64
4.2. INTRODUCTION 64
4.3. MATERIALS AND METHODS 65
4.4. RESULTS 67
4.5. DISCUSSION AND CONCLUSION 71
4.6. REFERENCE LIST 77

5 THE DISTRIBUTION OF *FENESTRULINA* SPECIES (BRYOZOA) IN THE MEDITERRANEAN: THE ROLE OF TEMPERATURE AND OF PLASTIC AND NATURAL DEBRIS IN THE DISPERSAL OF *F. COMMUNIS* 82

5.1. ABSTRACT 82
5.2. INTRODUCTION 82
5.3. MATERIALS AND METHODS 84
5.4. RESULTS 85
5.5. DISCUSSION 89
5.6. REFERENCE LIST 92

6 ASSESSING HABITAT SUITABILITY AND DISTRIBUTION PATTERNS OF THE INVASIVE BRACHYURAN CRABS *CALLINECTES SAPIDUS* AND *PORTUNUS SEGNIS* IN THE MEDITERRANEAN BASIN 95

6.1. ABSTRACT 95
6.2. INTRODUCTION 95

6.3. MATERIALS AND METHODS 97
6.4. RESULTS 101
6.5. DISCUSSION AND CONCLUSION. 108
6.6. REFERENCE LIST 114

7 HEAT NESTS: THE IMPACT OF CLIMATE CHANGE ON LOGGERHEAD TURTLE (*CARETTA CARETTA*) NESTING DISTRIBUTION IN SICILY (ITALY) 120

7.1. ABSTRACT 120
7.2. INTRODUCTION 121
7.3. MATERIALS AND METHODS 122
7.4. RESULTS 126
7.5. DISCUSSION 132
7.6. REFERENCE LIST 136

8 MONITORING RARE SPECIES THROUGH SCIENTIFIC COLLABORATION: THE CASE OF *OCYPODE CURSOR* 143

8.1. ABSTRACT 143
8.2. INTRODUCTION 143
8.3. RESULTS 144
8.5. CONCLUSION 146
8.6. REFERENCE LIST 147

9 CONTRIBUTION OF UNPUBLISHED RECORDS TO THE MAPPING OF NON-INDIGENOUS, CRYPTOGENIC, AND NEONATIVE SPECIES IN THE MEDITERRANEAN SEA 150

9.1. ABSTRACT 150
9.2. INTRODUCTION 151
9.3. MATERIALS AND METHODS 152
9.4. RESULTS 153
9.5. DISCUSSION AND CONCLUSION 157
9.6. REFERENCE LIST 160

10 COMPLEMENTARY DATA SOURCES FOR MAPPING TARGET MEDITERRANEAN NON-INDIGENOUS AND CRYPTOGENIC SPECIES: THE ROLE OF LOCAL KNOWLEDGE AND CITIZEN SCIENCE 166

10.1. ABSTRACT 166
10.2. INTRODUCTION 166
10.3. MATERIALS AND METHODS 169
10.4. RESULTS 177
10.5. DISCUSSION 188
10.6. REFERENCE LIST 196

11 THE MULTISOURCE DATABASE 210

11.1. INTRODUCTION 210
11.2. MATERIALS AND METHODS 210
11.3. STRUCTURAL ANALYSIS OF THE MULTISOURCE DATABASE 211
11.4. MAIN RESULTS AND COMMENTS ON NATIVE THERMOPHILIC SPECIES 213
11.5. MAIN RESULTS AND COMMENTS ON NIS AND CRYPTOGENIC SPECIES 215
11.6. DISCUSSION 216
11.7. REFERENCE LIST 219

12 CONCLUSIONS AND FUTURE PERSPECTIVES 221

12.1. CONNECTING METHODOLOGICAL INNOVATION AND ECOLOGICAL FINDINGS 221
12.2. RANGE VARIATION AND MECHANISMS OF DISPERSAL 222
12.3. SPECIES DISTRIBUTION MODELS (SDMS): MAPPING INVASIONS AND CLIMATE-DRIVEN SHIFTS 223
12.4. NEW FRAMEWORK FOR MEDITERRANEAN MARINE BIODIVERSITY MONITORING: INTEGRATING MULTI-SOURCE DATA AND CLIMATE-DRIVEN PATTERNS 225
12.5. REFERENCE LIST 228

LIST OF FIGURES

Figure 2.1 ..... *29*
Figure 3.1 ..... *49*
Figure 3.2 ..... *51*
Figure 3.3. ..... *52*
Figure 4.1 ..... *66*
Figure 4.4 ..... *72*
Figure 5.1 ..... *86*
Figure 5.2 ..... *87*
Figure 5.3 ..... *90*
Figure 6.1 ..... *98*
Figure 6.2 ..... *102*
Figure 6.3 ..... *103*
Figure 6.4 ..... *104*
Figure 6.5 ..... *105*
Figure 6.6 ..... *106*
Figure 6.7 ..... *107*
Figure 6.8 ..... *108*
Figure 6.9 ..... *109*
Figure 6.10 ..... *110*
Figure 7.1 ..... *126*
Figure 7.2 ..... *127*
Figure 7.3 ..... *128*
Figure 7.4 ..... *128*
Figure 7.5 ..... *130*
Figure 7.6 ..... *131*
Figure 7.7 ..... *132*
Figure 8.1 ..... *144*
Figure 8.2 ..... *145*
Figure 10.1 ..... *171*
Figure 10.2 ..... *176*

Figure 11.1..... *214*
Figure 11.2..... *215*

LIST OF TABLES

Table 6.1 ..... *102*
Table 6.2 ..... *104*
Table 6.3 ..... *111*
Table 7.1 ..... *124*
Table 7.2 ..... *129*
Table 7.3 ..... *130*
Table 7.4 ..... *135*
Table 9.1 ..... *154*
Table 10.1 ..... *176*
Table 11.1 ..... *212*

GLOSSARY

Citizen Science (CS): The active engagement and voluntary participation of the general public (non-professional scientists) in scientific research, data collection, and monitoring activities, bridging the gap between professional researchers and local stakeholders (Dickinson et al., 2010; Shirk et al., 2012).

Cryptic species: Two or more distinct biological species assigned to a single name due to their nearly indiscernible appearance or extreme similarity. Their identification and separation rely heavily on non-morphological traits, such as genetic markers, bioacoustics, or chemical signals (Bickford et al., 2007; Pfenninger and Schwenk, 2007).

Cryptogenic species: A species whose status as either native or non-indigenous in a given geographical region cannot be definitively determined due to a lack of clear historical data, paleontological evidence, or definitive genetic tracking (Carlton, 1996).

Dark data: Heterogeneous, non-standardised biodiversity records that are not included in formal monitoring programmes or continuously curated databases, but are instead dispersed across alternative sources such as expert knowledge, Local Ecological Knowledge (LEK), citizen science contributions, unpublished datasets, and incidental observations. Although often not immediately accessible or systematically structured, these data can provide valuable complementary information to conventional monitoring systems and substantially improve spatial and temporal coverage of biodiversity assessments. The concept of “dark data” is rooted in the broader discussion on underutilised scientific information (Heidorn, 2008) and is closely related to efforts in ecological data sharing and integration of non-traditional biodiversity datasets (Michener, 2015; Chandler et al., 2017).

Data mining: Automated or semi-automated process of extracting, filtering, and analyzing unstructured or semi-structured biodiversity data voluntarily uploaded by the public to the internet (Di Minin et al., 2015).

Early-warning signals: Statistical indicators (such as critical slowing down, rising variance, or shifting behavioral patterns) or early biological detection metrics that indicate when an ecosystem, community, or population is approaching a tipping point, a sudden regime shift, or an imminent demographic transition (Scheffer et al., 2009; Carpenter et al., 2011).

Established: The stage in the biological invasion process where a non-indigenous/non-indigenous species successfully overcomes environmental barriers in the recipient ecosystem, forms self-sustaining, actively reproducing wild populations, and survives without requiring recurrent human introductions (Blackburn et al., 2011).

Invasive species: A non-indigenous species whose introduction and subsequent establishment and spread outside its native range actively threatens local biodiversity, alters ecosystem functions, impacts human health, and/or causes significant socio-economic damage (CBD, 2002; Ricciardi, 2012).

Local Ecological Knowledge (LEK): The cumulative body of knowledge, practices, and beliefs regarding local ecosystems and natural resources held by specific groups of people living in close, continuous contact with their immediate environment. Unlike Traditional Ecological Knowledge (TEK), LEK focuses primarily on experiential knowledge gained by individuals over their lifetimes rather than cross-generational cultural transmission (Berkes et al., 2000; Ruddle and Davis, 2013).

Marine Heatwave (MHW): A prolonged discrete warm water event that can be described by its duration, intensity, rate of onset, and spatial extent. To be considered an MHW, temperatures must be warmer than 90% of the historical observations for that time of year, for at least five days, with no more than a two-day break (Hobday et al., 2016).

Megafauna: Large-bodied organisms within an ecosystem, whose operational definition in marine environments depends on the structural compartment investigated. In pelagic and megafaunal conservation contexts, it formally denotes large ocean-dwelling functional groups - including marine mammals, sea turtles, sharks, rays, and large bony fishes - that reach a maximum reported body mass equal to or greater than 45 kg (Martin and Klein, 1984; McCauley et al., 2015). Conversely, in marine benthic ecology, the definition shifts from weight to visual detectability: benthic megafauna encompasses all macro-organisms that are large enough to be clearly visible and identifiable to the naked eye in situ, or via remote photographic and video sampling, traditionally corresponding to a body dimension greater than 1 cm (Gage and Tyler, 1991). This visual threshold is particularly relevant for habitat-forming target taxa, such as structural cnidarians and large decapod crustaceans, which are monitored via citizen science and divers' reports regardless of their biomass.

Native species: A species living within its natural distribution range and sustainable dispersal potential (i.e., within the range it occupies naturally or could occupy without direct or indirect human introduction or care) (IUCN, 2000).

Neonative species: A species that has expanded its geographic range into a new region independently (via autonomous dispersal mechanisms) in response to human-induced environmental changes—such as climate change or habitat modification—rather than through direct human transport or translocation (Essl et al., 2019).

Non-indigenous species (NIS): Species occurring in the wild that have overcome their innate dispersal thresholds and native biogeographical boundaries, typically via anthropogenic transport, to establish themselves in foreign geographic territories (Falk-Petersen et al., 2006; Foxcroft et al., 2017, Bonanno and Orlando-Bonaca, 2019).

REFERENCE LIST

Berkes, F., Colding, J. and Folke, C., 2000. Rediscovery of traditional ecological knowledge as adaptive management. Ecological applications, 10(5), pp.1251-1262.

Bickford, D., Lohman, D.J., Sodhi, N.S., Ng, P.K., Meier, R., Winker, K., Ingram, K.K. and Das, I., 2007. Cryptic species as a window on diversity and conservation. *Trends in Ecology & Evolution*, 22(3), pp.148-155

Blackburn, T.M., Pyšek, P., Bacher, S., Carlton, J.T., Duncan, R.P., Jarošík, V., Wilson, J.R. and Richardson, D.M., 2011. A proposed unified framework for biological invasions. *Trends in ecology & evolution*, *26*(7), pp.333-339.

Bonanno, G. and Orlando-Bonaca, M., 2019. Non-indigenous marine species in the Mediterranean Sea—Myth and reality. *Environmental Science & Policy*, *96*, pp.123-131.

Carlton, J.T., 1996. Biological invasions and cryptogenic species. Ecology, 77(6), pp.1653-1655.

Carpenter, S.R., Cole, J.J., Pace, M.L., Batt, R., Brock, W.A., Cline, T., Coloso, J., Hodgson, J.R., Kitchell, J.F., Seekell, D.A. and Smith, L., 2011. Early warnings of regime shifts: a whole-ecosystem experiment. Science, 332(6033), pp.1079-1082.

Chandler, M., See, L., Copas, K., Bonde, A.M., López, B.C., Danielsen, F., Legind, J.K., Masinde, S., Miller-Rushing, A.J., Newman, G. and Rosemartin, A., 2017. Contribution of citizen science towards international biodiversity monitoring. *Biological conservation*, *213*, pp.280-294.

Dickinson, J.L., Zuckerberg, B. and Bonter, D.N., 2010. Citizen science as an ecological research tool: challenges and benefits. Annual review of ecology, evolution, and systematics, 41(1), pp.149-172.

Dickinson, J. L., Zuckerberg, B., and Bonter, D. N., 2010. Citizen science as an ecological research tool: challenges and benefits. *Annual review of ecology, evolution, and systematics*, *41*(1), 149-172.

Di Minin, E., Tenkanen, H. and Toivonen, T., 2015. Prospects and challenges for social media data in conservation science. *Frontiers in Environmental Science*, *3*, p.63.

Essl, F., Dullinger, S., Genovesi, P., Hulme, P.E., Jeschke, J.M., Katsanevakis, S., Kühn, I., Lenzner, B., Pauchard, A., Pyšek, P. and Rabitsch, W., 2019. A conceptual framework for range-expanding species that track human-induced environmental change. BioScience, 69(11), pp.908-919.

Falk-Petersen, J., Bøhn, T. and Sandlund, O.T., 2006. On the numerous concepts in invasion biology. *Biological invasions*, *8*(6), pp.1409-1424.

Foxcroft, L.C., Pyšek, P., Richardson, D.M., Genovesi, P. and MacFadyen, S., 2017. Plant invasion science in protected areas: progress and priorities. *Biological Invasions*, *19*(5), pp.1353-1378.

Gage, J.D. and Tyler, P.A., 1991. *Deep-sea biology: a natural history of organisms at the deep-sea floor*. Cambridge University Press.

Heidorn, P.B., 2008. Shedding light on the dark data in the long tail of science. *Library trends*, *57*(2), pp.280-299.

Hobday, A.J., Alexander, L.V., Perkins, S.E., Smale, D.A., Straub, S.C., Oliver, E.C., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Feng, M. and Holbrook,

N.J., 2016. A hierarchical approach to defining marine heatwaves. *Progress in oceanography*, *141*, pp.227-238.

International Union for Conservation of Nature and Natural Resources. Invasive Species Specialist Group, 2000. IUCN guidelines for the prevention of biodiversity loss caused by alien invasive species. Species Survival Commission.

Martin, P.S. and Klein, R.G., 1984. Prehistoric overkill: the global model. *Quaternary extinctions: a prehistoric revolution*, pp.354-403.

McCauley, D.J., Pinsky, M.L., Palumbi, S.R., Estes, J.A., Joyce, F.H., Warner, R.R., 2015. Marine defaunation: animal loss in the global ocean. Science. 2015 Jan 16;347(6219):1255641. doi: 10.1126/science.1255641. PMID: 25593191.

Michener, W.K., 2015. Ecological data sharing. *Ecological informatics*, *29*, pp.33-44.

Pfenninger, M. and Schwenk, K., 2007. Cryptic animal species are homogeneously distributed among taxa and biogeographical regions. BMC evolutionary biology, 7(1), p.121.

Ricciardi, A., 2012. Invasive species. In *Ecological systems: selected entries from the Encyclopedia of sustainability science and technology* (pp. 161-178). New York, NY: Springer New York.

Ruddle, K. and Davis, A., 2013. Local ecological knowledge (LEK) in interdisciplinary research and application: a critical review. Asian Fisheries Science, 26(2), pp.79-100.

Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., Held, H., Van Nes, E.H., Rietkerk, M. and Sugihara, G., 2009. Early-warning signals for critical transitions. Nature, 461(7260), pp.53-59.

Shirk, J.L., Ballard, H.L., Wilderman, C.C., Phillips, T., Wiggins, A., Jordan, R., McCallie, E., Minarchek, M., Lewenstein, B.V., Krasny, M.E. and Bonney, R., 2012. Public participation in scientific research: a framework for deliberate design. *Ecology and society*, *17*(2).Somero, G.N., 2010. The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine ‘winners’ and ‘losers’. *Journal of Experimental Biology*, *213*(6), pp.912-920.

Chapter 1



Introduction

1 INTRODUCTION

1.1. GLOBAL CONTEXT: THE MEDITERRANEAN AS AN EXAMPLE FOR STUDYING THE IMPACTS OF CLIMATE CHANGE ON BIODIVERSITY

The Mediterranean basin is one of the most complex and vulnerable marine systems on the Planet, in which global climate processes are accelerated by its special historical evolution and present-day geomorphological and hydrodynamic configuration (Cramer et al., 2018). Although it represents a minimal fraction of the world's ocean surface, its biogeographic importance is defined by the exceptional degree of endemic and biotic richness that places it among the main global biodiversity hotspots (Coll et al., 2010). However, the stability of this ecosystem is currently threatened by the radiative forcing, which leads to significantly faster warming of surface waters than the average for open oceans.

The alteration of thermal regimes in the Mediterranean is not limited to a linear drift in mean temperatures but manifests itself with an increasing frequency of extreme thermal events called Marine Heat Waves (MHWs). These phenomena, characterized by increasingly high, frequent and persistent positive thermal anomalies, apply unprecedented selective pressure on marine communities, leading to the overcoming of physiological tipping points of numerous species (Darmaraki et al., 2024). The intensification of marine heat waves, as observed during the 2019 thermal peaks, induces a destructuring of the water column, exacerbating thermal stratification and limiting vertical nutrient exchanges, with direct consequences on primary productivity and the survival of secondary consumers (Hamdeno and Alvera-Azcárate, 2023). For shallow-water benthic biodiversity, thermal stress often results in increasing diseases, necrosis and mass mortality events (Mass Mortality Events - MMEs) that disproportionately affect sessile organisms and ecosystem engineers, whose thermal tolerance windows are systematically violated during summer months (Garrabou et al., 2022). The vulnerability of these taxa is closely linked to the loss of suitable thermal habitat, a process that drives predictable local extinctions for species of both “boreal and temperate affinity” or “species belonging to both boreal and temperate assemblages (Reddin et al., 2022). The collapse of benthic invertebrate populations is not only an isolated event, but reflects a profound ecological transition in which global warming acts as a catalyst for the replacement of native species with communities more resilient to heat stress (Rivetti et al., 2014).

In this context of biotic transition, the Mediterranean is undergoing two parallel processes of reconfiguration of distributional ranges: meridionalization and tropicalization. While the first involves the expansion towards northern latitudes of native thermophilic species, previously confined to the southern sectors of the basin, the second is driven by the introduction and establishment of warm-origin non-indigenous species (NIS). These dynamics are not influenced exclusively by increasing surface temperatures (SST), but are mediated by a complex interaction of environmental variables and anthropogenic vectors that facilitate dispersal and biological invasiveness in an increasingly anthropized basin (Boero, 2015).

1.2. Drivers of Change: Thermophilia, Non-Indigenous Species (NIS) and Environmental Stress

The reshaping of Mediterranean biodiversity is driven by a combined interaction between climate forcings and anthropogenic impacts, which act by altering environmental filters that have historically limited species distribution. This tropicalization process does not exclusively suggest an increase in species richness due to the introduction of exotic taxa, but a profound functional transformation in which temperate communities are progressively replaced by warm-affinity biotic assemblies (Bianchi, 2007; Torreblanca and Báez, 2025). In this scenario, thermophilia emerges as the determining biological trait for competitive success in the new thermal regime of the basin, favouring more thermic-tolerant species and the expansion of warm-tropical Non-Indigenous Species (NIS) whose diffusion now transcends geopolitical borders (Galanidi et al., 2023; Zenetos et al., 2024).

The dynamics of biological invasions are driven by a combination of natural and artificial vectors operating at different spatial scales. While the opening (since 1869) and subsequent doubling of the Suez Canal (2015) has ensured a constant flow of propagules, merchant shipping, liner shipping and recreational boating – usually responsible for redistributing non-indigenous species from main harbours – act as main vectors for intra- and extra-basin dispersal, facilitating the overcoming of biogeographical barriers otherwise much more difficult to overcome (Galil et al., 2014; Ulman, 2018). Risk mapping associated with ports of origin highlights how maritime connectivity represents a critical vulnerability for Mediterranean biosecurity, facilitating and spreading the arrival of species in distant otherwise unconnected areas where establishment can be allowed by local thermal ongoing changes (Kalyvioti et al., 2024).

From an ecophysiological point of view, the success of thermophilic species is regulated by thermal tolerance limited by aerobic capacity (OCLTT - Oxygen- and Capacity-Limited Thermal Tolerance). Increased temperatures raise basal metabolic costs, narrowing the window of energy available for growth and reproduction, a phenomenon that penalizes native stenothermal species that already operate within their critical limits (Pörtner, 2010; Somero, 2010). On the contrary, thermophilic taxa and non-indigenous taxa from warmer seas are equipped with molecular adaptations, such as highly efficient heat shock proteins and thermostable cell membranes, which give them a clear competitive advantage during marine heatwaves, facilitating the occupation of niches vacated by mass mortality processes (Belmaker et al., 2015).

In addition to the complex driver architecture of global change, the accidental transfer of species linked to mariculture, shipping (ballast waters and hull fouling), and other human activities represents a primary pathway for marine introductions. While these vectors often facilitate the initial arrival of non-indigenous species in specific hotspots - such as harbours or aquaculture facilities - passive transport vectors play a decisive role in their subsequent regional spread.

In this context, floating plastic debris (macroplastics) have emerged as a permanent anthropogenic substrate that complements traditional vectors. Unlike most natural substrates (e.g., wood or seaweed), biodegradable during time, synthetic polymers offer high longevity, allowing associated organisms to survive more successfully transoceanic or trans-basin transport through the phenomenon of “rafting” (Barnes, 2002; Gregory, 2009). This mechanism acts as a strict selective filter that favors taxa characterized by high phenotypic plasticity and opportunistic life strategies. Some bryozoan species, in particular, are among the most successful groups in colonizing the “plastisphere” (Kiessling et al., 2015). Their exceptional affinity for synthetic debris relies on a combination of opportunistic life-history traits and specific larval behavior. As typical components of marine *fouling* communities, many cheilostome bryozoans act as pioneer encrusting organisms. Floating plastics represent newly introduced, smooth, and hard anthropogenic substrates that are initially devoid of biofilms or biological competitors. Some bryozoans are uniquely adapted to exploit these uncolonized spatial niches due to their rapid attachment capabilities and high fertility rates, which allow them to out-compete later-successional species before high spatial competition establishes (Barnes, 2002, Kiessling et al., 2015). Furthermore, the mineralised skeletons of cheilostomes provide structural resilience against the mechanical stresses of

the sea surface film, such as wave action and continuous friction. This physical protection is accompanied by a notable physiological tolerance to high solar radiation and ultraviolet (UV) exposure, common at the ocean surface where plastics float (Barnes, 2002). For NIS species introduced via human activities, the availability of plastic "rafts" provides an additional, ubiquitous vector for passive dispersal, facilitating their secondary spread and possible establishment into new areas, significantly accelerating the homogenization of Mediterranean coastal biota. Floating plastic not only facilitates the expansion of native species ranges, but also acts as a “Trojan horse” for NIS, increasing propagule pressure in sensitive areas and interacting with surface circulation to create preferential corridors between eastern and western basins, (Deudero and Alomar, 2015; Çevik et al., 2025). The resilience of several cheilostome bryozoans to osmotic stress and UV radiation, typical of the neuston layer, makes rafting a driver of change in benthic biodiversity that is as important as global warming (Rech et al., 2018). The ecological impact of these organisms relies on their high invasive potential of some species and their ability to act as ecosystem engineers. Once introduced into new areas via floating debris, invasive cheilostomes can rapidly overgrow native biota due to their high growth rates and continuous larval recruitment. Species belonging to genera such as *Watersipora* or *Celleporaria* form dense, heavily calcified, multi-layered colonies that physically monopolize hard substrates, outcompeting native encrusting organisms for space and food (Lodola et al., 2015; Lauer, 2016). Furthermore, by modifying the structural complexity of the pristine benthic habitat, outside of their native range, these non-indigenous bryozoans deeply alter local community composition, shifts in dominant species, and the degradation of native biodiversity hotspots. The combination of high temperatures and the availability of new artificial substrates is therefore permanently reshaping the ecology of the Mediterranean, favouring generalist and eurythermic species capable of exploiting anthropogenic vectors for their spatial expansion (Zerebecki and Sorte, 2011).

1.3. The Data Gap: The need for a multi-source approach for more robust mapping

The efficiency of marine biodiversity conservation and management strategies is highly dependent on the availability of high-resolution spatiotemporal data. However, the monitoring of Mediterranean ecosystems faces significant “data gaps”, mainly attributable to the Wallacean shortfall (gaps in knowledge of the

geographical distribution of species) and the Linnean shortfall (lack of up-to-date taxonomic and systematic knowledge) (Whittaker et al., 2005).

These barriers often prevent a comprehensive, basin-wide overview, particularly in remote regions or along the southern Mediterranean coastlines (Azzurro et al., 2011; Crocetta et al., 2017). However, beyond these logistical hurdles lies a more systemic issue: the chronic scarcity of resources allocated to fundamental biodiversity research. In the current scientific funding landscape, financial support is increasingly prioritized for "applied" or "thematic" projects that target specific, immediate socioeconomic or policy outcomes. This trend often occurs at the expense of basic taxonomic studies and large-scale baseline distribution mapping—the very disciplines required to identify and track shifting biotas (Hortal et al., 2015). This institutional framework is further constrained by the operational limits of official monitoring programs, such as those governed by the Marine Strategy Framework Directive (MSFD). While essential, these programs frequently suffer from a narrow taxonomic focus, primarily targeting a predefined list of 'priority' species and habitats, thereby neglecting rare or newly introduced non-indigenous species (NIS) (Katsanevakis et al., 2012). Furthermore, a significant 'data-flow bottleneck' often persists at the regional level; despite consistent field activities by environmental agencies, the resulting raw data frequently remain inaccessible or siloed due to prolonged validation phases and bureaucratic fragmentation. Direct observations during regional validation processes in the Mediterranean (e.g., Sicily) confirm that while monitoring occurs, the actual availability of granular data for the scientific community is often restricted or delayed.

This "taxonomic impediment" is further exacerbated by a lack of specific projects dedicated to the morphological and systematic identification of less "charismatic" taxa. Consequently, institutional datasets often reflect these funding biases, leading to significant gaps in our basic understanding of where species are and how they are moving. The multisource approach adopted in this thesis is, therefore, a necessary strategy to overcome these limitations. By integrating participatory data, we can bypass the financial and thematic constraints of traditional funding models, which are frequently characterized by short-term grant cycles, high operational costs, and a systemic bias toward specific applied topics at the expense of fundamental monitoring. Citizen science effectively mitigates these limitations by decentralizing data collection, eliminating the prohibitive costs of large-scale field campaigns, and mobilizing an omnipresent network of volunteers. This approach turns structural economic challenges into a sustainable, long-term monitoring strategy, ensuring that

baseline biodiversity knowledge—fundamental for any applied conservation strategy—is maintained and updated in real-time.

Furthermore, in a context of rapid biotic reshaping driven by climate change, the time lag involved in conventional scientific research—from collecting samples in the field to publishing results—is often unsuitable for the need for early-warning systems for invasive species. While formal protocols for early notification to competent authorities exist for several high-impact NIS, these preliminary reports are seldom immediately accessible to the broader scientific community. Issues related to intellectual property, data ownership, and the inherent delays of institutional validation often prevent these records from being used in real-time ecological modelling or cross-basin analysis. Consequently, even when institutional warning systems are triggered, a significant gap remains between the official notification and the availability of open, actionable data for researchers, often hindering a timely and coordinated response (Groom et al., 2017).To fill these gaps, a multi-source approach is needed to combine peer-reviewed literature with unconventional data sources. Local Ecological Knowledge (LEK), based on the direct experience of local actors such as craft fishermen, has proven to be an extraordinarily accurate analytical tool for reconstructing historical trends and detecting early signs of change in the distribution of marine fauna (Azzurro et al., 2011, 2019). However, the reliability of LEK is inherently modulated by taxonomic and ecological biases. This approach is highly effective for specific target groups - namely species that are commercially valuable, ecologically harmful, morphologically conspicuous (e.g., large or colorful), or easily identifiable by non-experts. Conversely, cryptic, small, or non-commercial taxa (such as many encrusting invertebrates) remain largely underrepresented in anecdotal reports, requiring targeted professional validation within the multi-source framework. The structured use of LEK allows information to be acquired over large spatial scales and extended time periods, overcoming the limitations of spot sampling and providing crucial data on the presence of NIS and their interaction with native species (Azzurro et al., 2019).

At the same time, Citizen Science (CS) and digital platform monitoring (Social Network Mining) have revolutionised the ability to intercept reports of rare or NIS/cryptogenic species. The active involvement of citizens, divers and recreational fishermen transforms the population into a widespread network of real-time biological sensors, capable of producing massive datasets that integrate global databases such as GBIF and OBIS (Crocetta et al., 2017).

The effectiveness of this multisource approach is particularly evident in the monitoring of charismatic, usually large-sized, and macroscopically identifiable species. For instance, in the case of large shallow-water invasive crustaceans, the cross-analysis between social media reports and expert scientific validation allows expansion fronts to be mapped with a timeliness that is precluded by traditional academic methods.

However, it is essential to acknowledge a significant inherent limitation of participatory data: the bathymetric bias. Most observations from Citizen Science and digital data mining are concentrated in the uppermost layers of the water column, primarily within the infralittoral and shallow circalittoral zones. This "surface-dwelling bias" arises because the vast majority of human-marine interactions - such as recreational snorkeling, standard holiday diving, and the most accessible coastal activities - are heavily skewed toward shallow waters (< 30–40 m). Although small-scale artisanal fishing and technical diving regularly operate well beyond these depths, extending their reach down to the mid-to-deep circalittoral zones (up to 80–100 m), a critical data void remains for the mesophotic ecosystems. Consequently, participatory frameworks experience a sharp decline in data density as depth increases, leaving deep-sea benthic habitats chronically under-monitored by non-professional networks..

Consequently, while the participatory approach provides high-resolution data for the epibenthic and epipelagic zones, it offers progressively less information for deeper habitats, including mesophotic ecosystems and deep benthic environments. As depth increases beyond the range routinely accessible to recreational divers and coastal users, the availability of participatory observations declines markedly, becoming particularly scarce in offshore and deep-sea habitats. Beyond this bathymetric constraint, participatory data are inherently susceptible to other well-documented structural distortions, including observer, taxonomic, and spatial biases. First, observer bias and uneven sampling effort are common, given that data collection predominantly focuses on easily accessible coastal areas, regions with higher human populations, or popular recreational diving spots (Dickinson et al., 2010; Isaac et al., 2014). This generates artificial spatial groups that correspond to human presence instead of genuine species distribution. Second, there is a significant taxonomic bias towards charismatic, colorful, or large species, at the expense of cryptic, small, or visually unappealing taxa, which are severely underrepresented (Troudet et al., 2017). Nonetheless, validation remains a significant obstacle; misidentifications by non-experts can lead to high false positive rates,

demanding thorough filtering and expert validation to uphold taxonomic standards (Bird et al., 2014; Kosmala et al., 2016). To mitigate these multi-faceted biases, this thesis ensures that for taxa requiring specialized equipment or deeper sampling, precise microscopic identification, direct field sampling and institutional oceanographic data remain the primary sources of information. This hybrid structure ensures that the database maintains a balanced perspective across the Mediterranean's complex vertical and horizontal gradients.

Multisource integration is not only an economical alternative, but also a methodological necessity for generating more robust distribution models. Combining data from heterogeneous sources mitigates the biases inherent in each individual method: while the literature – including not only recent collections but also data coming from historical samples gathered from natural history museums – provides taxonomic rigour. Historical depth is shared between natural history museum collections—offering long-term, baseline physical data—and LEK, which provides a multi-decadal record of ecological shifts and species trends based on fishers' memories; meanwhile, CS guarantees spatial capillarity. This holistic approach allows us to answer global research questions about how environmental variables are effectively shaping the future biodiversity of the Mediterranean (Azzurro et al., 2019).

1.4. THESIS OBJECTIVES AND RESEARCH QUESTIONS

The primary objective of this doctoral thesis is to investigate the distributional dynamics of shallow-water marine biodiversity in the Mediterranean basin, with a specific focus on benthic taxa and their response to climate change drivers. The core of the research lies in the desire to overcome the fragmentation of existing data by constructing a comprehensive and structured dataset of marine species occurrences capable of integrating information from heterogeneous sources. The aim is to provide a solid knowledge base that will allow the distribution of species to be analysed not only on a local scale, but with a perspective extended to the entire Mediterranean basin (see chapter 2).

Specifically, the research is structured around three scientific macro-objectives, aimed at answering fundamental questions for current marine ecology:

I. Analysis of Differential Responses: Investigate whether native thermophilic species and NIS exhibit divergent or similar responses to changes in the environmental conditions of their habitats. This objective

aims to understand how large-scale shared trajectories - driven by regional climate warming - combine with, or are modulated by, the unique biological traits and specificities of each taxonomic group.

II. Environmental Correlations and Drivers of Change: Identify and quantify the degree of correlation between species distribution and oceanographic variables most affected by global warming, such as surface temperature anomalies, sea level fluctuations, and chemical-physical changes in water masses. Identifying these relationships is essential to clarify the deterministic mechanisms driving distributional shifts, while simultaneously accounting for historical legacies and biogeographical inertia. This approach recognizes that contemporary environmental drivers do not operate in isolation, but constantly interact with the historical baseline distributions, past colonization pathways, and long-standing biotic interactions, which continue to exert a structural influence on present-day spatial patterns.

III. Spatial Projections and Predictive Modelling: Develop distribution maps that go beyond simply photographing the current situation but use Species Distribution Models (SDMs) to hypothesise future trends in the expansion or contraction of geographical ranges. This approach is fundamental for predicting the potential invasiveness of NIS and the resilience of native populations under different climate scenarios. Avoiding overpredictions and spatial artifacts, these projections do not rely solely on broad-scale oceanographic variables; instead, they integrate the actual biological and ecological boundaries of each organism. As detailed in Chapter 2 (Materials and Methods) and operationally applied in Chapters 6 and 7, the Mediterranean basin area is constrained and tailored to match the target species' biology. Environmental predictors were carefully selected based on the physiological requirements of each taxon. Furthermore, strict habitat-related constraints were applied, such as specific depth limits for benthic crustaceans or the availability of sandy beaches for nesting marine vertebrates. This approach ensures that future projections reflect areas where the species can genuinely find suitable habitat, rather than just places where the water temperature looks favorable on paper.

Through the use of participatory data and the synthesis of records from multiple sources, the thesis aims to provide a robust monitoring tool capable of detecting even rare species or those with limited formal records, thus contributing to the definition of more effective conservation strategies in an era of climate instability. In this context, species are operationally defined as "rare" based on their low frequency of occurrence in historical literature and standard scientific surveys, often corresponding to small population sizes, localized distributions, or early-stage NIS introductions characterized by an initial lag phase.

1.5. REFERENCE LIST

Azzurro, E., Moschella, P. and Maynou, F., 2011. Tracking signals of change in Mediterranean fish diversity based on local ecological knowledge. *PloS one*, *6*(9), p.e24885.

Azzurro, E., Sbragaglia, V., Cerri, J., Bariche, M., Bolognini, L., Ben Souissi, J., Busoni, G., Coco, S., Chryssanthi, A., Fanelli, E. and Ghanem, R., Garrabou, J., Gianni, F, Grati F., Kolitari, J., Letterio, G., Lipej, L., Mazzoldi, C., Milone, N., Pannacciulli, F., Pešić, A., Samuel-Rhoads, Y., Saponari, L., Tomanic, J., Eda Topçu, N., Vargiu, G., Moschella, P., 2019. Climate change, biological invasions, and the shifting distribution of Mediterranean fishes: A large-scale survey based on local ecological knowledge. *Global change biology*, *25*(8), pp.2779-2792.

Barnes, D.K., 2002. Invasions by marine life on plastic debris. *Nature*, *416*(6883), pp.808-809.

Belmaker, J. and Jetz, W., 2015. Relative roles of ecological and energetic constraints, diversification rates and region history on global species richness gradients. *Ecology Letters*, *18*(6), pp.563-571.Bianchi, C.N., 2007. Biodiversity issues for the forthcoming tropical Mediterranean Sea. *Hydrobiologia*, *580*(1), pp.7-21.

Bird, T. J., Bates, A. E., Lefcheck, J. S., Hill, N. A., Thomson, R. J., Edgar, G. J., Stuart-Smith, R.D., Wotherspoon, S., Krkosek, M., Stuart-Smith, J.F., Pecl, G.T., Barrett, N., Frusher, S., 2014. Statistical solutions for error and bias in global citizen science datasets. *Biological Conservation*, *173*, 144-154.

Boero, F., 2015. The future of the Mediterranean Sea Ecosystem: towards a different tomorrow. *Rendiconti Lincei*, *26*(1), pp.3-12.

Çevik, C., Özcan, T., Gündoğdu, S. and Dağlı, E., 2025. Floating plastics as a vector for range expansion: First record of *Lepas (Lepas) pectinata* Spengler, 1793 (Cirripedia: Lepadidae) in Turkish waters (Eastern Mediterranean). *Marine Pollution Bulletin*, 221, p.118550.

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Ben Rais Lasram, F., Aguzzi, J., Ballesteros, E., Bianchi, C.N., Corbera, J., Dailianis, T. and Danovaro, R., Estrada, M., Froglia, C., Galil, B.S., Gasol, J.M., Gertwagen, R., Gil, J., Guilhaumon, F., Kesner-Reyes, K., Kitsos, M.S., Koukouras, A., Lampadariou, N., Laxamana, E., López-Fé de la Cuadra, C.M., Lotze, H.K., Martin, D., Mouillot, D., Oro, D., Raicevich, S., Rius-Barile, J., Saiz-Salinas, J.I., San

Vicente, C., Somot, S., Templado, J., Turon, X., Vafidis, D., Villanueva, R. and Voultsiadou, E., 2010. The biodiversity of the Mediterranean Sea: estimates, patterns, and threats. *PLoS One*. 2010 Aug 2;5(8):e11842. doi: 10.1371/journal.pone.0011842. PMID: 20689844; PMCID: PMC2914016.

Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J.P., Iglesias, A., Lange, M.A., Lionello, P., Llasat, M.C., Paz, S., Peñuelas, J., Snoussi, M., Toreti, A., Tsimplis, M.N. and Xoplaki, E. 2018. Climate change and interconnected risks to sustainable development in the Mediterranean. Nature climate change, 8(11), pp.972-980.

Crocetta, F., Gofas, S., Salas, C., Tringali, L.P. and Zenetos, A., 2017. Local ecological knowledge versus published literature: a review of non-indigenous Mollusca in Greek marine waters. *Aquatic Invasions*, *12*(4), pp 415–434.

Darmaraki, S., Krokos, G., Genevier, L., Hoteit, I. and Raitsos, D.E., 2025. Drivers of marine heatwaves in coral bleaching regions of the Red Sea. Communications Earth & Environment, 6(1), 120.

Decision, V.I., 2002. 23: Alien species that threaten ecosystems, habitats and species. In Conference of the Parties to the Convention on Biological Diversity, VIth Meeting, The Hague, The Netherlands (p. 341).

Deudero, S. and Alomar, C., 2015. Mediterranean marine biodiversity under threat: reviewing influence of marine litter on species. *Marine Pollution Bulletin*, *98*(1-2), pp.58-68.

Galanidi, M., Aissi, M., Ali, M., Bakalem, A., Bariche, M., Bartolo, A.G., Bazairi, H., Beqiraj, S., Bilecenoglu, M., Bitar, G. and Bugeja, M., Carbonell, A., Castriota, L., Chalabi, A., Cinar, M.E., Dragicevic, B., Dulcic, J., El-Haweet, A.E.A., Farrag, M.M.S., Evans, J., Galil, B., Guérin, L., Hyams-Kaphzan, O., Kapedani, R., Kamberi, E., Livi, S., Macic, V., Massé, C., Mavric, B., Orlando-Bonaca, M., Ouerghi, A., Petovic, S., Png-Gonzalez, L., Schembri, P.J., Shenkar, N., Sghaier, Y.R., Shakman, E., Yahyaoui, A., Yokeş, M.B. and 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.

Galil, B.S., Marchini, A., Occhipinti-Ambrogi, A., Minchin, D., Narščius, A., Ojaveer, H. and Olenin, S., 2014. International arrivals: widespread bioinvasions in European Seas. *Ethology Ecology & Evolution*, *26*(2-3), pp.152-171.

Garrabou, J., Gómez-Gras, D., Medrano, A., Cerrano, C., Ponti, M., Schlegel, R., Bensoussan, N., Turicchia, E., Sini, M., Gerovasileiou, V., Teixido, N., Mirasole, A., Tamburello, L., Cebrian, E., Rilov, G., Ledoux, J.B., Souissi, J.B., Khamassi, F., Ghanem, R., Benabdi, M., Grimes, S., Ocaña, O., Bazairi, H., Hereu, B., Linares, C., Kersting, D.K., la Rovira, G., Ortega, J., Casals, D., Pagès-Escolà, M., Margarit, N., Capdevila, P., Verdura, J., Ramos, A., Izquierdo, A., Barbera, C., Rubio-Portillo, E., Anton, I., López-Sendino, P., Díaz, D., Vázquez-Luis, M., Duarte, C., Marbà, N., Aspillaga, E., Espinosa, F., Grech, D., Guala, I., Azzurro, E., Farina, S., Gambi, M.C., Chimienti, G., Montefalcone, M., Azzola, A., Mantas, T.P., Fraschetti, S., Ceccherelli, G., Kipson, S., Bakran-Petricioli, T., Petricioli, D., Jimenez, C., Katsanevakis, S., Kizilkaya, I.T., Kizilkaya, Z., Sartoretto, S., Elodie, R., Ruitton, S., Comeau, S., Gattuso, J.P. and Harmelin, J.G., 2022. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Global Change Biology*, *28*(19), pp.5708-5725.

Gregory, M.R., 2009. Environmental implications of plastic debris in marine settings—entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), pp.2013-2025.

Groom, Q., Weatherdon, L. and Geijzendorffer, I.R., 2017. Is citizen science an open science in the case of biodiversity observations?. *Journal of Applied Ecology*, *54*(2), pp.612-617.

Hamdeno, M. and Alvera-Azcarate, A., 2023. Marine heatwaves characteristics in the Mediterranean Sea: Case study the 2019 heatwave events. *Frontiers in Marine Science*, *10*,1093760.

Hortal, J., de Bello, F., Diniz-Filho, J.A.F., Lewinsohn, T.M., Lobo, J.M. and Ladle, R.J., 2015. Seven shortfalls that beset large-scale knowledge of biodiversity. *Annual Review of Ecology, Evolution, and Systematics*, *46*(1), pp.523-549.

Isaac, N.J., van Strien, A.J., August, T.A., de Zeeuw, M.P., and Roy, D.B., 2014. Statistics for citizen science: extracting signals of change from noisy ecological data. *Methods in Ecology and Evolution*, *5*(10), 1052-1060.

Kalyvioti, G., Galanidi, M. and Zenetos, A., 2024. Risk assessment to identify high-risk voyage origin ports and a watch list for NIS introduction in the Mediterranean with vessels: the case of Saronikos Gulf, Greece. *Management of Biological Invasions*, *15*(3), 337–370 .

Katsanevakis, S., Bogucarskis, K., Gatto, F., Vandekerkhove, J., Deriu, I. and Cardoso, A.C., 2012. Building the European Alien Species Information Network (EASIN): a novel approach for the exploration of distributed alien species data. *BioInvasions Record*, *1*(4), 235–245.

Kiessling, T., Gutow, L. and Thiel, M., 2015. Marine litter as habitat and dispersal vector. In Bergmann, M. et al. (Eds) Marine Anthropogenic Litter. Springer, Cham. https://doi.org/10.1007/978-3-319-16510-3_6

Kosmala, M., Wiggins, A., Swanson, A. and Simmons, B., 2016. Assessing data quality in citizen science. *Frontiers in Ecology and the Environment*, *14*(10), 551-560.

Lauer, A., 2016. *Watersipora subtorquata* and the Possible Role of Its Associated Microbes: An Attempt to Explain the Extraordinary Invasion Success of This Marine Bryozoan Species. In *The Mechanistic Benefits of Microbial Symbionts* (pp. 239-268). Cham: Springer International Publishing.

Lodola, A., Ferrario, J. and Occhipinti-Ambrogi, A., 2015. Further Mediterranean expansion of the non-indigenous bryozoan *Celleporaria brunnea*: multiple records along the Italian coasts. *Scientia Marina*, *79*(2), pp.263-274.

Pörtner, H.O., 2010. Oxygen-and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. *Journal of Experimental Biology*, *213*(6), pp.881-893.

Reddin, C.J., Aberhan, M., Raja, N.B. and Kocsis, Á.T., 2022. Global warming generates predictable extinctions of warm-and cold-water marine benthic invertebrates via thermal habitat loss. *Global Change Biology*, *28*(19), pp.5793-5807.

Rech, S., Borrell Pichs, Y.J. and García-Vazquez, E., 2018. Anthropogenic marine litter composition in coastal areas may be a predictor of potentially invasive rafting fauna. *PloS one*, *13*(1), p.e0191859.

Rivetti, I., Fraschetti, S., Lionello, P., Zambianchi, E. and Boero, F., 2014. Global warming and mass mortalities of benthic invertebrates in the Mediterranean Sea. *PloS one*, *9*(12), e115655.

Somero, G.N., 2010. The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine 'winners' and 'loosers'. *Journal of Experimental Biology*, *213*(6), pp.912-920.

Torreblanca, D. and Báez, J.C., 2025. Tropicalization of the Mediterranean Sea Reflected in Fish Diversity Changes: A Case Study from Spanish Waters. *Journal of Marine Science and Engineering*, *13*(6), 1119.

Troudet, J., Grandcolas, P., Blin, A., Vignes-Lebbe, R., and Legendre, F., 2017. Taxonomic bias in biodiversity data and societal preferences. *Scientific reports*, *7*(1), 9132.

Ulman, A., 2018. *Recreational boating as a major vector of spread of nonindigenous species around the Mediterranean* (Doctoral dissertation, Sorbonne Université).

Whittaker, R.J., Araújo, M.B., Jepson, P., Ladle, R.J., Watson, J.E. and Willis, K.J., 2005. Conservation biogeography: assessment and prospect. *Diversity and Distributions*, *11*(1), pp.3-23.

Zenetos, A., Doğan, A., Bakir, A.K., Chatzigeorgiou, G., Corsini-Foka, M., Dağli, E., Evangelopoulos, A., Meriç, E., Stoumboudi, M., Taşkin, E., Yokeş, M.B., and Galanidi M. 2024. Non-Indigenous Species (NIS) know no geopolitical borders—an update of NIS in the Aegean Sea. *Diversity*, *17*(1), 12.

Zerebecki, R.A. and Sorte, C.J., 2011. Temperature tolerance and stress proteins as mechanisms of invasive species success. *PLOS one*, *6*(4), e14806.

Chapter 2



General methodology and construction of the multisource database

2. GENERAL METHODOLOGY AND CONSTRUCTION OF THE MULTISOURCE DATABASE

This chapter outlines the general methodological framework, the core criteria for data integration, and the overarching architecture used to construct the multisource database. Rather than providing an exhaustive description of every analytical tool, this section serves as the common structural foundation for the entire thesis. To ensure readability and context-specific clarity, the detailed, fine-scale methodologies - including specific modeling parameters, statistical treatments, and protocols adopted for each target topic - are fully detailed within their respective experimental sections.

2.1. THE MULTISOURCE DATABASE

The construction of a multisource database represents the primary methodological focus of this thesis. This strategic choice stems from the clear awareness that conventional monitoring systems, while ensuring high standards of validation and taxonomic rigor, often fail to keep pace with the unprecedented speed of biogeographical changes currently taking place in the Mediterranean Sea. Within a basin recognized as a global “hotspot” for both climate change (Garrabou et al., 2022) and biological invasions (Zenetos and Galanidi, 2020), the traditional scientific pipeline is frequently too slow to capture the real-time dynamics of shifting ecosystems.

A critical obstacle in this context is the significant time lag that occurs between the initial field observation of a thermophilic or non-indigenous species (NIS) and its eventual publication in formal catalogues or peer-reviewed literature. This delay can span several years, creating a data vacuum that hinders the timely management of marine resources and the implementation of effective conservation strategies (Azzurro et al., 2019). In an era of rapid "tropicalization" and "southernization" of the Mediterranean biota, relying solely on historical or institutionally validated records risks underestimating the true extent of species' expansion fronts. While modern academic journals have significantly accelerated their publishing timelines, traditional monitoring programs are still constrained by discrete, seasonal, or intermittent sampling schedules. Consequently, they may lag in capturing the immediate arrival or initial expansion of thermophilic species and NIS. Integrating participatory data helps bridge this gap by providing continuous spatial and temporal coverage, acting as an early-warning system that registers new occurrences well before formal scientific surveys are planned or executed.The approach adopted in this

research responds to the urgent need for the integration of heterogeneous data sources to overcome the structural limitations of “traditional” datasets. These datasets often suffer from significant spatial and temporal gaps, colloquially known in biogeography as the Wallacean and Linnean shortfalls. The Wallacean shortfall refers to the incomplete knowledge regarding the geographic distribution of species, while the Linnean shortfall describes the lack of taxonomic clarity or data for specific groups in rapidly changing environments (Hortal et al., 2015).

By synthesizing formal records (oceanographic surveys, institutional databases, and indexed literature) with participatory and digital streams (Citizen Science, Local Ecological Knowledge, and social media), this multisource database aims to fill these gaps. This integration is essential for generating accurate Species Distribution Models (SDMs) in contexts of rapid ecological transition. Ultimately, this methodology transforms fragmented observations into a robust, basin-wide dataset that reflects the complex anthropogenic pressures and environmental gradients currently reshaping the Mediterranean biodiversity.

2.2. Selection of Biological Targets: Thermophilic Species and Non-Indigenous Species (NIS)

The database has been structured around 36 target species, selected for their ability to act as biological indicators of the ongoing transformations. The selection was not random but guided by criteria of ecological relevance and the availability of data from various information sources. In this study, ecological relevance is defined based on the functional role of the taxa within Mediterranean communities, focusing on organisms that act either as ecosystem engineers, key predators, or sensitive bioindicators. Specifically, species were selected if their range shifts, demographic collapses, or structural impacts directly alter local food webs and habitat complexity, or clearly reflect ecosystem-scale responses to warming. This selection was guided by the need to identify organisms that act as true indicators of the environmental transformations taking place in the Mediterranean. The selection criteria were not limited to geographical expansion capacity (southernisation or tropicalisation alone) but also considered the intrinsic vulnerability of these taxa to climate change drivers, such as water acidification and the increased frequency of marine heatwaves (MHWs) (Garrabou et al., 2022). Vulnerability was considered by balancing two contrasting ecological responses within the target list: thermal sensitivity and ecological resilience. On one hand, we selected structural native species (such as sessile cnidarians) whose high

physiological vulnerability to thermal anomalies triggers documented mass mortality events, serving as indicators of ecosystem decline. On the other hand, the selected NIS often possess a high tolerance to chemical-physical shifts, allowing them to opportunistically colonize niches left vacant by more vulnerable native taxa. This dual approach ensures that the database captures both the direct impacts of climate stress on sensitive organisms and the systemic reorganization of communities driven by more resilient invaders.

Native Thermophilic Species and Ecosystem Health: The inclusion of native taxa such as Cnidarians, Crustaceans and Fish species responds to the necessity of monitoring not only latitudinal shifts, but also the health status of benthic and pelagic ecosystems. Cnidarians, particularly scleractinian corals and gorgonians, are key ecosystem engineers and habitat-forming species. By creating complex three-dimensional structures, they significantly enhance environmental heterogeneity, providing essential niches, refugia, and nursery areas for a wide array of associated organisms (Jones et al., 1994). Consequently, they play a pivotal role in promoting and maintaining Mediterranean marine biodiversity. Partial mortality and mass mortality have been widely documented in the Mediterranean as a direct consequence of thermal anomalies, making these species critical indicators of the resilience of the basin (Cerrano et al., 2005; Garrabou et al., 2009). The choice of these organisms therefore allows us to distinguish between simple distributional response and physiological decline of native populations under anthropogenic and climatic stress (Lejeusne et al., 2010).

NIS and Cryptogenic Species as Bioindicators: This group, including foraminifera, cnidarians, bryozoans, molluscs, crustaceans and fish, was selected for its ecosystem relevance and ability to colonise ecological niches empty after the decline of native species. The selection of these taxa was based on the following criteria:

- Ecosystemic Relevance: Many of these species, such as predatory fish (*Pterois miles*) or invasive crustaceans (*Callinectes sapidus* and *Portunus segnis*), exert significant pressure on local food webs, altering the structure of native communities (Giakoumi et al., 2019) and posing serious issues to local ecosystem services.

- Identifiability and Detectability: A key criterion was ease of morphological recognition. Charismatic or macroscopically distinguishable species facilitate data collection via Citizen Science and social media, reducing identification errors and increasing the critical mass of data available for spatial modelling (Galanidi et al., 2018; Encarnação et al., 2021). To

explicitly address the taxonomic limitations and reporting biases inherent in citizen-led datasets, the target species list was intentionally restricted only to organisms possessing unmistakable macroscopic traits. Cryptic species or taxa requiring laboratory-level diagnostic dissection were strictly excluded from the participatory data-mining pipeline. By limiting our targets to easily identifiable species, we prioritized data certainty and minimized the risk of misidentification, turning a structural limitation of the approach into a controlled data-quality filter.

- Data Accessibility and Sampling Methods: For less visible but equally significant groups, such as bryozoans and foraminifera, the choice was dictated by the availability of direct sampling conducted on specific vectors. In particular, the study of colonies on floating plastics (rafting) has opened up new perspectives on the passive dispersion of NIS, highlighting how the interaction between anthropogenic pollution and surface currents facilitates the spread of cryptogenic organisms in previously uncolonised areas (Rech et al., 2016; Rosso and Siddiolo, 2024).

This diverse and stratified selection allows us to bridge critical knowledge gaps regarding not only the raw occurrence and arrival of biological invasions but also the underlying ecology and ecological capacity of specific taxa. By developing a multisource framework, we can effectively correlate the "observational accessibility" of a species—ranging from high-visibility taxa like teleost fish to more cryptic, moderate-detectability groups such as bryozoans—with their broader ecosystemic functional roles. However, this approach does not imply a "one-size-fits-all" methodology; rather, the data streams are weighted and utilized differently depending on the taxon. While opportunistic citizen science records provide robust distributional boundaries for charismatic macrofauna, they act merely as preliminary qualitative indicators for cryptic or microscopic groups. For these less conspicuous taxa, participatory data are not used as direct inputs for broad spatial modeling, but rather as tactical guides to direct targeted, professional field sampling and laboratory validation, thereby adjusting our analytical resolution to the specific biological constraints of each target group**.** This approach creates a comprehensive, macro-ecological dataset that captures broad-scale geographic trends, helping to document how specific biological targets respond to ongoing environmental transformations in the Mediterranean basin (Bianchi et al., 2012; Katsanevakis et al., 2014).

Furthermore, the integration of these different biological targets serves to mitigate the bias often associated with "charismatic" megafauna, ensuring that microscopic or less conspicuous organisms, which are often the first to respond to subtle chemical or thermal shifts, are equally represented. In this methodological framework, the target species are no longer treated as mere isolated points on a map; instead, they are interpreted as ecological descriptors and functional indicators of the profound structural shifts within a Mediterranean Sea undergoing a rapid and historically unprecedented thermal transition (Schroeder et al., 2016). This holistic perspective is crucial for moving beyond simple presence-absence data, allowing for an analysis that captures the systemic reorganization of marine communities in response to the climate crisis. Specifically, the multisource database does not merely collect geographic coordinates; it systematically integrates metadata regarding the physiological state, ecological behaviors, and life-history traits associated with each occurrence. For instance, for NIS and expanding species, the database links occurrences to operational vectors - such as plastic debris for rafting bryozoans - or critical reproductive events, such as shifting nesting dynamics for marine megafauna. By contextualizing raw presences with these explicit biological and behavioral responses, the dataset provides the mechanistic baseline needed to understand how climate drivers are actively reshaping the functional ecology of target species across the basin.

2.3. Participatory Data Collection Methodology: Local Ecological Knowledge and Citizen Science

The integration of LEK and CS within multisource databases is now widely recognized as an indispensable strategy for filling the chronic knowledge gaps regarding marine biodiversity. This is especially true in highly dynamic basins such as the Mediterranean Sea, where biological shifts occur at a pace that often outstrips traditional monitoring capabilities (Azzurro et al., 2019). These traditional capabilities primarily rely on standardized institutional programs, such as large-scale scientific trawl surveys, seasonal oceanographic cruises, and localized underwater visual censuses (UVC) conducted by research institutes. While statistically rigorous, these conventional methods are structurally constrained by discrete temporal schedules - often occurring on an annual or semi-annual basis - and limited spatial grids due to high logistical and economic costs. Consequently, they are poorly suited for detecting episodic ecological events, localized population collapses, or the rapid, fine-scale advancement of species expansion fronts. While institutional databases and museum records provide a consolidated, long-term historical basis for biodiversity assessment (Shaffer et al., 1998; Magurran et al., 2010), they serve

as critical 'time capsules' that allow researchers to establish the most reliable baselines possible prior but also posterior to major anthropogenic disturbances. For the restricted areas where they are available (the Gulf of Naples being possibly the best example thanks to the Stazione Zoologica Anton Dohrn) natural history collections, in particular, offer a unique opportunity to track morphological and distributional shifts over centuries, providing the taxonomic backbone necessary to validate modern observations. Building upon this historical foundation, participatory data allow for the detection of emerging phenomena with a temporal resolution that standard academic research can rarely guarantee. This operational advantage stems from the near-real-time, daily frequency of opportunistic observations, driven by hundreds of coastal stakeholders acting as decentralized observers throughout the entire year. In contrast, standard academic or institutional monitoring is structurally constrained to discrete seasonal, semi-annual, or annual frequencies due to high funding requirements and ship-time availability. Consequently, standard research tracks ecosystem states through periodic snapshots—often leaving gaps of several months between sampling events—whereas participatory monitoring operating on a continuous, multi-season daily scale can intercept episodic ecological events or early biological arrivals immediately as they occur. This near-real-time detection is crucial for identifying the early stages of biological invasions or documenting the sublethal effects of warming—such as behavioural shifts or localized health declines—before they become irreversible on a basin scale (Catford et al., 2012; Ahmed et al., 2022). Operationally, this early warning window allows environmental managers and policymakers to transition from passive documentation to proactive, localized mitigation strategies. First, for NIS, early detection triggers rapid response protocols and targeted eradication or containment efforts within restricted introduction areas (such as ports, marinas, or coastal lagoons) before the organisms establish a self-sustaining open-sea population. Second, for native populations undergoing climate stress or sublethal health declines, immediate spatial notifications allow for the adaptive management of local stressors. This includes temporary spatial closures or restrictions on anchoring, coastal discharges, and commercial diving in the affected zones, thereby minimizing cumulative anthropogenic pressures during critical thermal anomalies. Finally, for high-impact commercial invaders, real-time spatial data enable the rapid lifting of fishing restrictions, turning local fleets into dynamic biological containment tools before community-wide trophic shifts become irreversible.

2.4. Synergistic Integration of Data Inflow

To provide a comprehensive overview of the methodological architecture developed in this study, the complete procedural flow - from the initial conceptual framework to the final scientific outputs - is represented in Figure 2.1. This conceptual layout illustrates the sequential relationship between target

selection, multisource data harvesting, quality control filtering, and analytical modeling, serving as a visual roadmap for the entire thesis pipeline.

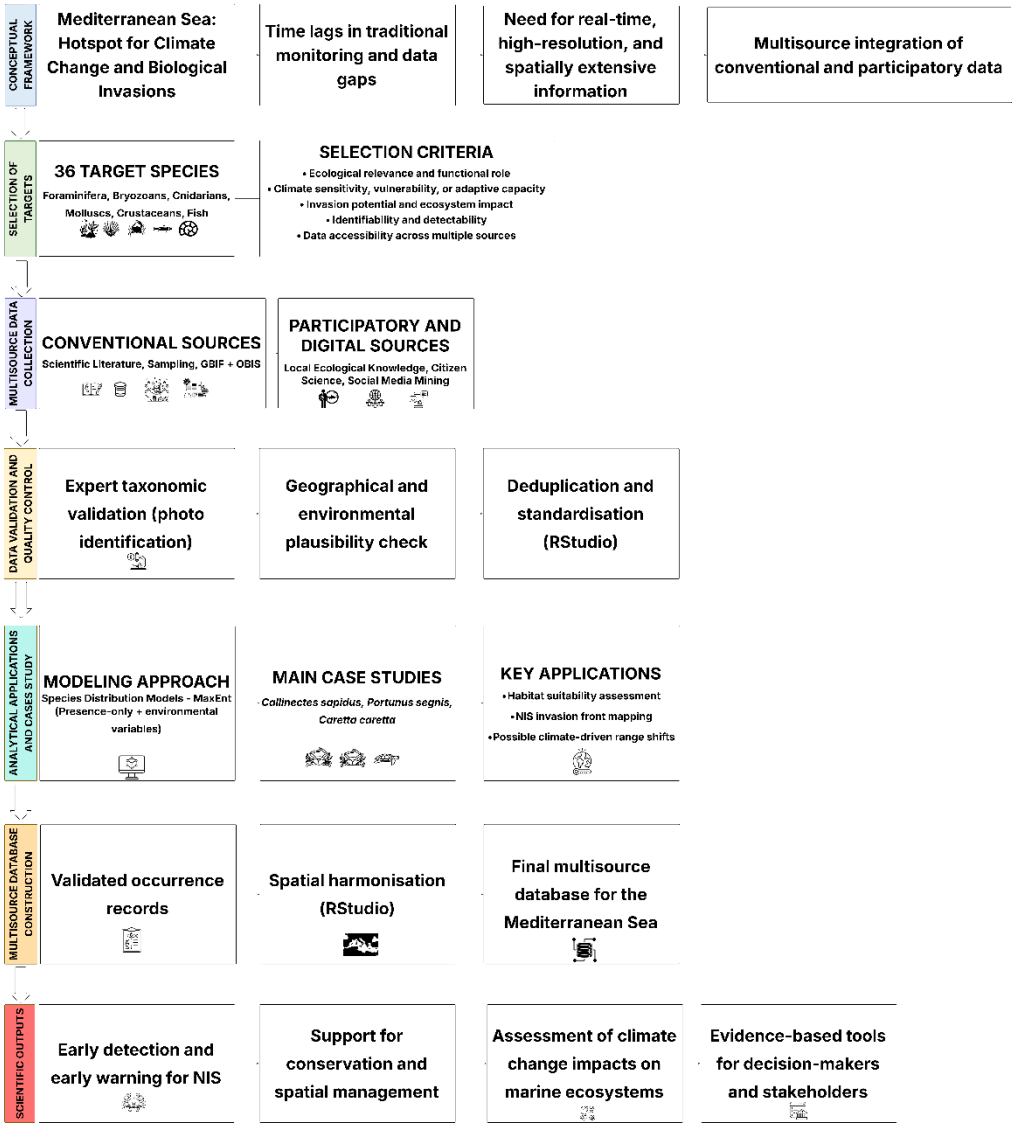

Figure 2.1: Methodological and operational workflow of the multisource database architecture. The diagram outlines the seven core structural phases of the research: (1) the conceptual framework addressing Mediterranean data gaps; (2) the selection of targets focusing on 36 target species based on specific ecological and accessibility criteria; (3) Multisource data collection splitting inflows into conventional sources and participatory/digital Sources; (4) Data validation and quality control protocols including

taxonomic, geographic, and de-duplication filters; (5) Analytical applications and cases study utilizing MaxEnt modeling for main target species; (6) Multisource database construction yielding the final harmonized dataset; and (7) the expected scientific outputs acting as evidence-based tools for decision-makers.

- To ensure a rigorous data architecture, the incoming information streams were compartmentalized into separate pipelines based on their operational nature, shifting from qualitative stakeholder testimonies to highly structured global repositories: LEK: By drawing directly on the empirical experience of professional stakeholders, such as fishermen, and recreational experts, such as divers, LEK provided a unique Long-term temporal perspective. These individuals act as daily observers of the marine environment, making them instrumental in gathering data on rare or cryptic species that seldom appear in standardized scientific surveys. Furthermore, LEK proved vital in reconstructing local historical series and first-occurrence timelines that were not officially documented in the scientific literature, providing a "pre-invasion" baseline for many areas (Johannes et al., 2000; Oteros-Rozas et al., 2014). Most importantly, the scientific validity and robustness of LEK do not rest on isolated, anecdotal reports, which are inherently prone to individual subjectivity and memory bias. Instead, the methodological core of LEK relies on the continuous frequency of observations and the high number of independent observers. A single, unverified report from a single stakeholder is scientifically inconclusive; conversely, when multiple decentralized observers independently report identical taxonomic traits, temporal timelines, or environmental patterns across high observational frequencies, the data can be cross validated. This process of data triangulation effectively filters out individual false positives, transforming collective qualitative testimonies into reliable, structured historical baselines. The LEK approach was mainly applied with the development and distribution of a structured interview focused on the target species that also facilitated the acquisition of data on species not included in the main survey. The overview of the survey methodology, including the design of structured interviews and the cross-border distribution of questionnaires, is presented in Chapter 10.
  However, it is important to underline that the final database also includes LEK data derived from interviews conducted in person or digitally in Sicily on target populations.

- CS and Social Media Mining: To ensure full reproducibility of the digital extraction workflow, explicit spatial and keyword-based mining protocols were deployed across selected web platforms. Digital data mining targeted primary social networks to enabled the acquisition of georeferenced data on a basin scale, which is particularly effective for charismatic and easily identifiable species (Encarnação et al., 2021). Specifically, data mining targeted public groups on Facebook – in particular, “Oddfish” and “Fauna Marina Mediterranea” - dedicated to identifying Mediterranean marine species through photos or videos uploaded by members.
- Global Biodiversity Repositories: In parallel, the global open-access repositories Global Biodiversity Information Facility (GBIF) and Ocean Biodiversity Information System (OBIS) were queried at multiple intervals during the three years of the doctoral candidacy. Data harvesting, spatial subsetting, and tabular manipulation from these platforms were executed programmatically within the Rstudio statistical environment (R version 4.4.2). Spatial occurrences were programmatically pulled using the robis package (Provoost and Bosch, 2022), the raster and dismo packages (Hijmans et al., 2024; Hijmans, 2025). Once leaned, compiled datasets were systematically structured and exported using the openxlsx package (Schauberger and Walker, 2025) to maintain strict data-logging control.

The use of unconventional information flows has led to the adoption of rigorous filtering protocols, aimed at ensuring that the heterogeneity of sources does not compromise the scientific reliability of the final database. To overcome the taxonomic limitations inherent in CS, a validation system based on the nature of the data and the morphology of the species was implemented (Wiggins et al., 2011; Siddiolo et al., submitted):

I. Expert Validation and Photographic ID: For records from digital platforms and social media (see above), the presence of photographic documentation was considered a fundamental requirement for data confirmation. In these cases, the records underwent taxonomic review by specialists, ensuring the correctness of identification even for those taxa that have morphological similarities with congeneric species. Crucially, the dedicated Facebook groups utilized for data mining are directly administered and moderated by subject-matter experts, primarily taxonomists and professional marine scientists. All biological targets integrated into our database consist of species that are macroscopically identifiable via high-resolution photographic assessment. While certain taxa present significant identification

challenges and potential sources of confusion for regular group users - such as distinguishing *Callinectes sapidus* from *Portunus segnis*, *Siganus luridus* from *Siganus rivulatus*, *Oculina patagonica* from *Cladocora caespitosa*, or *Fistularia commersonii* from *Fistularia petimba* - the expert administrators can reliably and straightforwardly diagnose these species based on diagnostic characters visible in the shared images. This expert-based verification process ensures that participatory data meet quality standards comparable to those of scientific literature (Encarnação et al., 2021).

II. Simplified Taxonomic Diagnosis in LEK: For most of the target species included in the LEK questionnaires, validation was facilitated by the choice of organisms with unmistakable macroscopic diagnostic traits. To ensure taxonomic rigor and prevent ambiguity prior to the detailed presentation of these target taxa in Chapter 10, the field questionnaires were systematically paired with high-resolution photographic plates and standardized visual diagnostic aids. During the interviews, respondents were asked to validate their historical reports against these morphological plates, which explicitly highlighted the unique macroscopic features of each species. This visual verification step anchored the stakeholder's local knowledge to verified taxonomic baselines, drastically reducing the risk of cognitive misidentification before any data entry. This strategic choice in the study design was specifically adopted because questionnaires and interviews do not always yield accompanying photographic evidence; therefore, the robust assessment of historical or observational data must rely on a targeted species list that minimizes taxonomic ambiguity by default. The basic simplicity in identifying these specific target organisms drastically reduces the risk of confusion with other native or NIS taxa, granting high intrinsic reliability to the verbal or written reports provided by local stakeholders (such as professional fishermen and recreational divers), even in the absence of direct photographic support (Azzurro et al., 2019). However, when respondents did proactively attach or provide photographs to corroborate their interview answers, an additional strict validation procedure was enforced. The overwhelming majority of these submitted images successfully depicted one of our core biological targets. However, in exactly four instances, the attached photographs revealed different species that had been misidentified by the respondents as target taxa. Following our strict quality control protocol for photographically ambiguous or inaccurate submissions, these four records were excluded from the

modeling database to prevent taxonomic inflation and ensure maximum data purity (See chapter 10).

III. Geographical and Environmental Plausibility Check: Each report was subjected to a spatial consistency filter. The geographical coordinates and bathymetry reported were cross-referenced with ecological parameters extracted from environmental databases. Records that showed clear inconsistencies with the known ecology of the species — such as sightings in habitats or bathymetric ranges incompatible with the biology of the organism — were discarded to avoid distortions in subsequent distribution models (Elith et al., 2011).

IV. De-duplication and Traceability: Given the multi-source nature of the dataset, particular attention was paid to removing redundant records (double counting). Database filtering, date synchronization, and coordinate parsing were fully scripted and executed by the author within the R environment (Rstudio 4.4.2). String coordinate data from heterogeneous sources were standardized, and geographic positions in Degrees/Minutes/Seconds were converted to Decimal Degrees via a custom parsing function. Duplicate occurrence records were identified between the GBIF and OBIS streams when sharing identical geographic coordinates for the same species. For each duplicated combination, a single representative record was retained through a randomized selection procedure automated via the dplyr and stringr packages (Wickham et al., 2023; Wickham, 2025). To ensure absolute reproducibility, the selection process was governed by a fixed pseudo-random seed (set.seed(123)), preventing systematic bias toward either data portal. Occurrence records from literature and local ecological knowledge were not altered. The final clean dataset and a mirror file of the excluded records were exported using the writexl package (Ooms, 2024) to guarantee full traceability and auditability.

A recognized limitation of macro-ecological databases targeting invasive or expanding species is that global repositories (such as OBIS and GBIF) are continuously dynamic, receiving daily updates. Simultaneously, the volume of scientific literature for high-profile invasive targets like *Callinectes sapidus* or *Pterois miles* increases at a rate that is materially impossible to track in real-time by a single investigator. To resolve this issue and provide an auditable, reproducible workflow for spatial modeling, strict temporal boundaries had to be enforced. Distinct cut-off thresholds ("last access" dates) were established

individually for each of the 36 target species. These hard dates represent the definitive temporal endpoints of data collection for this thesis and are explicitly cataloged within the metadata of the final shared dataset on Zenodo.

Consequently, while the database is structurally designed to be eventually updated, its current state represents a curated, frozen baseline. It stands as a reliable, fully auditable empirical snapshot capturing the high-velocity biogeographical transitions of Mediterranean shallow-water ecosystems during a critical historical period of climate stress.

2.5. SPECIES DISTRIBUTION MODELS (SDMS)

In a rapidly shifting environment like the Mediterranean Sea and its shallow waters, raw occurrence points from a multisource database provide only a fragmented snapshot of species distributions. Species Distribution Models are, however, capable of translating these heterogeneous data into continuous spatial surfaces, mathematically correlating occurrence records with macro-ecological and thermal predictors to quantify how environmental variables such as climate change drivers are actively reshuffling marine communities (Elith and Leathwick, 2009; Miller, 2010). The importance of this modeling framework is directly demonstrated through two core pillars of this research

1. Assessing Habitat Suitability and Distribution Patterns of the Invasive Brachyuran Crabs *Callinectes sapidus* and *Portunus segnis* in the Mediterranean Basin (chapter 6): for highly dispersive and aggressive NIS species, SDMs were crucial to transform opportunistic reports into detailed maps of habitat suitability. This allowed us to identify possible uncolonized but highly invadible niches, trying to predict the future expansion fronts of these two ecosystem engineers across complex horizontal gradients in the Mediterranean.
2. Heat Nests: The Impact of Climate Change on Loggerhead Turtle (*Caretta caretta*) Nesting Distribution in Sicily (Italy) (chapter 7): In the context of climate-driven behavioral responses, SDMs allowed us to model the shifts in nesting sites along the sicilian coast. By cross-referencing occurrence data with Sea Surface Temperature (SST) and beach thermal profiles, the models successfully identified emerging climate refugia or "heat nests" in Sicily, predicting where critical

reproductive habitats could clip or expand under future climate scenarios.

A defining structural characteristic of the data assembled for this thesis is its strict reliance on species presence-only records. When dealing with online databases, social media extraction, and historical LEK testimonies, we operated within a framework that naturally documents occurrence but inherently lacks the standardized, negative-replicated sampling protocols required to confirm that a species is truly absent from a given site. In a marine context, validating a true ecological absence is notoriously difficult, but when the geographical scope expands to encompass the entire Mediterranean basin, this difficulty becomes an absolute operational barrier.

The choice to deploy a presence-only modeling framework was therefore dictated mainly by the macro-ecological scale of this study. Tracking thirty-six highly diverse target species across a cross-border basin, characterized by sharp socio-economic disparities, fragmented local monitoring efforts, and uneven coastal access, precludes any realistic possibility of generating a reliable presence-absence matrix. Relying on heterogenous data sources across such a vast spatial extent means that any recorded "absence" would almost certainly be a artifact of observer omission or lack of local sampling effort, rather than a genuine reflection of ecological exclusion. Forcing these data into traditional presence-absence algorithms would introduce severe false-negative biases, structurally undermining the predictive validity of the models.

To resolve this issue without compromising the basin-wide scale of the investigation, we relied on Maximum Entropy (MaxEnt) model for some of the species within our database (*C. sapidus*, *P. segnis*, *C. caretta*). Rather than guessing at questionable absences, this model evaluates the specific environmental and thermal conditions where a species has been confirmed against a representative, randomized sample of the background environment across the entire Mediterranean basin. This approach effectively converts the opportunistic and decentralized nature of the multisource database into a distinct analytical advantage. By shifting the mathematical focus from raw distribution boundaries to environmental niche characterization, a presence-only approach allows us to utilize data from several scattered coastal observers. It maximizes the informational value of citizen-led and historical data, providing a robust, macro-ecological perspective on shallow-water biodiversity shifts that

localized, presence-absence frameworks simply could not achieve at this geographical scale.

2.6. METHODOLOGICAL LIMITATIONS

Recognizing the limitations of a multi-source database, which is partially based on opportunistic and participatory data, is a crucial prerequisite for its accurate ecological interpretation. Datasets compiled through CS and LEK are structurally distinct from standardized oceanographic monitoring and possess non-random biases that must be explicitly quantified and addressed

The geographical coordinates were not uniformly available or highly accurate across all data sources, particularly for primary data derived from social networks and direct stakeholder engagement. While global biodiversity repositories (GBIF, OBIS) and indexed literature provided explicit or high-resolution coordinates in most of the cases, placeholder or descriptive localities from opportunistic sources required a strict, multi-tier georeferencing protocol to minimize spatial uncertainty:

- High-Precision References: Whenever respondents or social media users provided a highly specific localized reference (e.g., a specific beach, harbor, or small coastal cove), a precise pair of geographical coordinates corresponding to that exact site was manually assigned using high-resolution digital mapping tools.
- Vague Urban or Geographical References: When the reporting provided a broader local context (e.g., the name of a town, a wide bay, or a general landmark), coordinates were inferred - wherever biologically plausible - by cross-referencing the location with validated, high-resolution occurrence data for the same species from independent sources (such as published literature or GBIF/OBIS records in that immediate sector) to align the point with known suitable habitats. If no previous data were available for cross-referencing, a conservative, approximate centroid coordinate for that specific geographical feature was assigned.
- Exclusion of Highly Ambiguous Data: To preserve the spatial integrity of our dataset and avoid artificial inflation of the species' range, any records featuring overly vague geographical descriptions (e.g., indicating only the name of an entire nation or an expansive macro-region like "Southern Italy" or "Tunisia") were strictly excluded from the final

database. This systematic approach ensured that only spatially reliable records were retained for mapping and baseline synthesis.

In this research, all validated reports were treated strictly as single occurrence points on the map, without considering individual specimen counts. The vast majority of opportunistic reports and historical LEK testimonies do not provide quantitative data on population density. Since the fundamental objective of this thesis is to track macro-ecological geographic distributions and documented updates across the Mediterranean basin - rather than estimating absolute demographic density - flock or sample sizes were omitted from the analytical pipeline. To prevent any further ambiguity regarding this data structure, any terminology implying absolute "abundance" has been removed from the text and rephrased, clarifying that density clusters in our maps refer exclusively to the spatial grouping and frequency of reports in a given area, not to individual species abundance.

Taxonomic and Observer Bias: Participatory data are strongly influenced by the "charismatic" status or socioeconomic impact of the target species. High-profile, visually striking, or potentially hazardous invaders, such as the Atlantic blue crab (*Callinectes sapidus*) and the lionfish (*Pterois miles*), trigger a disproportionately high reporting rate from the public. On the other hand, native thermophilic species or small, cryptic organisms (such as bryozoans and foraminifera, considering, however, that one of our target bryozoan, *Amathia verticillata*, is not to be considered as cryptic) suffer from under-reporting due to lower public engagement or lack of macroscopic visibility. This taxonomic bias means that the high volume of records for certain species often reflects public interest and detectability rather than a proportional biological dominance over less conspicuous taxa.

Uneven Reporting Effort: The geographic distribution of data points is heavily skewed by coastal accessibility, population density, and local digital literacy. Highly populated coastal zones, prominent touristic diving spots, and marine protected areas with active citizen networks generate a dense concentration of records. In contrast, remote coastal sectors, industrial zones, or regions with limited cross-border data-sharing infrastructure present artificial lacks of data that do not necessarily correspond to an actual biological absence of the target species.

Survey Execution and Interpretation: To ensure methodological consistency and minimize inter-observer bias during field operations, all primary structured surveys and face-to-face or digital interviews conducted in the field (specifically

across the Sicilian target areas) were executed personally by the PhD candidate. By centralizing data collection under a single investigator, the framing of the taxonomic questions, the explanation of diagnostic traits, and the initial filtering of stakeholder accounts remained strictly standardized, eliminating the operator-induced variances that typically arise when multiple interviewers conduct field campaigns.

2.7. SUPPORTING SCIENTIFIC RESULTS

The integration of Citizen Science (CS) and Local Ecological Knowledge (LEK) served as an essential methodological pillar for enhancing the robustness and spatial resolution of the results presented throughout the subsequent thematic chapters of this thesis. By harnessing the ability of these decentralized sources to provide high-frequency data, it was possible to overcome the traditional "observation gap" that often limits marine spatial planning and invasion biology. This synergy provided several critical advantages:

- Mapping Active Invasion Fronts: The participatory approach allowed for a much more granular mapping of the rapid expansion fronts of highly dispersive and aggressive NIS, specifically the Atlantic blue crab (*Callinectes sapidus*) and the blue swimming crab (*Portunus segnis*). While formal scientific surveys are often constrained by seasonal or localized sampling, the constant presence of fishers and coastal observers provided a continuous stream of data that was pivotal for the habitat suitability assessments and distribution patterns analyzed in Chapter 6.
- Identification of Critical Habitats for Thermophilic and Protected Species: Participatory data were instrumental in identifying new or shifting nesting sites and presence areas for species of high conservation and ecological value. This was particularly evident for the loggerhead sea turtle (*Caretta caretta*), which is exhibiting northward shifts in nesting behaviour due to rising sand temperatures, and the ghost crab (*Ocypode cursor*), which is colonizing new Mediterranean beaches. The inclusion of LEK and CS records ensured that the spatial models developed in Chapters 6 and 9 accounted for the most recent and geographically peripheral occurrences, which are often the most informative for predicting future range expansions under climate change scenarios.

- Informing Targeted Sampling for Microscopic non-charismatic Taxa: A unique application of this multisource approach was the use of macroscopic reports to guide the search for microscopic organisms. By monitoring participatory reports of anthropogenic vectors—specifically floating plastic debris and marine litter—sampling efforts could be strategically targeted toward these "rafts." This led to the detection of NIS bryozoan colonies, such as *Microporella hastingsae* and *Microporella browni*, in areas far beyond their previously known ranges (Rosso and Siddiolo, 2024; Rosso et al., 2025). This illustrates how "low-resolution" citizen observations (finding plastic), especially considering the rise of many plastic free/cleaning initiatives promoted by associations, can successfully catalyse "high-resolution" taxonomic discoveries (identifying microscopic bryozoans).

In summary, the strategic involvement of participatory sources has fundamentally transformed the database from a static, retrospective collection of historical records into a more comprehensive and spatially informative dataset supporting species distribution modelling. This evolved dataset is uniquely capable of reflecting the current, high-velocity state of transition of Mediterranean biota, providing the empirical foundation necessary to model the systemic ecological shifts triggered by the ongoing climate crisis.

2.8. REFERENCE LIST

Ahmed, D.A., Hudgins, E.J., Cuthbert, R.N., Kourantidou, M., Diagne, C., Haubrock, P.J., Leung, B., Liu, C., Leroy, B., Petrovskii, S. Beidas, A., and Chourchamp F., 2022. Managing biological invasions: the cost of inaction. *Biological Invasions*, *24*(7), pp.1927-1946.

Azzurro, E., Sbragaglia, V., Cerri, J., Bariche, M., Bolognini, L., Ben Souissi, J., Busoni, G., Coco, S., Chryssanthi, A., Fanelli, E. and Ghanem, R., Garrabou, J., Gianni, F, Grati F., Kolitari, J., Letterio, G., Lipej, L., Mazzoldi, C., Milone, N., Pannacciulli, F., Pešić, A., Samuel-Rhoads, Y., Saponari, L., Tomanic, J., Eda Topçu, N., Vargiu, G., Moschella, P., 2019. Climate change, biological invasions, and the shifting distribution of Mediterranean fishes: A large-scale survey based on local ecological knowledge. *Global change biology*, 25(8), pp.2779-2792.

Bianchi, C.N., Morri, C., Chiantore, M., Montefalcone, M., Parravicini, V. and Rovere, A., 2012. Mediterranean Sea biodiversity between the legacy from the past and a future of change. *Life in the Mediterranean Sea: a look at habitat changes*, Stambler N. Ed., Nova Publisher, 1, 55 pp.

Catford, J.A., Vesk, P.A., Richardson, D.M. and Pyšek, P., 2012. Quantifying levels of biological invasion: towards the objective classification of invaded and invasible ecosystems. Global Change Biology, 18, pp.44-62.

Cerrano, C., Arillo, A., Azzini, F., Calcinai, B., Castellano, L., Muti, C., Valisano, L., Zega, G. and Bavestrello, G., 2005. Gorgonian population recovery after a mass mortality event. Aquatic Conservation: Marine and Freshwater Ecosystems, 15, pp.147-157.

Elith, J., Phillips, S.J., Hastie, T., Dudík, M., Chee, Y.E. and Yates, C.J., 2011. A statistical explanation of MaxEnt for ecologists. Diversity and Distributions, 17(1), pp.43-57.

Encarnação, J., Teodósio, M.A. and Morais, P., 2021. Citizen science and biological invasions: a review. Frontiers in Environmental Science, 8, 602980.

Galanidi, M., Zenetos, A. and Bacher, S., 2018. Assessing the socio-economic impacts of priority marine invasive fishes in the Mediterranean with the newly proposed SEICAT methodology. Mediterranean Marine Science, 19, p.107.

Garrabou, J., Gómez-Gras, D., Medrano, A., Cerrano, C., Ponti, M., Schlegel, R., Bensoussan, N., Turicchia, E., Sini, M., Gerovasileiou, V., Teixido, N., Mirasole, A., Tamburello, L., Cebrian, E., Rilov, G., Ledoux, J.B., Souissi, J.B., Khamassi, F., Ghanem, R., Benabdi, M., Grimes, S., Ocaña, O., Bazairi, H., Hereu, B., Linares, C., Kersting, D.K., la Rovira, G., Ortega, J., Casals, D., Pagès-Escolà, M., Margarit, N., Capdevila, P., Verdura, J., Ramos, A., Izquierdo, A., Barbera, C., Rubio-Portillo, E., Anton, I., López-Sendino, P., Díaz, D., Vázquez-Luis, M., Duarte, C., Marbà, N., Aspillaga, E., Espinosa, F., Grech, D., Guala, I., Azzurro, E., Farina, S., Gambi, M.C., Chimienti, G., Montefalcone, M., Azzola, A., Mantas, T.P., Fraschetti, S., Ceccherelli, G., Kipson, S., Bakran-Petricioli, T., Petricioli, D., Jimenez, C., Katsanevakis, S., Kizilkaya, I.T., Kizilkaya, Z., Sartoretto, S., Elodie, R., Ruitton, S., Comeau, S., Gattuso, J.P. and Harmelin, J.G., 2022. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. Global Change Biology, 28(19), pp.5708-5725.

Giakoumi, S., Katsanevakis, S., Albano, P.G., Azzurro, E., Cardoso, A.C., Cebrian, E., Deidun, A., Edelist, D., Francour, P., Jimenez, Mačić, V., Occhipinti-Ambrogi, A., Rilov, G. and Sghaier, Y.R., 2019. Management priorities for marine invasive species. *Science of the Total Environment*, *688*, pp.976-982. doi: 10.1016/j.scitotenv.2019.06.282.

Elith, J. and Leathwick, J.R., 2009. Species distribution models: ecological explanation and prediction across space and time. Annual review of ecology, evolution, and systematics, 40(1), pp.677-697.

Hijmans, R.J., 2018. raster: Geographic data analysis and modeling. R package version, 2, p.8. https://rspatial.org/raster/

Hijmans, R.J., Phillips, S., Leathwick, J. and Elith, J., 2024. dismo: species distribution modeling. 10.32614. *CRAN. package. dismo*.

Hortal, J., de Bello, F., Diniz-Filho, J.A.F., Lewinsohn, T.M., Lobo, J.M. and Ladle, R.J., 2015. Seven shortfalls that beset large-scale knowledge of biodiversity. Annual Review of Ecology, Evolution, and Systematics, 46(1), pp.523-549.

Jones, C.G., Lawton, J.H. and Shachak, M., 1994. Organisms as ecosystem engineers. In Ecosystem management: Selected readings (pp. 130-147). New York, NY: Springer New York.

Katsanevakis, S., Coll, M., Piroddi, C., Steenbeek, J., Ben Rais Lasram, F., Zenetos, A. and Cardoso, A.C., 2014. Invading the Mediterranean Sea:

biodiversity patterns shaped by human activities. Frontiers in Marine Science, 1, 00032.

Lejeusne, C., Chevaldonné, P., Pergent-Martini, C., Boudouresque, C.F. and Pérez, T., 2010. Climate change effects on a miniature ocean: the highly diverse, highly impacted Mediterranean Sea. Trends in Ecology & Evolution, 25(4), pp.250-260.

Magurran, A.E., Baillie, S.R., Buckland, S.T., Dick, J.M., Elston, D.A., Scott, E.M., Smith, R.I., Somerfield, P.J. and Watt, A.D., 2010. Long-term datasets in biodiversity research and monitoring: assessing change in ecological communities through time. Trends in Ecology & Evolution, 25(10), pp.574-582.

Miller, J., 2010. Species distribution modeling. Geography Compass, 4(6), pp.490-509.

Ooms, J., 2024. writexl: Export data frames to Excel “xlsx” format. R package version, 1(1).

Provoost, P., Bosch, S. and Appeltans, W., 2022. robis: ocean biodiversity information system (OBIS) client. *R package version*, *2*(3).

Rech, S., Borrell Pichs, Y.J. and García-Vazquez, E., 2018. Anthropogenic marine litter composition in coastal areas may be a predictor of potentially invasive rafting fauna. PloS one, 13(1), p.e0191859.

Rosso, A. and Siddiolo, C., 2024. *Microporella hastingsae* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011 (Bryozoa, Cheilostomatida): a possible new Lessepsian species in the Mediterranean Sea? *Mediterranean Marine Science*, *25*(1), pp.73-83.

Rosso, A., Di Martino, E., Donato, G., Figuerola, B., Gerovasileiou, V., Siddiolo, C., Sinagra, A., Sanfilippo, R. and Sciuto, F., 2025. Unlocking Mediterranean bryozoan diversity: seven new species unveiled after fixing a neotype for *Fenestrulina malusii* (Audouin & Savigny, 1826) (Cheilostomatida, Fenestrulinidae). *ZooKeys*, *1254*, pp.1-74.

Schauberger, P. and Walker, A. (2023) *openxlsx: Read, Write and Edit xlsx Files*. R package version 4.2.5.2.

Schroeder, K., Chiggiato, J., Bryden, H.L., Borghini, M. and Ben Ismail, S., 2016. Abrupt climate shift in the Western Mediterranean Sea. *Scientific reports*, *6*(1), 23009.

Shaffer, H.B., Fisher, R.N. and Davidson, C., 1998. The role of natural history collections in documenting species declines. *Trends in Ecology & Evolution*, *13*(1), pp.27-30.

Wickham, H. and Bryan, J., 2023. R packages. " O'Reilly Media, Inc.".

Zenetos, A. and Galanidi, M., 2020. Mediterranean non indigenous species at the start of the 2020s: recent changes. *Marine Biodiversity Records*, *13*,10, pp.1-17.

Chapter 3

Microporella hastingsae Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011 (Bryozoa, Cheilostomatida): a possible new Lessepsian species in the Mediterranean Sea?

This chapter is widely based on the following publication:

Rosso A., Siddiolo C., (2024) *Microporella hastingsae* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011 (Bryozoa, Cheilostomatida): a possible new Lessepsian species in the Mediterranean Sea? Mediterranean Marine Science, 25(1), 73–83. https://doi.org/10.12681/mms.35863.

3. *Microporella hastingsae* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011 (Bryozoa, Cheilostomatida): a possible new Lessepsian species in the Mediterranean Sea?

3.1. ABSTRACT

The introduction of Non-Indigenous Species (NIS) in the Mediterranean Sea is one of the main threats to biodiversity and its increasing frequency could bring a significant ecological prevalence on native species. However, knowledge of marine bioinvasions, the spreading patterns of NIS and their possible pathways of dispersion is still limited, especially for particular taxonomic groups. In this paper, we report the first Mediterranean record of a colony of a non-indigenous bryozoan, *Microporella hastingsae* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011, found on plastic litter stranded south of Catania (Sicily, western Ionian Sea) during spring 2023. Based on this colony, a formal taxonomic description of *M. hastingsae* is provided for this species, which was recently erected for old, misidentified material collected in the early twentieth century in the Suez Canal and the north Red Sea. We suggest that the species could be considered a Lessepsian migrant assuming it entered the Mediterranean Sea at at some point in the recent past, through larval dispersal and/or the possible facilitation by human activities, presumably shipping. Further surveys in coastal localities of Sicily and the eastern Mediterranean are needed to confirm the status of *M. hastingsae* and to understand if the present colony only represents an occasional record of the species, a forerunner of a arrivals powered by surface circulation, or even the witness of a local established population that still remains to be accertained.

3.2. INTRODUCTION

The establishment of Non-Indigenous Species (NIS) in the Mediterranean Sea is ongoing, leading to an in- crease of ca 28% of NIS between October 2012 and December 2021 (from data in Zenetos et al., 2022, cf Zenetos et al., 2012) and 40% of NIS that became established since 2010 (Zenetos et al., 2022).

Owing to different frameworks and terminology used for the attribution of a specific status to each individual species (e.g., Blackburn et al., 2011; Marchini et al., 2015; Zenetos et al., 2022), the number of species and the composition of inventories of NIS at local and regional scale is highly dynamic and subject to refinements, and even to significant changes through time (e.g., for the Mediterranean: Zenetos and Galanidi, 2020; Zenetos et al., 2022, and therein references to the numerous

updates since 2005), occasionally leading to inconsistencies (see Rosso and Di Martino, 2023, for bryozoans). Owing to continuous changes in the distribution ranges and status of each species, reviews and updates of records are frequent for providing policymakers and stakeholders with refined validated inventories for the

management of NIS at local and basinal scale, also in the frame of the EU's Marine Strategy Framework Directive (e.g., Marchini et al., 2015; Tsiamis et al., 2019).

Some major problems in inventory compilations concern the criteria applied to the definition of the status of each species (Marchini et al., 2015; Zenetos et al., 2022), following its detection and correct identification. Therefore, the number of species in the inventories (especially the number of records) can show a disproportion between large-sized, motile, conspicuous, relevant species and small-sized, less "notable" ones (e.g., sessile, not edible, not exploited and/or not particularly harmful to humans) among which are bryozoans (e.g., Katsanevakis et al., 2020; Ragkousis et al., 2023). In fact, most bryozoans often grow as small colonies in cryptic microhabitats and can be overlooked (e.g., Rosso et al., 2013), if targeted investigation is not carried out. Furthermore, bryozoan identification is based on fine morphological characters requiring the routine use of Scanning Electron Microscopy (SEM) by skilled taxonomists (e.g., Harmelin and Rosso, 2023, and references therein), especially when NIS are part of species complexes (e.g., Harmelin et al., 2012) which include both native species and NIS which differ by only few inconspicuous features (e.g., Harmelin et al., 2011). Hence, the correct identification is crucial for detecting NIS introduction and for monitoring their possible establishment.

For sessile species, introduction is driven by different possible pathways, including transport on floating items, regardless of their natural or artificial origin (see Barnes and Sanderson, 2000; Belmonte, 2019; Garcia-Gómes et al., 2021) besides voluntary and involuntary human-mediated transfer, including shipping (e.g., Zenetos et al., 2012). Owing to the massive use and waste of plastics, such drift material – usually hosting a plethora of encrusting species – could represent a relevant vector in facilitating the spread of species (e.g., Barnes, 2002; Garcia-Gómes et al., 2021; Subías-Baratau et al., 2022; Kannan et al., 2023), often doubling the chances of species dispersal in the tropics (Barnes and Milner, 2004). Winston et al. (1997) and Winston (2012) have considered rafting among the possible dispersal modes for encrusting and pseudo-planktonic organisms that can be transported for long distances over relatively short timescales, as demonstrated through simulated scenarios by Soares et al. (2023). Bryozoans, known for having short-lived larvae (e.g., Winston, 1988) with reduced range spreading ability, benefit

from the availability of drift plastic, on which they form species-rich communities (Winston et al., 1997).

In this context, we report the occurrence of a colony of *Microporella hastingsae* on a piece of plastic debris, stranded in the south of Catania (Sicily, western Ionian Sea). This species has only been recently described by Harmelin et al. (2011) for colonies reported by Hastings (1927) as *M. ciliata* var. *coronata* from the Suez Canal, at Km. 157, near its connection to the Red Sea. The significance of the new record within the species distribution and the spreading of NIS in the Mediterranean Sea, is discussed.

3.3. MATERIALS AND METHODS

Stranded material, including shells and other skeletal remains, wood and plant remains and plastic items were collected during a periodic walking survey along selected pathways at the Plaia, a ca 20 km long beach located in the south of Catania (Ionian coast of Sicily: Fig. 1.1). The survey was performed on the 4th of April 2023, also in the framework of the PhD sampling activities of one of us (C.S.), and included a 30-minutes walking survey in the area of the Simeto river-mouth, in the central sector of the Plaia (coordinates: between 37.390916° N, 15.090242° E and 37.385563° N, 15.090070° E). Collected items were visually inspected to identify the hosted fouling communities and one plastic fragment bearing bryozoans was selected for the present study. Bryozoans were examined under stereomicroscope and colonies of *M. hastingsae* were first documented usinga digital camera and ZEN 3.1 imaging software. After detachment, the colony was photographed, untreated and uncoated under a Tescan Vega 2 LMU, Low Vacuum Scanning Electron Microscope (SEM) at the Microscopical Laboratory of the Department of Biological, Geological and Environmental Sciences of the University of Catania (DipBioGeo). Images were generated using back-scattered electrons. The material is housed at the Palaeontological Museum (PMC) of the DipBioGeo, in the Rosso collection, under the catalogue number PMC Rosso-Collection I. H. B.111a.

3.4. RESULTS

Collected items included an irregularly shaped plastic fragment (possibly the edge of a fruit box), partly burned and solidified after melting, around 20 x 8 x 5 cm in size (Fig. 1). Plant remains, serpulid tubes, encrusting ostreid valves and Anomia adhesion thickenings, byssate (arcid) molluscs, barnacles and encrusting foraminifera fouled this item together with few bryozoan colonies. The latter included

Cryptosula pallasiana (Moll, 1803), *Hagiosynodos latus* (Busk, 1856) and the basal worn parts of undetermined representatives of *Entalophoroecia* sp., *Aetea* sp. and a possible species of *Candidae* detected only by its rhizoids. A single colony of *Microporella hastingsae* was also present (Fig. 3.1) showing evidence of partial breakage and detachment at least of the ancestrula and some periancestrular autozooids, seemingly after stranding. The colony was presumably recently dead because some autozooids still showed opercula and avicularian mandibles and only a few showed some evidence of the iridescent cuticle.

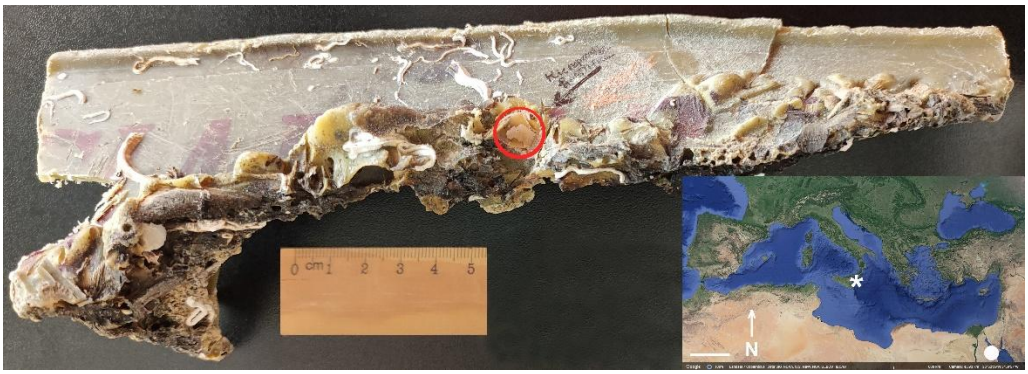

Figure 3.1*: Microporella hastingsae* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011 on its plastic substratum collected at the Simeto river-mouth (Sicily, Ionian Sea). The sole colony is indicated within the red circle. Known distribution of the species. Asterisk: present record; dot: records by Harmelin et al. (2011). Scale bar: 500 km.

The examined colony is encrusting, unilaminar, mul- tiserial, forming a sub-elliptical patch (Fig. 3.2A); zooids communicating via two proximolateral, two distolateral and two, rarely three distal pore-chamber windows, situated along the lateral walls (Fig. 3.2F, 3.3B, C).

Autozooids rhomboidal, usually elongated (mean size 489 x 392 µm), distinct, the boundaries marked by narrow grooves between the slightly raised vertical walls (Figs 3.2 E, F, 3.3D). Frontal shield slightly convex, evenly covered with low, moderately coarse granules, interspersed with 17–45 subcircular pseudopores (15–20 µm in diameter, occasionally larger). Pseudopores usually evenly distributed but missing in the central, proximal and distal portions of some autozooids, seemingly irrespective of their position in periancestrular or peripheral growing areas (Figs 3.2E, F, 3.3A); the area between orifice and ascopore always imperforate (Fig. 3.3B, C). Marginal areolae numbering 6–8 (Fig. 3.2F), barely distinguishable, especially in late ontogeny. Primary orifice (Fig. 3.3B, C) transversely D-shaped (mean size

87×112 μm,) with a mean OL/OW = 0.8; occupying ca 1/5–1/6 of autozooidal length (mean ZL/OL = 5.7); distal rim smooth, the lateral sides slightly converging proximally; hinge-line straight, smooth, without condyles and denticles. Four articulated oral spines, detached in the available colony, rare remnants pointing to their possible shortness (ca 70 μm; see Fig. 3.2C, E); spine bases situated along the distal half of the orifice (Fig. 3.3B, C), the proximal pair often larger (diameter of ca 15 μm) than the distal ones (diameter of ca 10 μm). Only two spines have been observed on regenerated autozooids (Fig. 3.3D).

Ascopore field, consisting of smooth gymnocystal calcification, located 40–60 μm below the orifice, subcircular, ca 50 μm in diameter, encircled by a thick and smooth rim, often more raised proximally. Ascopore widely and transversely C-shaped, with tiny radial denticles and a small, median tongue projecting from the distal edge, often consisting of 1–3 more prominent denticles (Fig. 3.3B, C).

Avicularia paired (mean size 115 × 84 μm), located just proximolaterally to the orifice (Figs 3.2B, D, 3.3A); crossbar complete, usually level with the space between the ascopore and orifice; rostrum short, truncated distally and open-ended, distally directed. Mandible brown, 220–320 μm long, setiform and straight, lying on the distal autozooid (Fig. 3.3A) or on the frontal shield when open (Fig. 3.2D). Avicularia single, located more proximally than the paired ones and directed distolaterally on presumed periancestrular autozooids (Fig. 3.2A, C), or placed and directed more irregularly on regenerated autozooids (Figs 3.2B; 3.3D, E).

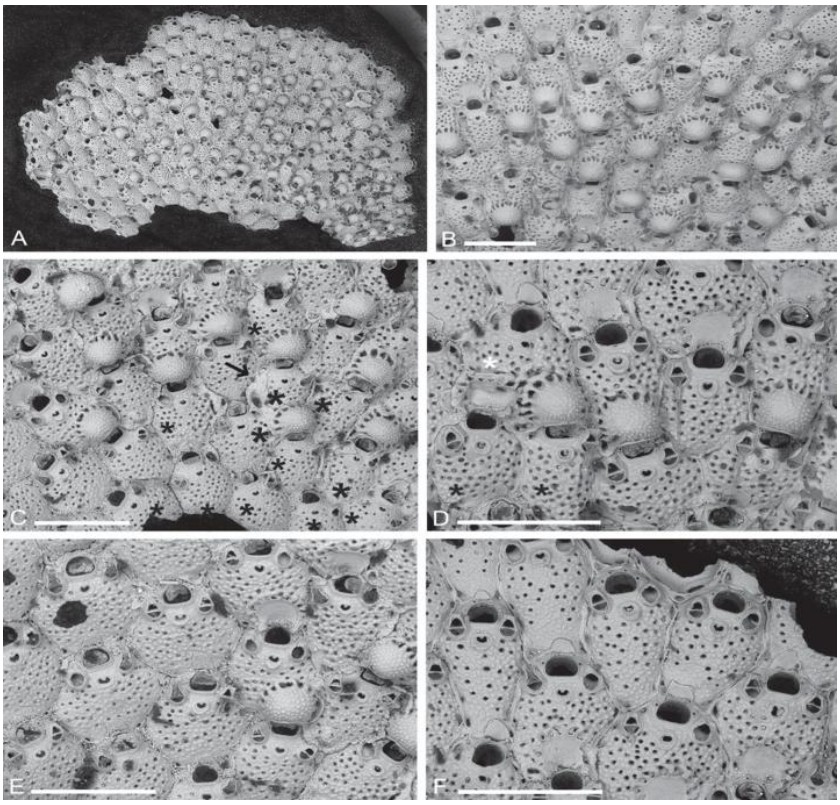

Figure 3.2: *Microporella hastingsae* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011: colony and autozooidal appearance. (A) General view of the examined colony (PMC Rosso-Collection I. H. B.111a) collected at the Simeto mouth (Sicily, Ionian Sea). (B) Colony portion showing ovicellate and non-ovicellate autozooids. (C) The possible periancestrular area with several autozooids showing single avicularia (black asterisks), some (large asterisks) in connection with kenozooidal production from marginal areolae. (D) Subsequent autozooid rows with complete and incomplete ovicells. Black asterisks: autozooids with a single avicularium, that on the left showing internal budding; white asterisk: an autozooid missing both avicularia. (E) Wide rhomboidal autozooids. (F) Autozooids at the colony margin. Scale bars: 2 mm: (A); 500 μm (B-F).

Ovicell subglobular prominent (mean size 206 × 238 μm), non-personate, not obscuring the proximal part of the orifice, leaving visible the proximal-most pair of spines; produced by and continuous with the frontal shield of the distal autozooid but with the distal boundary marked by a row of 11–14 (commonly 13) large marginal areolae; calcification fabric non-porous and more finely and regularly granular than the frontal shield; proximal margin of gymnocystal calcification forming a raised visor-like band.

Ancestrula missing from the partly broken observed colony.

Reparative budding frequent, leading to the formation of 1) irregularly shaped, kenozooid-like structures with extensive cryptocyst produced by frontal budding from autozooidal marginal areolae (e.g., Fig. 3.2C, arrowed) and 2) autozooids with extremely irregular shapes and orientations (Figs 3.2B, 3.3D-E) originating from broken autozooids, even including an hourglass shape with an apparently proximally located orifice and a very distal single avicularium (Figs 3.2B, 3.3D).

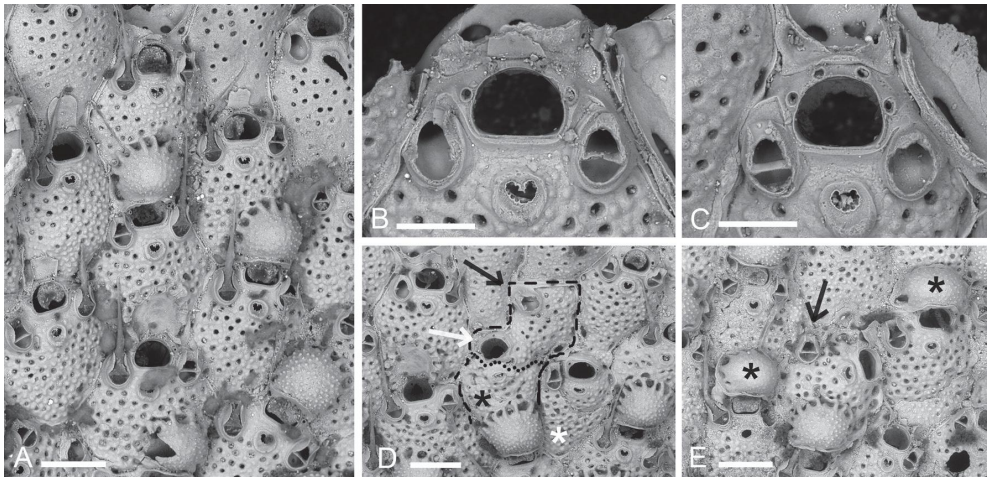

Figure 3.3*: Microporella hastingsae* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011: details of diagnostic features and reparative regeneration. (A) Close-up of ovicellate and non-ovicellate autozooids with avicularia, some setiform mandibles still present. (B) Distal part of an autozooid: note the complete ascopore, the smooth-rimmed D-shaped orifice and the orificial spine bases, the distal-most smaller. (C) As (B), but with four equally sized spine bases. (D) Regeneration and fusion of two neighbouring autozooids forming an hourglass new module (marked with a dashed line). The regenerated autozooid (regeneration line marked by dots) develops an inclined, irregular, proximally placed orifice (white arrow), an incomplete ascopore, and a unique distally placed avicularium (black arrow) unrelated with the orifice. Another autozooid (white asterisk), regenerated as a miniature autozooid without avicularia and only two distal spines. (E) A damaged area of the colony showing an irregularly oriented regenerated autozooid with only one irregularly placed avicularium (black arrow) inherited from the preceding broken autozooid, and two ovicells, possibly regenerated from marginal areolae (black asterisks). Scale bars: 200 μm: (A) (D), (E); 100 μm: (B), (C).

3.5. DISCUSSION AND CONCLUSION

According to Harmelin et al. (2011), *Microporella hastingsae* only occurred in the Red Sea and the southern entrance of the Suez Canal. In fact, all known colonies were collected in that area at the beginning of the last century, in 1904 (Crossland, 1907, for material examined by Waters, 1909), in 1924 (Hastings, 1927) and between December 1928 and January 1929 (Balavoine, 1959), though they were reported later on and under different names (see above). This is the first record of

the species following its erection, and the only colony from the Mediterranean Sea documented with SEM images.

Harmelin et al. (2011) suggested that at least some of the records of *Microporella coronata* from the Mediterranean Sea reported as *M. umbracula* Harmer, 1957 that they doubtfully synonymised with *M. coronata*, could partially belong to *M. hastingsae*. These include the ones from Turkey (Nicoletti et al., 1995), the Ionian Sea (Di Geronimo et al., 1998); Milos Island, Aegean Sea (Morri et al., 1999) and Cyprus, Levantine Sea (Koçak et al., 2002). Some of the aforementioned records seem to correspond to *M. appendiculata* (see Di Martino and Rosso, 2021), but re-examination of these colonies is necessary, especially considering the high morphological variability previously assigned to the *Microporella ciliata-M. coronata* group of species, the absence of SEM images, and the lack of any photographic documentation for those records. However, in our opinion, the two species (*M. hastingsae* and *M. coronata*) can be distinguished based on their morphological characters (see Harmelin et al., 2011 and above) through careful microscopical and/or SEM examination. The differences in morphology are more obvious in fertile colonies owing to the ovicell characteristics, but differences such as the shape of the orifice and the number of oral spines, are also visible in non-ovicellate autozooids.

In this scenario, the interpretation of the occurrence of *M. hastingsae* from the Simeto river-mouth is challenging. The species has so far been surely identified only from ca one hundred-year-old material originating from the Red Sea and the Red Sea-facing portions of the Suez Canal. It has not been detected in the Levantine Sea, despite the extensive sampling performed at the beginning of this century along the coasts of Cyprus (Achilleos et al., 2020, on surveys of the 2011–2018 period) and Lebanon (Harmelin, 2014; Harmelin et al., 2016, on surveys performed between 1992 and 2003, except for one in 1968, oddly without *Microporella* species listed in the former one). We can confidently rule out the overlooking of *M. hastingsae* by Harmelin et al. (2016) because he coauthored the description of the species (Harmelin et al., 2011). Furthermore, from the examination of photos kindly provided by Katerina Achilleos (University of Otago, New Zealand), we can also exclude the conspecificity of *M. hastingsae* and the colony that Achilleos et al. (2020) reported as *Microporella* aff. *coronata* from a shipwreck off Cyprus. *Microporella hastingsae* has not been found either in the Aegean Sea, between the Levantine Sea and Sicily, notwithstanding some recent bryozoan investigations and checklists in the area (Koçak and Aydin Önen, 2014; Gerovasileiou and Rosso, 2016; Rosso et al., 2019a, b; 2022) confirming the doubtfulness of records of the species under different names in these areas (see above).

Indeed, no further record of *M. hastingsae* is available subsequent to those by Harmelin et al. (2011) from the Red Sea and Harmelin et al. (2016) did not reported the species from the Lebanese coast where they found at least four *Microporella* NIS, i.e., *M. browni* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011, *M. coronata*, *M. genisii* (Audouin and Savigny 1826) and *M. harmeri* Hayward, 1988, omitting an undescribed *Microporella cf ciliata* (see also the updated checklist of NIS bryozoan species by Ferrario et al., 2018). Leaving aside the problematic records of *M. coronata*, the NIS *Microporella* species reported by Harmelin seem to be restricted to the Lebanese coast not spreading westward in the Mediterranean, and they were absent from the samples collected in the last decades around Sicily and southern Italy recently examined by Di Martino and Rosso (2021).

Consequently, if we discard the possibility of a rafting displacement directly from the Red Sea and the Suez Canal to eastern Sicily, we could assume that *M. hastingsae* possibly entered the Mediterranean Sea, within the last dozen years, presumably after Harmelin's surveys. It is reasonable to assume that it was transferred from the Red Sea to the Mediterranean through the intense shipping in the Suez Canal, as suggested for other species by Harmelin et al. (2016, and references therein) or even through larval dispersal (also possibly aided by relays or the stepping stones provided by local hard substrata, including working boats). If this is true and established populations will be surely detected in that area, the species can be considered as a Lessepsian migrant and a Mediterranean NIS, like other congeners (see above).

However, whereas we know that a living or very recently dead colony of *M. hastingsae* reached the Catania Plaia by rafting on drift plastic debris, we have no information about the origin of that material. Especially, we do not know if the studied colony derives from a population established in the very eastern sector of the Mediterranean or from localities in between, and further investigation is required to ascertain if self-sustaining populations occur in the basin. Geographically distinct records of NIS bryozoans in the Mediterranean are not uncommon, and at least one other species, *Smittina nitidissima* (Hincks, 1880), is known from Lebanon and from the shallow-water submarine Granchi Cave in the western Ionian Sea (Plemmirio Peninsula, near Siracusa, south-eastern Sicily). However, in that case living colonies were found on a plastic settlement panel deployed for six months inside the cave (Rosso et al. 2018) and the rapid colonization could indicate the occurrence of fertile colonies in the area and possibly a self-sustaining population of the species.

In contrast, the so far unique colony of *M. hastingsae* was not alive at the time of collection, and it was not found within the coastal benthos or attached on a natural substratum. Consequently, it cannot be considered, tout court, as a proof of the possible expansion of the species geographical range in the Mediterranean. Indeed, species can be absent in natural habitats although detected on drifted plastics in the same area. For example, Winston et al. (1997) reported that *Thalamoporella evelinae* Marcus, 1939 was not detected in coastal habitats of Florida, despite its occurrence (and with brooding colonies) on drift plastic in the same area. The occurrence of ovicellate autozooids in the *M. hastingsae* colony indicates its reproductive status. However, it is not possible to know whether the larvae were released in the Plaia coastal area or elsewhere during drifting, and if they were able to settle and survive in the local natural environment. We also lack colonies of the species collected in the area. As a matter of fact, single findings, especially from drifting items or boat hulls are not considered as NIS occurrences. Such records, although previously considered as valid, have been recently discarded in updated inventories or considered as uncertain occurrences (e.g., Marchini et al., 2015; Zenetos et al., 2022).

It is worth noting that plastic items can be displaced for long distances by wind and currents, potentially transporting species in areas far beyond their original range where successful larval release and larval recruitment on the coast could produce new self-sustaining populations, as remarked for bryozoans and other benthic organisms (e.g., Soares et al., 2023). Winston (2012) cites the example of *Schizoporella pungens* Canu and Bassler, 1928, a species unknown from the Indian River area until the early 21st century. This species was first detected there in 2002 on drift plastic, later found on fouling panels at Fort Pierce inlet (2003) and soon after on natural and artificial substrata in the same and neighbouring areas, thus clearly hinting at drift-plastic items as its transfer vector.

Soares et al. (2023) showed that drift-plastic debris could travel by current for hundreds of kilometres from north Brazil to the Caribbean, taking about 180 days. It has also been proven by Fazey and Ryan (2016) that plastic debris can float for a considerable amount of time with- out sinking to the bottom by the increasing weight of the epibionts' load. Assuming comparable travel times, it is likely that drift material could serve as an effective vector for transporting encrusters from the Levantine basin to the western Ionian Sea.

To conclude, the stranded *M. hastingsae* colony could represent the vanguard of an ongoing spreading of the species from putative, still undiscovered, eastern Mediterranean populations to the Ionian Sea, through drift plastic, either as the result

of a single travel event, or possible multiple “stepping stones” displacement, also favoured by rafting. Because of the Red Sea subtropical origin of the species (Harmelin et al., 2011), its possible expansion following transport events could be facilitated by climate change and the current warming of the Mediterranean (e.g., Wesselmann et al., 2021, and references therein). Further investigation is needed to assess the status of the species in Sicily and the Mediterranean Basin after ascertaining if self-sustaining populations of the species already to support species establishment in these areas.

3.6. REFERENCE LIST

Achilleos, K., Jimenez, C., Berning, B. and Petrou, A., 2020. Bryozoan diversity of Cyprus (eastern Mediterranean Sea): first results from census surveys (2011–2018). *Mediterranean Marine Science*, 21(1), pp.228-237.

Barnes, D.K., 2002. Invasions by marine life on plastic debris. *Nature*, 416(6883), pp.808-809.

Barnes, D.K. and Sanderson, W.G., 2000. Latitudinal patterns of colonization of marine debris. In Herrera Cubilla, A. and Jackson, J.B.C. (Eds) Proceedings of the 11th International Bryozoology Association Conference. Smithsonian Tropical Research Institute, Balboa (pp. 154-160).

Barnes, D.K.A. and Milner, P., 2005. Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. *Marine Biology*, 146(4), pp.815-825.

Belmonte, G., 2019. Floating Objects of Non Marine Origin, Rafting of Marine Organisms, and the Interfering Role of Man in Mediterranean Sea. *International Journal of Oceanography & Aquaculture*, 3, 000168.

Belmonte, G., 2019. Floating objects of non marine origin, rafting of marine organisms, and the interfering role of man in Mediterranean Sea. *International Journal of Oceanography & Aquaculture*, 3, 000168.

Blackburn, T.M., Pyšek, P., Bacher, S., Carlton, J.T., Duncan, R.P., Jarošík, V., Wilson, J.R. and Richardson, D.M., 2011. A proposed unified framework for biological invasions. *Trends in Ecology & Evolution*, 26(7), pp. 333-339.

Bock, P., 2016. The bryozoan Home Page. bryozoa.net (Accessed 28.8.2023).

Crossland, C.M.A., 1907. Reports on the Marine Biology of the Sudanese Red Sea.–II. Narrative of the Expedition. *Zoological Journal of the Linnean Society*, 31, 3-10.

Di Geronimo, I., La Perna, R., Rosso, A. and Sanfilippo, R., 1998. Notes on two upper-circalittoral assemblages from the Amendolara Bank (Northern Ionian Sea). *Bollettino Accademia Gioenia di Scienze Naturali*, 30, pp.243-262.

Di Martino, E. and Liow, L.H., 2021. Larger offspring associated with lower temperatures across species of *Microporella*, a widespread colonial invertebrate. *Marine Ecology Progress Series*, 662, pp.1-13.

Di Martino, E. and Liow, L.H., 2022. Changing allometric relationships among fossil and Recent populations in two colonial species. *Evolution*, 76(10), pp.2424-2435.

Di Martino, E. and Rosso, A., 2021. Seek and ye shall find: new species and new records of *Microporella* (Bryozoa, Cheilostomatida) in the Mediterranean. *Zookeys*, 1053, pp.1-42.

Fazey, F.M. and Ryan, P.G., 2016. Biofouling on buoyant marine plastics: An experimental study into the effect of size on surface longevity. *Environmental Pollution*, 210, pp.354-360.

Ferrario, J., Rosso, A., Marchini, A. and Occhipinti-Ambrogi, A., 2018. Mediterranean non-indigenous bryozoans: an update and knowledge gaps. *Biodiversity and Conservation*, 27(11), pp.2783-2794.

García-Gómez, J.C., Garrigós, M. and Garrigós, J., 2021. Plastic as a vector of dispersion for marine species with invasive potential. A review. *Frontiers in Ecology and Evolution,* 9, p.629756.

Gerovasileiou, V. and Rosso, A., 2016. Marine Bryozoa of Greece: an annotated checklist. *Biodiversity Data Journal*, 4, e10672.

Harmelin, J.G., 2014. Alien bryozoans in the eastern Mediterranean Sea—new records from the coast of Lebanon. *Zootaxa*, 3893 (3), 301-338.

Harmelin, J.G. and Rosso, A., 2023. On some "*Hemicyclopora*" Norman, 1894 and "*Escharella*" Gray, 1848 species (Bryozoa, Cheilostomatida) from the Atlantic-Mediterranean region. Re-examination of their generic status and description of new species and a new genus. *Zoosystema*, 45(10), pp.373-407.

Harmelin, J.G., Ostrovsky, A.N., Caceres-Chamizo, J.P. and Sanner, J., 2011. Bryodiversity in the tropics: taxonomy of *Microporella* species (Bryozoa, Cheilostomata) with personate maternal zooids from Indian Ocean, Red Sea and southeast Mediterranean. *Zootaxa*, 2798(1), pp.1-30.

Harmelin, J.G., Vieira, L.M., Ostrovsky, A.N., Cáceres-Chamizo, J.P. and Sanner, J., 2012. *Scorpiodinipora costulata* (Canu and Bassler, 1929) (Bryozoa, Cheilostomata), a taxonomic and biogeographic dilemma: complex of cryptic species or human-mediated cosmopolitan colonizer?. *Zoosystema*, 34(1), pp.123-138.

Harmelin, J.G., Bitar, G. and Zibrowius, H., 2016. High xenodiversity versus low native diversity in the south-eastern Mediterranean: bryozoans from the coastal zone of Lebanon. *Mediterranean Marine Science*, 17(2), pp.417-439.

Hastings, A.B. 1927. Cambridge expedition to the Suez Canal, 1924. Pt. 20. Report on the Polyzoa. *Transactions of the Zoological Society, London*, 22 (3), 331-353.

Kannan, G., Mghili, B., Di Martino, E., Sanchez-Vidal, A. and Figuerola, B., 2023. Increasing risk of invasions by organisms on marine debris in the Southeast coast of India. *Marine Pollution Bulletin*, 195, p.115469.

Katsanevakis, S., Poursanidis, D., Hoffman, R., Rizgalla, J., Rothman, S.B.S., Levitt-Barmats, Y.A., Hadjioannou, L., Trkov, D., Garmendia, J.M., Rizzo, M. Bartolo, A.G., Bariche, M., Tomas, F., Kleitou, P., Schembri, P.J., Kletou, D., Tiralongo, F., Pergent, C., Pergent, G., Azzurro, E., Bilecenoglu, M., Lodola, A., Ballesteros, E., Gerovasileiou, V., Verlaque, M., Occhipinti-Ambrogi, A., Kytinou, E., Dailianis, T., Ferrario, J., Crocetta, F., Jimenez, C., Evans, J., Ragkousis, M., Lipej, L., Borg, J.A., Dimitriadis, C., Chatzigeorgiou, G., Albano, P.G., Kalogirou, S., Bazairi, H., Espinosa, F., Ben Souissi, J., Tsiamis, K., Badalamenti, F., Langeneck, J., Noel, P., Deidun, A., Marchini, A., Skouradakis, G., Royo, L., Sini, M., Bianchi, C.N., Sghaier, Y.R., Ghanem, R., Doumpas, N., Zaouali, J., Tsirintanis, K., Papadakis, O., Morri, C., Çinar, M.E., Terrados, J., Insacco, G., Zava, B., Soufi-Kechaou, E., Piazzi, L., Ben Amor, K.O., Andriotis, E., Gambi, M.C., Ben Amor, M.M., Garrabou, J., Linares, C., Fortič, A., Digenis, M., Cebrian, E., Fourt, M., Zotou, M., Castriota, L., Di Martino, V., Rosso, A., Pipitone, C., Falautano, M., García, M., Zakhama-Sraieb, R., Khamassi, F., Mannino, A.M., Ktari, M.H., Kosma, I., Rifi, M., Karachle, P.K., Yapıcı, S., Bos, A.R., Balistreri, P., Esplá, A.A.R., Tempesti, J., Inglese, O., Giovos, I., Damalas, D., Benhissoune, S., Huseyinoglu, M.F., Rjiba-Bahri, W., Santamaría, J., Orlando-Bonaca, M., Izquierdo, A., Stamouli, C., Montefalcone, M., Cerim, H., Golo, R., Tsioli, S., Orfanidis, S., Michailidis, N., Gaglioti, M., Taşkın, E., Mancuso, E., Žunec, A., Cvitković, I., Filiz, H., Sanfilippo, R., Siapatis, A., Mavrič, B., Karaa, S., Türker, A., Monniot, F., Verdura, J., El Ouamari, N., Selfati, M. and Zenetos, A., 2020. Unpublished Mediterranean records of marine alien and cryptogenic species. *BioInvasions Records*, 9(2), pp.165-182.

Koçak, F. and Aydin Önen, S., 2014. Checklist of Bryozoa on the coasts of Turkey. *Turkish Journal of Zoology*, 38(6), 880-891.

Koçak, F., Balduzzi, A., Benli, H.A., 2002. Epiphytic bryozoan community of *Posidonia oceanica* (L.) Delile meadow in the northern Cyprus (Eastern Mediterranean). *Indian Journal of Marine Science*, 31, 235-238.

Marchini, A., Galil, B.S. and Occhipinti-Ambrogi, A., 2015. Recommendations on standardizing lists of marine alien species: Lessons from the Mediterranean Sea. *Marine Pollution Bulletin*, 101(1), 267-273.

Morri, C., Bianchi, C.N., Cocito, S., Peirano, A., Biase, A.D., Aliani, S., Pansini, M., Boyer, M., Ferdeghini, F., Pestarino, M. and Dando, P., 1999. Biodiversity of marine sessile epifauna at an Aegean island subject to hydrothermal activity: Milos, eastern Mediterranean Sea. *Marine Biology*, 135(4), 729-739.

Ragkousis, M., Zenetos, A., Souissi, J., Hoffman, R., Ghanem, R., Taşkin, E., Muresan, M., Karpova, E., Slynko, E., Dağli, E. and Fortič, A., 2023. Unpublished Mediterranean and Black Sea records of marine alien, cryptogenic, and neonative species. *BioInvasions Records*, 12(2).

Rosso, A. and Di Martino, E., 2023. Capturing the moment: a snapshot of Mediterranean bryozoan diversity in the early 2023. *Mediterranean Marine Science*, 24(2), 426-445.

Rosso, A., Di Martino, E., Pica, D., Galanti, L., Cerrano, C. and Novosel M., 2018. Non-indigenous bryozoan species from natural and artificial substrata of Mediterranean submarine caves. *Marine Biodiversity*, 48, 1345-1355.

Rosso, A., Di Martino, E., Sanfilippo, R. and Di Martino, V., 2013. Bryozoan Communities and Thanatocoenoses from Submarine Caves in the Plemmirio Marine Protected Area (SE Sicily). In Ernst, A. et al. (Eds) Bryozoan Studies 2010. Proceedings of the 15th IBA Conference, 2010 Kiel, Germany. *Lecture Notes in Earth System Sciences*, 143, 251-269.

Rosso, A., Gerovasileiou, V. and Digenis, M., 2022. New insights into the bryozoan diversity of marine caves of the Aegean Sea (Eastern Mediterranean). p. 75-79. In Bouafif, C., and Ouerghi, A. (Eds) *Proceedings of the 3rd Mediterranean Symposium on the conservation of Dark Habitats*. SPA/RAC, Tunis.

Rosso, A., Gerovasileiou, V., Sanfilippo, R. and Guido, A., 2019a. Bryozoans assemblages from two submarine caves in the Aegean Sea (Eastern Mediterranean). *Marine Biodiversity*. 49 (2), 707-726.

Rosso, A., Gerovasileiou, V., Sanfilippo, R. and Guido, A., 2019b. Undisclosed bryodiversity of submarine caves of the Aegean Sea (Eastern Mediterranean). p. 47-52. In: *Proceedings of the 2nd Mediterranean Symposium on the conservation of Dark Habitats*. Langar H. and Ouerghi A. (Eds). SPA/RAC, Tunis.

Soares, M.O., Garcia, T.M., Giarrizzo, T., Filho, J.E.M., Tavares, T.C.L. et al., 2023. Marine debris provide long-distance pathways for spreading invasive corals. Science and the Total Environment, 23, 165637.

Subías-Baratau, A., Sanchez-Vidal, A., Di Martino, E., Figuerola, B., 2022. Marine biofouling organisms on beached, buoyant and benthic plastic debris in the Catalan Sea. *Marine Pollution Bulletin*, 175, 113405.

Tsiamis, K., Palialexis, A., Stefanova, K., Gladan, Z.N., Skejic, S., Despalatović, M., Cvitković, I., Dragičević, B., Dulčić, J., Vidjak, O., Bojanić, N., Žuljević, A., Aplikioti, M., Argyrou, M., Josephides, M., Michailidis, N., Jakobsen, H.H., Staehr, P.A., Ojaveer, H., Lehtiniemi, M., Massé, C., Zenetos, A., Castriota, L., Livi, S., Mazziotti, C., Schembri, P.J., Evans, J., Bartolo, A.G., Kabuta, S.H., Smolders, S., Knegtering, E., Gittenberger, A., Gruszka, P., Kraśniewski, W., Bartilotti, C., Tuaty-Guerra, M., Canning-Clode, J., Costa, A.C., Parente, M.I., Botelho, A.Z., Micael, J., Miodonski, J.V., Carreira, G.P., Lopes, V., Chainho, P., Barberá, C., Naddafi, R., Florin, A.B., Barry, P., Stebbing, P.D. and Cardoso, A.C., 2019. Non-indigenous species refined national baseline inventories: A synthesis in the context of the European Union's Marine Strategy Framework Directive. Mar Pollut Bull. 2019 Aug;145:429-435. doi: 10.1016/j.marpolbul.2019.06.012.

Waters, A.W., 1909 Reports on the marine biology of the Sudanese Red Sea, from the collections made by Cyril Crossland, M.A., B.Sc., F.Z.S.; together with collections made in the Red Sea by Dr. Hartmeyer. XII. The Bryozoa. Part I, Cheilostomata. *Journal of the Linnean Society of London, Zoology*, 31, 123-181.

Wesselmann, M., Chefaoui, R.M., Marbà, N., Serrao, E.A., Duarte, C.M., 2021. Warming Threatens to Propel the Expansion of the Exotic Seagrass *Halophila stipulacea*. *Frontiers in Marine Science*, 8, 759676.

Winston, J.E., 1988. Life histories of free-living bryozoans. *National Geographic Research*, 4, 528-539.

Winston, J.E., 2012. Dispersal in Marine Organisms without a Pelagic Larval Phase. *Integrative and Comparative Biology*, 1-11.

Winston, J.E., Gregory, M.R., Stevens, L.M., 1997. Encrusters, epibionts, and other biota associated with pelagic plastics: a review of biogeographical, environmental, and conservation issues. p. 81-97. In: *Marine debris: sources, impact and solutions*. Coe, J.M. and Rogers, D.B. (Eds). Springer, New York.

Zenetos, A., Galanidi, M., 2020. Mediterranean non-indigenous species at the start of the 2020s: recent changes. *Marine Biodiversity Records*, 13, 10.

Zenetos, A., Gofas, S., Morri, C., Rosso, A., Violanti, D., Garcia Raso, J., Cinar, M., Almogi-Labin, A., Ates, A., Azzurro, E., Ballesteros, E., Bianchi, C., Bilecenoglu, M.,

Gambi, M., Giangrande, A., Gravili, C., Hyams-Kaphzan, O., Karachle, V., Katsanevakis, S., Lipej, L., Mastrototaro, F., Mineur, F., Pancucci-Papadopoulou, M., Ramos-Esplá, A., Salas, S., San Martin, G., Sfriso, A., Streftaris, N. and Verlaque, M., 2012. Alien species in the Mediterranean Sea by 2012. A contribution to the application of European Union's Marine Strategy Framework Directive (MSFD). Part 2. Trends in introduction and pathway. *Mediterranean Marine Science*, 13 (2), 328-352.

Zenetos, A., Albano, P.G., López Garcia, E., Stern, N., Tsiamis, K. and Galanidi, M., 2022. Established non-indigenous species increased by 40% in 11 years in the Mediterranean Sea, *Mediterranean Marine Science*, 23(1). doi: 10.12681/mms.29106.

Chapter 4

Going west: the spread of non-indigenous *Microporella* (Bryozoa) species on drift plastic debris

This chapter is widely based on the following publication:

Rosso A., Di Martino E., Siddiolo C., (2025) Going west: the spread of non-native *Microporella* (Bryozoa) species on drift plastic debris. Mediterranean Marine Science, 26(1), 71–89. https://doi.org/10.12681/mms.38996.

Note: This chapter has been rearranged with respect to the original paper and focuses mainly on ecological, geographical and distributional aspects, reducing or omitting details strictly related to taxonomy. The species discussed below are only some of those discussed in the paper (i.e. the two introduced ones plus *M. ichnusae*, whose discovery in Sicily resulted directly from sampling activities planned within this thesis), although some figures (from the paper) represent them all.

4 Going west: the spread of non-indigenous *Microporella* (bryozoa) species on drift plastic debris

4.1. ABSTRACT

Despite being a major threat to biodiversity, the understanding of marine bioinvasions remains limited, especially regarding newly emerging vectors or dispersion pathways. In this paper, we report the finding of viable colonies of *Microporella ichnusae*, *M. hastingsae* and *M. browni* on plastic debris stranded on sandy beaches. The native species *M. ichnusae*, previously known only from its type locality in northwestern Sardinia, now widens its known distribution range to the west coast of Sicily, following its recovery on a plastic fragment at Magaggiari beach. Conversely, findings of the non-indigenous *M. hastingsae* and *M. browni*, particularly abundant on lifejackets stranded in the western Ionian Sea (Catania), represent localities far from their previously known distributions in the Suez Canal and the Levantine and Red Sea-Indian Ocean regions, respectively. We suggest that these pioneering colonies, found on drift plastics between April 2023 and May 2024, may have arrived through rafting by surface currents. Fouling on buoyant plastics could originate directly from unknown populations in the eastern Mediterranean, or secondarily through shipping, which may have introduced larvae that subsequently attached to plastics along the coast of Sicily. These findings point to the need for further investigations to confirm the status of these species in Sicily and the Mediterranean and whether established populations of *M. hastingsae* and *M. browni* exist in coastal habitats in these areas and specifically where.

4.2. INTRODUCTION

The ongoing introduction of Non-Indigenous Species (NIS) is a significant and increasing threat to global biodiversity, including in the Mediterranean (e.g., Tsirintanis et al., 2022; Zenetos et al., 2022a). This consideration extends to bryozoans, with a continuous increase in species records (e.g., Katsanevakis et al., 2020; Ragkousis et al., 2023) and new species becoming established (Zenetos et al., 2022b). While shipping and aquaculture are well-recognised pathways, the role of drift plastic and other waste materials has not been thoroughly examined. Plastic debris is colonised by various species, especially opportunistic and non-indigenous ones, that can establish dense, specialised populations, with shallow-water filter-feeding invertebrates particularly adapted (e.g., Kiessling et al., 2015). Since the introduction of plastics, the volume of anthropogenic drift material has surged, with

its buoyancy enabling long-distance transport via surface currents, increasing the risk of species dispersal.

The potential role of rafting on drift material in species spread (e.g., Winston et al., 1997; Lewis et al., 2005; Audrézet et al., 2021; Kannan et al., 2023) has likely been underestimated, especially in the Mediterranean Sea. Similarly, the contribution of these substrata to local transfer of NIS remains underexplored, although plastic panels and nets have proven effectiveness in recruiting and could be useful for monitoring first arrivals of new species (e.g., Miralles et al., 2018; Giacobbe et al., 2024). In this context, we document the presence of two NNS of the genus *Microporella* found on plastic litter beached in Sicily, specifically focusing on findings from lifejackets and plastic fragments. *Microporella browni* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011 is first reported from locations outside the coast of Lebanon, where it was previously known within the Mediterranean. We also confirm the occurrence of *M. hastingsae* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011 in the western Ionian Sea, following the discovery of colonies on plastic waste (including lifejackets) collected south of Catania. Furthermore, we document the presence of the native Mediterranean species *M. ichnusae* on plastic fragments from Magaggiari beach, widening its known distribution range. We provide information about morphological variability of these species and discuss potential pathways for their transport from previously known distribution areas.

4.3. Materials and Methods

The material examined was collected after surveys conducted between April 2023 and May 2024. For the purpose of this study, we focus on material recovered from Magaggiari beach in Cinisi, Palermo (SW Tyrrhenian Sea), Ponente Beach (Milazzo peninsula, SE Tyrrhenian Sea), Torre Faro, north to Messina (NW Ionian Sea), the coastline near Catania in the western Ionian Sea (specifically Aci Castello, Spiaggia libera n. 1 and the mouth of the Simeto River) and the Santa Maria del Focallo Beach (E Sicily Channel) (Fig. 4.1). The surveys were part of a monitoring project focused on fouling communities found on drift items that usually wash ashore after storms. The material was collected either by picking encrusted plastic debris during 30- or 45-minute walks or along 1 meter wide, 100-meter-long transects roughly parallel to the coastline. The stranded material predominantly consisted of plastic items, including lifejackets and various plastic fragments. Upon visual inspection, items containing colonies of Microporella species were selected.

Bryozoans were examined under a stereomicroscope, and selected colonies were photographed, untreated and uncoated, using a Tescan Vega 2 LMU Scanning

Electron Microscope (SEM) at the the Microscopical Laboratory of the Department of Biological, Geological and Environmental Sciences of the University of Catania (DSBGA). Images were generated using back-scattered electrons. Measurements were taken from SEM micrographs using ImageJ. Abbreviations for the measurements are: O (orifice), Ov (ovicell), L (length), and W (width).

The studied material is housed in the Paleontological Museum (PMC) of the DSBGA, under the following catalogue numbers for the target species:

- *M. hastingsae*: PMC AR-EDM Collection I. H. B.111a, a1 from Catania, 2023, 2024 and Santa Maria del Focallo, respectively.
- *M. browni*: PMC AR-EDM Collection I. H. B.117a, a1, a2, b and c for colonies from Catania, 2023, 2024, Aci Castello, Capo Milazzo Peninsula, and Torre Faro, respectively.
- *M. ichnusae:* PMC AR-EDM Collection I. H. B.118a for colonies from Magaggiari beach, Palermo.

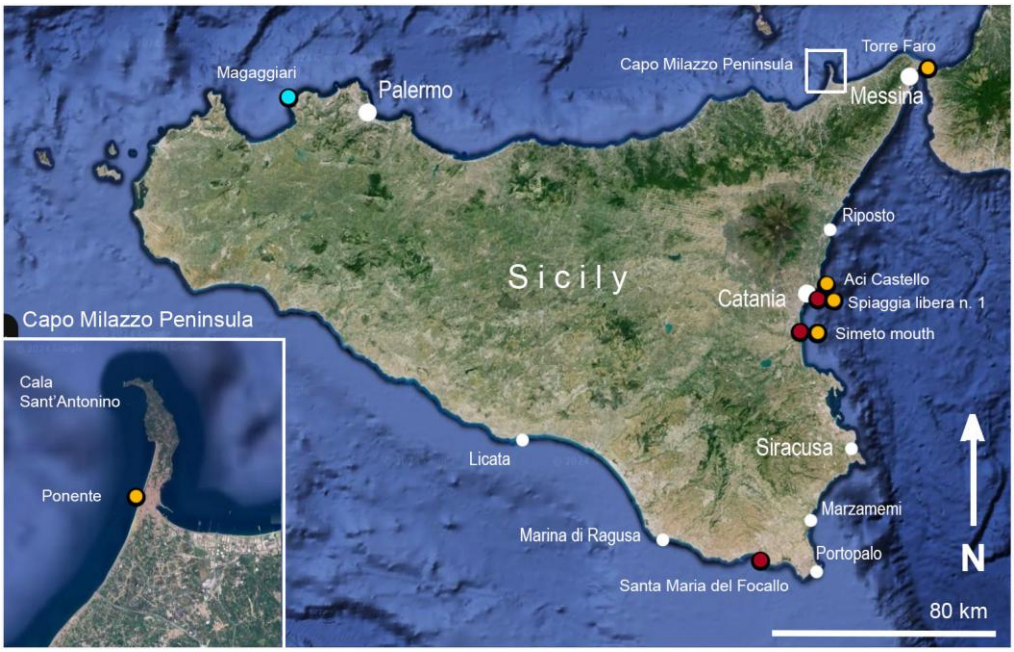

Figure 4.1: Map of Sicily with an inset showing the Capo Milazzo Peninsula (sourced from Google Earth), highlighting the survey locations from 2023 and 2024 where the here studied *Microporella* species were recorded. *Microporella browni*: yellow; *M. hastingsae*: red; *M. appendiculata*: green; *M. ichnusae*: pale blue; *M. modesta*: purple. Main towns/cities either near the surveyed beaches or simply cited in the text are indicated by white small and large dots, respectively.

4.4. RESULTS

Beached litter items, including *Microporella* colonies, were frequently recovered, particularly at Magaggiari beach (Palermo) and Spiaggia libera n. 1 (Catania). Notably, at the Catania site, *Microporella* colonies were found on both occasions (September 2023 and April 2024) (Fig. 2 A-D). Several colonies of both *M. hastingsae* and *M. browni* were found specifically on lifejackets, encrusting various surfaces: the hard-plastic buckles, the lighter straps, and the carbonate shells of the oyster *Ostrea stentina* Payraudeau, 1826 which had colonised the nylon fabric. While *M. hastingsae* was predominant in southeastern Sicily, including the Catania and the Santa Maria del Focallo sites, *M. browni* was found in the 2024 lifejacket sample with very abundant populations, including both young and ovicellate (fertile) colonies and subordinately in the Ponente beach in the Milazzo Peninsula. In contrast, numerous colonies of the native *M. ichnusae,* including one large colony and several smaller ones, were recovered from plastic fragments at Magaggiari beach. These specimens provided the first observation of the ancestrula for this species. The ancestrula is often eccentrically located within the colony remaining marginal in relatively large colonies; it is tatiform, 287 µm x 185 µm, with nine spines and buds two distolateral asymmetrical autozooids. In one case, the ancestrula was found occluded by a tuberculate cryptocystidean cover, possibly due to intramural regeneration as a kenozooid.

Analogously, the colonies of *M. hastingsae* found on the lifejackets allowed for the first SEM documentation of the ancestrula. Like in the previous species it is tatiform with 9, occasionally 10 spines) but larger (260-300 µm x 210-240 µm). The ancestrula buds two distolateral autozooids, sometimes abutting or delayng budding on one side, leading to asymmetrical colonies. Periancestrular autozooids have 5-6 oral spines and lack avicularia whereas subsequent ones possess only a single avicularium proximally located on either. As the colony develops, the avicularia shift distally, eventually forming the diagnostic pair lateral to the orifice orifice and distally directed. However, the occurrence of a single avicularium on periancestrular autozooids, a character shared with other species, including the co-occurring *M. browni*, complicates species identification of young colonies.

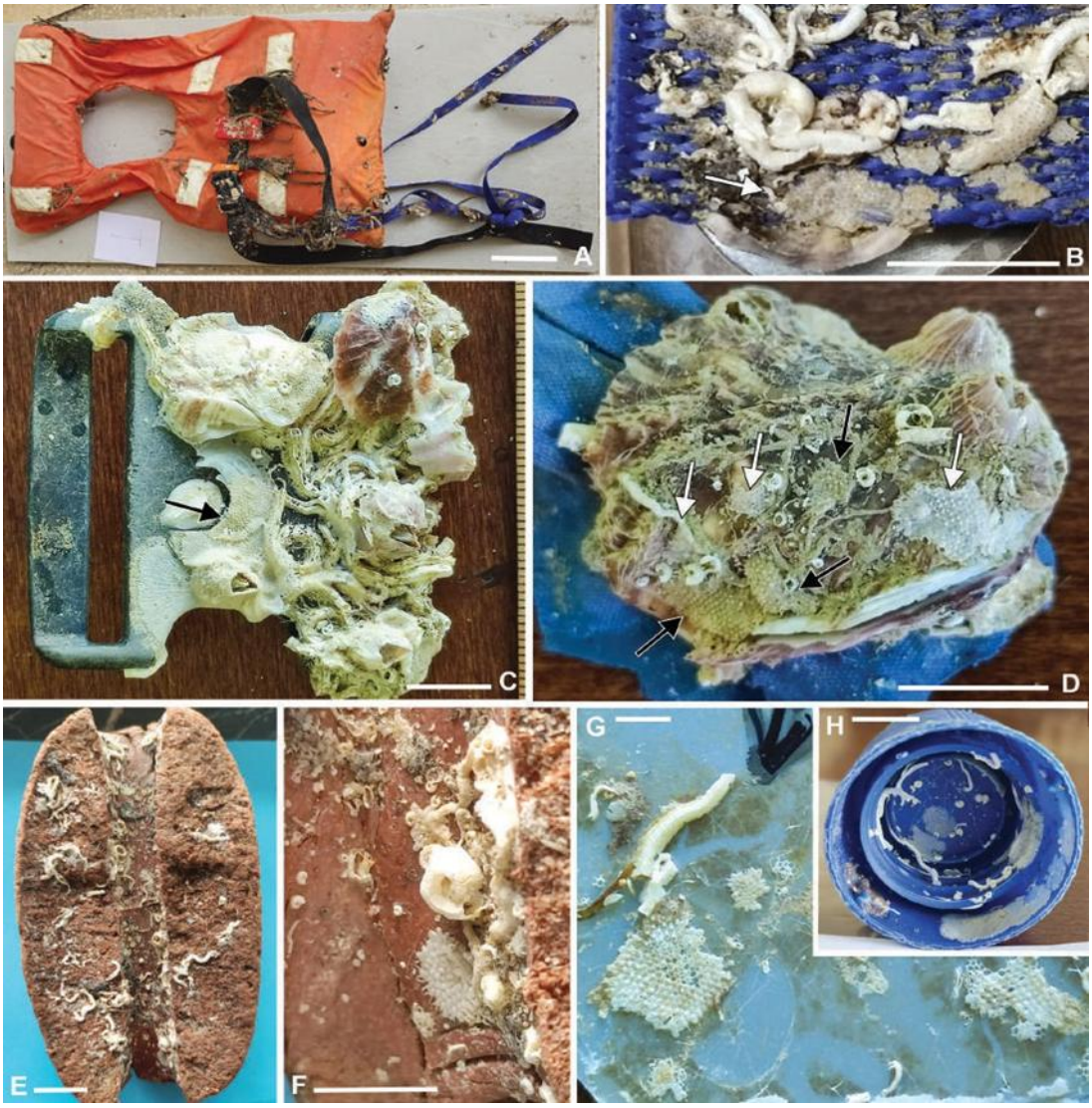

Figure 4.2.: Selection of substrata where *Microporella* species were found. (A) Lifejacket stranded at Plaia, south of Catania (Spiaggia libera n. 1), in September 2023, with obvious encrusters mostly on the straps and buckles. (B) An ovicellate colony of *M. browni* (white arrow) on a strap from the lifejacket in (A). (C) A plastic buckle from the lifejacket stranded at Plaia, south of Catania (Spiaggia libera n. 1) in April 2024. *Microporella browni* (black arrow) encrusts an almost entirely detached bivalve. (D) Colonies of *M. browni* (white arrows) and *M. hastingsae* (black arrows) on the same shell of the bivalve *Ostrea stentina*, encrusting the plastic fibers of the 2024 lifejacket. (E) and (F) A heavily encrusted broken buoy collected at the Simeto River mouth in April 2023, and close-up showing several young bryozoan

colonies, many of which belong to *M. browni*. (G) A young colony of *M. ichnusae* between *Fenestrulina* colonies and serpulids on a plastic container collected in December 2023 at Magaggiari beach (Cinisi, Palermo) (H) Colonies of *M. browni* on a plastic cap collected at Torre Faro (Messina) in April 2024. Scale bars: 10 cm: (A); 1 cm: (B), (C), (D), (E), (H); 5 mm: (F), (G).

M. browni colonies were confidently identified on lifejackets and other plastic debris using main diagnostic features consisting especially of primary orifice and ovicell (Fig. 4.3). The primary orifice is transversely semicircular and shows a denticulate distal margin with 11-13 denticles and a straight proximal margin with shoulder-shaped condyles at the corners and a corrugated edge in between. The ovicell is personate with a distinctive granular collar that encircles the orifice and develops distally to the ascopore adjoining the proximal wall of the ovicell which exposes an evenly perforated ectoecium. The elevation of the collar distal to the ascopore creates a tubular structure with two lateral sutures and a single terminal transversally elliptical secondary orifice. This feature sets *M. browni* apart from *M. bicollaris* Di Martino and Rosso, 2021, the only other species with personate ovicells reliably reported from Sicily and the western Mediterranean. In *M. bicollaris*, the collar also embraces the ascopore and, in addition to the secondary orifice, forms a second smaller proximal aperture that connects the ascopore to the ambient water. Both orifice and ovicell characters allow to distinguish *M. browni* from other species reported from Sicily and the Western Mediterranean. The occurrence of ovicellate colonies also showing periancestrular area, supports the first doubtful identification of some young non-ovicellate colonies as belonging to this species. On the lifejacket straps, colonies were observed growing directly on and between the nylon fibers, with frontal calcification locally covering the plastic threads (Fig. 4.2.B).

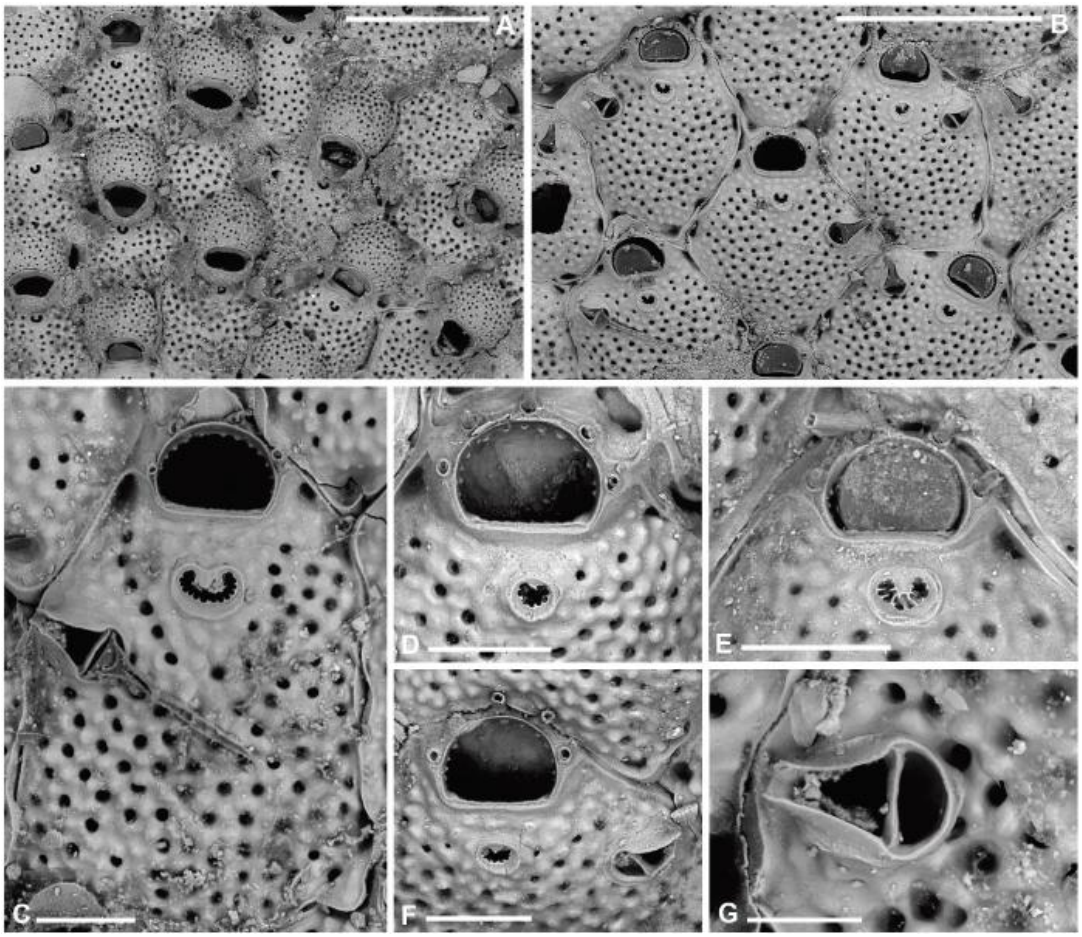

Figure 4.3.: *Microporella browni* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011. Main diagnostic characters. Colonies found on the lifejacket collected in April 2024 at Spiaggia libera n. 1, Plaia, Catania (A-C and G), on a different lifejacket found at the same locality in September 2023 (E), and on a buoy stranded at the Simeto River mouth in April 2023 (D and F). (A) Cluster of “personate” ovicells most with the typical peristome developed distally to the ascopore. (B) Non ovicellate autozooids. Note the local consistent presence of the frontal avicularium with the long and brittle setiform mandible. (C) An autozooid. Note the reniform ascopore field with large subrectangular distal process and the straight setiform mandible. (D), (E), (F) Details of some autozooids’ distal half showing the variability of the orifice, number of oral spines and morphology of the ascopore sometimes with anastomosing denticles forming bars. (G) Close-up of an avicularium. Scale bars: 500 µm: (A), (B); 100 µm: (C), (D), (E), (F); 50 µm: (G).

4.5. DISCUSSION AND CONCLUSION

This report marks the second recorded occurrence of *M. hastingsae* (Fig.4.4) outside its originally documented range in the Red Sea and Suez Canal (Harmelin et al., 2011). Following the first discovery of a single fertile colony on plastic debris at the Simeto River mouth in April 2023 (Rosso and Siddiolo, 2024), our subsequent collections confirm the recurring occurrence of this presumable Lessepsian migrant on plastics in the Gulf of Catania. We also report the second finding of *M. browni* (Fig. 4.4) in the Mediterranean and its first occurrence outside the Levantine Sea where it was initially reported by Harmelin et al., 2011. These authors proposed that *M. browni* was introduced to the Levantine Sea via shipping through the Suez Canal, with its native distribution centered in the Indian Ocean, from the Oman Sea to the Maldive Islands, including the Gulf of Aden. Colonies of *M. browni* were collected on material stranded in the northeastern Ionian Sea and were predominantly found along the coastal sector near Catania but further colonies were also collected on plastics on the eastern side of the Tyrrhenian Sea at the Capo Milazzo peninsula (Ponente beach) and at Torre Faro, close to the Messina Strait, in the northwestern Ionian Sea. Focusing on the area of Catania, the transition from finding only one senescent colony of *M. hastingsae* in April 2023 to several vibrant, living colonies with many ovicells and polypides by late 2023 and early 2024 suggests a rapid increase in its abundance. Similarly, while the initial 2023 collection of *M. browni* yielded only young colonies on a single item, the new collections, particularly from the lifejackets, show very abundant populations with fertile (ovicellate) colonies.

The new collections over the past year suggest that both species are now commonly found on floating plastics in wider coastal areas of Sicily but we lack historical data regularly monitoring the occurrence of *Microporella* species in both natural habitats and antropogenic litter and boats in these localities, except for the documented absence of both *M. hastingsae* and *M. browni* from fouling communities on plastic items collected in various occasions and localities. Consequently, we postulate that colonies of both species are becoming increasingly common on drift plastics in the area.



Figure 4.4: Global known distribution of *Microporella browni* (yellow symbols) and *M. hastingsae* (red symbols). Circles indicate sites from which the new colonies studied here (i.e., Sicily) originate; triangles refer to records previously published in Harmelin et al. (2011) (i.e., Lebanon and localities outside the Mediterranean.

Both species are considered warm-water indicators with a clear Indo-Pacific and Red Sea affinity (Harmelin et al., 2011). As typical Lessepsian migrants, their presence on drift plastic in the Central Mediterranean represents a significant westward possible expansion of their previously known distribution. If self sustaining populations will be detected in the same areas where stranded plastic have been found, this could represent a geographical shift not merely incidental but strongly linked to the ongoing "tropicalization" of the Mediterranean Sea. The rapid increase in abundance of *M. hastingsae* and *M. browni* in stranded material along the eastern coasts of Sicily (Ionian Sea, southeastern Tyrrhenian Sea and northeastern Sicily Channel) correlates with the rising trend in Sea Surface Temperatures (SST), which increasingly provides thermal conditions suitable for the survival and reproduction of erythraean taxa.

The ability of these species to colonize anthropogenic substrates like plastic debris further accelerates this process. Floating plastics act as "rafts" that facilitate the crossing of environmental barriers and deep-water stretches, allowing thermophilic bryozoans to navigate toward new suitable habitats in response to regional warming. Consequently, the recurring findings of fertile, vibrant colonies outside the Levantine Sea suggest that *M. hastingsae* and *M. browni* are effectively integrating into the Central Mediterranean fouling communities, driven by the synergy between anthropogenic dispersal vectors and climate-driven sea-surface temperature raising.

The recent arrival of *M. hastingsae* and *M. browni* in the Ionian Sea at the westernmost part of the eastern Mediterranean appears highly plausible, followed by a rapid increase in their abundance on drift plastic debris. For *M. hastingsae*, it has been suggested that the species might have been introduced via the Suez Canal within the last decades (Rosso and Siddiolo, 2024), possibly favored by its recent enlargement (Zenetos, 2017). These findings represent the first evidence of an ongoing spread from the Red Sea through the Levantine basin. Similarly, *M. browni*, established in Lebanese waters since 2002 (Harmelin et al., 2011), underwent a long-distance transfer, without known intermediate populations between the Levant and the Sicilian coasts, whose possible existence must still be discovered.

This expansion could have occurred through drift plastics, following single travel events or " displacements, also favoured by rafting. This hypothesis is supported by surface circulation patterns in the eastern Mediterranean (Pinardi et al., 2015). According to Berline et al. (2021), the general surface circulation of the Ionian Sea is influenced by three main water bodies: one from the west, likely originating from the Sicily Channel, one from the north, probably from northern Ionian Sea and/or the southern Adriatic Sea, and a third, from the south, Peloponnese in the Aegean Sea. The provenance of the latter water body from an eastern region close to the Levantine Sea suggests a potential pathway for the transport of plastic items colonized by both *Microporella* species from that area in the eastern Mediterranean. Furthermore, currents alongshore the Ionian coast of Sicily flow southwards from the Messina area (e.g., Bohm et al., 1987; Raffa and Hopkins, 2004). However, the transit of these waters toward the Sicily Strait, and even to the easternmost part of the southern Sicilian coast, seems hampered by the formation of local gyres that persist from seasonal to decadal timescales (e.g., Reyes Suarez et al., 2019). Furthermore, the fertility of several colonies and the presence of juveniles and recently metamorphosed ancestrulae indicate a robust reproductive capability, suggesting that these species have established self-sustaining populations on plastic items. It is also plausible that larvae can release from these "rafts" upon reaching coastal zones and settle on natural substrata, leading to local establishment (Fig. 4.5). Although, in the present instance, surveys must still be planned to ascertain the occurrence of colonies of the investigated *Microporella* species in Sicilian natural habitats, a similar case has been documented for *Schizoporella pungens* Canu and Bassler, 1928. Winston (2012) reported that this species, originally from the Caribbean and south Florida, became established in the Indian River area of northeast Florida within a couple of years after being first detected on drift plastic in 2002, and subsequently on fouling panels just one year later.

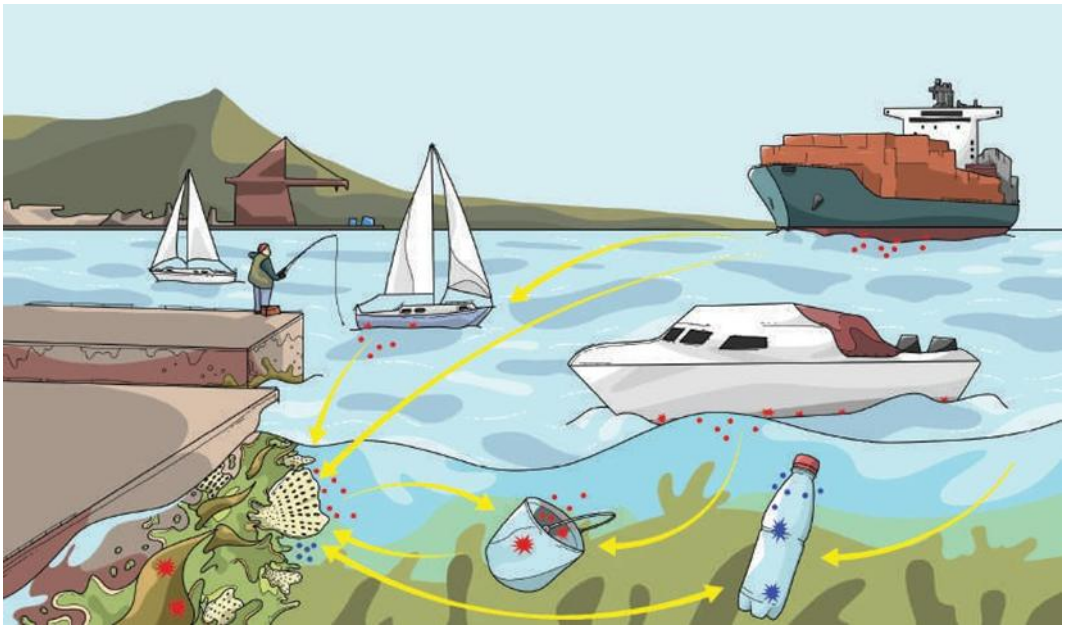

Figure 4.5: Possible diffusion paths of non-indigenous species. Blue: on drift debris transported by surface currents, potentially releasing larvae colonizing anthropogenic fixed installations and/or natural habitats; red: on long-distance commercial vessels spreading to harbours and recreational boats in marinas. Star-shaped patches indicate colonies; dots are for short-living larvae; arrows: possible paths. See text for further explanation. Illustration by Petter Nordenhaug (University of Oslo, Norway).

While the passive long-distance transport on drift plastic reported above could explain the direct arrival of both *Microporella* species along the Sicilian Ionian coast, the presence of *M. hastingsae* in the Sicily Strait and of *M. browni* in the Tyrrhenian Sea (Milazzo) suggests additional vectors. The minimal connectivity between the Ionian and Tyrrhenian basins (e.g., Celentano et al., 2020) and the seasonal to decadal persistence of local gyres in the easternmost part of the Sicilian coast (e.g., Reyes Suarez et al., 2019) suggests that that the direct surface drift transfer is hampered in these areas.

These considerations suggest that at least fouling communities from the Tyrrhenian Sea may be sustained by larvae of different origin, implying different and/or additional vectors and pathways to drift transport. It is possible that plastics could be locally colonized by larvae released from colonies arrived on boats (Fig. 4.5), path for red colonies and larvae). Several ports and marinas occur all along the coast of Sicily, including a major commercial port near the beach in Milazzo where *M. browni* was found. Similarly, important commercial and touristic ports are located in the

southeast coast of Sicily, an area directly connected through trade routes to ports at the eastern Mediterranean and the Suez Canal (Ship Traffic Density Map of Mediterranean Sea, 2014). Ports, especially those frequented by tourist boats, experience heavy maritime traffic and usually host a number of NIS (Ulman et al., 2017; Tempesti et al., 2020; 2022; Xavier et al., 2021). Whereas main commercial ports harbouring long-distance boats may act as primary hubs for the introduction of non-indigenous species, recreational boating has been identified as a key vector for their local transfer (e.g., Ferrario et al., 2017; 2024; Castro et al., 2022).

In this scenario, the stranded plastic items may be colonized secondarily at a local level directly from larvae released from colonies on the boats or assuming an intermediate transit of species to local anthropogenic structures (e.g., pontoons) in ports and/or marinas. To fully support this hypothesis, it would be crucial to investigating the potential presence of our target *Microporella* species within ports or marinas along the coasts of Sicily, as well as on boats moored in these ports. Organizing localized surveys and monitoring NIS in these contexts, preferably within large focused projects, is urgently needed to provide baseline data on their presence and abundance.

To date, and to the best of our knowledge, only a few marinas (i.e., Palermo on the Tyrrhenian side, Riposto, Siracusa and Marzamemi along the Ionian side, and Marina di Ragusa and Licata along the Sicily Strait) have been surveyed for non-indigenous bryozoans by Ulman et al. (2017). However, none of these marinas have yielded colonies of *M. hastingsae* or *M. browni*. Given that these surveys were conducted a few years ago (2016), and considering how rapidly marine communities can change –see above– it is likely that these species were simply not present at the time of the previous surveys but may likely be now established in these areas. However, local populations of *M. hastingsae* and *M. browni* need to be discovered and documented in Sicily before confirming the establishment of these two species in the region, in accordance with guidelines for monitoring the spread of NIS (e.g., Marchini et al., 2015; Zenetos et al., 2022b).

It can be also be remarked that *M. hastingsae* and *M. browni* are found more frequently on plastic items than native species, reflecting the opportunistic behavior and ecological flexibility of non-indigenous taxa (Giacobbe et al., 2024). Given the rapid increase in marine temperatures, these Lessepsian species will increasingly be favored, spreading westward and northward and, if becoming established,

contributing significantly to the tropicalization and homogenisation of the Mediterranean biota.

4.6. REFERENCE LIST

Audrézet, F., Zaiko, A., Lear, G., Wood, S.A., Tremblay, L.A. and Pochon, X., 2021. Biosecurity implications of drifting marine plastic debris: current knowledge and future research. *Marine Pollution Bulletin*, 162, 111835.

Berline, L., Doglioli, A.M., Petrenko, A., Barrillon, S., Espinasse, B., Le Moigne, F.A., Simon-Bot, F., Thyssen and M. and Carlotti, F., 2021. Long-distance particle transport to the central Ionian Sea. *Biogeosciences*, *18*(24), pp.6377-6392.

Böhm, E., Magazzu, G., Wald, L., and Zoccolotti, M.L., 1987. Coastal currents on the Sicilian shelf south of Messina. *Oceanologica Acta, 10*, 137-142.

Castro, N., Gestoso, I., Marques, C. S., Ramalhosa, P., Monteiro, J. G., Costa, J. L., and Canning-Clode, J., 2022. Anthropogenic pressure leads to more introductions: Marine traffic and artificial structures in offshore islands increases non-indigenous species. *Marine pollution bulletin*, *181*, 113898. https://doi.org/10.1016/j.marpolbul.2022.113898

Ferrario, J., Caronni, S., Occhipinti-Ambrogi, A., and Marchini, A., 2017. Role of commercial harbours and recreational marinas in the spread of non-indigenous fouling species. *Biofouling*, 33, 651-660.

Ferrario, J., Marchini, A., Gazzola, F. and Occhipinti-Ambrogi, A., 2024. The influence of recreational boat traffic in the introduction of non-indigenous fouling species in three Ligurian marinas (Mediterranean Sea, Italy). *Estuarine, Coastal and Shelf Science*, *303*, p.108810.

Giacobbe, S., Cosentino, A., and Rosso, A., 2024. Primary colonization and small-scale dynamics of non-indigenous benthic species: a case study. *Aquatic Ecology*, 1-18.

Harmelin, J.-G., Ostrovsky, A.N., Cáceres-Chamizo, J.P., and Sanner, J., 2011. Bryodiversity in the tropics: taxonomy of *Microporella* species (Bryozoa, Cheilostomata) with personate maternal zooids from Indian Ocean, Red Sea and southeast Mediterranean. *Zootaxa*, 2798, 1-30.

Kannan, G., Mghili, B., Di Martino, E., Sanchez-Vidal, A., and Figuerola, B., 2023. Increasing risk of invasions by organisms on marine debris in the Southeast Coast of India. *Marine Pollution Bulletin*, 195, 115469.

Katsanevakis, S., Poursanidis, D., Hoffman, R., Rizgalla, J., Rothman, S.B.S., Levitt-Barmats, Y.A., Hadjioannou, L., Trkov, D., Garmendia, J.M., Rizzo, M. and Bartolo,

A.G., Bariche, M., Tomas, F., Kleitou, P., Schembri, P.J., Kletou, D., Tiralongo, F., Pergent, C., Pergent, G., Azzurro, E., Bilecenoglu, M., Lodola, A., Ballesteros, E., Gerovasileiou, V., Verlaque, M., Occhipinti-Ambrogi, A., Kytinou, E., Dailianis, T., Ferrario, J., Crocetta, F., Jimenez, C., Evans, J., Ragkousis, M., Lipej, L., Borg, J.A., Dimitriadis, C., Chatzigeorgiou, G., Albano, P.G., Kalogirou, S., Bazairi, H., Espinosa, F., Ben Souissi, J., Tsiamis, K., Badalamenti, F., Langeneck, J., Noel, P., Deidun, A., Marchini, A., Skouradakis, G., Royo, L., Sini, M., Bianchi, C.N., Sghaier, Y.R., Ghanem, R., Doumpas, N., Zaouali, J., Tsirintanis, K., Papadakis, O., Morri, C., Çinar, M.E., Terrados, J., Insacco, G., Zava, B., Soufi-Kechaou, E., Piazzi, L., Ben Amor, K.O., Andriotis, E., Gambi, M.C., Ben Amor, M.M., Garrabou, J., Linares, C., Fortič, A., Digenis, M., Cebrian, E., Fourt, M., Zotou, M., Castriota, L., Di Martino, V., Rosso, A., Pipitone, C., Falautano, M., García, M., Zakhama-Sraieb, R., Khamassi, F., Mannino, A.M., Ktari, M.H., Kosma, I., Rifi, M., Karachle, P.K., Yapıcı, S., Bos, A.R., Balistreri, P., Esplá, A.A.R., Tempesti, J., Inglese, O., Giovos, I., Damalas, D., Benhissoune, S., Huseyinoglu, M.F., Rjiba-Bahri, W., Santamaría, J., Orlando-Bonaca, M., Izquierdo, A., Stamouli, C., Montefalcone, M., Cerim, H., Golo, R., Tsioli, S., Orfanidis, S., Michailidis, N., Gaglioti, M., Taşkın, E., Mancuso, E., Žunec, A., Cvitković, I., Filiz, H., Sanfilippo, R., Siapatis, A., Mavrič, B., Karaa, S., Türker, A., Monniot, F., Verdura, J., El Ouamari, N., Selfati, M. and Zenetos, A., 2020. Unpublished Mediterranean records of marine alien and cryptogenic species. *BioInvasions Records*, 9(2), pp.165-182.

Kiessling, T., Gutow, L. and Thiel, M., 2015. Marine litter as habitat and dispersal vector. In Bergman, M. et al. (Eds) *Marine anthropogenic litter* (pp. 141-181). Springer Open.

Lewis, P.N., Riddle, M.J., and Smith, S.D.A., 2005. Assisted passage or passive drift: a comparison of alternative transport mechanisms for non-indigenous coastal species into the Southern Ocean. *Antarctic Science*, 17 (2), 183-191.

Marchini, A., Galil, B. S. and Occhipinti-Ambrogi, A, 2015. Recommendations on standardizing lists of marine alien species: Lessons from the Mediterranean Sea. *Marine Pollution Bulletin*, 101(1), 267–273. https://doi.org/10.1016/j.marpolbul.2015.09.054

Pinardi, N., Zavatarelli, M., Adani, M., Coppini, G., Fratianni, C., Oddo, P., Simoncelli, S., Tonani, M., Lyubartsev, V., Dobricic, S. and Bonaduce, A., 2015. Mediterranean Sea large-scale low-frequency ocean variability and water mass formation rates from 1987 to 2007: A retrospective analysis. *Progress in Oceanography*, 132, 318-332.

Raffa, F. and Hopkins, T. S., 2004. Circulation and water mass structure over a narrow shelf, Augusta Gulf (Sicily), *Chemistry and Ecology*, 20(sup1), pp. 249–266. doi: 10.1080/02757540410001699857.

Reyes Suarez, N. C., Cook, M. S., Gačić, M., Paduan, J. D., Drago, A. and Cardin, V., 2019. Sea Surface Circulation Structures in the Malta-Sicily Channel from Remote Sensing Data. *Water*, *11*(8), 1589. https://doi.org/10.3390/w11081589

Rosso, A., and Siddiolo, C., 2024. *Microporella hastingsae* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011 (Bryozoa, Cheilostomatida): a possible new Lessepsian species in the Mediterranean Sea? *Mediterranean Marine Science*, 25 (1), 73-83.

Tempesti, J., Mangano, M. C., Langeneck, J., Lardicci, C., Maltagliati, F. and Castelli, A., 2020. Non-indigenous species in Mediterranean ports: A knowledge baseline. *Marine Environmental Research*, *161*, 105056. https://doi.org/10.1016/j.marenvres.2020.105056

Tempesti, J., Langeneck, J., Romani, L., Garrido, M., Lardicci, C., Maltagliati, F. and Castelli, A., 2022. Harbour type and use destination shape fouling community and non-indigenous species assemblage: A study of three northern Tyrrhenian port systems (Mediterranean Sea). *Marine Pollution Bulletin*, *174*, 113191. https://doi.org/10.1016/j.marpolbul.2021.113191

Tsirintanis, K., Azzurro, E., Crocetta, F., Dimiza, M., Froglia, C., Gerovasileiou, V., Langeneck, J., Mancinelli, G., Rosso, A., Stern, N., Triantaphyllou, M., Tsiamis, K., Turon, X., Verlaque, M., Zenetos, A. and Katsanevakis, S., 2022. Bioinvasion impacts on biodiversity, ecosystem services, and human health in the Mediterranean Sea. *Aquatic Invasions*, 17(3), 308-352.

Ulman, A., Ferrario, J., Occhpinti-Ambrogi, A., Arvanitidis, C., Bandi, A., Bertolino, M., Bogi, C., Chatzigeorgiou, G., Çiçek, B. A., Deidun, A., Ramos-Esplá, A., Koçak, C., Lorenti, M., Martinez-Laiz, G., Merlo, G., Princisgh, E., Scribano, G. and Marchini, A., 2017. A massive update of non-indigenous species records in Mediterranean marinas. *PeerJ*, *5*, e3954. https://doi.org/10.7717/peerj.3954

Winston, J.E., Gregory, M.R., and Stevens L.M., 1997. Encrusters, epibionts, and other biota associated with pelagic plastics: a review of biogeographical, environmental, and conservation issues, p. 81-97. In: *Marine debris: sources, impact and solutions*. Coe, J.M. and Rogers, D.B. (Eds). Springer-Verlag, New York.

Winston J. E., 2012. Dispersal in marine organisms without a pelagic larval phase. *Integrative and comparative biology*, *52*(4), 447–457. https://doi.org/10.1093/icb/ics040

Xavier, E. A., Almeida, A. C. S. and Vieira, L. M., 2021. The role of artificial habitats on fouling bryozoan fauna in the southwestern Atlantic. *Marine Pollution Bulletin*, *167*, 112310. https://doi.org/10.1016/j.marpolbul.2021.112310

Zenetos, A., Gofas, S., Verlaque, M., Cinar, M., Garcia Raso, J., Bianchi, C., Morri, C., Azzurro, E., Bilecenoglu, M., Froglia, C., Siokou, I., Violanti, D., Sfriso, A., San Martin, G., Giangrande, A., Katagan, T., Ballesteros, E., Ramos-Espla, A., Mastrototaro, F., Ocana, O., Zingone, A., Gambi, M. and Streftaris, N., 2010. Alien species in the Mediterranean Sea by 2010. A contribution to the application of European Union's Marine Strategy Framework Directive (MSFD). Part I. Spatial distribution, *Mediterranean Marine Science*, 11(2), p. 381. doi: 10.12681/mms.87.

Zenetos, A., 2017. Progress in Mediterranean bioinvasions two years after the Suez Canal enlargement. *Acta Adriatica*, 58 (2), 347-358.

Zenetos, A., Albano, P.G., Garcia, E.L., Stern, N., Tsiamis, K. and Galanidi, M., 2022b. Established non-indigenous species increased by 40% in 11 years in the Mediterranean Sea. *Mediterranean Marine Science*, 23(1), 196-212.

Zenetos, A., Tsiamis, K., Galanidi, M., Carvalho, N., Bartilotti, C., Canning-Clode, J., Castriota, L., Chainho, P., Comas-González, R., Costa, A.C. and Dragičević, B., 2022a. Status and trends in the rate of introduction of marine non-indigenous species in European seas. *Diversity*, 14(12), 1077.

Chapter 5

The distribution of *Fenestrulina* species (Bryozoa) in the Mediterranean: the role of temperature and of plastic and natural debris in the dispersal of *F. communis*.

This chapter is based on the following publication:

Rosso A., Di Martino E., Donato G., Figuerola B., Gerovasilieiou V., Siddiolo C., Sinagra A., Sanfilippo R., Sciuto F., (2025) Unlocking Mediterranean bryozoan diversity: seven new species unveiled after fixing a neotype for *Fenestrulina malusii* (Audouin and Savigny, 1826) (Cheilostomatida, Fenestrulinidae); https://doi. org/10.3897/zookeys.1254.157989

Note: The chapter has been deeply rearranged from the original paper and focuses mainly on ecological, geographical and distribution aspects, reducing or omitting taxonomic description of species. Focusing on the Mediterranean, it summarises the distribution of *Fenestrulina* species in relation to sea temperatures, information is provided for *F. communis*, the only species found on floating plastics – seemingly partly responsible for its distribution - in the Mediterranean so far.

5 The distribution of *Fenestrulina* species (bryozoa) in the Mediterranean: the role of temperature and of plastic and natural debris in the dispersal of *F. communis*

5.1. ABSTRACT

The understanding of marine bryozoan diversity has been recently enhanced by the taxonomic revision of the genus *Fenestrulina*. Following the designation of a neotype for *Fenestrulina malusii* (Audouin and Savigny, 1826) whose holotype is lost, and the description of seven new Mediterranean species, this chapter focuses on the distribution of *Fenestrulina* species in the Mediterranean and the ecological significance of *Fenestrulina communis*. Specifically, we report the finding of viable colonies of this species on drift debris (plastic items) stranded along the coast of Cinisi (Palermo, NW Sicily) and on natural substrata in other Mediterranean localities. While most species in this genus appear to be habitat-specific or geographically restricted, *F. communis* stands out for its broader occurrence and its ability to colonize artificial substrates. We suggest that its presence on beach-cast plastic materials highlights the role of rafting as a potential pathway for the local and regional spread of this species. These findings provide new insights into the ecological preferences and dispersal dynamics of *F. communis*, pointing to its opportunistic potential within the coastal ecosystems of the Southern Tyrrhenian Sea. Furthermore, our analysis of literature and survey data reveals a significant absence of *Fenestrulina* records from the warmer sectors of the Mediterranean, particularly the Levantine Sea. This distributional gap suggests that the genus is primarily composed of "temperate to cold-temperate" organisms, whose range is limited by increasing Sea Surface Temperatures (SST).

5.2. INTRODUCTION

Fenestrulina malusii (Audouin and Savigny, 1826) has long been considered one of the most frequently reported and widespread bryozoan species, with thousands of records spanning more than a century (GBIF 2024; OBIS 2024). However, literature points at the concept that *F. malusii* has been historically subjective and overly broad, hosting a wide range of taxonomic entities under a single name. The species was illustrated by Savigny on material collected during Napoleon's Egyptian campaign unfold along the Mediterranean coast (Blondeau and Aubert 1803), making its Mediterranean origin highly probable, also considering the drawing of the

species on a thallum of the Mediterranean species *Sargassum vulgare* C. Agardh (M. Verlaque and J.-G. Harmelin, pers. comm.). Taxonomic uncertainty largely derives from missing examination of the original colonies by former bryozoologists and the subsequent loss of the type material unfortunately destroyed during World War II (d'Hondt 2006). Consequently, several species have been misidentified as *F. malusi* worldwide even after its recognition as a "species complex" (e.g., Hayward and Thorpe, 1989), leading to a consequent significant confusion, in range analyses and particularly in ecological studies. Even in its increasingly recognized restricted Atlantic-Mediterranean range, (e.g., Hayward and Ryland, 1999), because considered the only Mediterranean species of the genus and easily distinguished from other species, *F. malusii* has often been cited as an ubiquitous component of several communities (e.g., Gautier 1962; Harmelin 1976). Occasionally, it has been cited as an indicator for *Posidonia* meadows. In recent years, Scanning Electron Microscopy (SEM) has revealed that many Mediterranean colonies previously identified as *F. malusii* actually belong to distinct taxa, some yet undescribed. Taxonomic uncertainty is particularly problematic for ecological research conducted by non-taxonomists, as the absence of reference material and clear diagnostic features has delayed the accurate monitoring of regional bryozoan diversity and dispersal potential and pathways of individual species.

In this context, a thorough revision of the Mediterranean *Fenestrulina* species species was undertaken by Rosso et al. (2025) to resolve these uncertainties after the selection of a suitable neotype for *F. malusi* fixing its specific characters and based on colonies associated to *Laminaria rodriguezii* Bornet collected at ca 60 m depth, off Ustica in southern Tyrrhenian Sea. This allowed the description of further seven new species from this basin, i.e. *F. cavernicola* Rosso and Di Martino, 2025, from the semi-dark and dark zones of a submarine cave in Lesvos Island (NE Aegean Sea); *F. communis* Rosso and Di Martino, 2025, from beach-cast plastic near Palermo (NW Sicily); *F. foveolata* Rosso and Di Martino, 2025, from Ile-Rousse Bank (Corsica); *F. granulosa* Rosso and Di Martino, 2025, from *Posidonia* meadows in Dhiaporia (Chios Island, Aegean Sea); *F. kalliste* Rosso and Di Martino, 2025, from outer-shelf coarse sediments off Calvi (NW Corsica); *F. ovata* Rosso and Di Martino, 2025, from Trémies submarine cave, near Marseille (Gulf of Lion); and *F. variorugosa* Rosso and Di Martino, 2025, from *Posidonia* rootlets off Formica Isle (Egadi Archipelago, near the Sicily Strait). Five of these species are currently known only from their type localities, while *F. communis* and *F. variorugosa* occur from several localities. A further species is probably present but was left in open nomenclature because of the absence of the ovicell for its complete description. All these species can be distinguished based on the morphology of the ascopore, the

orifice, as well as the morphology and ornamentation of the ovicell and the frontal shield, including number, distribution and fine morphology of the frontal pseudopores.

Among the new species identified in the Mediterranean, *Fenestrulina communis* Rosso and Di Martino, 2025, emerges as a particularly significant species. Unlike many other members of the genus that appear confined to specific habitats like submarine caves or deep-water banks, *F. communis* exhibits a more opportunistic ecological profile.

Specifically, this study focuses on the occurrence of *F. communis* on drift plastic debris stranded along the coast of Cinisi (NW Sicily). This finding is of particular interest as it highlights the role of anthropogenic litter as a dispersal vector. While *Fenestrulina* species have been traditionally associated with natural substrates such as algal fronds (e.g., *Sargassum vulgare*) or seagrasses, the colonization of buoyant plastic items by *F. communis* suggests a high potential for rafting-mediated dispersal in the Southern Tyrrhenian Sea. Resolving the identity of this species is therefore not only a taxonomic necessity but a fundamental step toward understanding the ecological dynamics and connectivity of bryozoan populations in changing Mediterranean coastal environments.

The distribution of all *Fenestrulina* species in the Mediterranean Sea has been also investigated, because presumably climatically relevant, given that this genus is highly diverse, including more than 70 extant species spread worldwide (Bock, 2025, bryozoa.net), with a preference for high latitudes.

5.3. MATERIALS AND METHODS

This study is based on the analysis of samples collected during long-term biodiversity surveys (spanning 40 years) conducted by the University of Catania, integrated with new material obtained from the French bryozoologist J.G. Harmelin at Station Marine d'Endoume, and museum institutions, as well as from target surveys on marine litter.

The primary focus of this thesis chapter is the unpublished material collected from Magaggiari beach, Cinisi, NW Sicily (38.159651°N, 13.083972°E; stranded on the beach; Dec. 2023; C. Siddiolo leg). This site was selected as part of this doctoral research project and joined to further projects at the University of Catania aimed at investigating fouling communities associated with drift plastic debris. *Fenestrulina*

communis Rosso and Di Martino, 2025 was particularly abundant at this location. Colonies were encrusting a flat, smooth plastic item stranded on the beach, with a total of 16 colonies including juveniles recorded on a small surface of approximately 4 cm^2. For ecological and distribution context, additional colonies from other localities were examined, including plastic marine litter from the Catalan Sea (100 m depth: 4 colonies) and plastics stranded at the Tono beach (2 just dead colonies). The species was also detected on natural substrates (algae, shells, cobbles and bryozoan fragments) from submarine caves in the Ustica Island MPA (1 m depth: 1 dead colony) and the Plemmirio MPA (ca 20 m depth: 1 living and 3 dead colonies) as well as on fotophilic algae inthe Ciclopi Islands Islands (9 m depth: 1 living colony) and in deeper bottoms at 45-50 m depth in the Gulf of Catania and the Gulf of Noto (1 living colony at each locality). Uncoated specimens were analyzed using Scanning Electron Microscopy (SEM), and particularly a TESCAN VEGA 2 LMU in backscattered-electron/low-vacuum mode at the Department of Biological, Geological and Environmental Sciences of the University of Catania. This allowed for high-resolution imaging of the skeletal structures without damaging the delicate colonies on plastic. Measurements of autozooids, orifices, and ovicells were taken from SEM micrographs using ImageJ software (https://imagej.nih.gov/). These colonies were used to describe the new species *F. communis*, selecting both the Holotype and Paratype specimens from the Cinisi material that was more representative and using all material to compare features of colonies on plastic and natural substrates. Specific attention was paid to colony interactions (overgrowth, fusion, or "stand-off" behavior), regeneration through intramural budding, and the presence of kenozooids, which indicate the colony's response to the constraints of the substrate and competition.

5.4. RESULTS

Although showing a certain variability and overlap of specific characters with other Mediterranean congenerics, *Fenestrulina communis* is remarkably distinguished from other species because of the large dimentions of its autozooids, orifices, and ovicells, the smooth frontal shield, the high number of the distally located frontal pseudopores, their large size and the particular morphology of the irregularly spiny, star-shaped calcification process partly occluding their lumen (Rosso et al., 2025; Figs 5.1., 5.2.).

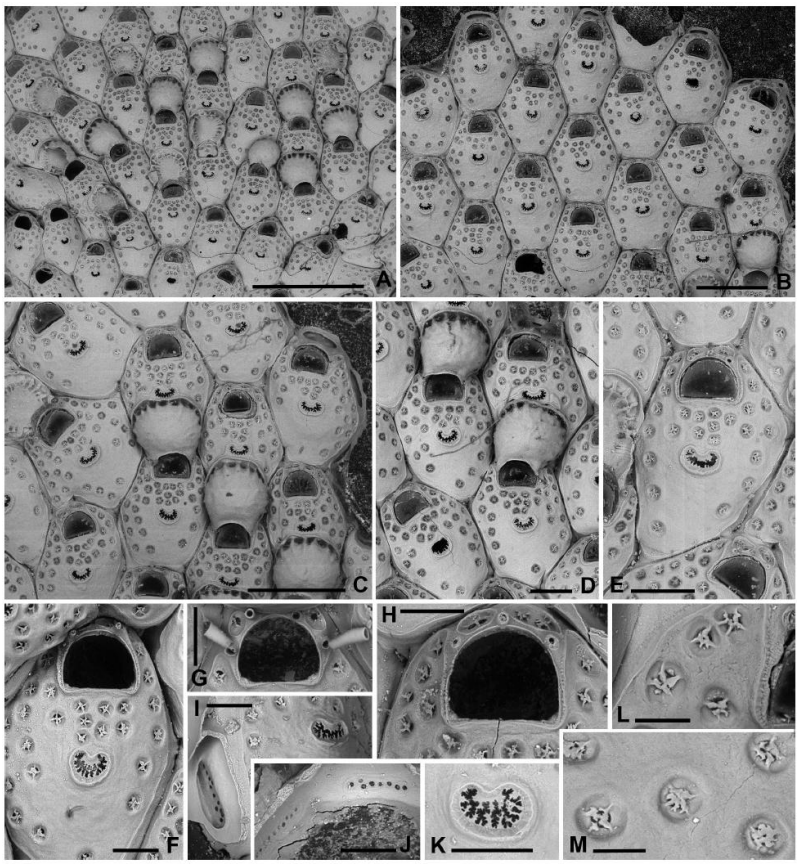

Figure 5.1: *Fenestrulina communis* Rosso and Di Martino, 2025 from a plastic item stranded on Magaggiari beach, Cinisi (Palermo), NW Sicily, Tyrrhenian Sea. **A, C, D**. Paratype PMC.B43.23.2.2024.b8; **B, F, G, K**. Holotype PMC.B39.23.2.2024.a; **E, H, I.** Paratype PMC. B39.23.2.2024.b9; **J, L, M**. Paratype PMC. B39.23.2.2024.b10. **A**. General view of a colony portion showing common ovicellate autozooids; **B**. Non-ovicellate autozooids regularly arranged near the colony margin; **C**. Non-ovicellate autozooids, some distal to ovicells, illustrating morphological variation; **D**. Ovicells with moderately tuberculate surfaces and scalloped distal rims; **E**. Non-ovicellate autozooid; **F**. Autozooid with two oral spines placed very distally and semicircular orifice; **G, H**. Close-up of two orifices with four and three spines, respectively. Note the arched distal rim with few faint denticles and the straight proximal rim with shouldered corners; **I, J**. Multiporous septula seen externally (**I**) and internally (**J**) along lateral and distal walls; **K**. Ascopore with some denticles merging; **L, M**. Frontal pseudopores showing different degrees of development of the stellate process. Note that few pseudopores are present in the proximal frontal shields in panels **A–F**. Scale bars: 1 mm (**A**); 500 µm (**B, C**); 200 µm (**D, E**); 100 µm (**F–K**); 50 µm (**L, M**).

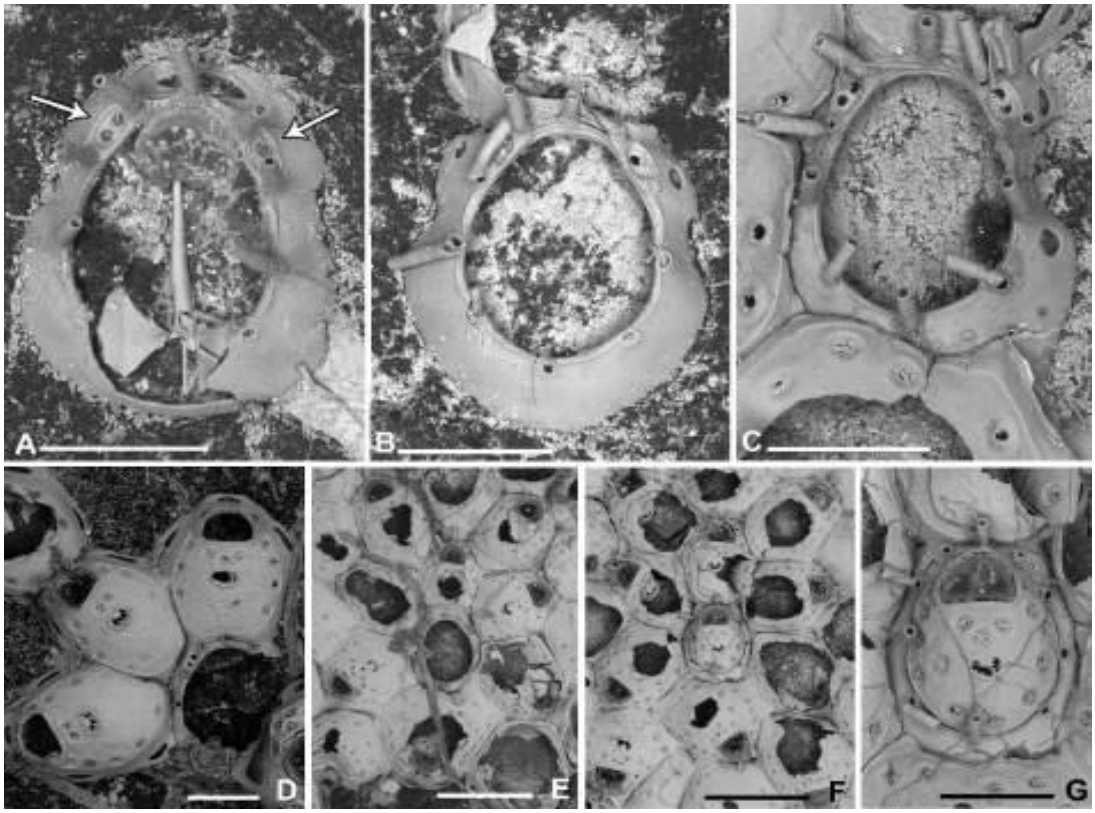

Figure 5.2: *Fenestrulina communis* Rosso and Di Martino, 2025. (**A**–**G**)Tatiform ancestrula and periancestrular autozooids from a plastic item stranded on Magaggiari beach, Cinisi (Palermo), NW Sicily, Tyrrhenian Sea, Paratypes PMC. B39.23.2.2024.b. Note the regeneration of the ancestrula as a miniaturised autozooid in the colony depicted in **F** and **G**. Scale bars: 200 µm (**A**–**D**, **G**); 500 µm (**E**, **F**).

With the exception of the Cinisi plastic substrata, colonies of *F. communis* were always rare at every site where they were collected. Given that, it is highly probable that colonies actually belonging to this species have been collected during time but have been historically identified as *F. malusii*, before the splitting of this species complex into several taxonomic entities by Rosso et al. (2025).

On the Cinisi plastic substrata, colonies appear glassy and form large, irregularly lobate patches (up to 1.5 cm^2), showing a high degree of morphological plasticity. They appear to be highly competitive overgrowing small bivalves and the engrusting skeletal parts of other bryozoan species. In contrast, colony lobes apparently fuse

at contact and tend to fill all available space by developing very irregularly shaped autozooids and kenozooids of very different sizes. Numerous evidences of possible mechanical damages followed by reparation or regeneration of autozooids were documented.

Fenestrulina communis exhibits a remarkably broad ecological range being able to colonise:

Natural Habitats: It has been found in restricted and shaded shelf environments, such as submarine caves in the 1-20 m depth (Ustica MPA: Di Geronimo et al., 1990; Plemmirio MPA; Rosso et al., 2013) and circalittoral detritic bottoms at 45-50 m depth range (Rosso et al., 2025). It is also observed associated with fleshy algae in Infralittoral habitats (e.g., Hayward and McKinney, 2002).

Anthropogenic Substrates: The species shows an opportunistic behavior, thriving on floating plastic items. The colonies found at Cinisi demonstrate that this species can settle and reach reproductive maturity, producing numerous ovicells and brooding larvae that are able to settle on the same substratum, as indicated by the abundance of observed young colonies and ancestrulae associated with large mature colonies. This, while the substrate is still buoyant in shallow, well-lit waters (Rosso et al., 2025). It is highly plausible that when encrusted debris are floating in shallow waters of coastal areas, some of these larvae can reach the bottom settling on local substrata.

Marine litter: The presence of this species on plastic litter deposited at 100 m depth off Catalonia suggests that the weight of the bryozoan encrustation, combined with other foulers, eventually causes the plastic to sink, transporting the species from the surface to the deep seafloor (Subías-Baratau et al., 2022) where the colonies still continued to grow.

F. communis is an Atlanto-Mediterranean species. Its range extends from the British Isles (Hayward and Ryland, 1999) to the western Mediterranean (Ionian, Tyrrhenian, and Catalan Seas) and the northern Adriatic (Hayward and McKinney, 2002). Its high ecological flexibility, including the ability to colonize floating anthropogenic debris, facilitates its wide distribution and the possible connectivity of its populations across the Mediterranean basin, where it is also able to act as a primary pioneer in new substrata (Rosso et al., 2025).

5.5. DISCUSSION

The review of all available literature reporting *Fenestrulina* from the Mediterranean and new data data from material collected during time at the Catania University and examined from museums collections reveal a clear distributional patternof *Fenestrulina* records. Regardless of the species they belong to, reported occurrences of *Fenestrulina* are abundant in the Western Mediterranean the Adriatic and sectors of the Adriatic, Ionian and Aegean Sea, but decline significantly towards the south-eastern sector of the basin. Records are completely absent in the Levantine Sea, including Lebanon, Israel, and Cyprus (Fig. 5.3) from where no *Fenestrulina* species has been reported after intensive surveys (Harmelin et al., 2016; Sokolover et al., 2016; Achilleos et al., 2020) and regional syntheses (Kocak and Aydin Önen, 2024). The unique record of *Fenestrulina* form the eastern Mediterranean is that relating to the first finding of the genotype species *F. malusii*, but dating back to the early 1800s (collections by Savigny during the Napoleone's campaign to Egypt), when SST were seemingly lower than those occurring presently, and presumably suitable for this species to thrive.

The present-day observed decline in records from north-western to south-eastern localities and their absence from wide south-eastern sectorsof the Mediterranean Sea correlate with the map of Sea Surface Temperatures (SST). This suggests that *Fenestrulina* species may be negatively influenced by temperature. Although a few species of *Fenestrulina* have also been reported from tropical seas, the genus *Fenestrulina* appears to have a "cold-temperate" general distribution, with a preferred SST range for putative "*F. malusii*" *sensu lato* of 10–15 °C (OBIS, 2024; Rosso et al., 2025). Under the current scenario of Mediterranean warming, a northward and westward shift, implying a contraction of the distribution range of these bryozoans, is expected, driven by the ongoing rise in sea-water temperatures associated with global change.

In this critical context, the opportunistic behaviour of *F. communis* represents a significant ecological advantage. Rather than enabling an expansion into warmer waters - to which the species seemingly remains physiologically sensitive - its ability to colonize diverse substrates, including drift plastic, may facilitate its persistence within its current temperate range. By exploiting anthropogenic debris as a dispersal vector, *F. communis* can maintain high levels of population connectivity and effectively saturate available habitats within the Western Mediterranean and Adriatic basins. This "substrate flexibility" allows the species to occupy a variety of ecological niches in the same geographic area, potentially buffering the negative impacts of habitat fragmentation caused by rising temperatures.

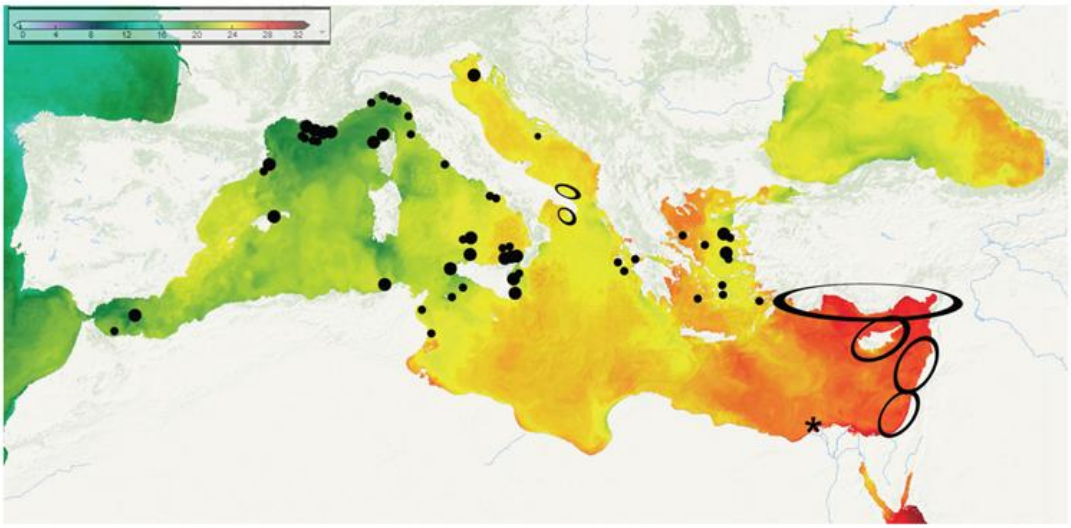

Figure 5.3: Geographical distribution of all known records of *Fenestrulina* in the Mediterranean, plotted against current summer Sea-Surface Temperatures data from IFREMER-LOPS Data Visualization Portal https://syntool.ifremer.fr/, accessed Sept. 2024). An asterisk marks the probable origin of the original material of *F. malusii* collected more than 200 years ago, before the starting of the industrial revolution and the consequent raise in temperature and global change inception. Large dots: collection sites of specimens with confirmed species attribution in Rosso et al., 2025; small dots: records of putative *F. malusii* requiring taxonomic revision, but with known provenance; open ellipses: sites, covered by dedicated monographs, from which *Fenestrulina* species are absent.

A key finding of this study is the abundance of *F. communis* on drift plastic at Cinisi. While most *Fenestrulina* species are scarce and restricted to specific natural habitats, such as submarine caves, *F. communis* shows a high opportunistic potential:

Connectivity and Habitat Saturation: Plastic debris act as a "long-distance vector", but for *F. communis*, the primary advantage of this vector is not necessarily a shift toward warmer waters. Instead, its ability to settle on buoyant objects may facilitate a more diffuse and capillary distribution within its known geographic range (Rosso et al., 2025). Thanks to its remarkable ecological flexibility, *F. communis* can exploit anthropogenic substrates to "fill" available ecological space. However, the interpretation of current distributional data requires caution. Its present-day apparent lack in wide Mediterranean regions like Sardinia and the Balearic Islands, may be due to a lack of targeted sampling and available specimens, not a genuine absence

of the species. Until extensive surveys are performed in these under-studied areas, the full extent of its colonization remains a hypothesis, highlighting the need for further surveys to determine whether *F. communis* is present or not, and in the former hypothesis, if it is already widespread or still in the process of expanding its local footprint. Its opportunistic behaviour allows the species to occupy diverse habitats - from submarine caves to floating debris - effectively saturating the local environment. Rather than just a means of escaping rising temperatures, rafting serves as a mechanism to strengthen population connectivity and ensure survival through the colonization of multiple, varied substrates within the same temperate context.

Expansiveness potential: The broad distribution of *F. communis* across the Atlanto-Mediterranean region poses an intriguing biogeographical question. While it is currently recorded from the British Isles to the Central Mediterranean, it remains unclear whether this wide range is truly "native" or the result of recent anthropogenically mediated expansion. At present, data are insufficient to determine if *F. communis* colonizes plastic debris only within its pre-existing natural range, or if its ability to settle on such substrates has actually facilitated the expansion of its distribution from a more restricted core area. The opportunistic colonization of buoyant items observed at Cinisi suggests that this species possesses the traits necessary for long-distance transport, potentially blurring the lines between its original and current distribution.

Comparison with *Fenestrulina delicia* Winston, Hayward and Craig, 2000: This uncertainty regarding the origin and extent of the present distribution of *F. communis* highlights the need for comparisons with known invasive congeners, most notably *F. delicia*. Unlike *F. communis*, the spreading history of the presumed invasive *F. delicia* is well-documented: originally described from the Western North Atlantic, it has successfully expanded its range into the north-eastern and the southern Atlantic and the Pacific through anthropogenic transport (De Blauwe et al., 2014; Wasson and De Blauwe, 2014). Although *F. delicia* has not yet been detected in the Mediterranean, its ecological behaviour - characterized by high recruitment on artificial and drift substrates - is strikingly similar to that observed for *F. communis* in Sicily. This parallel suggests that *F. communis* may follow a similar trajectory within the Mediterranean, using plastic debris as a primary vehicle to saturate the basin, regardless of its original point of origin.

5.6. REFERENCE LIST

Achilleos, K., Jimenez, C., Berning, B. and Petrou, A., 2020. Bryozoan diversity of Cyprus (eastern Mediterranean Sea): First results from census surveys (2011–2018). *Mediterranean Marine Science* 21(1): pp.228-237. https://doi.org/10.12681/mms.21201

Audouin, J.V., 1826. Explication sommaire des planches de Polypes de l'Egypte et de la Syrie, publiées par Jules-César Savigny, Membre de l'Institut; offrant un exposé des caractères naturels des genres avec la distinction des espèces. In: Jomard EF (Ed.) Description de l'Égypte. Histoire naturelle. Imprimerie Nationale: 225–244.

Blondeau, A., and Aubert, J.B.L., 1803. Carte physique & politique de la Syrie, pour servir à l'histoire des conquêtes du général Bonaparte en Orient.

Bock, P.E., 2025. bryozoa.net, Bryozoa Home Page. http://www.bryozoa.net/ [accessed 30 March 2025]

De Blauwe, H., Kind, B., Kuhlenkamp, R., Cuperus, J., Van der Weide, B. and Kerckhof, F., 2014. Recent observations of the introduced *Fenestrulina delicia* Winston, Hayward & Craig, 2000 (Bryozoa) in western Europe. In Rosso, A. Wyse Jackson P.N. and Porter J. (Eds) Bryozoan Studies 2013. Proceedings of the 16th International Bryozoological Association Conference, Catania, Italy. *Studi Trentini di Scienze Naturali* 94: 53–78.

Di Geronimo, I., Giacobbe, S., Rosso, A., Sanfilippo, R., 1990. Popolamenti e tanatocenosi del Banco Apollo (Ustica, Mar Tirreno meridionale). *Bollettino del Museo Regionale di Scienze Naturali Torino vol. spec*.: 697–729.

Gautier, Y.V., 1962. Recherches écologiques sur les Bryozoaires chilostomes en Méditerranée occidentale. *Recueil des Travaux de la Station marine d'Endoume* 38(24): 1–434.

Harmelin, J.-G., 1976. Le sous-ordre des Tubuliporina (Bryozoaires Cyclostomes) en Méditerranée. Écologie et systématique. *Mémoires de l'Institut océanographique* 10: 1–326.

Harmelin, J.-G., 1997. Diversity of bryozoans in a Mediterranean sublittoral cave with bathyal-like conditions: role of dispersal processes and local factors. *Marine Ecology Progress Series*, *153*, pp.139–152.

Harmelin, J.-G., Bitar, G. and Zibrowius, H., 2016. High xenodiversity versus low native diversity in the south-eastern Mediterranean: bryozoans from the coastal zone of Lebanon. *Mediterranean Marine Science*, *17*(2), pp.417–439.

Hayward, P.J. and McKinney, F.K., 2002. Northern Adriatic Bryozoa from the vicinity of Rovinj, Croatia. *Bulletin of the American Museum of Natural History*, 270(1): 1–139.

Hayward, P.J. and Ryland, J.S., 1999. Cheilostomatous Bryozoa. Part 2. Hippothoidea – Celleporoidea. In Barnes R.S.K. and Crothers J.H. (Eds) Synopses of the British Fauna (New Series) Field Studies Council, Shrewsbury 14: 1–416.

Hondt, J.-L. d', 2006. Nouvelles explications des planches de "Polypes" de la Description de l'Egypte dessinées sous la direction de Jules-César Savigny, et commentées som¬mairement à l'origine par Victor Audouin. II. Bryozoaires (planches 6 à 13) accompagnées de précisions et commentaires scientifiques et historiques. In Iinuma E. and Sidhom N.M. (Eds) Nouvelle Description de l'Egypte. Institut d'Orient, Paris, 86 pp.

Rosso, A., Di Martino, E., Sanfilippo, R. and Di Martino, V., 2012. Bryozoan Communities and Thanatocoenoses from Submarine Caves in the Plemmirio Marine Protected Area (SE Sicily) Bryozoans from Submarine Caves. In *Bryozoan Studies 2010* (pp. 251-269). Berlin, Heidelberg: Springer Berlin Heidelberg.

Rosso, A., Di Martino, E. and Siddiolo, C., 2025. Going west: the spread of non-native *Microporella* (Bryozoa) species on drift plastic debris. *Mediterranean Marine Science*, *26*(1), pp.71-89.

Sokolover, N., Taylor, P.D. and Ilan, M., 2016. Bryozoa from the Mediterranean coast of Israel. *Mediterranean Marine Science*, *17*(2), pp.440-458.

Subías-Baratau, A., Sanchez-Vidal, A., Di Martino, E. and Figuerola, B., 2022. Marine biofouling organisms on beached, buoyant and benthic plastic debris in the Catalan Sea. *Marine Pollution Bulletin*, *175*, p.113405.

Wasson, B. and De Blauwe, H., 2014. Two new records of cheilostome Bryozoa from British waters. *Marine Biodiversity Records*, *7*, p.e123.

Chapter 6

Assessing Habitat Suitability and Distribution Patterns of the Invasive Brachyuran Crabs *Callinectes sapidus* and *Portunus segnis* in the Mediterranean Basin

This chapter is widely based on the following publication:

Siddiolo C**.,** Palummo V., Milisenda G., Pipitone C., Rosso A., Chemello R., (2025a); Assessing Habitat Suitability and Distribution Patterns of the Invasive Brachyuran Crabs *Callinectes sapidus* and *Portunus segnis* in the Mediterranean Basin; https://doi.org/10.12681/mms.38715

6 Assessing Habitat Suitability and Distribution Patterns of the Invasive Brachyuran Crabs *Callinectes sapidus* and *Portunus segnis* in the Mediterranean Basin

6.1. ABSTRACT

In this study, we investigate the habitat suitability and distribution patterns of two invasive non-indigenous crab species, *Callinectes sapidus* and *Portunus segnis*, in the Mediterranean basin. Using a comprehensive dataset compiled from multiple sources, including bibliographic records, online databases, and online informal sources, we mapped the occurrences of these species and overlaid them with environmental variables obtained from the Copernicus Marine Service. We employed MaxEnt species distribution models to predict habitat suitability, considering variables such as sea surface temperature, salinity, chlorophyll, and oxygen. Our results indicate widespread distribution of *C. sapidus* across the basin, with notable concentrations in certain areas, while *P. segnis* exhibits a predominantly southern distribution. Model evaluations demonstrate high predictive performance, with average AUC (area under the receiver operating characteristic curve) values exceeding 0.85. Additionally, we assessed potential habitat overlap between the two species at different probability thresholds, revealing regions where coexistence is likely. Our findings provide valuable insights into the spatial dynamics of invasive NIS crab species in the Mediterranean and contribute to ongoing efforts in biodiversity conservation and management.

6.2. INTRODUCTION

Biological invasions in the Mediterranean Sea are a focal point within the scientific community due to the significant prevalence of NIS on native biodiversity and ecosystems. In the past few decades, the introduction and establishment of non-indigenous species (NIS) through the Suez Canal and the Strait of Gibraltar have increased by 40% (Zenetos et al., 2022). Climate change and the increase in commercial and tourist shipping play a key role in facilitating the entry of NIS (Pinsky et al., 2020). Among the non-indigenous decapods in the Mediterranean, the Atlantic blue crab *Callinectes sapidus* Rathbun, 1896 and the African blue crab *Portunus segnis* (Forskål, 1775) are among the most widespread and have an increasingly dramatic impact on Mediterranean ecosystems and the economy associated with fishery and aquaculture industry (Kampouris et al., 2019). *Callinectes sapidus* – coming from the western Atlantic Ocean from Nova Scotia to northern Argentina

(Millikin and Williams, 1984) – is one of the most invasive crab species (Streftaris and Zenetos, 2006) due to its great adaptability to different environmental conditions. Typically considered a predator (Mancinelli et al., 2016), it is a generalist omnivorous that mainly feeds on algae, fish, mollusks, and other small invertebrates, depending on availability (Hines, 2007; Aslan and Polito, 2024; Prado et al., 2024; Vivas et al., 2025). *Callinectes sapidus* colonizes multiple habitats, mainly in shallow waters, from seagrass to soft bottoms and estuarine habitats, depending on its life stage and needs (Millikin and Williams, 1984; Mancinelli et al., 2016). Females spawn several times during summer, with multiple clutches of eggs in each spawning event (Dickinson et al., 2006). Its invasiveness is further worsened by current rising sea temperatures (Nehring, 2011; Mancinelli et al., 2017; Marchessaux et al., 2022). First recorded in the Mediterranean in 1949 (as *Neptunus pelagicus*: Giordani Soika, 1951), its presence is now widely documented throughout the basin (Deidun et al., 2022). *Callinectes sapidus* likely went through sev- eral independent introductions from the Atlantic Ocean, mainly with ballast water as a vector (Nehring, 2011). The Lessepsian migrant *P. segnis* is considered the first crustacean to have approached the Mediterranean, where it arrived shortly after the opening of the Suez Canal (as N. pelagicus: Fox, 1924; Galil, 2011). Since then, it has expanded its range significantly, colonizing vast areas of the central Mediterranean basin (Katsanevakis et al., 2020) and, more recently, the Sicilian Strait (Shaiek et al., 2021; Castriota et al., 2022). It usually inhabits coastal waters, especially seagrass beds and mangroves (Giraldes et al., 2016), feeding mainly on fish, invertebrates, and algae (Zainal, 2013; Giraldes et al., 2016; Mancinelli et al., 2022; Vivas et al., 2025). *Portunus segnis* has at least two seasonal spawning events per year, one between December and March and the other between August and October (Giraldes et al., 2016; Hadj Hamida et al., 2022). Previous studies on the distribution of invasive species, such as the blue crabs *C. sapidus* and *P. segnis* (Mancinelli et al., 2021; Shaiek et al., 2021), and on larval connectivity (Marchessaux et al., 2023) have been conducted. Monitoring the distribution of NIS, particularly crustaceans such as *C. sapidus* and *P. segnis*, whose larval stages exhibit complex mechanisms of dispersion over time and space (Criales et al., 2019), is crucial for a better understanding of their ecology, in order to mitigate the impact of invasive NIS on the native biota and its linked economy in the Mediterranean. It is crucial to detect any connections between the occurrence of these species and environmental factors, particularly those associated with ongoing climate change. The main purpose of this study is to understand the current distribution ranges of *C. sapidus* and *P. segnis* and how environmental variables connected to climate change may affect their spread and establishment in the Mediterranean Sea. The use of species distribution models for the development of habitat suitability maps allows, among other things,

the identification of areas where the two species have not yet been found but would potentially encounter ideal conditions for their survival.

6.3. MATERIALS AND METHODS

Dataset

The records of *C. sapidus* and *P. segnis* have been organized into a database from multiple sources:

a) bibliographic sources, particularly collective articles and first records in the Mediterranean (https://doi.org/10.12681/mms.38715);

b) online databases, specifically inaturalist.org and GBIF (last accessed on 07/02/2024);

c) Facebook pages and groups, especially “Oddfish” and “Mediterranean Marine Fauna” (last accessed on 07/02/2024).

The records used to populate our database always include geographical coordinates, year of occurrence, country of occurrence, and references. In most records coming from Facebook groups and inaturalist.org, photos and the date of the occurrence are also included. The data were collected in spreadsheets where, if available, additional information such as the number of observed individuals, habitat, and depth were added. Subsequently, the data were processed using R studio, standardizing coordinates from different databases when in different formats. Finally, they were represented on a shapefile of the Mediterranean basin (Fig. 6.1).

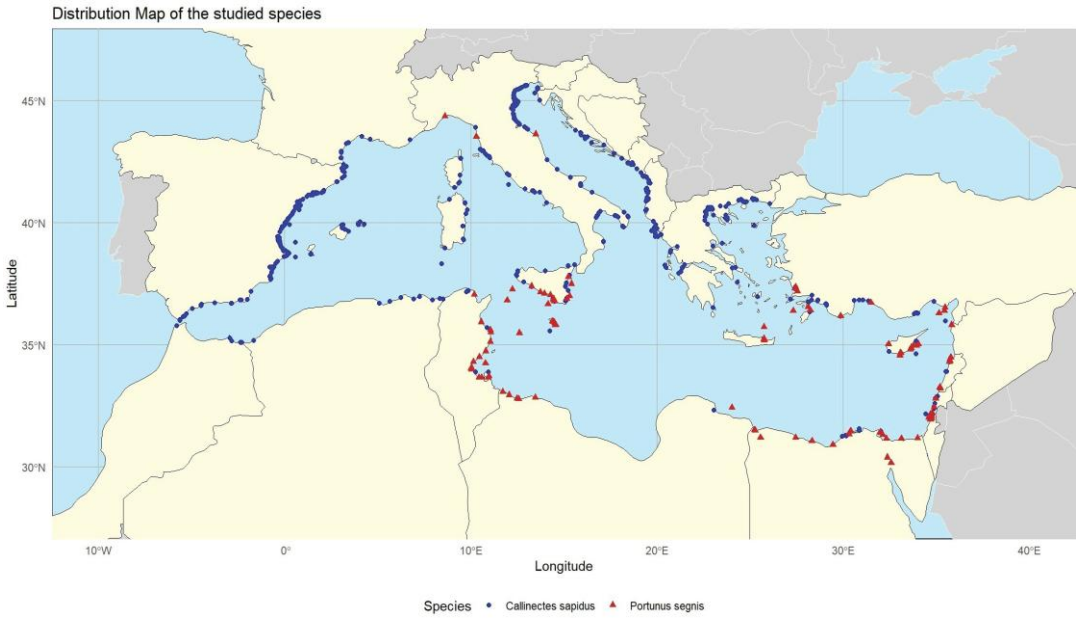

Figure 6.1: Distribution map of *Callinectes sapidus* (in blue) and *Portunus segnis* (in red) in the Mediterranean Sea.

Environmental variables

Environmental variables were downloaded from the Copernicus Marine Service in raster files with a resolution of 0.042°× 0.042° (MEDSEA_MULTI-YEAR_PHY_006_004; MEDSEA_MULTIYEAR_BGC_006_008), over a time span of 20 years, from 2001 to 2021, according to data availability. The selection of environmental variables considers the physiology of the species in larval and adult stages. Sea surface temperature (SST), salinity, chlorophyll, and oxygen raster files were processed, and for each variable, a 20-year mean was calculated, obtaining a single value per pixel using the R studio library Raster. During the initial selection of environmental variables, phytoplankton was also included, but it was later excluded due to its strong correlation with chlorophyll (0.99). The coordinates of the occurrences for the two species under consideration were overlaid to the raster of environmental variables. Data related to the averages of environmental variables were then graphically represented along with the species distribution, allowing an initial overview of the correlation between the presence of individual species and the single environmental variable.

Species Distribution Models

Habitat suitability maps for the two species were performed using the maximum entropy model (MaxEnt; Elith et al., 2006; Phillips et al., 2006; Merow et al., 2013), allowing us to process only presence data to calculate the probability distribution for *C. sapidus* and *P. segnis* in the Mediterranean. Habitat suitability maps for the two species were developed using the Maximum Entropy algorithm (MaxEnt; Phillips et al., 2006). MaxEnt was selected because the occurrence dataset consisted primarily of presence-only records collected from heterogeneous sources (scientific literature, citizen-science databases, and social media observations), whereas reliable absence data were not available. Among species distribution modelling approaches, MaxEnt is one of the most widely applied methods for presence-only data and has consistently shown competitive predictive performance compared with alternative algorithms, particularly when occurrence records are unevenly distributed in space or limited in number (Elith et al., 2006; Phillips et al., 2006; Elith et al., 2011; Merow et al., 2013). Nevertheless, as with all presence-only approaches, model outputs should be interpreted considering potential sampling biases and assumptions regarding detectability and representativeness of occurrence records (Yackulic et al., 2013). MaxEnt was employed to develop a model linking each georeferenced observation with a series of predictor variables to forecast habitat distribution based on the probability of suitability for species distribution. We assessed the level of intercorrelation using R Studio by calculating pairwise Pearson's correlation coefficient. Therefore, we identified the most significant factors among variable pairs with a Pearson correlation coefficient $|r| > 0.85$. Variables exhibiting strong correlations were omitted to avoid reduced model interpretability due to collinearity. Weakly correlated environmental variables were then analyzed to determine the percentage contribution of each. To assess the importance of each variable, we performed a jackknife test by running the model multiple times, each time excluding an environmental variable, and comparing the performance of the model with and without that variable. The performed MaxEnt model – trained using batch files – maintained several parameters as default, such as a convergent threshold of 10–5, a maximum interaction value of 500, and a maximum of 10,000 randomly selected background points, as recommended by previous studies (Phillips et al., 2006; Phillips and Dudík, 2008; Anderson et al., 2016; Bargain et al., 2017). For the modeling evaluations, we considered the area under the receiver operating characteristic (ROC) curve (AUC) values, the standard deviation, and the true skill statistic (TSS) mean, as used in previous studies (Phillips et al., 2006; Liu et al., 2016; Palummo et al., 2023). The ROC curve displays the true positive rate (sensitivity) in relation to the false positive rate (1 – specificity) at different thresholds.

The AUC identifies the total performance of the model (AUC ≥ 0.9: Excellent model performance, with a very high ability to distinguish between positive and negative cases: 0.7 ≤ AUC < 0.9: Good performance, the model has some misclassifications; 0.6 ≤ AUC < 0.7: Fair performance; AUC < 0.6: Poor performance; Bargain et al., 2017). TSS measures the accuracy of the model by combining both sensitivity and specificity. The range spans from –1 to +1 (TSS ≥ 0.8: Excellent performance, the model has high accuracy; 0.6 ≤ TSS < 0.8: Good performance, the model provides useful predictions; 0.4 ≤ TSS < 0.6: Fair performance, the model requires improvements; TSS < 0.4: Poor performance. The model's predictions are not reliable; Li et al., 2023).

However, since the available dataset consisted exclusively of presence records, the resulting habitat suitability models should be interpreted within the limitations inherent to presence-only approaches. Occurrence data compiled from scientific literature, online databases, and social media may be spatially biased towards areas that are more frequently surveyed or reported. Furthermore, the lack of true absence data prevents direct estimation of species occupancy and may result in an overprediction of suitable habitat. Model outputs may also be influenced by the selection of background points, which define the environmental conditions available to the species within the study area. Consequently, habitat suitability maps should be interpreted as indicators of relative environmental suitability rather than as direct estimates of occurrence probability or abundance (Phillips et al., 2009; Elith et al., 2011; Merow et al., 2013; Yackulic et al., 2013).

Response curves

The response curves delineate the influence of each environmental variable on the MaxEnt predictions for both species. They demonstrate how the predicted probability of presence changes as each environmental variable is varied while keeping others at their average sample value. The curves provide insight into variable marginal effects and their impact on model predictions.

The records for the two species were overlayed on their respective maps in order to detect any possible areas where habitat suitability indicates the presence of the species. The two resulting maps – one for *C. sapidus* and one for *P. segnis* – were then cropped by applying a bathymetric filter ranging from 0 to 100 meters in depth in order to define habitat suitability areas likely to support the presence of both species. This approach was adopted because both species are known to occur predominantly in shallow coastal environments, and the selected depth range

represents a well-established ecological constraint rather than an environmental gradient to be modelled. The MaxEnt models were therefore calibrated using environmental variables expected to influence species performance and distribution (e.g., SST, salinity, chlorophyll, and oxygen), while the bathymetric filter was subsequently used to exclude areas that are environmentally suitable but fall outside the depth range where the species are known to occur. This procedure allowed us to focus model predictions on ecologically realistic habitats and to avoid overestimating suitable areas in deeper offshore waters.

Finally, the maps were overlaid to underline areas with the potential presence of both species. Then, the degree of potential competition was assessed using different approaches. Each model aimed to delineate areas where there is a specific likelihood threshold of habitat overlaps. Specifically, we created maps highlighting regions where there is a 40%, 60%, and 80% probability of habitat overlap between the two species (highlighted in red) and areas where only one species can be found (highlighted in yellow).

This approach offers important insights into the spatial dynamics of the species distributions within the Mediterranean environment and provides an understanding of potential coexistence between the species.

6.4. RESULTS

Distribution

Data collection on both species, using multiple sources, yielded 1378 occurrences for *C. sapidus* and 125 occurrences for *P. segnis* (Fig. 6.1) in the Mediterranean basin. The distribution maps reveal that the presence of *C. sapidus* widely covers the entire basin, while *P. segnis* maintains a predominantly southern distribution, primarily centered in North Africa, the southern Italian peninsula, and Greece.

Callinectes sapidus

The provided results from the MaxEnt model analysis offer comprehensive insights into the predictive performance and variable contributions of the species model. Response curves (Fig. 6.2) highlight how individual environmental variables influence MaxEnt predictions, while the analysis of variable contributions quantifies the relative importance of each variable. Notably, chlorophyll-a (chl) emerges as the most influential variable *for C. sapidus*, contributing 81.1% to the model, while

oxygen also plays a significant role, particularly in distinguishing the species from background data (Table 6.1).

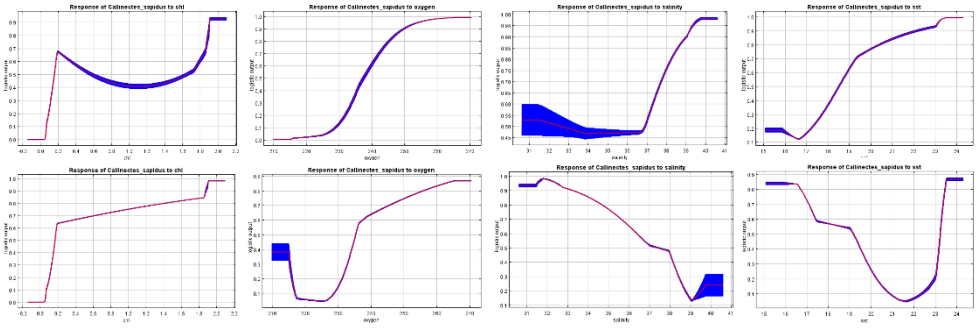

Figure 6.2: Curves of predicted probability of presence for *Callinectes sapidus*. The curves in the top row show changes as each environmental variable is varied, keeping all other environmental variables at their average sample value. The curves in the bottom row derive from the MaxEnt model using only the corresponding variable. These plots reflect the dependence of predicted suitability both on the selected variables and on dependencies induced by correlations between the selected variable and other variables.

Variable	Percent contribution	Permutation importance
sst	64.6	46.5
chl	16.8	19.1
salinity	11.4	13.3
oxygen	7.2	21.2

Table 6.1 Estimate of relative contributions of environmental variables to the MaxEnt model for *Callinectes sapidus*

.

The jackknife test further underscores variable importance, with oxygen and chl identified as the variables with the highest gain when used in isolation, emphasizing chl predictive power. The provided command line offers a means to replicate the

species model, outlining the specific parameters and data sources used in the MaxEnt analysis. The resulting habitat suitability map (Fig. 6.3) shows a wide range along the Mediterranean coasts for this species. In the Western Mediterranean, the most suitable areas for the species, depicted in red, correspond to the Alboran Sea and to several areas, particularly along the North-West African coasts. Along the northern coast of the Mediterranean, the areas deemed most suitable by the MaxEnt model are homogeneous from the coasts of Spain to those of northern Italy, with greater adaptability in areas with a high concentration of river mouths and brackish zones.

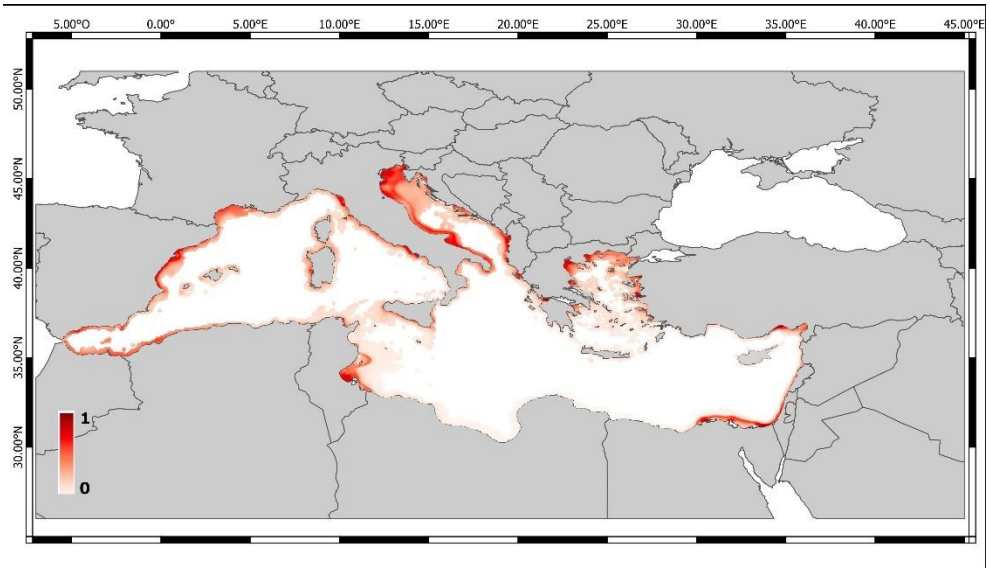

Figure 6.3: Habitat suitability map for *Callinectes sapidus* in the Mediterranean Sea. The increasingly dark shades, from 0 (white) to 1 (red), indicate areas where the chance of encountering the species is increasingly higher according to the environmental variables tested with the MaxEnt model.

The Adriatic coast features areas more suitable for the species' presence in the entire coastal area until the Gulf of Taranto, as well as along the coastal areas of Montenegro and Albania. Proceeding along the Aegean Sea, the suitable areas embrace Greece and Turkey. Further south, the most suitable areas are between Israel and Egypt (especially along the mouth of the Nile) on the east side and between the Gulf of Gabes in Tunisia and Morocco.

Portunus segnis

Table 6.2 presents the estimate of the relative contributions of environmental variables to the MaxEnt model. Response curves (Fig. 6.4) show how each environmental variable shapes the MaxEnt predictions, while the analysis of variable contributions quantifies the relative importance of each variable. SST emerges as the most influential variable, contributing 64.6% to the model, followed by chlorophyll-a (chl), salinity, and oxygen. The jackknife test confirms SST as the variable with the highest gain when used in isolation and the most significant decrease in gain when omitted.

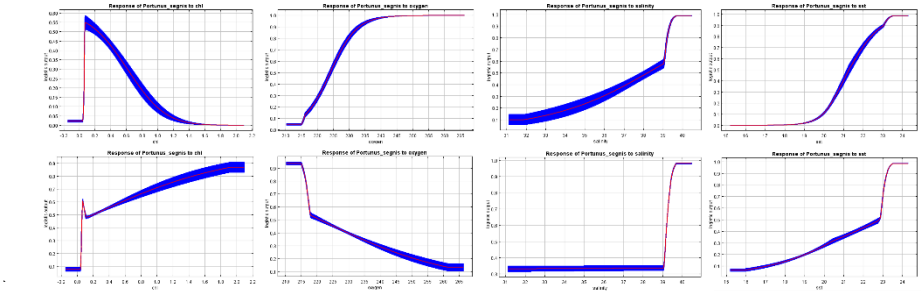

Figure 6.4: Curves of predicted probability of presence for *Portunus segnis*. The curves in the top row show changes as each environ- mental variable is varied, keeping all other environmental variables at their average sample value. The curves in the bottom row derive from the MaxEnt model using only the corresponding variable. These plots reflect the dependence of predicted suitability both on the selected variables and on dependencies induced by correlations between the selected variable and other variables.

Variable	Percent contribution	Permutation importance
sst	64.6	46.5
chl	16.8	19.1
salinity	11.4	13.3
oxygen	7.2	21.2

Table 6.2: Estimate of relative contributions of environmental variables to the MaxEnt model for *Portunus segnis*

.

The suitability map for this species (Fig. 6.5) remarks an imaginary border between the north of the basin, where *P. segnis* meets less suitable areas, remarked with light red, and the central-south basin, where we see more suitable habitats. The Italian peninsula shows good suitability in its southern part, and the same is true for the entire Sicilian and Maltese coasts. The coasts of Greece, in the Aegean Sea, are suitable for the presence of the species, together with the entire coastal areas of Turkey, Cyprus, Syria, Lebanon, and Israel. The same high suitability is displayed in the entire Mediterranean African coast from Egypt to Morocco.

Modeling evaluation

Both MaxEnt models underwent cross-validation, resulting in an average AUC value exceeding 0.85 and a standard deviation ranging from 0.014 to 0.044. This indicates a significant improvement over random prediction. Table 1 displays the AUC values, standard deviations, and mean TSS for both models, serving as indica- tors of model accuracy.

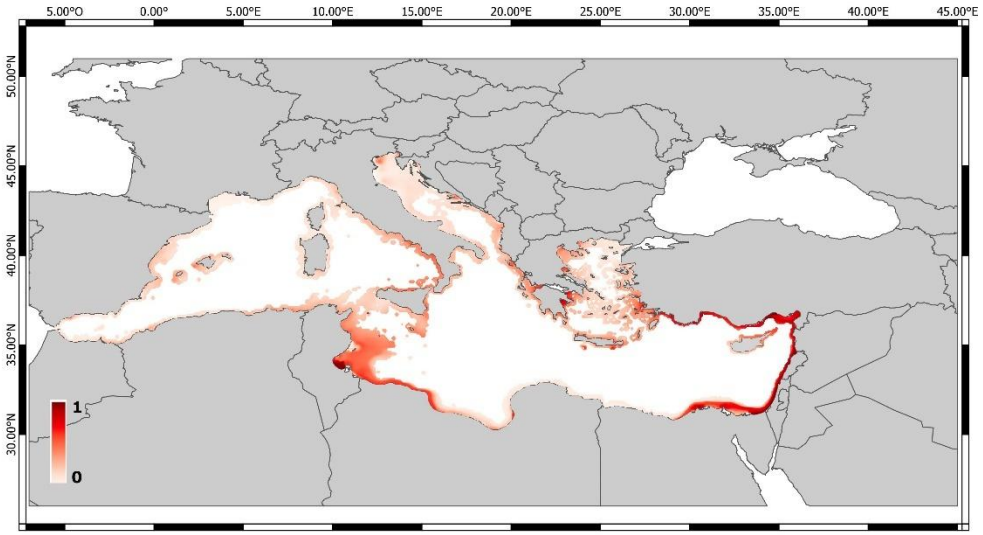

Figure 6.5: Habitat suitability map for *Portunus segnis* in the Mediterranean Sea. The increasingly dark shades, from 0 (white) to 1 (red), indicate areas where the chance of encountering the species is increasingly higher according to the environmental variables tested with the MaxEnt model.

Coexistence

In the first model (Fig. 6.6), where the probability of finding habitat suitability for both *C. sapidus* and *P. segnis* is set at 40%, the areas affected by a possible overlap are many. These include the area around the Strait of Gibraltar, a significant portion of the Spanish and French coasts, almost the entire Italian peninsula, part of northern Sicily and the Strait of Sicily, and all the coasts of the Eastern Mediterranean. However, the areas highlighted in red represent the regions where the probability of coexistence of the two species is higher. On the Tyrrhenian side, the area of overlap is limited to the Italian Gulf of Naples. On the Ionian side, a localized red area is highlighted on the eastern coast of Sicily, between Catania and Siracusa. On the Adriatic coast, only some enclosed areas are affected by this overlap: a part of the Gulf of Venice, a portion of south Croatia, and a wider area within the border of Albania and Greece, which includes the eastern side of Corfu Island. Lastly, in the Eastern Mediterranean, several other gulfs in Greece are contained in the overlap, along with the eastern coasts of Turkey, part of the coast of Lebanon, and the entire coasts of Israel, as well as the entrance of the Suez Canal and the eastern coast of Egypt. The Tunisian coast is almost entirely highlighted in red, especially in the whole area of the Gulf of Gabes.

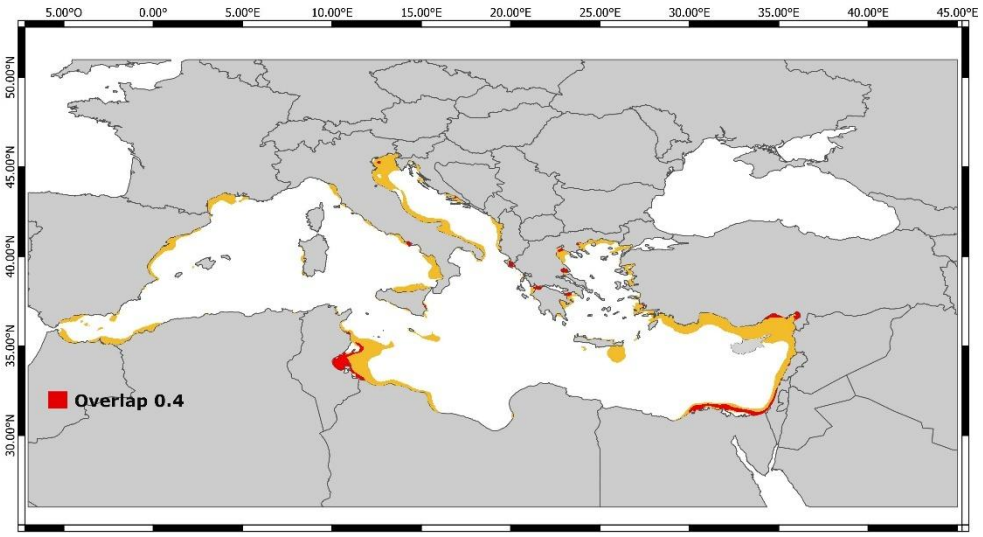

Figure 6.6: Habitat suitability maps for *Callinectes sapidus* and *Portunus segnis* with overlap at 40% possibility. Areas with 40% opportunity to find both crab species are highlighted in red; those with 40% chance of finding only one of the two species are highlighted in yellow.

The second model (Fig. 6.7) displays the areas where the probability of coexistence is higher than 60%, and the areas affected by the possibility of coexistence between the two species are reduced throughout the entire Mediterranean basin. The highlighted areas along the Spanish, French, and Italian coasts almost disappear, with no red areas for the Northern and Western coasts. The only remarked area is a small portion of the coast in Greece, between the main Island and Zante. Moving to the Eastern Mediterranean, the Gulf of Antalya in Turkey is still marked in red. Israel and Egypt show again a high possibility of overlapping, but the red areas are more limited. The Gulf of Gabes, in Tunisia, is the only remarkable spot along the North African coast.

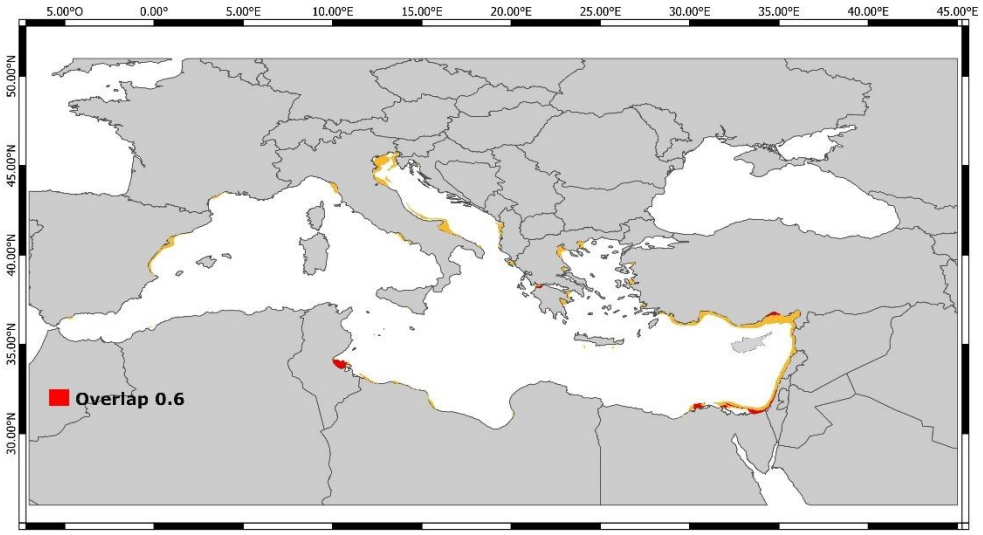

Figure 6.7: Habitat suitability maps for *Callinectes sapidus* and *Portunus segnis* with overlap at 60% possibility. Areas with 60% opportunity to find both crab species are highlighted in red; those with 60% chance of finding only one of the two species are highlighted in yellow.

Finally, the third model (Fig. 6.8) depicts the areas where the probability of coexistence is greater than 80% and highlights only a few areas throughout the entire basin. The areas that were highlighted in red in the previous models are now less frequent and yellow, marking the same areas. However, the red areas are limited to a small portion of the Turkish coast, in the Gulf of Antalya, a few areas in Egypt, between the Suez Canal and the Nile, and a tiny portion of the Gulf of Gabes, in Tunisia.

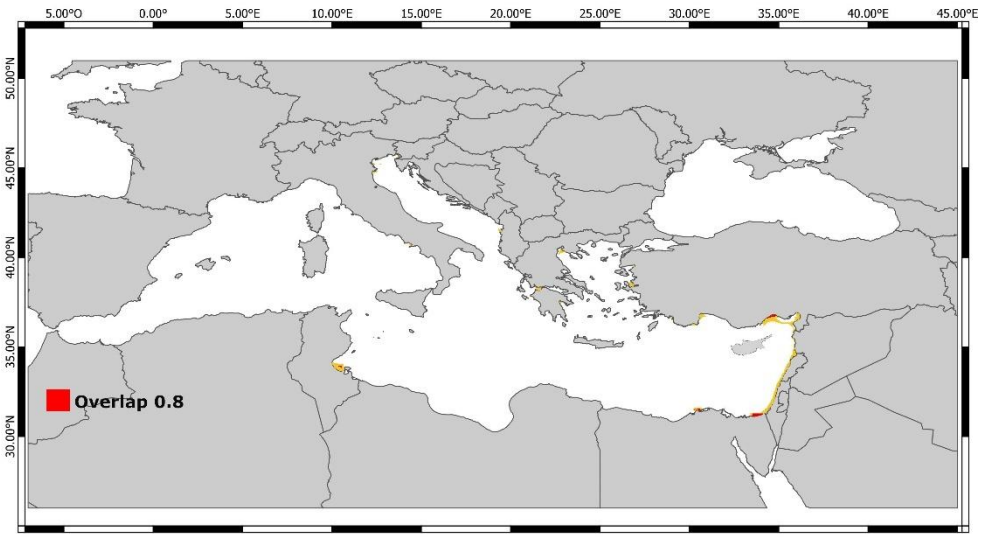

Figure 6.8: Habitat suitability maps for *Callinectes sapidus* and *Portunus segnis* with overlap at 80% possibility. Areas with 80% opportunity to find both crab species are highlighted in red; those with 80% chance of finding only one of the two species are highlighted in yellow.

6.5. DISCUSSION AND CONCLUSION.

The Mediterranean Sea is witnessing increasing concern within the scientific community due to the escalating impact of biological invasions, particularly from NIS, on native biodiversity and ecosystems. The introduction and establishment of NIS, facilitated by human activities and global environmental changes, pose significant threats to the region's ecological balance and socio-economic stability. The invasion dynamics of NIS, such as *C. sapidus* and *P. segnis*, highlight the challenges posed by biological invasions in the Mediterranean. Both species have rapidly expanded their ranges, with *C. sapidus* displaying extensive coverage across the entire basin, while *P. segnis* maintains a predominantly southern distribution, concentrated in regions such as North Africa, southern Italy, and Greece. The spread of these species is attributed to various factors, including the widening connectivity facilitated by the Suez Canal – for *P. segnis* – alongside climate change–induced alterations in marine environments (Harley et al., 2006; Pecl et al., 2017; Santojanni et al., 2023).

The implementation of MaxEnt modeling techniques provided insights into the habitat suitability and potential distribution patterns of *C. sapidus* and *P. segnis* across the Mediterranean basin. The points indicating every occurrence for *C. sapidus* and *P. segnis* (collected data) are overlayed to the suitability distribution models (MaxEnt) to highlight how most of the red areas, where the environmental conditions are ideal, already have several occurrences of each species (Figs 6.9; 6.10).

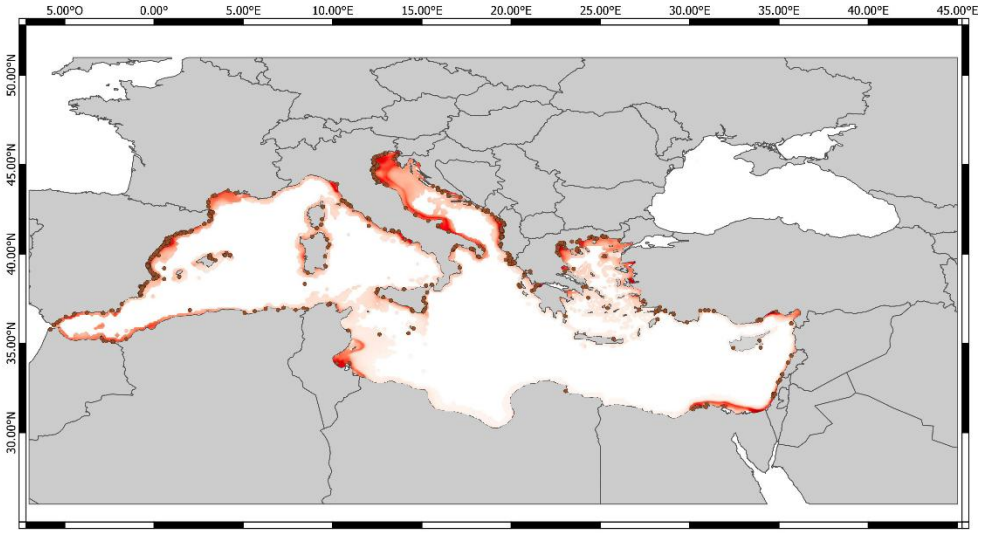

Figure 6.9: Occurrences of *Callinectes sapidus* collected from the Mediterranean Sea and used to build the MaxEnt model, overlaid to the habitat suitability map. The suitability surface represents a continuous gradient (0–1), where low values may appear visually similar to background due to colour scaling. The figure highlights areas where the species has not yet been reported despite suitable environmental conditions, as well as occurrence records falling within low but non-zero suitability values.

The habitat suitability map provided by MaxEnt also highlights some areas where the two species have not yet been found but where the environmental conditions suggest their possible presence. *Callinectes sapidus* is spread in most of the areas highlighted by the suitability map: the only areas highlighted in red where the species does not show occurrences are on the western coast of Algeria and in Syria. For *P. segnis*, the red areas where the species does not occur include the western coast of Lybia, the Syrian coast, some areas in Turkey, and some portions of southern Greece.

Through the integration of species occurrence data and environmental variables, our study developed robust predictive models capable of accurately forecasting the current species distributions across varying temporal and spatial scales. The achievement of consistently high average AUC values exceeding 0.85, coupled with minimal standard deviations, attests to the effectiveness of the MaxEnt models in discerning suitable habitat conditions from unsuitable ones.

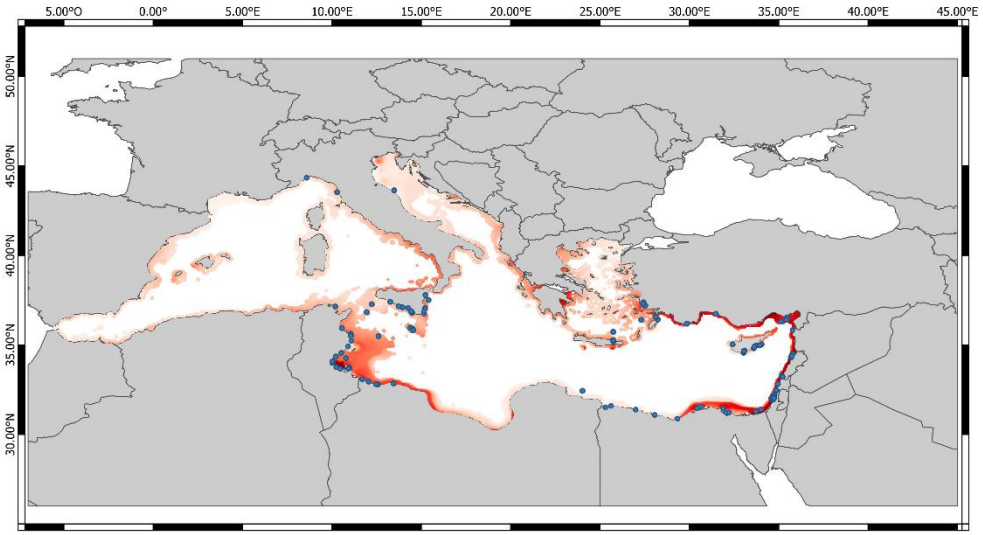

Figure 6.10: Occurrences of *Portunus segnis* collected from the Mediterranean Sea and used to build the MaxEnt model, overlaid to the habitat suitability map. To emphasize areas where the species has not yet been reported, but which have suitable environmental conditions for its occurrence. The suitability surface represents a continuous gradient (0–1), where low values may appear visually similar to background due to colour scaling. The figure highlights areas where the species has not yet been reported despite suitable environmental conditions, as well as occurrence records falling within low but non-zero suitability values.

These results underscore the reliability of our models in capturing the intricate relationships between species occurrences and environmental factors. These findings highlight the effectiveness of the models and the accuracy of their predictions regarding the habitat distribution of *C. sapidus* and *P. segnis* in the Mediterranean region (Table 6.3).

Species	Threshold	TSS	AUC	Dev/st
Callinectes sapidus	0.2455	0.7512	0.901	0.014
Portunus segnis	0.2857	0.6811	0.891	0.044

Table 6.3. Modelling evaluation showing the Threshold, TSS, AUC and Dev/st values for both species, highlighting the accuracy of the MaxEnt models.

An in-depth analysis of the contribution from different variables revealed the pivotal environmental drivers shaping the habitat suitability of both *C. sapidus* and *P. segnis*. Variables such as chlorophyll-a and oxygen emerged as significant predictors for *C. sapidus*, reflecting the species' preference for nutrient-rich and thermally suitable habitats. However, SST exhibited the highest in- fluence on the habitat suitability of *P. segnis*, underscoring its critical role as an environmental determinant for the species' distribution. Moreover, response curves provided nuanced insights into the marginal effects of individual environmental variables on species distributions, elucidating how changes in environmental conditions influence habitat suitability probabilities. These findings contribute to a deeper understanding of the ecological niche requirements of invasive decapod species, thereby informing targeted conservation efforts and management strategies aimed at mitigating their impacts.

The assessment of habitat overlaps between *C. sapidus* and *P. segnis* unveiled intriguing spatial dynamics with profound implications for species coexistence and potential interspecific competition. By delineating areas of high probability of habitat overlap, our study identified regions where interspecific interactions may occur, thereby influencing community dynamics and ecosystem functioning. It is important to note that habitat overlap derived from species distribution models does not represent direct evidence of ecological interaction or competition, but rather indicates potential co-occurrence based on shared environmental suitability. Given the presence-only nature of the occurrence data and the spatial resolution of environmental predictors, these outputs should be interpreted as broad-scale approximations of overlapping suitable conditions rather than as direct estimates of competition intensity. In the first model, depicting a 40% probability of habitat overlap, extensive areas across the Mediterranean basin were identified as potential hotspots for both species' coexistence.

Particularly noteworthy were regions around the Strait of Gibraltar, the Spanish and French coasts, the Italian peninsula, and the Eastern Mediterranean, suggesting widespread opportunities for interspecific interactions and ecological niche overlap.

As the probability threshold for habitat overlap increased to 60% in the second model, the extent of overlapping areas decreased, indicating a more constrained range of potential coexistence. This reduction in overlap was particularly pronounced in Greece and Turkey, as well as in Israel, Egypt, and Tunisia, suggesting a decreased likelihood of interspecific interactions in these regions. In the third model, where the probability of habitat overlap exceeded 80%, only a few localized areas throughout the basin exhibited significant overlaps, highlighting specific regions of increased potential for coexistence. Despite the overall reduction in overlapping areas, certain hotspots of coexistence persisted along the Egyptian and Tunisian coasts, underscoring areas of elevated interspecific interaction potential and ecological significance.

These maps confirm expectations indicating that areas with a chance of a high coexistence of *C. sapidus* and *P. segnis* are the ones where the environmental conditions are suitable for both species, allowing their presence. However, it is important to consider not only the presence of a suitable habitat but also their biology and ecology.

A key ecological factor at the base of coexistence is competition. The two species are both predators, so they might compete for food resources. Habitat is another aspect of paramount importance. Although *C. sapidus*, unlike *P. segnis*, needs brackish-water environments to complete its life cycle, they could cooccur in the open sea because they can inhabit coastal sandy bottoms at least for a part of their life cycle. Lastly, temperature, which we have already identified as a key parameter, especially for *P. segnis*, may help explain the current and future distribution of the two species. On the one hand, *P. segnis*, which comes from the Red Sea and the western Indian Ocean, tends to prefer the warmer areas of the Mediterranean; on the other hand, the temperate west-Atlantic origin of *C. sapidus* might have favored its wide spreading throughout the Mediterranean basin (Marchessaux *et al*., 2022; 2024).

Our study offers comprehensive insights into habitat suitability and potential coexistence dynamics of invasive decapod species within the Mediterranean basin. By integrating MaxEnt modeling techniques with habitat overlap analysis, we have provided a holistic understanding of species distributions and ecological interactions, there- by informing targeted conservation efforts and invasive species management strategies. Future research endeavors should prioritize the refinement and validation of predictive models, the inclusion of additional environmental variables, and the integration of spatiotemporal dynamics to enhance the accuracy and applicability of habitat suitability assessments. Continued monitoring efforts and

collaborative initiatives are imperative for addressing the ongoing challenges posed by biological invasions and safeguarding the ecological integrity of the Mediterranean ecosystem. The possibility that *C. sapidus* and *P. segnis* may coexist in certain areas of the Mediterranean is made plausible not only by the environmental conditions of the entire basin and their evolution but also by the ecology of the two species.

Along the Atlantic coast of America, *C. sapidus* has been observed competing with the lady crab, *Ovalipes ocellatus* (Herbst, 1799), and the Atlantic rock crab, *Cancer irroratus* (Say, 1817), at the mouths of several rivers (Stehlik *et al.*, 2004). Dietary overlap has been identified with *Callinectes similis* (Williams, 1966) and *Callinectes ornatus* (Ordway, 1863). In general, the genus *Callinectes* is particularly competitive and aggressive (Ben Abdallah-Ben Hadj Hamida *et al.*, 2019). The future coexistence of *C. sapidus* and *P. segnis* in certain areas of the Mediterranean could result in significant ecological interactions. Given the competitive nature of *C. sapidus*, known for its aggressive behavior and dietary overlap with other species, it is likely that both species will compete for similar resources. Both species are carnivores and feed on a wide variety of prey items (Mancinelli *et al.*, 2017; Ben Abdallah-Ben Hadj Hamida *et al.*, 2019). Moreover, the introduction of these crabs might affect the local biodiversity and ecosystem dynamics, potentially leading to unforeseen consequences for the marine environment. To fully understand the implications of their coexistence, comprehensive studies are necessary, focusing on their ecological roles, competition mechanisms, and potential influence on native species and habitats in the Mediterranean.

6.6. REFERENCE LIST

Aslan, H. and Polito, M.J., 2021. Trophic ecology of the Atlantic blue crab *Callinectes sapidus* as an invasive non-native species in the Aegean Sea. *Biological Invasions*, 23 (7), 2289-2304.

Bargain, A., Marchese, F., Savini, A., Taviani, M., Fabri and M.-C., 2017. Santa Maria di Leuca province (Mediterranean Sea): identification of suitable mounds for coldwater coral settlement using geomorphometric proxies and maxent methods. *Frontiers in Marine Science*, 4, 338.

Ben Abdallah-Ben Hadj Hamida, O., Ben Hadj Hamida, N., Ammar, R., Chaouch, H. and Missaoui, H., 2019. Feeding habits of the swimming blue crab *Portunus segnis* (Forskål, 1775) (Brachyura: Portunidae) in the Mediterranean. *Journal of the Marine Biological Association of the United Kingdom*, 99 (6), 1343-1351.

Castriota, L., Falautano, M., Maggio, T. and Perzia, P., 2022. The blue swimming crab *Portunus segnis* in the Mediterranean Sea: invasion paths, impacts and management measures. *Biology*, 11 (10), 1473.

Criales, M.M., Chérubin, L., Gandy, R., Garavelli, L., Ali Ghannami, Crowley, C., 2019. Blue crab larval dispersal highlights population connectivity and implications for fishery management. *Marine Ecology Progress Series*, 625, 53-70.

Deidun, A., Galdies, J., Marrone, A., Sciberras, A., Zava, B., Corsini-Foka, M., Gianguzza, P., 2022. The first confirmed record of the Atlantic blue crab *Callinectes sapidus* Rathbun, 1896 (Decapoda, Brachyura) from Maltese waters. *BioInvasions Records*, 11 (1), 238-243.

Dickinson, G., Rittschof, D. and Latanich, C., 2006. Spawning biology of the blue crab, *Callinectes sapidus*, in North Carolina. *Bulletin of Marine Science*, 79 (2), 273-285.

Elith*, J., H. Graham*, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., J. Hijmans, R., Huettmann, F., R. Leathwick, J., Lehmann, A. and Li, J., 2006. Novel methods improve prediction of species' distributions from occurrence data. *Ecography*, *29*(2), pp.129-151.

Elith, J., Phillips, S.J., Hastie, T., Dudík, M., Chee, Y.E. and Yates, C.J., 2011. A statistical explanation of MaxEnt for ecologists. *Diversity and distributions*, *17*(1), pp.43-57.

Fox, H.M., 1924. The migration of a Red Sea crab through the Suez Canal. *Nature*, 113 (2846), 714-715.

Galil, B.S., 2011. The alien crustaceans in the Mediterranean Sea: an historical review. In In the wrong place-alien marine Crustaceans: distribution, biology and impacts (pp. 377-401). Dordrecht: Springer Netherlands.

Giordani Soika, A., 1951. Il *Neptunus pelagicus* (L.) nell'Alto Adriatico. *Natura*, 42 (1-2), 18-20.

Giraldes, B.W., Al-Maslamani, I., Al-Ashwel, A., Chatting, M. and Smyth, D., 2016. Basic assessment of *Portunus segnis* (Forskål, 1775). A baseline for stock management in the Western Arabian Gulf. *Egyptian Journal of Aquatic Research,* 42 (1), 111-119.

Hadj Hamida, O.B.A.B., Hadj Hamida, N.B., Chaouch, H., Nafkha, B., Ben Ali, N., Abidi, D. and Missaoui, H., 2022. Reproductive biology of the blue swimming crab *Portunus segnis* (Forskål, 1775)(Brachyura: Portunidae) in the Gulf of Gabes (southeastern Tunisia, central Mediterranean Sea). African Journal of Marine Science, 44(1), pp.11-20.

Harley, C.D., Randall Hughes, A., Hultgren, K.M., Miner, B.G., Sorte, C.J., Thornber, C.S., Rodriguez, L.F., Tomanek, L. and Williams, S.L., 2006. The impacts of climate change in coastal marine systems. Ecology letters, 9(2), pp.228-241.

Hines, A.H., 2007. Ecology of juvenile and adult blue crabs. The Blue Crab *Callinectes sapidus*. Maryland Sea Grant College, College Park, Maryland, pp.565-654.

Kampouris, T.E., Porter, J.S. and Sanderson, W.G., 2019. *Callinectes sapidus* Rathbun, 1896 (Brachyura: Portunidae): an assessment on its diet and foraging behaviour, Thermaikos Gulf, NW Aegean Sea, Greece: evidence for ecological and economic impacts. *Crustacean Research*, 48, 23-37.

Katsanevakis, S., Poursanidis, D., Hoffman, R., Rizgalla, J., Rothman, S.B.S., Levitt-Barmats, Y.A., Hadjioannou, L., Trkov, D., Garmendia, J.M., Rizzo, M. and Bartolo, A.G., 2020. Unpublished Mediterranean records of marine alien and cryptogenic species. BioInvasions Records, 9(2), pp.165-182.

Li, S., Wang, Z., Zhu, Z., Tao, Y. and Xiang, J., 2023. Predicting the potential suitable distribution area of *Emeia pseudosauteri* in Zhejiang Province based on the MaxEnt model. *Scientific Reports*, 13 (1), 1806.

Liu, C., Newell, G. and White, M., 2016. On the selection of thresholds for predicting species occurrence with presence-only data. *Ecology and Evolution*, 6 (1), 337-348.

Mancinelli, G., Bardelli, R. and Vizzini, S., 2022. Functional response and prey preference of the Atlantic blue crab *Callinectes sapidus* from a recently established population in a coastal Mediterranean lake. *Aquatic Invasions*, 17, 104-116.

Mancinelli, G., Bardelli, R. and Zenetos, A., 2021. A global occurrence database of the Atlantic blue crab *Callinectes sapidus*. *Scientific Data*, 8 (1), 111.

Mancinelli, G., Glamuzina, B., Petrić, M., Carrozzo, L., Glamuzina, L., Zotti, M., Raho, D. and Vizzini, S., 2016. The trophic position of the Atlantic blue crab *Callinectes sapidus* Rathbun 1896 in the food web of Parila Lagoon (South Eastern Adriatic, Croatia): a first assessment using stable isotopes. *Mediterranean Marine Science*, 17(3), pp.634-643.

Mancinelli, G., Chainho, P., Cilenti, L., Falco, S., Kapiris, K., Katselis, G. and Ribeiro, F., 2017. The Atlantic blue crab *Callinectes sapidus* in southern European coastal waters: Distribution, impact and prospective invasion management strategies. *Marine Pollution Bulletin*, 119(1), pp.5-11.

Marchessaux, G., Bosch-Belmar, M., Cilenti, L., Lago, N., Mangano, M.C, Marsiglia, N. and Sarà, G., 2022. The invasive blue crab *Callinectes sapidus* thermal response: Predicting metabolic suitability maps under future warming Mediterranean scenarios. *Frontiers in Marine Science*, 9, 1055404.

Marchessaux, G., Chevalier, C., Mangano, M.C. and Sarà, G., 2023. Larval connectivity of the invasive blue crabs *Callinectes sapidus* and *Portunus segnis* in the Mediterranean Sea: A step toward improved cross border management. *Marine Pollution Bulletin*, 194, 115272.

Marchessaux, G., Ghanem, R., Chaffai, A., Bahri, W.R., Marsiglia, N., Gjoni, V., Souissi, J.B. and Sarà, G., 2024. The use of thermal performance analysis to improve conservation management: The case of the invasive Red Sea swimming blue crab *Portunus segnis*. *Global Ecology and Conservation*, 54, p.e03071.

Merow, C., Smith, M.J. and Silander Jr, J.A., 2013. A practical guide to MaxEnt for 116odelling species' distributions: what it does, and why inputs and settings matter. *Ecography*, *36*(10), pp.1058-1069.

Millikin M.R. and Williams A.B., 1984. Synopsis of Biological Data on the Blue Crab, *Callinectes sapidus* Rathbun. *FAO Fisheries Synopsis*, 138, 32-39.

Nehring, S., 2011. Invasion history and success of the American blue crab *Callinectes sapidus* in European and adjacent waters. In In the wrong place-alien marine crustaceans: distribution, biology and impacts (pp. 607-624). Dordrecht: *Springer Netherlands*.

Palummo, V., Milisenda, G., Canese, S., Salvati, E., Pica, D., Passarelli, A., Spanò, N., Romeo, T. and Greco, S., 2023. Effect of environmental and anthropogenic factors on the distribution and co-occurrence of cold-water corals. *Frontiers in Marine Science*, 10, p.1272066.

Pecl, G.T., Araújo, M.B., Bell, J.D., Blanchard, J., Bonebrake, T.C., Chen, I.C., Clark, T.D., Colwell, R.K., Danielsen, F., Evengård, B. and Falconi, L., 2017. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, 355(6332), p.eaai9214.

Phillips, S.J., Anderson, R.P. and Schapire, R.E., 2006. Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, 190 (3-4), 231-259.

Phillips, S.J. and Dudík, M., 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography,* 31 (2), 161-175.

Phillips, S.J., Dudík, M., Elith, J., Graham, C.H., Lehmann, A., Leathwick, J. and Ferrier, S., 2009. Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. *Ecological Applications*, *19*(1), pp.181-197.

Pinsky, M.L., Selden, R.L. and Kitchel, Z.J., 2020. Climate-driven shifts in marine species ranges: scaling from organisms to communities. *Annual Review of Marine Science*, 12(1), 153-179.

Prado, P., Baeta, M., Mestre, E., Solis, M.A., Sanhauja, I., Gairin, I., Camps-Castellà, J., Falco, S. and Ballesteros, M., 2024. Trophic role and predatory interactions between the blue crab, *Callinectes sapidus*, and native species in open waters of the Ebro Delta. *Estuarine, Coastal and Shelf Science*, 298, p.108638.

Santojanni, F.B., Miner, H., Hain, H. and Sutton, G., 2023. The Impact of climate change on biodiversity in coastal ecosystems. *Jurnal Ilmu Pendidikan dan Humaniora*, 12 (3), 167-182.

Shaiek, M., El Zrelli, R., Crocetta, F., Mansour, L. and Rabaoui, L., 2021. On the occurrence of three exotic decapods, *Callinectes sapidus* (Portunidae), *Portunus segnis* (Portunidae), and *Trachysalambria palaestinensis* (Penaeidae), in northern

Tunisia, with updates on the distribution of the two invasive portunids in the Mediterranean Sea. *BioInvasions Records*, 10 (1), 158-169.

Streftaris, N. and Zenetos, A., 2006. Alien marine species in the Mediterranean-the 100 'Worst Invasives' and their impact. *Mediterranean Marine Science*, 7 (1), 87-118.

Vivas, M., Garcia-Rodriguez, E., Munoz-Vera, A., Barcala, E. and Guijarro-Garcia, E., 2025. Effect of the Invasive Blue Crab (*Callinectes sapidus* Rathbun, 1896) in a Protected Coastal Lagoon. *Estuaries and Coasts*, 48 (1), 1-13.

Yackulic, C.B., Chandler, R., Zipkin, E.F., Royle, J.A., Nichols, J.D., Campbell Grant, E.H. and Veran, S., 2013. Presence-only modelling using MAXENT: when can we trust the inferences?. *Methods in Ecology and Evolution*, *4*(3), pp.236-243.

Zenetos, A., Tsiamis, K., Galanidi, M., Carvalho, N., Bartilotti, C., Canning-Clode, J., Castriota, L., Chainho, P., Comas-González, R., Costa, A.C. and Dragičević, B., 2022. Status and trends in the rate of introduction of marine non-indigenous species in European seas. *Diversity*, 14(12), p.1077.

Chapter 7

Heat Nests: The Impact of Climate Change on Loggerhead Turtle (*Caretta caretta*) Nesting Distribution in Sicily (Italy)

This chapter is widely based on the following publication:

Siddiolo C., Rosso A., Orecchio G., Lo Valvo M. (2025b). Heat Nests: The Impact of Climate Change on Loggerhead Turtle (*Caretta caretta*) Nesting Distribution in Sicily (Italy). Ecology and Evolution, 15(4), e71177. https://doi.org/10.1002/ece3.71177

7 Heat Nests: The impact of climate change on Loggerhead turtle (*Caretta Caretta*) nesting distribution in Sicily (Italy)

7.1. ABSTRACT

This study aims to update and establish a comprehensive list of nesting sites in Sicily and its minor islands, investigate the distribution and environmental suitability of the loggerhead sea turtles' nesting in Sicily using spatial distribution models (SDMs), and perform a gap analysis considering the protected area network in Sicily. Location: Sicily (Italy). Time period: 1979–2022. Data on Loggerhead sea turtle's nests were collected through several sources, including literature, monitoring records from WWF's Progetto Tartarughe, reports from the local fauna haunting, online articles, referrals on websites and social networks often related to monitoring activities. GIS was used to realize distribution maps. Bioclimatic indicators were downloaded through Copernicus Climate Change Service. Predictors were eventually projected on the WorldClim's dataset. Suitability distribution models (SDMs) were realized using the maximum entropy model (MaxEnt software). *Caretta caretta*'s nests distribution map and environmental suitability map were overlaid with the Natura 2000 sites map in Sicily. The results confirm that the main nesting areas are mostly concentrated along the southern and eastern coasts of Sicily, with increasing numbers observed over recent years. Additionally, global warming has made some beaches even more suitable along the north coast of the main island. The variable affecting this species the most is the Mean Temperature of the Coldest Quarter (Bio11). Overlaying nesting distribution and environmental suitability maps with Natura 2000 sites revealed significant portions of nests occurring outside protected areas, highlighting the need for expanded conservation efforts. The demographic increase of nesting events in Sicily is induced by a northward shift of the species distribution led by rising temperatures and probably due to climate change.

7.2. INTRODUCTION

The loggerhead sea turtle, *Caretta caretta* (Linnaeus, 1758), is the most common of the Mediterranean sea turtles (Casale and Margaritoulis, 2010), and it has a cosmopolitan distribution, nesting in the widest geographical range of any sea turtle. It inhabits the Atlantic, Indian, and Pacific Oceans and the Mediterranean Sea. In the Mediterranean Sea, this species has a wide nesting area along the coasts of Greece, Turkey, Cyprus, and Libya, with minor breeding sites across Egypt, Israel, Lebanon, Syria, and Tunisia, but also occasional nesting concerning Spain, France, Italy, and their surrounding islands (Casale et al., 2018).

The interest in loggerhead sea turtles in the Mediterranean, particularly in Italy, has constantly increased during the last four decades, and nesting sites were recorded on the coasts of Sicily, Sardinia, Apulia, and the Ionic coasts of the Basilicata and Calabria regions, where nesting is considered occasional, except for the Ionic areas of southern Calabria and the Pelagian Islands (Linosa and Lampedusa). As with every other sea turtle species, loggerheads usually nest in specific areas, and nest counts represent the most common index of the population's size (Casale and Tucker, 2015; Mazaris et al., 2017). Nest-site selection in sea turtles is influenced by a combination of environmental and geomorphological factors. Beach characteristics such as substrate composition, slope, width, and exposure, together with climatic conditions affecting sand temperature and moisture, play a fundamental role in determining nesting suitability and reproductive success (Wood and Bjorndal, 2000; Miller et al., 2003). Consequently, understanding the environmental drivers associated with nesting habitats is essential for identifying suitable areas and supporting conservation planning.

There has been a significant increase in the number of recorded nests along the Italian shores over the years along with a growing number of reported nests, deposition sites and involved coastal areas in Sicily beyond the historically exploited and well-known Pelagian Islands (www.legambiente.it). Among the living tetrapods in Europe, the loggerhead sea turtle is one of the most protected under international agreements, national legislation, and directives: It is included in Annex A of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), in Appendix II of the Bonn Convention, in Annex II of the Barcelona Convention, in Annex III of the Berne Convention, and in Annexes II and IV of the Habitats Directive. Loggerhead sea turtle is globally listed as Vulnerable (VU) in the IUCN Red List of Threatened Species; the global population trend is decreasing due to fragmentation, fluctuations, and a continuous decline of mature individuals (Casale and Tucker, 2017; IUCN), while the Italian population is classified as endangered (EN) by the IUCN Italian Red List (Rondinini et al., 2022). Loggerheads

are affected by several threats (Tomás et al., 2008; Casale, 2010, 2011), including the human-induced alteration of coastal environments, the disturbance of the nesting sites, fishery, and pollution (Casale and Margaritoulis, 2010; Wallace et al., 2011).

The primary objective for the conservation of the species is to identify, protect, and manage the nesting sites; to achieve this goal, Special Areas of Conservation (SACs) have been established in Europe. Nowadays, the species distribution models (SDMs) are widely applied to understand various aspects of ecology, biogeography, and biodiversity conservation in order to investigate the distribution of threatened species (Engler et al., 2004; Bombi et al., 2009; Iannella et al., 2018) like the loggerhead sea turtle.
Therefore, the aims of this study are: (i) to establish and update the list of nesting sites in Sicily and its minor islands; (ii) to investigate the Sicilian distribution and nesting suitability using spatial distribution models (SDMs); (iii) to perform a gap analysis in a GIS environment considering the protected area network in Sicily.

7.3. MATERIALS AND METHODS

The region of Sicily is located in the center of the Mediterranean Sea, and it is composed of the largest island of the Mediterranean sea with an area of 25,711 km^2 and the surrounding 15 minor islands, with an area of 285.4 km^2. The main island has a remarkable coastline. Of the 1152 km, approximately 550 km (47.8%) consist of beaches and/or dune environments divided into 99 coastal segments (Corine Biotopes code: 16.1 sea beaches and 16.21 Shifting dunes).

Specific data on nesting areas of loggerhead sea turtles were collected through a bibliographic analysis, personal observations, reports from the local Wildlife division or local people witnessing the nesting events, referrals on websites and social networks often related to monitoring activities (WWF's Progetto Tartarughe in Sicily). Duplications (i.e., clutches laid by the same female) cannot be excluded. After georeferencing, all the locations of nests were analyzed by using GIS (ArcGis 10.5) to realize distribution maps.

Many ecological models predicting the spatial distribution of species have been developed. In order to define the suitability species distribution model (SDM) of *Caretta caretta* in the Sicily main island, therefore excluding minor islands, we used the maximum entropy method implemented through the MaxEnt Java software (version 3.4.3, November 2020) (Phillips et al., 2006, 2017; Phillips and Dudík, 2008), already used to assess the suitability of foraging areas for *Caretta caretta* (Fujisaki et al., 2020). This method has been widely applied in species distribution

modelling and is considered a robust and well-established approach for presence-only data under appropriate modelling settings (Elith et al., 2006; Phillips et al., 2006; Pearson et al., 2007; Merow et al., 2013). Unlike generalized linear models (GLMs) and generalized additive models (GAMs), which require true absence data, MaxEnt relies on machine-learning techniques to estimate species distributions from presence-only records. This makes it particularly suitable for our study case, as absence data are not available and we are unaware of sites where this species does not nest.

For the construction of the species distribution model pertaining to the major island, we used the nesting records of *Caretta caretta* spanning from 1979 to 2022 (included). The continuous bioclimatic variables from 1979 to 2018, at a 30-s arc resolution (original resolution ≈1 km2 grid cell; average for 1979–2018) were extracted from the Copernicus Climate Change Service's Downscaled Bioclimatic Indicators database for the designated regions (Wouters, 2021). The 19 bioclimatic variables selected from the Copernicus database correspond to those reported in the WorldClim database (Table 7.1), in order to allow a comparison over time.

These variables were selected because they are ecologically relevant to sea turtle nesting biology. In particular, temperature-related predictors (Bio05, Bio07, Bio11) act as proxies for thermal conditions influencing sand temperature regimes, incubation duration, and temperature-dependent sex determination, all of which are key processes in loggerhead turtle reproductive ecology. Precipitation-related variables (Bio12 and Bio13) were included as indicators of moisture availability and hydrological stability in nesting beaches, affecting nest site suitability, sand compaction, and the risk of nest flooding or erosion.

BIO1 = Annual Mean Temperature
BIO2 = Mean Diurnal Range (Mean of monthly (max temp—min temp))
BIO3 = Isothermality (BIO2/BIO7) (* 100)
BIO4 = Temperature Seasonality (standard deviation *100)
BIO5 = Max Temperature of Warmest Month
BIO6 = Min Temperature of Coldest Month
BIO7 = Temperature Annual Range (BIO5-BIO6)
BIO8 = Mean Temperature of Wettest Quarter
BIO9 = Mean Temperature of Driest Quarter
BIO10 = Mean Temperature of Warmest Quarter
BIO11 = Mean Temperature of Coldest Quarter
BIO12 = Annual Precipitation
BIO13 = Precipitation of Wettest Month
BIO14 = Precipitation of Driest Month
BIO15 = Precipitation Seasonality (Coefficient of Variation)
BIO16 = Precipitation of Wettest Quarter
BIO17 = Precipitation of Driest Quarter
BIO18 = Precipitation of Warmest Quarter

Note: BIO19 = Precipitation of Coldest Quarter.

Table 7.1: The dataset of the nineteen bioclimatic variables considered as candidate predictors (from Worldclim.org), with their codes and explication.

The Copernicus dataset provides bioclimatic indicators for 1979–2018, including 40-year average climatologies; in this study, we used the 1979–2018 average values multicollinearity among the 19 candidate predictors across the study area to perform a correlation test. We assessed the degree of intercorrelation by computing pairwise Pearson's correlation coefficient. Subsequently, we selected the most important factors within pairs of variables with Pearson $|r| > 0.85$ and excluding the ones having less ecological importance to the species based on its autoecology. Strongly correlated variables were excluded to reduce multicollinearity and improve model interpretability and stability. Therefore, weakly correlated environmental variables were considered to estimate their relative contribution to predicted habitat suitability for nesting. Five climate variables were selected: Bio05 (maximum daily temperature of the month with the highest monthly mean of daily mean temperature), Bio07 (maximum temperature of the warmest month minus minimum temperature of the coldest month), Bio11 (the mean of monthly mean temperature during the coldest quarter, defined as the quarter with the lowest monthly mean (of the daily mean) temperature using a moving average of 3 consecutive months), Bio12 (annual mean of the daily mean precipitation rate), and Bio13 (maximum of the monthly precipitation rate).

To perform the MaxEnt model, several default parameters were retained unchanged, such as a convergent threshold of 10−5, a maximum interaction value of 500, and a maximum of 10,000 randomly selected background points, as recommended by previous studies (Phillips and Dudík 2008; Anderson et al., 2016; Bargain et al., 2017). The predictive model was computed based on 10 replicates for the “Regularization Multiplier” (RM) parameter value. We opted for an RM of 1 to balance data adherence and model complexity and to minimize the risk of overfitting (Phillips et al. 2017; Bargain et al., 2018). For the modeling evaluations, we took into consideration the AUC values, the standard deviation, the TSS mean, and the TH value.

The environmental datasets used in this study were derived from both Copernicus Climate Change Service products and WorldClim climatological layers. This integration was necessary to balance complementary strengths of the two sources. Copernicus data provide high-resolution and physically consistent representations of recent climatic conditions derived from reanalysis and downscaled observations, whereas WorldClim offers widely used long-term climatological averages that ensure comparability with existing ecological modelling studies. Although the two datasets differ in their temporal reference periods, their combined use allowed us to maximise both spatial detail and methodological comparability across bioclimatic predictors. This approach is intended as a pragmatic integration of available climatic resources rather than a strictly temporally matched reconstruction of environmental conditions.

To assess the potential impact of climate change on the presence of nesting suitability sites for *Caretta caretta*, once the environmental suitability model was obtained using the Copernicus dataset, we projected the predictors onto the WorldClim dataset (ver.2.1), containing the average values of the same variables, relating to the period 1979–2000 (Fick and Hijmans, 2017). This was done to generate the corresponding environmental suitability map for the species. The projection onto the WorldClim climatological baseline (1979–2000) was performed to ensure consistency with a widely adopted reference period in ecological niche modelling and to reduce the influence of interannual variability present in the Copernicus-derived averages. In this context, the use of a historical climatological baseline is not intended as a reconstruction of past nesting conditions, but rather as a standardised climatic reference allowing model comparability and interpretability across studies. Future climate scenarios were not considered, as the objective of this work was to characterise current potential nesting suitability under baseline climatic conditions rather than to produce predictive forecasts under emission scenarios. The loggerhead sea turtle’s nests distribution map and environmental suitability map were overlaid with the Natura 2000 sites map in Sicily, in order to establish how many nests fit into Natura 2000 sites, including Special

Protection Areas (SPAs) and Special Conservation Areas (SACs). All model outputs should therefore be interpreted as estimates of habitat suitability rather than direct representations of nesting site selection processes. This modelling framework should be interpreted as a comparative climatological approach rather than a predictive future climate scenario analysis.

7.4. RESULTS

Between 1944 and 2022, 498 egg depositions occurred in the Sicilian Region (Prato et al. 2022; Table S1 (https://doi.org/10.1002/ece3.71177)): 363 in Sicily (Figure 7.1), and the remaining 135 in some of its smaller islands. Specifically, 3 egg depositions involved the Eolian Islands (1 in Panarea, 1 in Stromboli, and 1 in Lipari), and 132 the Pelagie Islands (80 in Lampedusa and 52 in Linosa) (Figure 7.2).

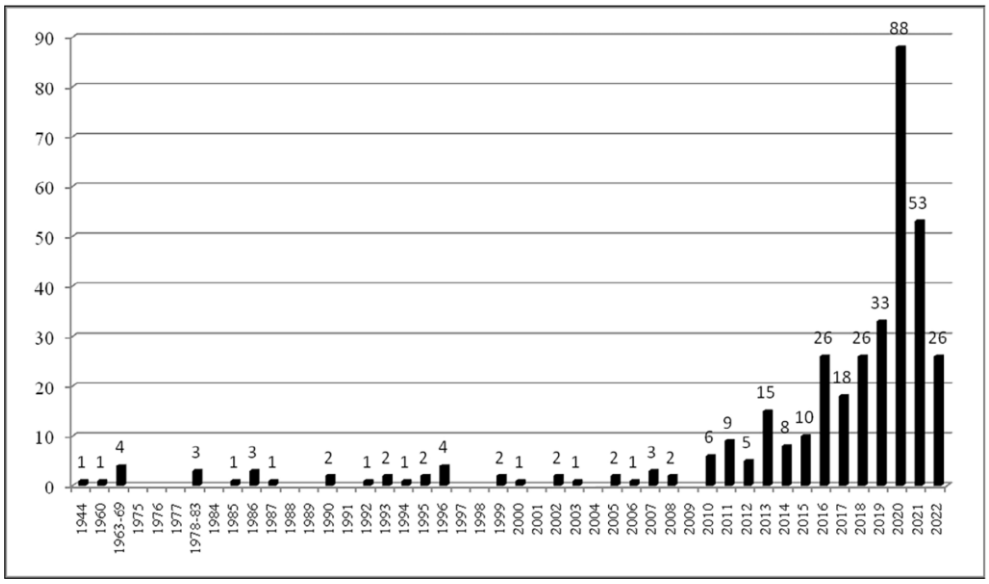

Figure 7.1: Temporal distribution of loggerhead turtle's nests (n = 363) recorded in Sicily (Italy) in the 1944–2022 period.

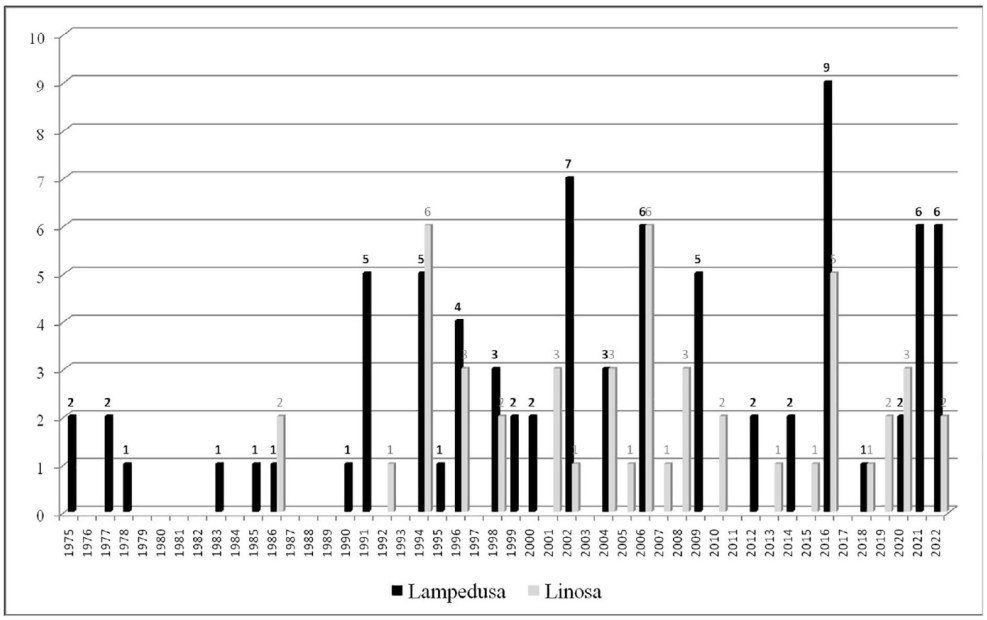

Figure 7.2: Temporal distribution of loggerhead turtle nests (n = 132) recorded in Pelagie Islands (Italy) in the 1975–2022 period.

The depositions observed in Sicily have included 99 coastal segments, with varying lengths spanning from 0.4 to 66 km. The majority of the sites are located along the entire southern coast, extending northward along half of the eastern coast of the island (Figure 7.3). About the environmental suitability, according to the classification of Swets (1988), the model of *C. caretta* obtained with the Copernicus dataset (Figure 5.4) showed very good overall performance (AUC = 0.961; SD = 0.011; threshold = 0.13; TSS = 0.832), thus indicating high predictive power for nest deposition.

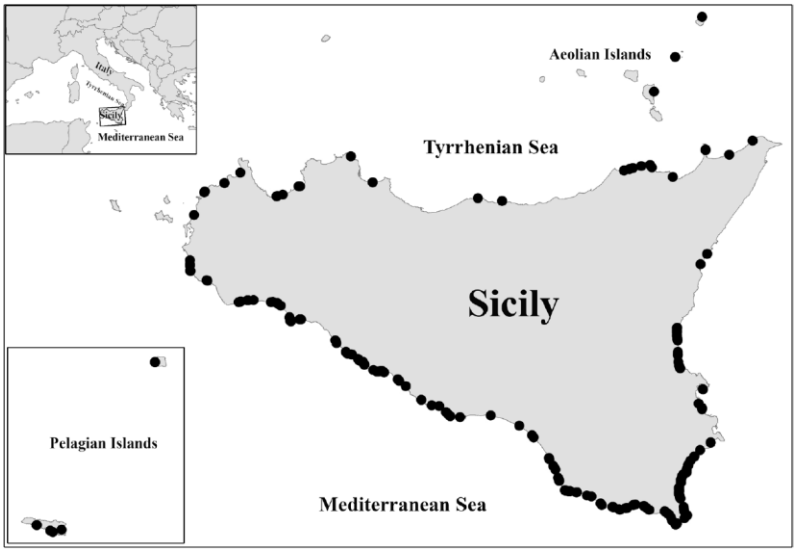

Figure 7.3: Geographical distribution of egg-laying sites in Sicily and its smaller islands from 1944 to 2022.

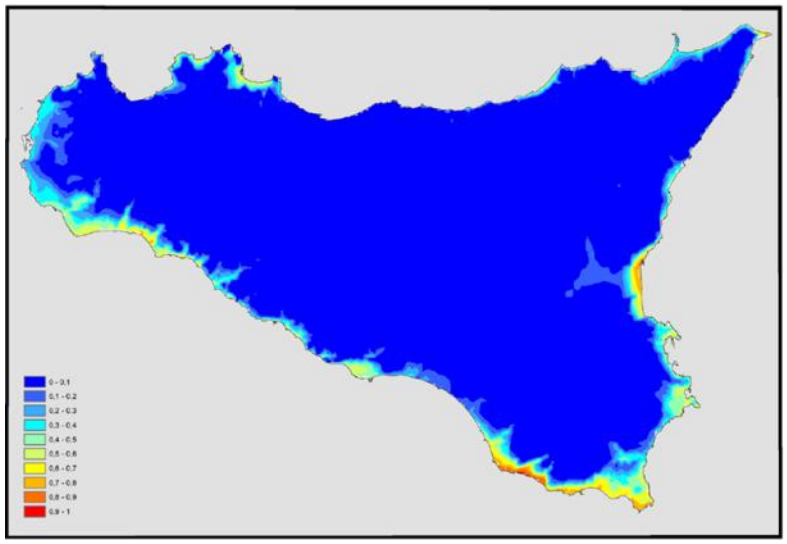

Figure 7.4: Suitability distribution areas of *Caretta caretta* in Sicily (dataset Copernicus 1979–2018).

The bioclimatic variable with the highest gain when used in isolation is the mean monthly temperature during the coldest quarter (Bio11), with a contribution of 89% (Copernicus). This suggests it provides the most useful information on its own. The contribution of the other considered variables is considerably lower (Table 7.2). The resulting map, obtained from the elaboration of nesting data, shows that the maximum value of the suitability estimate (red) by MaxEnt for these areas is equal to 0.97 and how areas of maximum suitability for nesting are mainly along the southern coast of the island, especially the southernmost area, located east of the island. Maximum suitability is also remarkable on the south-west coast, in the Sicilian Channel (from Mazara del Vallo to Sciacca and Licata), and south of the Ionian slope (from Catania's Gulf to Augusta). Specific areas with a high value of suitability (orange) are displayed along the northern side of the Ionian coast and along the Tyrrhenian coast of the island.

Figure 7.5 shows the model of the environmental suitability realized by projecting the predictive functions obtained with Copernicus onto the WorldClim dataset, which contains the annual averages of the variables for the period 1979–2000. Once again, it showed very good overall performance (AUC = 0.963; SD = 0.011; threshold = 0.164; TSS = 0.904).
Even so, the bioclimatic variable with the highest gain when used in isolation is the mean monthly temperature during the coldest quarter (Bio11), with a contribution of 89.7%, and the contribution of the other considered variables is considerably lower (Table 7.3). These values are very similar to the ones obtained in the Copernicus dataset (cfr. Table 7.2).

Variable	Percent contribution	Permutation importance
bio11	89	82.8
bio13	7.6	9.6
bio07	5.3	0.8
bio12	3.4	3.9
bio05	2.9	2.9

Table 7.2*:* The selected variables with their percent contribution and permutation importance (dataset Copernicus 1979–2018).

Variable	Percent contribution	Permutation importance
bio11	89.7	88.2
bio13	3.5	5.2
bio07	2.9	0.2
bio12	2.1	3.2
bio05	2.7	3.2

Table 7.3: The selected variables with their percent contribution and permutation importance (dataset Worldsclim 1979–2000).

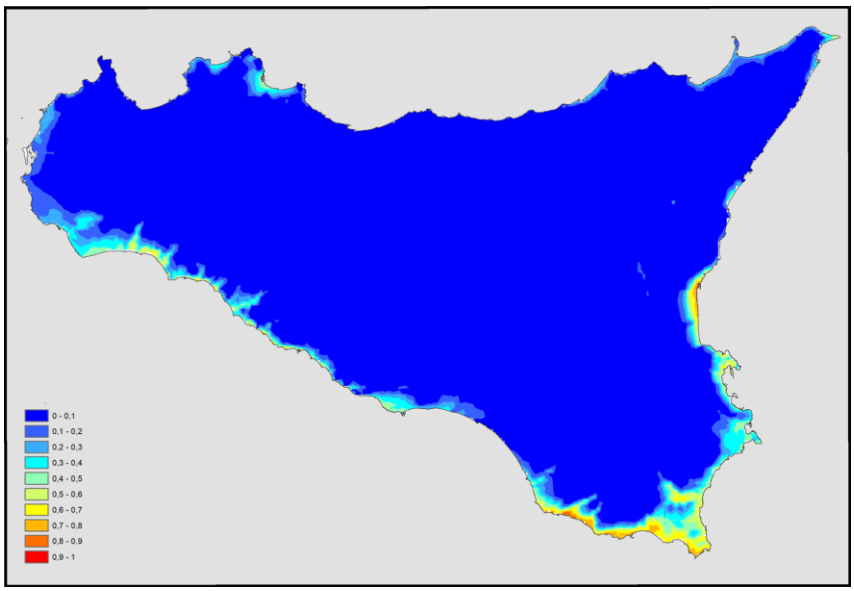

Figure 7.5: Suitability distribution areas of *Caretta caretta* in Sicily (dataset Worlclim 1979–2000).

Figure 7.6 shows how the trend of the environmental variable Bio11 affects the Maxent prediction obtained with the Copernicus and WorldClim datasets. The maxent suitability map is only based on the occurrence of deposition within the analyzed cells, regardless of the amount of depositions in each of them. Connecting the suitability degree of the cells in which the deposition occurred with the number

of depositions known, a significant correlation value emerged (p = 0.012). Comparing the suitability maps (Figures 7.4 and 7.5), it is possible to underline how some areas were, at first, less suitable and recently turned into more suitable sites for nesting, due to higher temperatures reached in the latest years, which led to new depositions along the Tyrrhenian coast of Sicily (Figure 7.3).

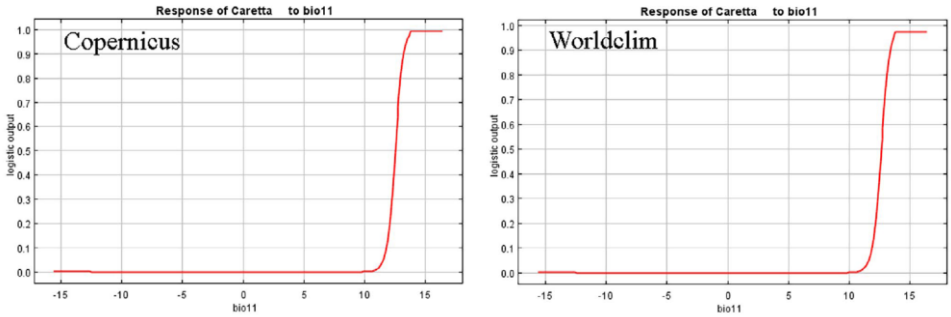

Figure 7.6: The response curves of the first variable that has the most contribution to the model.

Out of the 363 depositions that occurred in Sicily from 1944 to 2022, 169 of them affected 22 Natura 2000 sites, specifically 5 Special Protection Areas (SPAs), 2 Special Protection Areas/Special Areas of Conservation (SPA/SAC), and 15 (Special Areas of Conservation (SACs)) (Figure 7.7). Among these, only 8 sites (36.4%) reported *Caretta caretta* within the standard data form, which nevertheless refers to the protection of the species in relation to emerged areas. The remaining 194 (53%) depositions occurred outside of these sites: in some cases, the nests are very close to the edges of the Natura 2000 sites, although a considerable number (n = 77) of depositions occurred far from any of these sites.

Figure 7.7 shows UTM Map (gridcell 10x10km) update of *C. caretta* in Sicily, based on previous distribution atlases (Turrisi and Vaccaro, 1998; Lo Valvo and Longo, 2001; Bella and Turrisi, 2005; AA.VV., 2008; Giacoma et al. in Corti et al., 2010), new literatures and online sources, including depositions in 2022.

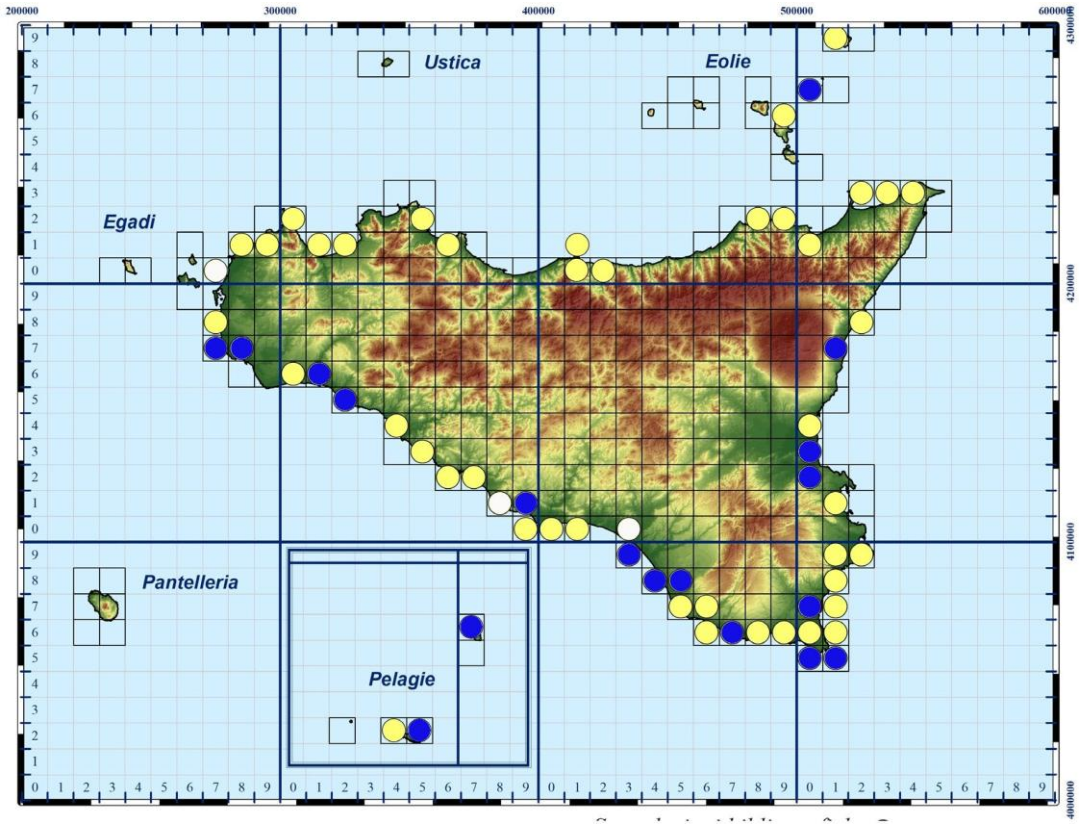

Figure 7.7: Atlas updated map (UTM WGS84) of *Caretta caretta*'s egg-laying sites in Sicily. Blue circle = confirmed previous atlas data; yellow circle = new data; white circle = non confirmed data.

7.5. DISCUSSION

Nesting events are known for Sicily since the XIX century (Doderlein 1871). The first distribution map of *Caretta caretta*, concerning the period between 1975 and 1997 and based on nesting events, defines Sicily island as an irregular nesting site (Turrisi and Vaccaro 1998), while nesting in Lampedusa and Linosa islands is classified as regular nesting events and sites (Turrisi and Vaccaro 1998; Lo Valvo and Longo 2001; Bella and Turrisi 2005; AA.VV 2008; Giacoma et al., in Corti et al. 2010). The higher frequency and regularity of nesting events recorded in Lampedusa and Linosa, compared to the main island of Sicily, may be related to a combination of favourable environmental and anthropogenic conditions. These islands are

characterised by a higher degree of coastal habitat integrity, including the presence of suitable sandy beaches and dune systems, as well as lower levels of coastal urbanisation and human disturbance. In addition, reduced artificial light pollution and limited coastal modification are known to positively influence nesting site selection and nesting success in sea turtles. Their southern geographical position within the central Mediterranean may also contribute to more suitable thermal conditions for incubation and embryonic development. These factors have been widely recognised as key drivers of nesting habitat suitability in loggerhead sea turtles in the Mediterranean basin (Margaritoulis et al., 2003; Casale and Margaritoulis, 2010; Mazaris et al., 2017). The produced map of Sicily (UTM WGS84; gridcell 10×10 km2) shows the presence of reproductive sites within 7 gridcells. A second map, corresponding to the period 1975–1999, reports instead the presence of reproductive sites falling in 6 gridcells (Giacoma et al. in Corti et al., 2010). The Italian herpetological atlas (Sindaco et al., 2006), updated to 2005, strangely did not consider the species as a nesting population on the island. A further distribution map, taking into account the nests observed between 1980 and 1999, reports 13 gridcells occupied, which are reduced to 9 by 2006 (AA.VV., 2008). From 2011, the number of nesting events has shown a significant increase compared to the past, and it appears to exhibit regular patterns over time, especially along the southern coast of the island (Casale et al., 2012). A very lacking map concerning 25 depositions in Sicily for the years 2017 and 2018 has been published by Surdo and Massa (2020), although the nesting events known for this same period are 37 (cf. Prato et al., 2022). A more comprehensive map is provided by Prato et al. (2022), which covers depositions from 1944 to 2021.

This abrupt increase of nests and colonizing individuals (cfr. Luna-Ortiz et al., 2024) in the past decade has been interpreted as the result of heightened beach monitoring efforts, associated with the activation and implementation of LIFE projects, as well as increased public awareness. Citizens have learned to recognize the tracks left on the sand by female turtles during their excursions for nesting and they report their presence to authorities (Pietroluongo et al., 2021). Furthermore, it is likely due to an actual increase in the number of nestings in Sicily, contrary to the statement made by Surdo and Massa (2020). This increase, which seems to be confirmed by nesting events on beaches characterized by high and constant human activities, where the presence of the species had never been reported before, is also highlighted by the increasing number of sea turtle rescues at marine turtle rehabilitation centers in recent years (cf. Caracappa et al., 2018), but also by the increasing number of sightings at sea and along the island's coasts (Atzori et al., 2021; Vecchioni et al., 2022). The hypothesis of an increase in the breeding sites in

Sicily is also supported by the comparison of the two suitability maps obtained for different periods.

It is reasonable to assume that the demographic increase of nesting events on the island is induced by the northward shift of the species, due to the increase in temperatures and the presence of beaches that have become suitable for nesting. Just at the beginning of the nesting season, the Tyrrhenian coast of Sicily already counts twelve nests only in the province of Palermo (Mondello Beach, Trappeto, Cefalù; Pozzillo, Balestrate, Isola delle Femmine, Lascari; source: firsthand data from WWF Italia). Like many thermophilic species (cfr. Ventura et al., 2019; Esposito et al., 2021; Iveša et al., 2021), loggerhead turtles could use warmer waters and enlarge their habitat to avoid competition for food and breeding. Northward displacement is likely to be facilitated by climate change and rising sea surface temperatures (SST) in recent years (Pastor et al., 2018; Reddin et al. ,2022; Hamdeno and Alvera- Azcarate, 2023). In support of this theory, the unusual but increasingly common nests is observed in the northern Tyrrhenian and northern Adriatic (Hochscheid et al., 2022). Therefore, Sicily has now become not only a regular site for loggerhead sea turtle oviposition but also an important area for the conservation of this turtle species in the central Mediterranean region. Consequently, it is essential to protect these new nesting sites through the implementation of already existing conservation measures and the institution of new conservation measures. Despite this increase, an update has not yet been undertaken.

In consideration of the importance of Sicily today as an egg-laying area for *Caretta caretta*, it would be essential to update the ecological network for the protection of this species, including, if not present, the taxon in the standard form of sites already established, modifying the boundaries of some sites already established by expanding their surfaces or establishing new ones by including areas suitable for deposition and inserting the species in the standard forms (Table 7.4). Eventually, it would be necessary to establish a new SAC coinciding with the Calabernardo Beach (Lido di Noto, Siracusa).

	Present	Newly established	Extension	Form	
ITA010011	SAC		X		Including the beach to the east up to the mouth of the Cavarretto torrent (UTM WGS84 33S 320202, 4159140)
ITA040003	SAC		X		Including the beach to the east up to Punta secca (UTM WGS84 33S 359700, 4130940)
ITA040015	SAC		X		Including the beach to the east up to Porto Empedocle harbor (UTM WGS84 33S 369130, 4127660)
ITA030032	SAC		X	X	Including the beach to the south (Angonia's Beach)
ITA070001	SPA	SAC	X	X	
ITA070029	SPA	SAC		X	
ITA070030	SAC			X	
ITA090002	SAC			X	
ITA090003	SAC			X	
ITA090004	SAC			X	
ITA090010	SAC			X	

Table 7.4: Suggested updates to sites of community importance for a better ecological network for the protection of *Caretta caretta* in Sicily.

7.6. REFERENCE LIST

AA.VV. (2008). Atlante della Biodiversità della Sicilia: Vertebrati terrestri. Studi e Ricerche, 6. Palermo: ARPA Sicilia, pp. 536.

Anderson, O.F., Guinotte, J.M., Rowden, A.A., Tracey, D.M., Mackay, K.A., and Clark, M.R. 2016. Habitat suitability models for predicting the occurrence of vulnerable marine ecosystems in the seas around New Zealand. *Deep Sea Research Part I: Oceanographic Research Papers*, 115, 265-292.

Atzori, F., Carosso, L., Cadoni, N., Frau, F., Gutierrez, M.L.G., De Lucia, G.A., Gregorietti, M., Pellegrino, G., Liubartseva, S., Lecci, R. and Coppini, G., 2021. Loggerhead sea turtle, *Caretta caretta*, presence and its exposure to floating marine litter in the Sardinia Channel and the Strait of Sicily: Results from seven years of monitoring using ferry as platform of observation. *Mediterranean Marine Science*, *22*(2), pp.422-435.

Bargain, A., Foglini, F., Pairaud, I., Bonaldo, D., Carniel, S., Angeletti, L., Taviani M., Rochette S. and Fabri, M.C. 2018. Predictive habitat 136odelling in two Mediterranean canyons including hydrodynamic variables. *Progress in Oceanography*, 169, 151-168. https://doi.org/10.1016/j.pocean.2018.03.004

Bargain, A., Marchese, F., Savini, A., Taviani, M., and Fabri, M.C. 2017. Santa Maria di Leuca Province (Mediterranean Sea): Identification of suitable mounds for cold-water coral settlement using geomorphometric proxies and Maxent methods. *Frontiers in Marine Science*, 4, 338. https://doi.org/10.3389/fmars.2017.00338

Bella, S., and Turrisi, G.F., 2005. Status e conservazione dei Testudinati in Sicilia. WWF Sicilia, 50 pp.

Bombi, P., Luiselli, L., Capula, M. and Salvi, D. 2009. Predicting elusiveness: potential distribution model of the Southern smooth snake, *Coronella girondica*, in Italy. *Acta Herpetologica*, 4, 7-13. https://doi.org/10.13128/Acta_Herpetol-4162

Caracappa, S., Persichetti, M.F., Piazza, A., Caracappa, G., Gentile, A., Marineo, S., Crucitti, D. and Arculeo, M. 2018. Incidental catch of loggerhead sea turtles (*Caretta caretta*) along the Sicilian coasts by longline fishery. *PeerJ*, 6, e5392

Casale, P. 2011. Sea turtle by-catch in the Mediterranean. *Fish and Fisheries*, 12, 299-316.

Casale, P. (Ed.). 2010. Sea turtles in the Mediterranean: distribution, threats and conservation priorities. IUCN.

Casale, P., and Tucker, A.D. 2015. *Caretta caretta*. The IUCN red list of threatened species 2015: e. T3897A83157651.

Casale, P. and Tucker, A.D. 2017. *Caretta caretta*. The IUCN red list of threatened species 2017: e. T3897A119333622.

Casale, P., Broderick, A.C., Camiñas, J.A., Cardona, L., Carreras, C., Demetropoulos, A., Fuller, W.J., Godley, B.J., Hochscheid, S., Kaska, Y., Lazar, B., Margaritoulis, D., Panagopoulou, A., Rees, A.F., Tomás, J., and Türkozan, O. 2018. Mediterranean sea turtles: current knowledge and priorities for conservation and research. *Endangered Species Research*, 36, 229-267. https://doi.org/10.3354/esr00901

Casale, P. and Margaritoulis, D. 2010. Sea Turtles in theMediterranean: Distribution, Threats and Conservation Priorities. IUCN/SSC Marine. Turtle Specialist Group, Gland. 294pp.

Corti, C., Capula, M., Luiselli, L., Razzetti, E. and Sindaco, R. 2010. Fauna d'Italia, Reptilia. Edizioni Calderini, Bologna. ISBN: 978-88-506-5390-4

Doderlein, P. 1871. Alcune generalità intorno la Fauna Sicula dei vertebrati. Classe dei Rettili e Batraci. Annali Società Naturalistica Modena, 4: 200-211.

Elith, J., Graham, C.H., Anderson, R.P., Dudík, M., Ferrier, S., Guisan, A., Hijmans, R.J., Huettmann, F., Leathwick, J.R., Lehmann, A., Li, J., Lohmann, L.G., Loiselle, B.A., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., Overton, J. McC. M., Townsend Peterson, A., Phillips, S.J., Richardson, K., Scachetti-Pereira, R., Schapire, R.E., Soberón, J., Williams, S., Wisz, M. S., and E. Zimmermann, N. 2006. Novel methods improve prediction of species' distributions from occurrence data. *Ecography*, 29, 129-151. https://doi.org/10.1111/j.2006.0906-7590.04596.x

Engler, R., Guisan, A. and Rechsteiner, L. 2004. An improved approach for predicting the distribution of rare and endangered species from occurrence and pseudo-absence data. *Journal of Applied Ecology*, 41, 263-274. https://doi.org/10.1111/j.0021-8901.2004.00874.x

Environmental Systems Research Institute (ESRI). (2016). *ArcGIS Desktop* (Version 10.5) [Software]. Redlands, CA

Esposito, G., Prearo, M., Menconi, V., Mugetti, D., Meloni, D., Tomasoni, M., Pizzul, E., Piras, P., Renzi, M., Gaspa, D. and Pastorino, P., 2021. Northward spread of the parrotfish *Sparisoma cretense* (137odelling: Scaridae) in the mediterranean sea: an

update on current distribution with two new records from 138odellin. *Journal of Marine Science and Engineering*, 9, 536. https://doi.org/10.3390/jmse9050536

Fick, S.E. and Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International journal of climatology*, 37, 4302-4315. https://doi.org/10.1002/joc.5086.

Fujisaki, I., Hart, K.M., Bucklin, D., Iverson, A.R., Rubio, C., Lamont, M.M., Miron, R.D.J.G.D., Burchfield, P.M., Peña, J. and Shaver, D.J., 2020. Predicting multi-species foraging hotspots for marine turtles in the Gulf of Mexico. *Endangered Species Research*, 43, 253-266.

Hamdeno, M. and Alvera-Azcarate, A., 2023. Marine heatwaves characteristics in the Mediterranean Sea: Case study the 2019 heatwave events. *Frontiers in Marine Science*, 10, 1093760. https://doi.org/10.3389/fmars.2023.1093760

Hochscheid, S., Maffucci, F., Abella, E., Bradai, M.N., Camedda, A., Carreras, C., Claro, F., de Lucia, G.A., Jribi, I., Mancusi, C., Marco, A., Marrone, N., Papetti, L., Revuelta, O., Urso, S. and Tomás, J., 2022. Nesting range expansion of loggerhead turtles in the Mediterranean: Phenology, spatial distribution, and conservation implications. G*lobal Ecology and Conservation*, 38, e02194. https://doi.org/10.1016/j.gecco.2022.e02194

Iannella, M., Cerasoli, F., D'Alessandro, P., Console, G. and Biondi, M., 2018. Coupling GIS spatial analysis and Ensemble Niche Modelling to investigate climate change-related threats to the Sicilian pond turtle Emys trinacris, an endangered species from the Mediterranean. *PeerJ*, 6, e4969. https://doi.org/10.7717/peerj.4969

Iveša, N., Piria, M., Gelli, M., Trnski, T., Špelić, I., Radočaj, T., Kljak, K., Jug-Dujaković, J. and Gavrilović, A., 2021. Feeding habits of predatory thermophilic fish species and species with subtropical affinity from recently extended distributional range in northeast Adriatic Sea, Croatia. *Diversity*, 13(8), 357. https://doi.org/10.3390/d13080357

Luna-Ortiz, A., Marín-Capuz, G., Abella, E., Crespo-Picazo, J.L., Escribano, F., Félix, G., Giralt, S., Tomás, J., Pegueroles, C., Pascual, M. and Carreras, C., 2024. New colonisers drive the increase of the emerging loggerhead turtle nesting in Western Mediterranean. *Scientific Reports*, *14*(1), p.1506.

Lo Valvo, F. and Longo, A.M. 2001. Anfibi e rettili in Sicilia. DoraMarkus ed. pp. 85.

Margaritoulis, D., Argano, R., Baran, I., Bentivegna, F., Bradai, M.N., Camiñas-Hernández, J.A., Metrio, G.D., Demetropoulos, A., Gerosa, G., Godley, B.J. and

Haddoud, D.A., 2003. Loggerhead turtles in the Mediterranean: present knowledge and conservation perspectives. *10000-04-30*.

Mazaris, A.D., Schofield, G., Gkazinou, C., Almpanidou, V. and Hays, G.C., 2017. Global sea turtle conservation successes. *Science Advances*, 3, e1600730. https://doi.org/10.1126/sciadv.1600730

Merow, C., Smith, M.J. and Silander Jr, J.A., 2013. A practical guide to MaxEnt for 139odelling species' distributions: what it does, and why inputs and settings matter. *Ecography*, 36, 1058-1069. https://doi.org/10.1111/j.1600-0587.2013.07872.x

Miller, J.D., Limpus, C.J. and Godfrey, M.H., 2003. Nest site selection, oviposition, eggs, development, hatching, and emergence of loggerhead turtles. *Loggerhead sea turtles*, *8*, pp.125-143.

Pastor, F., Valiente, J.A. and Palau, J.L., 2019. Sea surface temperature in the Mediterranean: Trends and spatial patterns (1982–2016). *Meteorology and Climatology of the Mediterranean and Black Seas*, 297-309.

Pearson, R.G., Raxworthy, C.J., Nakamura, M. and Townsend Peterson, A., 2007. Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. *Journal of Biogeography*, 34, 102-117. https://doi.org/10.1111/j.1365-2699.2006.01594.x

Phillips, S.J., Anderson, R.P., Dudík, M., Schapire, R.E. and Blair, M. E., 2017. Opening the black box: An open-source release of Maxent. *Ecography*, 40, 887-893. https://doi.org/10.1111/ecog.03049

Phillips, S.J. and Dudík, M., 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography*, 31, 161-175. https://doi.org/10.1111/j.0906-7590.2008.5203.x

Phillips, S.J., Anderson, R.P. and Schapire, R.E., 2006. Maximum entropy 139odelling of species geographic distributions. *Ecological Modelling*, 190, 231-259. https://doi.org/10.1016/j.ecolmodel.2005.03.026

Pietroluongo G., Miliou, A., Antichi, S., Ashok, K., Falquina F.J. and Montalvo, B.Q.M., 2021. The role of citizen reports in turtle nests discovery: the case of Samos Island, Greece. Proceedings of the 2021 IEEE International Workshop on Metrology for the Sea; Learning to Measure Sea Health Parameters (MetroSea), Reggio Calabria, Italy, 153-157, doi: 10.1109/MetroSea52177.2021.9611548

Prato, O.O., Paduano, V., Baldi, G., Bonsignore, S., Callea, G., Camera, C., Culmone, G., D'Angelo, S., Fiorentino, D., Galia, G., Coriglione, S., Genco, L., Mazzotta, G., Napolitano, N., Palazzo, F.P., Palilla, G., Pelletti, S.D., Mingozzi, T., Agresti, L. and Casale P., 2022. Minor sea turtle nesting areas may remain unnoticed without specific monitoring: the case of the largest Mediterranean Island (Sicily, Italy). *Animals*, 12: 1221. https://doi.org/10.3390/ani12101221

Reddin, C.J., Aberhan, M., Raja, N.B. and Kocsis, Á.T., 2022. Global warming generates predictable extinctions of warm-and cold-water marine benthic invertebrates via thermal habitat loss. *Global Change Biology*, 28, 5793-5807. https://doi.org/10.1111/gcb.16321

Rondinini, C., Battistoni, A. and Teofili, C., 2022. Lista Rossa IUCN dei vertebrati italiani 2022. Comitato Italiano IUCN e Ministero dell'Ambiente e della Sicurezza Energetica: Roma, Italy.

Surdo, S. and Massa, B., 2020. Aggiornamento sulla nidificazione della tartaruga marina *Caretta caretta* (Reptilia Cheloniidae) in Sicilia. Riflessioni sul valore della citizen science. *Naturalista siciliano*, 44: 115-126 https://doi.org/10.5281/zenodo.4050094

Tomás, J., Gozalbes, P., Raga, J.A. and Godley, B.J., 2008. Bycatch of loggerhead sea turtles: insights from 14 years of stranding data. *Endangered Species Research*, 5), 161-169. https://doi.org/10.3354/esr00116

Turrisi, G.F. and Vaccaro, A., 2001. Distribuzione altitudinale di anfibi e rettili sul monte Etna (Sicilia orientale). *Pianura*, 13: 335-338.

Vecchioni, L., Arculeo, M., Vamberger, M. and Marrone, F., 2022. Current status of and threats to Sicilian turtles. *Diversity*, *14*(10), p.798.

Ventura, D., Colloca, F. and Ardizzone, D., 2019. Settlement evidence of the Mediterranean parrotfish *Sparisoma cretense* (Teleostei: Scaridae) in the Central Tyrrhenian Sea (Giglio Island, Italy). *BioInvasions Records*, 8, 413-418. https://doi.org/10.3391/bir.2019.8.3.04

Wallace, B.P., DiMatteo, A.D., Bolten, A.B., Chaloupka, M. ., Hutchinson, B. J., Abreu-Grobois, F.A., Mortimer, J.A., Seminoff, J.A., Amorocho, D., Bjorndal, K.A., Bourjea, J., Bowen, B.W., Duenas, R.B., Casale, P., Choudhury, B.C., Costa, A., Dutton, P.H., Fallabrino, A., Finkbeiner, E.M., Girard, A., Girondot, M., Hamann, M., Hurley, B.J., López-Mendilaharsu, M., Marcovaldi, M.A., Musick, J.A., Nel, R., Pilcher, N.J., Troeng, S., Witherington, B. and Mast, R.B., 2011. Global conservation

priorities for marine turtles. *PloS One*, 6, e24510. https://doi.org/10.1371/journal.pone.0024510

Wood, D.W. and Bjorndal, K.A., 2000. Relation of temperature, moisture, salinity, and slope to nest site selection in loggerhead sea turtles. *Ichthyology & Herpetology*, *2000*(1), pp.119-119.

Wouters, H., 2021. Downscaled bioclimatic indicators for selected regions from 1979 to 2018 derived from reanalysis. Copernicus Climate Change Service (C3S) *Climate Data Store* (CDS). 10.24381/cds.f9d2963b.

Chapter 8

Monitoring Rare Species through Scientific Collaboration: The case of *Ocypode cursor*

This chapter is widely based on the contribution by

Pipitone C. and **Siddiolo C.** First record of the tufted ghost crab *Ocypode cursor* in northern Sicily (Tyrrhenian Sea**)** to the following publication:

Báez J.C., Akyol O., Azzurro E., Battaglia P., Belmonte-Gallegos A., Christidis G., Crocetta F., Dalyan C., Gönül Y., Grati F., Greco S., Gubili C., Kesici N.B., Lipej L., Mancini E., Mavrič B., Orenes-Salazar V., Ortega Ceacero J.A., Pipitone C., Poursanidis D., Romeo T., Sánchez- Tocino L., **Siddiolo C.,** Skarvelis K., Spinelli A., Tanduo V., Tiralongo F., Trkov D., Ünal V., Yücedağ Bakir E., Zamuda L.L. (2025). New records of rarely reported species in the Mediterranean Sea (March 2025). *Mediterranean Marine Science*, 26(1), 256–276. https://doi.org/10.12681/mms.40675.

8 Monitoring Rare Species Through Scientific Collaboration: The Case of *Ocypode cursor*

8.1. ABSTRACT

This chapter documents the first record of the tufted ghost crab Ocypode cursor along the northern coast of Sicily (Tyrrhenian Sea), highlighting a significant expansion of its Mediterranean range. By integrating multi-source data and field observations, the study analyzes how global warming facilitates the "tropicalization" of the basin, driving thermophilic species toward new northern latitudes. This sighting highlights the crucial role of citizen science and beach monitoring in the conservation of protected species. Furthermore, the findings emphasize the need for transnational research networks to bridge knowledge gaps arising from socio-economic gradients and uneven sampling efforts across Mediterranean ecoregions.

8.2. INTRODUCTION

The Mediterranean Sea is a biodiversity hotspot where temperate and subtropical biota converge (Bianchi and Morri, 2000; Coll et al., 2010). However, the distribution of many species remains poorly understood, particularly for those with cryptic behaviour or those currently expanding their range due to climate change. In this context, the Collective Article series, such as "New Records of Rarely Reported Species in the Mediterranean Sea" published in Mediterranean Marine Science, represents a fundamental platform to address these knowledge gaps.

These collaborative efforts allow for the periodic documentation of rarely encountered species, like the shoreline tufted ghost crab *Ocypode cursor*. By consolidating records from different countries and ecoregions, these articles provide a comprehensive "snapshot" of a sea in rapid transition. A key driver for these new records is the ongoing warming of the Mediterranean, which facilitates the northernward expansion of thermophilic species - a phenomenon known as "tropicalization" (Báez et al., 2019). The study of such shifts is essential for continuous updates on biodiversity distribution patterns. The presence of thermophilic species in new further northern localities exemplifies this northward spreading trend. These records are often obtained through a wide variety of methods, including professional fishing, SCUBA diving, and, crucially, onshore photography and collection in the case of shallow-water decapods.

The tufted ghost crab *Ocypode cursor* (Linnaeus, 1758) is the only member of family Ocypodidae Rafinesque, 1815 in the Mediterranean. It is known for its burrowing behaviour and nocturnal activity in sandy beaches and is a scavenger feeding on dead fish and human food remains, as well as a predator capturing mainly mollusks, crustaceans, and sea turtle eggs and hatchlings (Tiralongo et al., 2020a). Historically, *O. cursor* has shown a disjointed distribution with occurrences in the eastern Mediterranean and along the Atlantic coasts of Africa. However, more recently, its Mediterranean range has spread westwards along the Ionian coasts of Greece and Italy (Marchessaux et al., 2024). Recent studies have investigated this range expansion in the Mediterranean, possibly facilitated by rising sea temperatures due to climate change (Tiralongo et al., 2020a; Marchessaux et al., 2024). The westernmost documented occurrences relay on a first record in Lampedusa (Pelagian Islands, Strait of Sicily) in 1987, reported by Froglia (1995), and on later reports along the southern and eastern coasts of Sicily (Tiralongo et al., 2020, and references therein). In the Tyrrhenian Sea the species was first spotted from Palmi (southwestern Calabria) in July 2020 (Santin et al., 2021).

8.3. RESULTS

The sighting reported here (Fig. 8.1) was made during the night of 15 July, 2024 by Roberto D'Uscio, who was monitoring sea turtle nesting at Capaci Beach (northwestern Sicily: 38.183°N, 13.233°E) as a volunteer. He managed to photograph an individual before it hid in its burrow in the sand (Fig. 8.2).



Figure 8.1: Map depicting the site of the new record of *Ocypode cursor* at Capaci Beach, NW Sicily.



Figure 8.2: *Ocypode cursor* sight at Capaci Beach, NW Sicily. Photo credits: Roberto D'Uscio.

8.4. DISCUSSION

The present occurrence is significant as it represents the first record of the species along the Tyrrhenian coast of Sicily and the third Tyrrhenian record overall, after two previous records from Palmi (Santin et al., 2021) and from the Salerno area (Digenis et al., 2024), about 230 km ENE and 270 km NE from Capaci, respectively.

The presence of *O. cursor* at Capaci Beach also aligns with recent reports of the expanding range of this species in the central sector of the Mediterranean and highlights the ongoing changes in the distribution of marine species in response to climate change (Marchessaux et al., 2024). Although the sight from the Capaci area is situated at lower latitude than the record in Campania, it is noteworthy that the ideal connecting line between the two localities roughly follows the trend of SST isolines in the Tyrrhenian Sea (Bianchi, 2007) with both localities close

to the 14°C isotherm considered the boundary for the ongoing tropicalization of the Mediterranean.

The current range expansion of *O. cursor* possibly indicates its ability to face environmental stress. However, it is considered a threatened species and as such is protected under the Barcelona Convention (Annex II) and the Bern Convention (Annex II). A decline in its abundance, likely due to the pressure of recreational activities, has been observed in the Levant Sea along the Israeli coast, where it is an abundant and frequent inhabitant of sandy beaches (Galil et al., 2024). Further monitoring and research are needed to understand the ecological impacts of its range expansion and at the same time to develop appropriate conservation strategies.

8.5. CONCLUSION

The absence of records in certain ecoregions, such as the North African coast, often reflects a "socio-economic gradient" in research effort rather than a true biological absence (Digenis et al., 2024). Strengthening scientific collaborations and improving accessibility to taxonomic data—as demonstrated by this collective study—is essential to achieve a comprehensive understanding of Mediterranean biodiversity.

Furthermore, by integrating individual sightings, also derived from amateur information, into formal scientific databases, we ensure that rare occurrences are not lost but instead contribute to the effective management and conservation of threatened marine species.

8.6. REFERENCE LIST

Bianchi, C.N., 2007. Biodiversity issues for the forthcoming tropical Mediterranean Sea. *Hydrobiologia* 580, 7-21.

Bianchi, C.N. and Morri, C., 2000. Marine biodiversity of the Mediterranean Sea: situation, problems and prospects for future research. *Marine Pollution Bulletin*, 40 (5), 367-376.

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Ben Rais Lasram, F., Aguzzi, J., Ballesteros, E., Bianchi, C.N., Corbera, J., Dailianis, T. and Danovaro, R., Estrada, M., Froglia, C., Galil, B.S., Gasol, J.M., Gertwagen, R., Gil, J., Guilhaumon, F., Kesner-Reyes, K., Kitsos, M.S., Koukouras, A., Lampadariou, N., Laxamana, E., López-Fé de la Cuadra, C.M., Lotze, H.K., Martin, D., Mouillot, D., Oro, D., Raicevich, S., Rius-Barile, J., Saiz-Salinas, J.I., San Vicente, C., Somot, S., Templado, J., Turon, X., Vafidis, D., Villanueva, R. and Voultsiadou, E., 2010. The biodiversity of the Mediterranean Sea: estimates, patterns, and threats. *PLoS One*. 2010 Aug 2;5(8):e11842. doi: 10.1371/journal.pone.0011842. PMID: 20689844; PMCID: PMC2914016.

Digenis, M., Akyol, O., Benoit, L., Biel-Cabanelas, M., Çamlik, Öznur Y., Charalampous, K., Chatzispyrou, A., Crocetta, F., Deval, M. C., Di Capua, I., Domenichetti, F., Đorđević, N., Ferruzzi, S., Galiya, M. Y., Gammoudi, M., García-Charton, J. A., Grech, D., Hoffman, R., Langeneck, J., Martinelli, M., Mastrototaro, F., Mavrič, B., Navarro-Barranco, C., Okudan, E. S., Orenes-Salazar, V., Orlando-Bonaca, M., Othman, R. M., Petović, S., Putignano, M., Renoult P., J., Ruíz, J. M., Santín Muriel, A., Taşkin, E., Tiralongo, F., Tosunoğlu, Z., Tuney, I., Tursi, A., Vannini, J., Zacchetti, L., Zamuda, L. L. and Gerovasileiou, V., 2024. “New records of rarely reported species in the Mediterranean Sea (March 2024)”, *Mediterranean Marine Science*, 25(1), pp. 84-115. doi: 10.12681/mms.37214.

Froglia, C., 1995. In Minelli, A., Ruffo, S., La Posta, S.,(Eds), Checklist delle specie della Fauna italiana. vol. 31. Bologna, Calderini, pp. 1-17.

Galil, B.S., Goren, M., Gayer, K. and Bronstein, O., 2024. No place to call home: Distribution patterns of the tufted ghost crab, *Ocypode cursor*, populations in nature reserves, Israel, Eastern Mediterranean. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 34(3), e4116.

Marchessaux, G., Gjoni, V., Tantillo, M.F., Bejean, T. and Sarà, G., 2024. The expansion of the Atlantic–Mediterranean ghost crab *Ocypode cursor* (Linnaeus, 1758): Distribution, environmental niches and future perspectives. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 34(3), e4119.

Santin, A., Aguilar, R., Akyol, O., Begburs, C.R., Benoit, L., Chimienti, G., Crocetta, F., Dalyan, C., De La Linde Rubio, A., Dragicevic, B. and Dulcic, J., 2021. New records of rare species in the Mediterranean Sea (March 2021). *Mediterranean Marine Science*, 22(1), 199-217.

Tiralongo, F., Messina, G., Marino, S., Bellomo, S., Vanadia, A., Borzì, L., Tibullo, D., Di Stefano, A. and Lombardo, B.M., 2020. Abundance, distribution and ecology of the tufted ghost crab *Ocypode cursor* (Linnaeus, 1758) (Crustacea: Ocypodidae) from a recently colonized urban sandy beach, and new records from Sicily (central Mediterranean Sea). *Journal of Sea Research*, 156, 101832.

Chapter 9

Contribution of Unpublished Records to the Mapping of non-indigenous, Cryptogenic, and Neonative Species in the Mediterranean Sea

This chapter is widely based on the following multi-authored publication focusing particularly on my own contribution and on information on species particularly addressed in the present thesis also provided by coauthors:

Pistevos J.C.A., Zenetos A., Stranga Y., Teaca A., Begun T., Trkov D, Langeneck J., Muresan M., Comas-González R., Sempere-Valverde J., Toso A., Chebaane S., Navarro-Barranco C., Rosso A., Png-Gonzalez L., Giakoumi S., Vázquez-Luis M., Cañizares-González J.M., **Siddiolo C.,** Donato G.M.E., Giacobbe S., Carbonell A., Zakhama-Sraieb R., Di Martino E., et al., (2026), in press. Unpublished Mediterranean and Black Sea records of marine alien, cryptogenic, and neonative species (III) — *BioInvasions Records,* 15.

9 Contribution of Unpublished Records to the Mapping of non-indigenous, Cryptogenic, and Neonative Species in the Mediterranean Sea

9.1. ABSTRACT

To enhance regional knowledge of invasive (NIS, cryptogenic, and neonative species, this study compiles previously unpublished records from the Mediterranean and Black Seas, drawing from an extensive open-access dataset of 7,434 observations pertaining to 275 species.

The records, predominantly collected between 2021 and 2024, highlight critical presence data across multiple ecoregions, particularly in anthropogenic hotspots such as harbors, marinas, and aquaculture facilities. The high frequency of records for thermophilic species such as the rabbitfishes (*Siganus* spp.) and the lionfish (*P. miles*) underscores the ongoing tropicalization of the basin. Simultaneously, the documentation of fouling organisms such as *T. inopinata* and *B. neritina* emphasizes the persistent role of maritime transport as the primary dispersal pathway for both alien and cryptogenic species. In this context, maritime traffic — comprising commercial shipping, liner services, cruise vessels, and recreational boating — represents the dominant vector driving both introduction and secondary spread, while rafting on buoyant anthropogenic debris should be considered a complementary mechanism contributing mainly to local and regional redistribution of marine non-indigenous species. By synthesizing these “dark data” from 227 marine experts, this compilation provides a high-resolution spatiotemporal baseline essential for early detection, risk prioritization, and the development of targeted biosecurity strategies in a rapidly changing Mediterranean environment. This approach has been already implemented in Mediterranean operational frameworks such as port-based Early Warning Systems for non-indigenous species and coordinated regional monitoring and response programmes under the Barcelona Convention, which link early detection directly to rapid management actions and targeted surveillance protocols (e.g. UNEP/MAP Action Plan on NIS; Magaletti et al., 2018; IMO Ballast Water Management Convention implementation frameworks).

Among all taxa discussed in Pistevos et al. (in press), this chapter specifically analyzes the distribution and ecological relevance of 16 key taxa, included in the final database of this thesis: the bryozoans *Amathia verticillata*, *Bugula neritina*, and *Tricellaria inopinata*; the decapods *Callinectes sapidus*, *Portunus segnis*, and

Percnon gibbesi; the mollusks *Pinctada radiata* and *Lamprohaminoea ovalis*; the scleractinian coral *Oculina patagonica*; the foraminifer *Amphistegina lobifera*; and the fishes *Acanthurus monroviae*, *Lagocephalus sceleratus*, *Pterois miles*, *Seriola fasciata*, *Siganus luridus*, and *Siganus rivulatus*. Unlike Pistevos et al. (in press) also dealing with the Black Sea, the focus is on the Mediterranean only.

9.2. INTRODUCTION

Biological invasions represent one of the most significant and fast-growing threats to marine biodiversity worldwide, often leading to the disruption of native ecosystems and ecosystem services (Molnar et al., 2008; Çinar et al., 2014; Tsirintanis et al. 2022). The Mediterranean Sea, despite its relatively small size, has emerged as a hotspot for marine invasive NIS and hosts the highest number of introductions among European seas (Galil et al., 2014; Zenetos et al., 2022a). This phenomenon is facilitated by a combination of intense anthropogenic pressures, including maritime traffic, aquaculture, and the Suez Canal artificially connecting the Mediterranean to the Red Sea to the East, as well as regional warming that enhances the suitability of conditions for thermophilic species (Zenetos et al., 2010; Schroeder et al., 2016; Albano et al., 2021) fostering both human-mediated introduction and naturally expanded ranges of the so-called neonative species. Focusing on the Mediterranean only, due to its geopolitical complexity, being bordered by 22 countries with varying policies and capacities for marine monitoring, the Mediterranean faces significant challenges in implementing cohesive biosecurity and biodiversity monitoring frameworks (Zenetos and Galanidi, 2020).

Increasing attention is also being paid to neonative species — those undergoing climate-driven natural range expansions — which can also exert ecological pressures (Essl et al., 2019; Azzurro et al., 2022; Virgili et al., 2025). Whether NIS or neonative, their expanding presence continues to drive processes such as tropicalization in the Mediterranean (Bianchi and Morri, 2003; Peleg et al., 2020). Despite the ecological significance of these changes, a large volume of valuable distribution data remains unpublished or inaccessible as “dark data”, often stored in personal archives or institutional databases (Katsanevakis et al., 2020). This gap hinders comprehensive assessments of invasion dynamics, species trends, and the development of management responses under frameworks such as the European Marine Strategy Framework Directive (MSFD) and the Barcelona Convention/UNEP/MAP. The need for frequent updates to NIS inventories has led

to coordinated efforts to collect and disseminate such data via collaborative networks of marine scientists.

This paper builds upon two previous collaborative efforts to document unpublished records of NIS, cryptogenic and neonative species in the Mediterranean. The present study represents the third iteration of this initiative (after Katsanevakis et al., 2020 and Ragkousis et al., 2023) and aims to further strengthen regional inventories by collating newly gathered and previously unpublished records of NIS, cryptogenic, and neonative species. In doing so, it contributes to a growing open-access dataset that is essential for tracking bio-invasion dynamics and supporting efforts to monitor, manage, help reduce the prevalence of NIS in the region.

9.3. MATERIALS AND METHODS

Dataset Compilation and Expert Network

Following a collaborative Open Science approach, the dataset was compiled by engaging a network of 227 marine experts from 21 different countries working across the Mediterranean. Data were gathered using standardized templates to harmonize records of NIS, cryptogenic, and neonative species. To ensure high scientific standards, only records validated by marine scientists through direct visual identification (e.g., in situ SCUBA surveys, validated photographs) or specimen collection were included. This initiative specifically aimed to mobilize “dark data”—unpublished observations that provide critical spatio-temporal resolution often missing from official monitoring programs.

Biogeographic status for each record was assigned following established Mediterranean benchmarks (Zenetos et al., 2022b), classifying taxa into four categories: NIS, Neonative, Cryptogenic, and Data Deficient.

Taxonomic and Spatial Coverage of Target Species

While the broader initiative documented 275 taxa, this chapter focuses on the 16 priority species in this paper, also included in the main database, that were selected for their ecological impact and representative value of different dispersal pathways. The taxonomic coverage includes:

- Foraminifera: *Amphistegina lobifera* Larsen, 1976.

- Bryozoa: *Amathia verticillata* delle Chjaie, 1828 (Ctenostoma), *Bugula neritina* (Linnaeus, 1758) (Cheilostoma), *Tricellaria inopinata* d'Hondt and Occhipinti Ambrogi, 1985 (Cheilostoma).
- Cnidaria: *Oculina patagonica* (De Angelis, 1908) (Exacorallia).
- Mollusca: *Pinctada radiata* (Leach, 1814) (Bivalvia), *Lamprohaminoea ovalis* (Pease, 1868) *(*Gasteropoda).
- Arthropoda: *Callinectes sapidus* (Rathbun, 1896), *Portunus segnis* (Forskål, 1775), *Percnon gibbesi* (H. Milne-Edwards, 1853) (Crustacea, Decapoda).
- Chordata: *Acanthurus monroviae* (Steindachner, 1876), *Lagocephalus sceleratus* (Gmelin, 1789)*, Pterois miles* (Bennett, 1828), *Seriola fasciata* (Bloch, 1793), *Siganus luridus* (Rüppell, 1828), and *Siganus rivulatus* (Forsskål and Niebuhr, 1775).

Temporal Trends and Observation Methods

The temporal span for the analyzed species extends significantly toward the last decade, with 72% of the records collected between 2021 and 2024. This is probably linked to the inclusion of records up to June 2022 in previous collaborative compilations whereas the increase of data for the year 2024, representing the peak of reporting activity, may also reflect both the actual spread of thermophilic and opportunistic species and an intensification of expert survey efforts. In contrast, new data for overlapping years possibly result from the involvement of new researchers, allowing disclosing further still hidden information.

The observation types for these 16 species primarily involved:

Direct Expert Identification: High-visibility species like the rabbitfishes (*Siganus* spp.) and the lionfish (*Pterois miles*) were frequently documented via *in situ* visual census.

Specimen Collection: Cryptic or taxonomically challenging taxa, such as the bryozoans *Tricellaria inopinata* and *Amathia verticillata*, were largely verified through physical sampling and laboratory analysis.

9.4. RESULTS

The collaborative effort led to the documentation of 1,941 validated records for the 16 priority species analyzed in this study. The data (Tab. 9.1) show a high predominance of Chordata and Arthropoda, which together account for the majority

of the observations, likely due to their high visibility and ecological dominance in newly colonized habitats. The high frequency of records for thermophilic species such as rabbitfishes (*Siganus* spp.) and lionfish (*Pterois miles*) reflects the high occurrence of warm-affinity species in the dataset. The distribution of records across species also shows marked spatial heterogeneity, with higher reporting intensity for widely distributed and easily recognizable species such as *Siganus luridus*, *S. rivulatus*, and *Callinectes sapidus*, compared to less frequently reported taxa.

Taxonomic Group	Species	Number of Records
Foraminifera	*Amphistegina lobifera*	9
Cnidaria	*Oculina patagonica*	34
Bryozoa	*Amathia verticillata*	59
	Bugula neritina	16
	Tricellaria inopinata	4
Mollusca	*Lamprohaminoea ovalis*	14
	Pinctada radiata	187
Arthropoda	*Callinectes sapidus*	301
	Percnon gibbesi	159
	Portunus segnis	100
Chordata	*Acanthurus monroviae*	1
	Lagocephalus sceleratus	13
	Pterois miles	244
	Seriola fasciata	10
	Siganus luridus	447
	Siganus rivulatus	435

Table 9.1: Total number of occurrences for the 16 selected species (belonging to 6 different phyla) in the Mediterranean Sea

.

Foraminifera were represented by *Amphistegina lobifera* with 9 records, while the cryptogenic Exacorallia *Oculina patagonica* reached 34 observations. Bryozoa showed a total of 79 records, driven by *Amathia verticillata* (59), followed by *Bugula neritina* (16) and the less frequent *Tricellaria inopinata* (4). The Mollusca dataset was largely dominated by the pearl oyster *Pinctada radiata* (187 records), which showed significantly higher records compared to the gastropod *Lamprohaminoea ovalis* (14).

Within the Arthropoda, the records highlight the extensive spread of three key decapod species: the Atlantic blue crab *Callinectes sapidus* was the most frequently documented (301), followed by the cryptogenic *Percnon gibbesi* (159) and the swimming crab *Portunus segnis* (100). The Chordata group accounted for the highest volume of data, largely due to the presence of charismatic and ecologically impactful species. The rabbitfishes *Siganus luridus* (447) and *Siganus rivulatus* (435) emerged as the most abundantly spotted taxa in the entire study, collectively representing nearly 45% of all records. Significant data were also gathered for the lionfish *Pterois miles* (244), confirming its rapid expansion across the basin. In contrast, other fish species showed more localized or rare occurrences, including the pufferfish *Lagocephalus sceleratus* (13), the lesser-known *Seriola fasciata* (10), and a single, biogeographically significant record of the Monrovia surgeonfish, *Acanthurus monroviae* (1). *Lamprohaminoea ovalis* was recorded in Italy for the first time in the Adriatic Sea.

Whereas for many of these species the new records essentially locate within areas of previously known distributions, a significant range extensions was observed for the bryozoan *Tricellaria inopinata* d'Hondt and Occhipinti-Ambrogi, 1985, which was observed for the first time in the western Ionian Sea (Fig. 9.1). For this reason, a summary of its occurrence and spreading in the Mediterranean is traced. This species was described based on colonies found attached to the byssus threads of the bivalve *Mytilus galloprovincialis* Lamarck, 1819, collected from the intertidal zone of the Giudecca Canal, near central Venice (northern Adriatic Sea) in 1982 (d'Hondt and Occhipinti Ambrogi, 1985; Occhipinti Ambrogi, 2000).



Figure 9.1: Terminal part of branches of *Tricellaria inopinata* from the Faro lake (Sicily) showing both frontal side (left and central internodes) and lateral and dorsal sides (rights branch, bottom and top internodes, respectively).

Tricellaria inopinata forms small, erect, bush-like colonies a few centimeters high, composed of jointed, slightly mineralized biserial internodes, anchored to hard substrates by rhizoids in shallow waters. Colonies grow rapidly, intertwining to form dense, whitish mats/carpets. Although described from the Mediterranean, *T. inopinata* is a NIS in this basin. It was likely introduced accidentally, possibly through aquaculture or ship fouling, from its presumed native range in the Pacific Ocean (Occhipinti Ambrogi et al. 2011). Since its original description, *T. inopinata* has been recorded from several western Mediterranean localities (e.g., Ben Suissi et al., 2006; Lodola et al., 2012; Ulman et al., 2017; Ferrario et al., 2018; Fortič and Mavrič, 2018; Bensari et al., 2025), with its easternmost occurrence in the Old Venetian Harbor (Heraklion, Greece) (Ulman et al. 2017). The species has also spread globally (see Micael et al. 2016, and references therein). *Tricellaria inopinata* has been classified as invasive following monitoring of its rapid spread and increase in colony abundance and surface coverage, often to the detriment of native species that decline or disappear after its arrival and establishment. For instance, this has been documented in the Venice lagoon (Occhipinti Ambrogi 2000; Corriero et al., 2007) and in some localities along the western Atlantic coast (Jonson et al., 2012). Based on expert evaluations and direct observations, *T. inopinata* has demonstrated moderate to high impacts on biodiversity and ecosystem services, primarily through competition and fouling (Tsirintanis et al., 2022, and references therein). Moreover,

according to Gavira-O'Neil et al. (2016), it may act as a driver of potential invasion meltdown. *Tricellaria inopinata* was found in the channel connecting the Faro Lake (located in the NE corner of Sicily) to the Ionian Sea, based on samples collected in 2006 and 2008 at about 50 cm depth. This represents the first documented record for both Sicily and the western Ionian Sea; prior to this, *T. inopinata* was only known from the eastern Ionian sector, in the Old Venetian Harbor (Heraklion, Greece) (Ulman et al. 2017). At the time of collection, the species was by far dominating the community. However, subsequent targeted surveys conducted in summer 2021, and spring 2024 and 2025, failed to detect it, suggesting that its populations may underwent regression and even local disappearance, unlike in other localities. A focused investigation is needed to determine the environmental factors responsible for this short-term success.

While *Tricellaria inopinata* is discussed in greater detail due to its biogeographically relevant occurrence in the western Ionian Sea, all remaining species are reported in Table 9.1, which provides the complete species-level breakdown of the dataset. The Results section highlights representative taxa to illustrate key distributional patterns across taxonomic groups.

9.5. Discussion and Conclusion

This study further consolidates an open, region-wide evidence base for NIS, cryptogenic, and neonative species in the Mediterranean Sea. By mobilizing 1941 geo-referenced records, it demonstrates the utility of aggregating "dark data" (here defined as heterogeneous, non-standardised biodiversity records from expert knowledge and alternative data sources) to rapidly enrich regional inventories and improve the spatial resolution of knowledge. For the 16 target species analyzed, this collaborative approach has proven essential for enabling timely reassessments of invasion dynamics, which are critical for policy and management under the Marine Strategy Framework Directive (MSFD) (Katsanevakis et al., 2020).

The distribution of records for species such as *Siganus luridus*, *S. rivulatus*, and *Callinectes sapidus* highlights both monitoring strengths and geographical gaps (Azzurro et al., 2017; Castriota et al., 2024). High reporting volumes in Lebanon, Greece, Cyprus, and Italy reflect robust expert networks, while other regions, particularly parts of North Africa, remain underrepresented. These asymmetries are not purely ecological but stem from differences in researchers and observations

distribution, sampling effort and data-sharing practices. The high density of records in ports, marinas, and aquaculture areas underscores their role as primary gateways for fouling organisms like the bryozoans *Amathia verticillata*, *Bugula neritina*, and *Tricellaria inopinata* (Lodola et al., 2012; Bensari et al., 2020; Zavacki et al., 2024). The sharp increase in reporting post-2021, peaking in 2024, reflects a synergy between the actual spread of thermophilic species and intensified expert engagement, also solicitated by these collective calls for data.

The documented range extensions of species like *Pterois miles* illustrate the continuous westward and northward progression of Lessepsian migrants, a clear signal of the Mediterranean's tropicalization. Similarly, the secondary spread of the Atlantic blue crab *Callinectes sapidus* and the swimming crab *Portunus segnis* across different ecoregions highlights the high connectivity of Mediterranean coastal waters (Siddiolo et al., 2025a). The presence of the cryptogenic coral *Oculina patagonica* and the NIS pearl oyster *Pinctada radiata* in new localities further emphasizes the role of shipping and recreational boating as recurrent vectors, with *O. patagonica* being frequently associated with artificial substrates in ports and marinas, where its occurrence suggests a role of maritime infrastructure and shipping-related activities in facilitating its secondary spread at local and regional scales (Fortič et al., 2023). These findings suggest that human-mediated pathways frequently mimic natural range expansions, making expert-validated records indispensable for distinguishing between different introduction events.

The dataset also sheds light on the ecological integration of these species. The foraminifer *Amphistegina lobifera* and the mollusk *Lamprohaminoea ovalis* serve as indicators of structural shifts in benthic communities (Azzola et al., 2022; Guastella et al., 2023; Hallock et al., 2024). Furthermore, the rapid colonization of rocky infralittoral habitats by *Percnon gibbesi* and the establishment of self-sustaining populations of *Seriola fasciata* raise important questions about the long-term resilience of native ecosystems (Cillari et al., 2024).

While biases in sampling effort limit quantitative inference, the value of this dataset for early detection and range tracking remains undisputed. The systematic mobilization of unpublished records is a cost-effective way to sharpen regional situational awareness. This work demonstrates how sustained collaboration can fill critical knowledge gaps in a rapidly changing sea. By improving the spatiotemporal resolution of Mediterranean inventories for these 16 key species, the dataset provides actionable evidence for the prioritization of monitoring and the implementation of proactive biosecurity strategies, such as port-based monitoring programmes and Early Warning Systems for non-indigenous species implemented

in several Mediterranean harbours under regional frameworks (e.g. UNEP/MAP Action Plan on Species Introductions, Mediterranean ports surveillance initiatives, and ballast water management monitoring schemes), which are explicitly designed to support early detection and rapid response actions. Continued iterations of this effort will be essential to keep pace with ongoing introductions and the shifting distributions of marine biota.

9.6. REFERENCE LIST

Albano, P.G., Steger, J., Bošnjak, M., Dunne, B., Guifarro, Z., Turapova, E., Hua, Q., Kaufman, D.S., Rilov, G. and Zuschin, M., 2021. Native biodiversity collapse in the eastern Mediterranean. *Proceedings of the Royal Society B*, 288(1942), 20202469.

Azzola, A., Furfaro, G., Trainito, E., Doneddu, M. and Montefalcone, M., 2022. Seawater warming favours the northward range expansion of Lessepsian species in the Mediterranean Sea: the cephalaspidean *Lamprohaminoea ovalis*. *Journal of the Marine Biological Association of the United Kingdom*, *102*(3-4), pp.167-173.

Azzurro, E., Franzitta, G., Milazzo, M., Bariche, M. and Fanelli, E., 2017. Abundance patterns at the invasion front: the case of *Siganus luridus* in Linosa (Strait of Sicily, Central Mediterranean Sea). *Marine and Freshwater Research*, *68*(4), pp.697-702.

Azzurro, E., Smeraldo, S., Minelli, A. and D'Amen, M., 2022. ORMEF: a Mediterranean database of exotic fish records. *Scientific Data*, 9(1), 363.Bensari, B., Bahbah, L., Lounaouci, A., Fahci, S.E., Bouda, A. and Bachari, N.E.I., 2020. First records of non-indigenous species in port of Arzew (Algeria: southwestern Mediterranean). *Mediterranean Marine Science*, *21*(2), pp.393-399.

Bensari, B., Bahbah, L., Kacimi, A., Bachetarzi, R. and Bachari, N.E.I., 2025. Non-indigenous and cryptogenic marine species in the Port of Algiers (Western Mediterranean). *Mediterranean Marine Science*, 26(3), 592-603.

Ben Souissi, J., Ben Salem, M. and Zaouali, J., 2006. *Tricellaria inopinata* (Bryozoa, Cheilostome), récolté pour la première fois en Tunisie (Lagune sud de Tunis : Tunisie septentrionale). In *Actes de la 8ème Conférence Internationale des Limnologues d'Expression Française*, Hammamet (Tunisie), 17-21 Mars 2006

Bianchi, C.N. and Morri, C., 2003. Global sea warming and "tropicalization" of the Mediterranean Sea: biogeographic and ecological aspects. *Biogeographia–The Journal of Integrative Biogeography*, 24(1), 319-327.

Castriota, L., Falautano, M. and Perzia, P., 2024. When nature requires a resource to be used—The case of *Callinectes sapidus*: Distribution, aggregation patterns, and spatial structure in northwest Europe, the Mediterranean Sea, and adjacent waters. *Biology*, *13*(4), p.279.

Cillari, T., Falautano, M., Maggio, T., Perzia, P., Sinopoli, M. and Castriota, L., 2024. Spatial distribution of the range-expanding species *Seriola fasciata* (Bloch, 1793) in Mediterranean Sea: From past to future. *Marine Environmental Research*, *199*, p.106599.

Çinar, M.E., Arianoutsou, M., Zenetos, A. and Golani, D., 2014. Impacts of invasive alien marine species on ecosystem services and biodiversity: a pan-European review. *Aquatic Invasions*, 9(4), 391-423.

Corriero, G., Longo, C., Mercurio, M., Marchini, A. and Occhipinti-Ambrogi, A., 2007. Porifera and Bryozoa on artificial hard bottoms in the Venice Lagoon: Spatial distribution and temporal changes in the northern basin. *Italian Journal of Zoology*, 74:1, 21-29, DOI:10.1080/11250000601084100

Essl, F., Dullinger, S., Genovesi, P., Hulme, P.E., Jeschke, J.M., Katsanevakis, S., Kühn, I., Lenzner, B., Pauchard, A., Pyšek, P. and Rabitsch, W., 2019. A conceptual framework for range-expanding species that track human-induced environmental change. *BioScience*, 69(11), pp.908-919.

Ferrario, J., Rosso, A., Marchini, A. and Occhipinti-Ambrogi, A., 2018. Mediterranean non-indigenous bryozoans: an update and knowledge gaps. *Biodiversity and Conservation*, 27(11), pp.2783-2794.

Fortič, A. and Mavrič, B., 2018. First record of the bryozoan *Tricellaria Inopinata* (d'Hondt & Occhipinti Ambrogi, 1985) from the 161panish161g sea. *Annales: Series Historia Naturalis,* 28(2), pp.155-160.

Galil, B.S., Marchini, A., Occhipinti-Ambrogi, A., Minchin, D., Narščius, A., Ojaveer, H. and Olenin, S., 2014. International arrivals: widespread bioinvasions in European Seas. *Ethology, Ecology & Evolution*, 26(2-3), pp.152-171.

Gavira-O'Neill, K., Guerra-García, J.M., Moreira, J. and Ros, M., 2016. Mobile epifauna of the invasive bryozoan *Tricellaria inopinata*: is there a potential invasional meltdown? *Marine Biodiversity*, 48(2): pp.1169-1178. https://doi.org/10.1007/s12526-016-0563-5

Guastella, R., Evans, J., Mancin, N., Caruso, A. and Marchini, A., 2023. Assessing the effect of *Amphistegina lobifera* invasion on infralittoral benthic foraminiferal assemblages in the Sicily Channel (Central Mediterranean). *Marine Environmental Research*, *192*, pp.106247.

Hallock, P., Koukousioura, O. and BadrElDin, A.M., 2024. *Why Amphistegina lobifera*, a tropical benthic foraminiferal species, is thriving at temperate latitudes in the Mediterranean Sea. *Journal of Foraminiferal Research*, *54*(3), pp.237-248.

Hondt, J.-L. d' and Occhipinti Ambrogi, A., 1985. *Tricellaria inopinata*, n. sp., un nouveau bryozoaire Cheilostome de la faune méditerranéene. *Marine Ecology* 6(1): pp.35-46.

Johnson, C.H., Winston, J.E. and Woollacott, M.R., 2012. Western Atlantic introduction and persistence of the marine bryozoan *Tricellaria inopinata*. *Aquatic Invasions,* 7(3), pp.295–303.

Katsanevakis, S., Poursanidis, D., Hoffman, R., Rizgalla, J., Rothman, S.B.S., Levitt-Barmats, Y.A., Hadjioannou, L., Trkov, D., Garmendia, J.M., Rizzo, M. and Bartolo, A.G., 2020. Unpublished Mediterranean records of marine alien and cryptogenic species. *BioInvasions Records*, 9(2), pp.165-182.

Lodola, A., Savini, D. and Occhipinti-Ambrogi, A., 2012. First record of *Tricellaria inopinata* (Bryozoa: Candidae) in the harbours of La Spezia and Olbia, Western Mediterranean Sea (Italy). *Marine Biodiversity Records*, 5, p.e41.

Magaletti, E., Garaventa, F., David, M., Castriota, L., Kraus, R., Luna, G.M., Silvestri, C., Forte, C., Bastianini, M., Falautano, M. and Maggio, T., 2018. Developing and testing an early warning system for non indigenous species and ballast water management. *Journal of sea research*, *133*, pp.100-111.

Megalokonomou, A., 2022. Ballast water management convention from owner's perspective. University of Athens, 80 pp.

Micael, J., Jardim, N., Núñez, C., Occhipinti-Ambrogi, A. and Costa A.C., 2016. Some Bryozoa species recently introduced into the Azores: reproductive strategies as a proxy for further spread. *Helgoland Marine Research* 70, 7. https://hmr.biomedcentral.com/articles/10.1186/s10152-016-0458-7

Molnar, J.L., Gamboa, R.L., Revenga, C. and Spalding, M.D., 2008. Assessing the global threat of invasive species to marine biodiversity. *Frontiers in Ecology and the Environment*, 6(9), pp.485-492.

Occhipinti Ambrogi, A., 2000. Biotic invasions in a Mediterranean Lagoon. *Biological Invasions* 2, 165–176. https://doi.org/10.1023/A:1010004926405

Occhipinti Ambrogi, A., Marchini, A., Cantone, G., Castelli, A., Chimenz, C., Cormaci, M., Froglia, C., Furnari, G., Gambi, M.C., Giaccone, G., Giangrande, A., Gravili, C., Mastrototaro, F., Mazziotti, C., Orsi Relini, L. and Piraino, S., 2011. Alien species along the Italian coasts: an overview. *Biological Invasions* 13, 215–237.

Peleg, O., Guy-Haim, T., Yeruham, E., Silverman, J. and Rilov, G., 2020. Tropicalization may invert trophic state and carbon budget of shallow temperate rocky reefs. *Journal of Ecology*, 108(3), pp.844-854.

Ragkousis, M., Zenetos, A., Ben Souissi, J., Hoffman, R., Ghanem, R., Taşkın, E., Muresan, M., Karpova, E., Slynko, E., Dağli, E., Fortič, A., Surugiu, V., Mačić, V., Trkov, D., Rjiba Bahri, W., Tsiamis, K., Ramos-Espla, A.A., Petović, S., Ferrario, J., Marchini, A., Sconfietti, R., Ammar, I., Alo, A., Edelist, D., Begun, T., Teaca, A., Tari, G., Huseyinoglu, M.F., Karachle, P.K., Dogrammatzi, A., Apostolopoulos, G.A., Crocetta, F., Kytinou, E., Digenis, M., Skouradakis, G., Tomas, F., Bariche, M., Kaminas, A., Konida, K., Deidun, A., Marrone, A., Fraschetti, S., Mihneva, V., Nike Bianchi, C., Morri, C., Gerovasileiou, V., Lipej, L., Sini, M., Mangialajo, L., Zotou, M., Skolka, M., Azzurro, E., Vella, A., Dailianis, T., Grigoriou, P., Jimenez, C., Tsirintanis, K., Oikonomidis, G., Mancini, E., Papadakis, O., Di Martino, V., Chatzigeorgiou, G., Ben Amor, M.M., Vernadou, E., Arda, Y., Minasidis, V., Azzola, A., Hadjioannou, L., Montefalcone, M., Baldacchino, Y., Stancanelli, B., Bonifazi, A., Occhipinti-Ambrogi, A., Smeraldo, S., Evans, J., Kondylatos, G., Falautano, M., Castriota, L., Lamprou, A., Rizgalla, J., Mavrič, B., Papadimitriou, E., Kersting, D.K., Schembri, P.J., Khamassi, F., Nikolaou, A., Ballesteros, E., Dimitriadis C., García M., Anastasiadis A., Kalogirou S., Nalmpanti M., Altamirano M., Grech D., Mavrouleas D., Vella N., Agius Darmanin S., Dragičević B., Poursanidis D., Tsatiris A., Corsini-Foka M., Orlando Bonaca M., Insacco G., Tsalapatis A., Scannella D., Tiralongo F., Verdura J., Vitale S., Valsamidis M.A., Bazairi H., Mannino A.M., Virgili R., Collepardo Coccia, F., El Zrelli, R., Nikolidakis, S., Jilani Rabaoui, L., Yapıcı, S., Zaouali, J., Zava, B., Agrotis, N., Bilecenoglu, M., Çinar, M. E., Moraitis, M.L., Albano, P.G., Kaddouri, N., Kosma, J., Falsone, F., Fossati, V., Geraci, M.L., Lojze Zamuda, L., Mancuso, F.P., Petrou, A., Resaikos, V., Aydın, I., Batjakas, I.E., Bos, A.R., El Ouamari, N., Giallongo, G., Kampouris, T.E., Ounifi-Ben Amor, K., Doğan, A., Dulčić, J., Okudan, E.S., Rilov, G., Rosso, A., Royo, L., Selfati, M., Gaglioti, M., Giakoumi, S., Kousteni, V., Micu, D., Nicoară, M., Orfanidis, S., Papatheodoulou, M., Tempesti, J., Triantaphyllou, M., Tsourou, T., Yalgın, F., Baltag, E., Cerim, H., Filiz, H., Georgiadis, C.G., Papadamakis, P., Rammou, D.L., Samargiu, M.D., Sciuto, F., Sinopoli, M., Türker, A., Chiarore, A., Tamburello, L., Karray, S., Hassen, B. and Katsanevakis, S., 2023. Unpublished Mediterranean and Black Sea records of marine alien, cryptogenic, and neonative species. *BioInvasions Records*, 12(2), pp.339-369.

Samaha, Z., Bariche, M., Stephan, J., Bou Dagher Kharrat, M., Talhouk, S., and Pagad, S., 2020: Global Register of Introduced and Invasive Species — Lebanon. V1.1. Invasive Species Specialist Group ISSG. Dataset/Checklist. https://cloud.gbif.org/griis/resource?r=griis-lebanon&v=1.1

Schroeder, K., Chiggiato, J., Bryden, H.L., Borghini, M. and Ben Ismail, S., 2016. Abrupt climate shift in the Western Mediterranean Sea. *Scientific Reports*, 6(1), 23009.

Siddiolo, C., Palummo, V., Milisenda, G., Pipitone, C., Rosso, A. And Chemello, R., 2025a. Assessing Habitat Suitability and Distribution Patterns of the Invasive Brachyuran Crabs *Callinectes sapidus* and *Portunus segnis* in the Mediterranean Basin. *Mediterranean Marine Science*, 26(3), pp.428-439. https://doi.org/10.12681/mms.38715.

Tsirintanis, K., Azzurro, E., Crocetta, F., Dimiza, M., Froglia, C., Gerovasileiou, V., Langeneck, J., Mancinelli, G., Rosso, A., Stern, N. and Triantaphyllou, M., 2022. Bioinvasion impacts on biodiversity, ecosystem services, and human health in the Mediterranean Sea. *Aquatic Invasions*, 17(3), pp.308-352.

Ulman, A., Ferrario, J., Occhpinti-Ambrogi, A., Arvanitidis, C., Bandi, A., Bertolino, M., Bogi, C., Chatzigeorgiou, G., Çiçek, B.A., Deidun, A. and Ramos-Esplá, A., 2017. A massive update of non-indigenous species records in Mediterranean marinas. *PeerJ*, 5, p.e3954.

Virgili, R., Fasciglione, P., Tiralongo, F., Pannone, R., Palomba, M., Santoro, M., De Luca, P. and Crocetta, F., 2025. Interdisciplinary approaches at early invasion stages maximise the evidence on human-induced and climate-driven fish dispersal. *Hydrobiologia*, 852(8), pp.2241-2261.

Zavacki, E.M., Reyns, N.B., Crooks, J.A. and Boudrias, M.A., 2024. Temporal and spatial dynamics of the non-indigenous bryozoan, Amathia verticillata, and its associated invertebrate community. *Estuarine, Coastal and Shelf Science*, *311*, p.109021.

Zenetos, A., Albano, P.G., Garcia, E.L., Stern, N., Tsiamis, K. and Galanidi, M., 2022. Established non-indigenous species increased by 40% in 11 years in the Mediterranean Sea. *Mediterranean Marine Science*, 23(1), pp.196-212.

Zenetos, A. and Galanidi, M., 2020. Mediterranean non indigenous species at the start of the 2020s: recent changes. *Marine Biodiversity Records*, 13(1), pp.1-17.

Zenetos, A., Gofas, S., Verlaque, M., Cinar, M., Garcia Raso, J., Bianchi, C., Morri, C., Azzurro, E., Bilecenoglu, M., Froglia, C., Siokou, I., Violanti, D., Sfriso, A., San Martin, G., Giangrande, A., Katagan, T., Ballesteros, E., Ramos-Espla, A., Mastrototaro, F., Ocana, O., Zingone, A., Gambi, M. and Streftaris, N., 2010. Alien species in the Mediterranean Sea by 2010. A contribution to the application of European Union's Marine Strategy Framework Directive (MSFD). Part I. Spatial distribution. *Mediterranean Marine Science*, 11(2), pp.381-381.

Chapter 10

Complementary Data Sources for Mapping Target Mediterranean Non-Indigenous and Cryptogenic Species: the Role of Local Knowledge and Citizen Science

This chapter is widely based on the following publication, currently submitted in *Regional Studies in Marine Science*:

Siddiolo C., Rosso A., Chemello R. (2026) submitted to *Regional Studies in Marine Science*. Complementary Data Sources for Mapping Target Mediterranean Non-Native and Cryptogenic Species: The Role of Local Knowledge and Citizen Science

10 Complementary Data Sources for Mapping Target Mediterranean Non-Indigenous and Cryptogenic Species: the Role of Local Knowledge and Citizen Science

10.1. ABSTRACT

Citizen Science (CS) and especially Local Ecological Knowledge (LEK) play an increasingly crucial role in assessing the impacts of climate change on the biodiversity of Mediterranean shallow waters. We explored the use of multiple data sources — including CS, and particularly, LEK and social media — to assess the distribution of selected, especially NIS and cryptogenic thermophilic, marine species in the Mediterranean, which represented the target taxa of the present study. This case study aims to test the complementarity and reliability of adequately validated participatory and informal knowledge systems in documenting species occurrences. The approach highlights the potential of integrated methodologies to support biodiversity mapping and address data gaps in marine research.

10.2. INTRODUCTION

Citizen Science (CS), describes the active involvement of non-professional individuals in scientific research processes (Haklay et al., 2020; Bonn et al., 2022; Finger et al., 2023). Participants may contribute to data collection, validation, analysis, or dissemination, often in collaboration with academic institutions or research teams. This approach enhances the spatial and temporal scale of data acquisition, fosters public engagement with science, and supports inclusive knowledge production (Haklay et al., 2021). Among CS approaches, Local Ecological Knowledge (LEK) is an increasingly recognized tool for understanding environmental dynamics and for monitoring biodiversity changes (Azzurro et al., 2011; Azzurro et al., 2019; Bastari et al., 2022; Perzia et al., 2023; Garcia-Bustos, 2025). LEK can be defined as the cumulative body of ecological insights held by local resource users, derived from long-term, place-based interactions with the environment and transmitted through cultural and experiential practices (Bélisle et al., 2018; Gann et al., 2019). It refers to the experiential understanding that individuals or communities develop through prolonged interaction with their surrounding ecosystems. This knowledge encompasses observations of species occurrence and behavior, ecological dynamics, and environmental changes, often

embedded in cultural practices and transmitted across generations. LEK is context-specific, adaptive, and can provide valuable insights into ecological patterns that may be overlooked by formal scientific research and even monitoring (da Silva Lima et al., 2025).

In the Mediterranean Sea, climate change and rising Sea Surface Temperature (SST) are key drivers of environmental shifts, profoundly influencing marine biodiversity and ecosystem dynamics (e.g., Garrabou et al., 2022). Among their multiple ecological effects, including changes in species phenology, alterations of community structure, mass mortality events, and shifts in species interactions, these factors trigger alterations in species distribution, leading to northward range restriction or shifts of temperate and thermophilic species, respectively, and the expansion of tropical organisms into Mediterranean ecosystems (e.g., Boero et al. 2008, Occhipinti-Ambrogi and Galil, 2010; Raitsos et al., 2010; Giangrande et al., 2020). Such changes drive processes of meridionalisation — northward expansion of the distribution range of native thermophilic species (Bianchi, 2007) — and tropicalisation — introduction and spread of non-indigenous species of tropical origin (Azzurro et al., 2019) — favoring the spread of species adapted to warm conditions. As a result, local biological communities are reshaped, posing significant challenges to biodiversity conservation and sustainable ecosystem management (Aurelle et al., 2022).

Sea Surface Temperature (SST) increase not only drives Mediterranean species redistribution but also facilitates the establishment of non-indigenous, sometimes invasive, taxa as those introduced from the Suez Canal but not the Strait of Gibraltar (see Albano et al., 2024), hence adapted to warm temperatures, while stressing native populations (Harvell et al., 1999; Harris and Tyrell, 2001; Raitsos et al., 2010). These shifts in species composition can profoundly alter ecosystem structure and functioning, leading to disrupted ecological balances. Thermal anomalies, including heatwaves, further contribute to phenological changes, the spread of pathogens, and mass mortality events, collectively reshaping marine assemblages and threatening the integrity of already fragile ecosystems (Brierley and Kingsford, 2009; Garrabou et al., 2009; Rivetti et al., 2014).

The consequences of these transformations extend beyond biodiversity loss, impacting ecosystem services that sustain human life. Shifts in species distributions and community compositions affect fishery, coastal protection, and public health, with cascading effects on socio-ecological systems (Weatherdon et al., 2016; Cooley et al., 2022). These cascading effects underscore the urgent need for adaptive management and ecosystem-based approaches to conservation, integrating ecological resilience with sustainable resource use (Moullec et al., 2023).

In this context of NIS and thermophilic species expanding their range in the Mediterranean due to rising temperatures and related environmental changes, we selected representative species from different taxonomic groups to evaluate the contribution of diverse data sources in documenting their current distribution also testing potential differences in relation to the different taxa, their ecological traits (such as habitat preferences and catchability), and their socio-economic relevance (including commercial value, potential toxicity, or charismatic appeal). This approach allowed us to evaluate whether the performance of diverse data sources is influenced by the biological nature of the species or by the human dimensions associated with their presence. These taxa include the thermophilic *Ocypode cursor* (Arthropoda, Malacostraca), and the NIS/cryptogenic species *Oculina patagonica* (Cnidaria, Scleractinia), *Lamprohaminoea ovalis* (Mollusca, Gastropoda), *Amathia verticillata* (Bryozoa, Gymnolaemata), *Pterois miles*, *Acanthurus monroviae* and *Fistularia petimba* (Chordata, Actinopterygii).

Most of the selected species are NIS and have entered the Mediterranean only in the very last decades; therefore, any evidence of range expansion falls within the last twenty years (Serrano et al., 2013; Marchini et al., 2015; Kletou et al., 2016; Evans et al., 2017; Mancinelli et al., 2019; Azzola et al., 2022; Bottaccini et al., 2024), a period documenting an exacerbation of the increase in sea surface temperatures (Pisano et al., 2020; Garrabou et al., 2022). While most occurrence records analyzed in this study date from 2000 onwards — reflecting the recent surge in monitoring efforts and public awareness regarding NIS — earlier data were also included when available to provide a broader historical context. The selection of species was based on their scientific relevance or ease of identification, particularly through photographic documentation, to facilitate data collection via CS and LEK. Among them, the sea-crab *Ocypode cursor* stands out as the only thermophilic species on the list, with a long-time documented distribution in eastern Mediterranean and its habitat expansion already documented as a direct consequence of rising temperatures (e.g., Deidun et al., 2017; Marchessaux et al., 2024). *Oculina patagonica* is a cryptogenic coral species (e.g., Molinari et al., 2026; Pistevos et al. (2026) widely recorded in the Mediterranean shallow-water habitats, making it a key target for tracking and understanding the spread of non-indigenous corals. The ctenostome bryozoan *Amathia verticillata* is a cryptogenic species (e.g., Pistevos et al., 2006) frequently found in harbours and easily recognizable due to its large and apparent colonies often reaching 1 m height potentially dangerous for clogging submarine pipes when growing in dense mats (e.g., Gitay and Glazer, 1979). The nudibranch *Lamprohaminoea ovalis* is a NIS (e.g., Pistevos et al., 2026) expanding its range due to water warming in the Mediterranean (Azzola et al., 2022) and it is also extensively photographed, especially by divers, making it easily identifiable. The NIS fish *Fistularia petimba* is the second documented species of its genus in the Mediterranean, yet its distribution needs to be further investigated

(Stern et al., 2017; Cerim et al., 2021). In contrast, the NIS fish *Pterois miles* has been extensively studied, but efforts to curb its invasion have yet to yield significant large-scale results. Moreover, existing distribution models for this species have proven unreliable (Poursadinis et al., 2022), reinforcing the necessity of collecting extensive observational data to refine predictive frameworks. Unlike previous species, the NIS fish *Acanthurus monroviae* has a limited number of records in the Mediterranean (Deidun et al., 2021), unevenly distributed on almost the entire basin but leaving large sectors (such as the Tyrrhenian Sea) uncovered. This apparently patch distribution of reports makes this species a valuable target for gathering additional data on its presence, possibly additional to those originating from literature.

This study aims to explore how CS and LEK can complement traditional ecological data in monitoring species distribution changes. By integrating CS and LEK insights with established scientific datasets, we aim to enhance prediction models and support adaptive management strategies to address Mediterranean biodiversity changes and loss. Specifically, our objective is to assess the relative contributions of each dataset to overall species occurrences evaluating their geographic complementarity and practical limitations in documenting current species presence rather than 169panish169g temporal distribution shifts. Through this approach, we aim to test whether, and to what extent, the integration of LEK and CS with conventional sources—such as literature records, field sampling—enhances the analysis of ecological transformations. Specifically, our objective is to evaluate the actual added value of incorporating these complementary data streams, clarifying the tangible advantages they may support in improving the understanding of climate change impacts on Mediterranean marine ecosystems.

10.3. MATERIALS AND METHODS

Data were collected from multiple sources in order to develop a comprehensive understanding of the selected species distribution across the Mediterranean.

To improve transparency and reproducibility in data collection and screening, principles inspired by the PRISMA 2020 framework (Page et al., 2021) were adapted to the compilation and validation of heterogeneous occurrence records derived from scientific literature, biodiversity databases, CS/LEK surveys, and social media platforms (Fig. 1). Occurrence records for each of the seven target species were included when they met the following criteria:

1) Reliable taxonomic identification;

2) Occurrence located within the Mediterranean basin;

3) Availability of minimum associated information, including locality and temporal reference whenever possible. Records lacking sufficient geographic detail and duplicated observations were excluded from subsequent analyses unless independently validated through photographic evidence or expert assessment.

To minimize the risk of data redundancy and ensure dataset independence, a multi-step validation process was applied. First, whenever respondents provided records already published in scientific literature — often by explicitly citing the reference — such data were cross-referenced and reassigned to the 'Bibliographical Sources' category to avoid double counting. Then, all primary records were spatially and temporally audited; overlapping sightings (same location, date, and species) were treated as a single occurrence record. However, multiple distinct reports from the same area – but different sources or dates — were retained if they represented separate sightings, a common occurrence for high-density species like Pterois miles.

The workflow adopted for occurrence record identification, screening, validation, and inclusion is summarized in Figure 10.1.

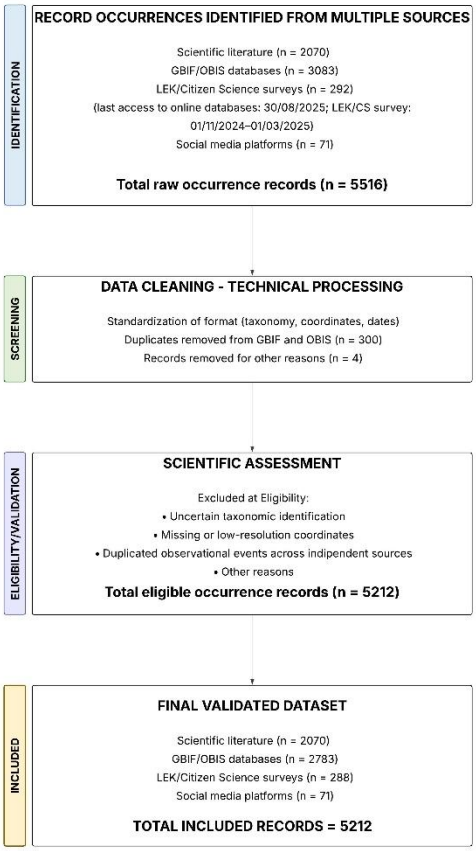

Figure 10.1: PRISMA-inspired flow diagram illustrating the identification, screening, validation, and inclusion of species occurrence records collected from multiple heterogeneous data sources, including scientific literature, global biodiversity databases (GBIF and OBIS), Local Ecological Knowledge/Citizen Science surveys, and social media platforms. The diagram represents an adapted implementation of the PRISMA 2020 framework (Page et al., 2021) for the synthesis of occurrence-based ecological datasets implementing traditional systematic literature reviews.

The occurrence records of the seven target species were gathered through the following methods:

a) Bibliographic Sources: an exhaustive literature review was conducted using SCOPUS, Google Scholar and ResearchGate for accessing scientific publications. Keywords for each species included its scientific name paired with terms such as “distribution,” “Mediterranean,” and “occurrence,” ensuring a broad

retrieval of relevant studies. This approach helped compile historical and peer-reviewed accounts of species presence in different regions.

b) Online Databases: global biodiversity databases such as GBIF and OBIS were leveraged (last access: 30/08/2025). These platforms provide geographically referenced species occurrence records, primarily derived from field observations, museum collections, and citizen science initiatives. Unlike literature-based data, which often reflect targeted sampling or specific ecological studies, these databases offer standardized, large-scale datasets that can be independent of published research. This distinction ensures broader spatial and temporal coverage, enabling researchers to assess distribution patterns across regions and timeframes while largely minimizing potential overlaps with literature-derived sources. Nevertheless, because researchers frequently upload primary datasets to global repositories upon publication, a complete separation cannot be guaranteed, and online database records should be understood as mainly complementary to published literature. For each species, data retrieval was performed using Rstudio (R version 4.4.2), utilizing specialized packages (robis, dismo, raster, sf, ggplot2, rnaturalearth, readxl and tidyverse) (Hijmans et al., 2010; Wickham, 2016; Hijmans, 2018; Wickham et al., 2019; Provoost et al., 2022; Pebesma and Bivand, 2023; Massicotte et al., 2023; Wickham, 2025) to streamline extraction, filtering, and spatial representation. It should be noted that these online databases also include records sourced from platforms such as iNaturalist.org, which frequently originate from citizen science initiatives. However, it was not possible to determine precisely which and how many records derive from this provenance; therefore, they were treated as part of the online databases in their entirety rather than classified separately as citizen science data.

c) Local Ecological Knowledge & Citizen Science (Survey-based): To systematically differentiate primary field observations from the citizen science data already compiled within global online repositories, this data stream was designated as LEK and CS (Survey-Based). For our purpose, we developed a multilanguage Google Form (English, French, Spanish, Italian, Arabic; Supplementary 1), containing standardized questions focused on the seven target species. For each target species, the questionnaire began with a picture and asked if the species was been seen in the Mediterranean. Eventually, it requested to provide detailed information about the occurrence, such as the most accurate location, date and any other useful data, including photos or videos. The survey was widely distributed via social media and email, targeting a diverse group of scientists, research institutions, fishing communities, and diving

professionals across all 22 Mediterranean riparian countries. To ensure maximum coverage, the questionnaire was distributed in five languages, i. e., English, French, Spanish and Italian, expecting a relatively wide diffusion of these languages in Mediterranean coastal countries, and Arabic, especially to attract answers from southern and eastern regions of the basin. Specifically, we contacted over a thousand stakeholders, including members of international networks. The questionnaire was sent directly via email to diving centers, university professors and researchers, marine researchers affiliated with national and international research institutes, and local fishermen. Each recipient was explicitly encouraged to further disseminate the form within their networks, maximizing outreach. This form was available from 01/11/2024 to 01/03/2025, allowing for a substantial data collection period. Additionally, semi-structured interviews were conducted with local communities, particularly fishermen, who provided insights into unusual catches and species appearances over recent years. These firsthand observations often revealed historical trends and ecological shifts that might not be captured through conventional scientific studies. This targeted, questionnaire-driven approach allowed us to isolate unique stakeholder insights and maintain the LEK and CS (Survey-Based) records as an independent dataset during the subsequent integration and spatial analysis.

d) Social Networks: social media platforms have become increasingly valuable tools for monitoring marine biodiversity, particularly through specialized user communities. Data collection from Facebook groups, especially, but not only, “Oddfish” and “Fauna Marina Mediterranea” (last access: 30/08/2025) (few occurrences come from other facebook groups focused on diving photography or on specific taxonomic groups: see supplementary materials) provided additional occurrences of target species shared not only by researchers but also by amateur naturalists, divers, and fishermen. These reports were evaluated based on accompanying photographs, geographic details, and correct identification of each occurrence before being incorporated into the dataset.

Once the species occurrence data were collected, all records were consolidated into a structured Excel file (https://doi.org/10.5281/zenodo.18428853), which included:

• Geographical coordinates for each observation, ensuring precise spatial mapping;

• Year of occurrence, available in most cases.

• Data source classification, differentiating records from literature, online databases (both GBIF and OBIS), LEK and CS (Survey-Based), and social networks.

Since geographical coordinates were not uniformly available or explicit across all opportunistic data streams (such as social networks and survey-based LEK/CS), a multi-tier georeferencing protocol was implemented to handle spatial uncertainty. For records featuring highly specific localized references (e.g., specific beaches, harbors, or coastal coves), precise coordinates were manually assigned using high-resolution digital mapping tools. Conversely, when reporting provided broader context (e.g., a town or a wide bay), coordinates were carefully inferred by cross-referencing locations with validated occurrence data for the same species from global repositories to align the point with biologically plausible habitats; when previous data were lacking, a conservative centroid coordinate for that geographical feature was assigned. Finally, to preserve spatial integrity and avoid artificial range inflation, records with overly vague or macro-regional descriptions (e.g., country-level data only) were strictly excluded from the final database.

When compiling large-scale datasets from heterogeneous and complementary sources, addressing potential data redundancy is crucial to ensure the statistical independence of the observations. In this study, data overlap was systematically managed through a combination of automated filtering and source-specific validation protocols.

For global biodiversity repositories, an automated, balanced deduplication algorithm was executed in R to eliminate exact spatial duplicates shared between GBIF and OBIS for the same species. However, managing the intersection between published literature, LEK/CS (survey-based) and social network reports requires a more nuanced approach. In these categories, records sharing identical geographic coordinates were retained as independent data points only if they corresponded to different observation dates or stemmed from distinct, verified reporting events. This approach is biologically justified for high-density or aggregate-forming species, such as Pterois miles, where multiple distinct encounters can naturally occur at the same popular diving spot or fishing ground over time.

Nevertheless, a degree of intrinsic, undetectable redundancy cannot be entirely ruled out. For instance, global platforms like GBIF and OBIS aggregate also records from open-source citizen initiatives such as iNaturalist.org. Because these records are fully absorbed into the massive data structures of online repositories, tracing and isolating the exact primary user who generated them is often technically impossible. Consequently, some contemporary citizen-led sightings might be double-counted if

the same event was independently scraped by a global database and logged via our targeted multi-lingual surveys or social media monitoring.

To mitigate this specific risk, our workflow included a spatial-temporal audit alongside geographical segregation. For example, our social media data collection (e.g., from specialized Facebook groups) showed a strong geographic focus on the Italian coastline due to user demographics, whereas the multilingual survey successfully captured distinct stakeholders across the wider Mediterranean basin (e.g., the Levant and the Maghreb). Furthermore, whenever survey respondents explicitly cited a published study for a record, the occurrence was immediately cross-referenced and reassigned to the “Bibliographical Sources” category. While minor overlapping residues are an unavoidable limitation in modern multi-source biogeographical syntheses, the multi-step validation and audit protocols applied here effectively minimized structural redundancy, preserving the overall reliability and geographical proportionality of the compiled dataset.

Both GBIF and OBIS are global biodiversity databases providing online occurrence records. Although their contributions are shown separately for transparency, they should be considered together when assessing the overall weight of online sources in documenting species distributions. Before proceeding with analysis, duplicates were carefully identified and removed to avoid overrepresentation of species occurrences. The cleaned dataset was then used to generate distribution maps for each target species, using Rstudio’s ggplot2 package (Wickham, 2016). These maps visually illustrate species distributions, with different colors representing each data source, facilitating comparisons between literature records and alternative biodiversity monitoring approaches such as online repositories, LEK, CS and social networks.

For literature-derived data, occurrence records were extracted as unique georeferenced records rather than as individual publication-based counts. Consequently, repeated reporting of the same occurrence across multiple sources was consolidated into a single record prior to analysis.

Records were compiled for the seven target species using multiple data sources, including scientific literature, online databases (GBIF, OBIS), LEK/CS (Survey-Based), and social networks (Table 10.1). To better contextualize heterogeneity in data sources, relative proportions were also calculated, highlighting the varying incidence of each source across species (Figure 10.2).

Species	Literature	Online GBIF/OBIS	CS/LEK (Survey-Based)	Social networks	TOTAL
Oculina patagonica	151	478	54	0	683
Amathia verticillata	138	332	39	1	510
Lamprohaminoea ovalis	56	41	42	16	155
Ocypode cursor	46	399	26	34	505
Acanthurus monroviae	30	1	6	0	37
Fistularia petimba	73	7	39	0	119
Pterois miles	1576	1525	82	20	3203
TOTAL	2070	2783	288	71	**5212**

Table 10.1: List of the seven target species with records from the five different sources used in this study

.

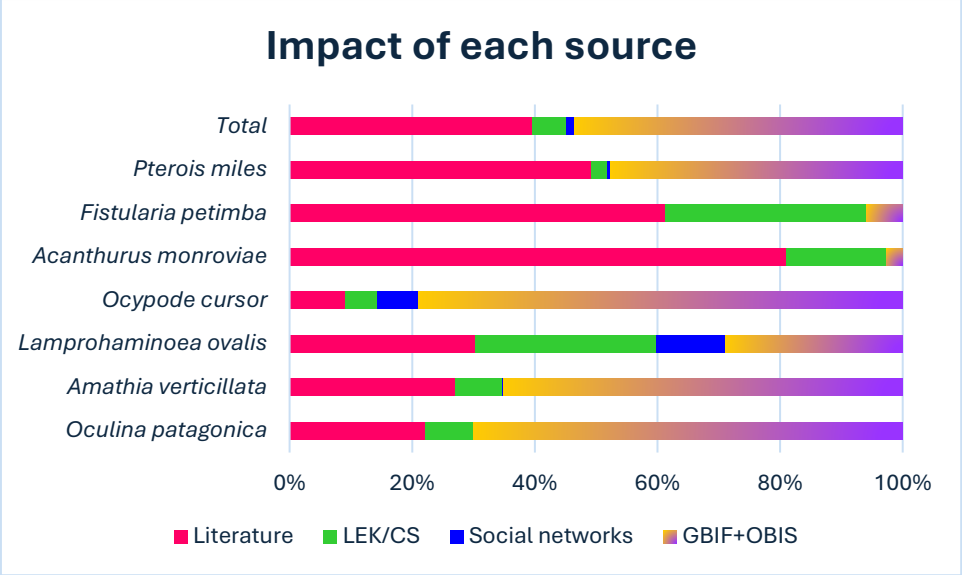

Figure 10.2: Percentage contribution of the different data sources utilized in this study on the total count of the target species occurrences in the Mediterranean.

10.4. RESULTS

A total of 5,212 reported records were compiled for the seven target species (Table 10.1). While these consolidated records offer a comprehensive baseline of documented observations across the basin, they primarily reflect the spatial distribution of reporting efforts and data availability rather than a verified biological range expansion over time. Although online databases contributed the largest portion of the dataset with 2,783 records, bibliographic sources still accounted for a substantial and critical component of the data with 2,057 records. Social networks provided additional records in new sites, particularly for *Ocypode cursor* and *Pterois miles*. Local Ecological Knowledge and Citizen Science surveys yielded 291 responses from 14 Mediterranean countries (Fig. 10.3 and Fig. 10.4), resulting in 288 species occurrences. Some of these questionnaires included additional information on local environmental conditions, such as anomalies in Sea Surface Temperature (SST), bottom temperatures, and algal blooms; furthermore, alongside photos of target taxa, stakeholders occasionally attached pictures of other non-target marine organisms—especially fish—that they failed to recognize. Photographic or video evidence supported 38 records enhancing the reliability of the dataset. A selection of these photos is reported in Fig. 10.5. For some species such as *O. patagonica*, *A. verticillata* and *O. cursor*, literature occurrences only represent less than one third of the total records and even 9% in the last case. In all these instances, the higher number of occurrences is given by online databases. *Lamprohaminoea ovalis* reported occurrences are almost equally divided between the sources, except for social network.

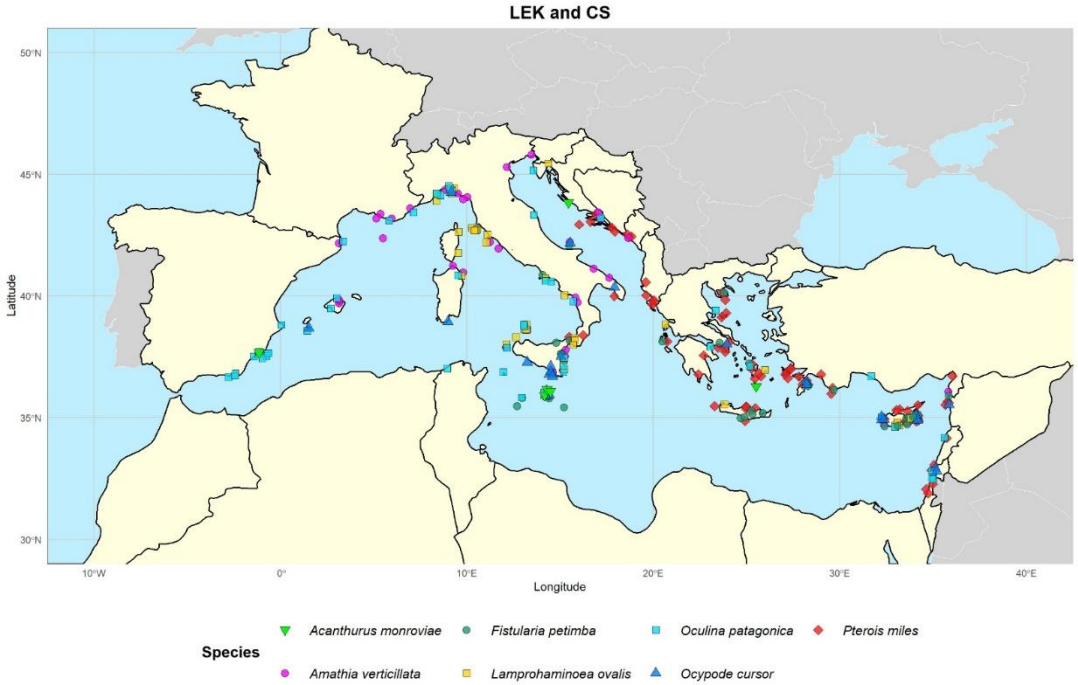

Fig. 10.3: Map showing the Mediterranean distribution of the target species based on data obtained from the structured interviews through Google form.

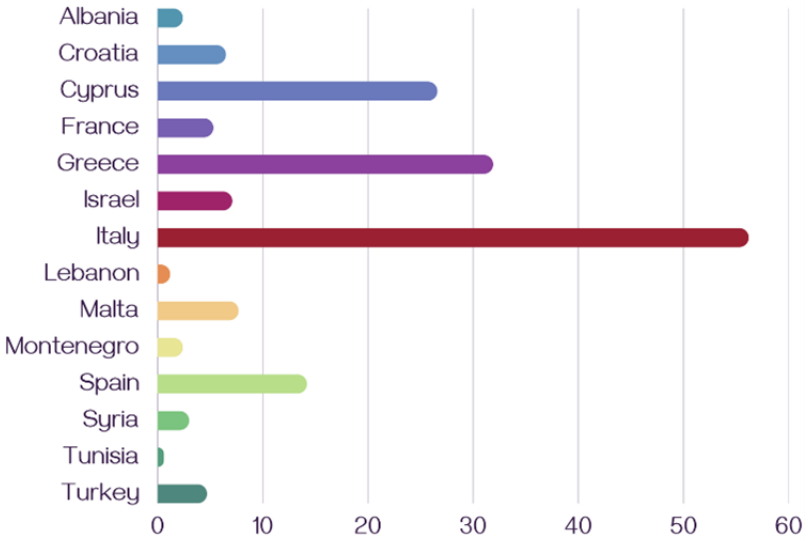

Fig. 10.4: Numbers of answers to the structured interviews through Google form, distributed for Mediterranean countries.

Among the studied species, *Pterois miles* was the most frequently reported species, with 3,203 occurrences, while *Acanthurus monroviae* was the least documented one, with only 37 records (Table 10.1). Details are provided in the following sections for each species.

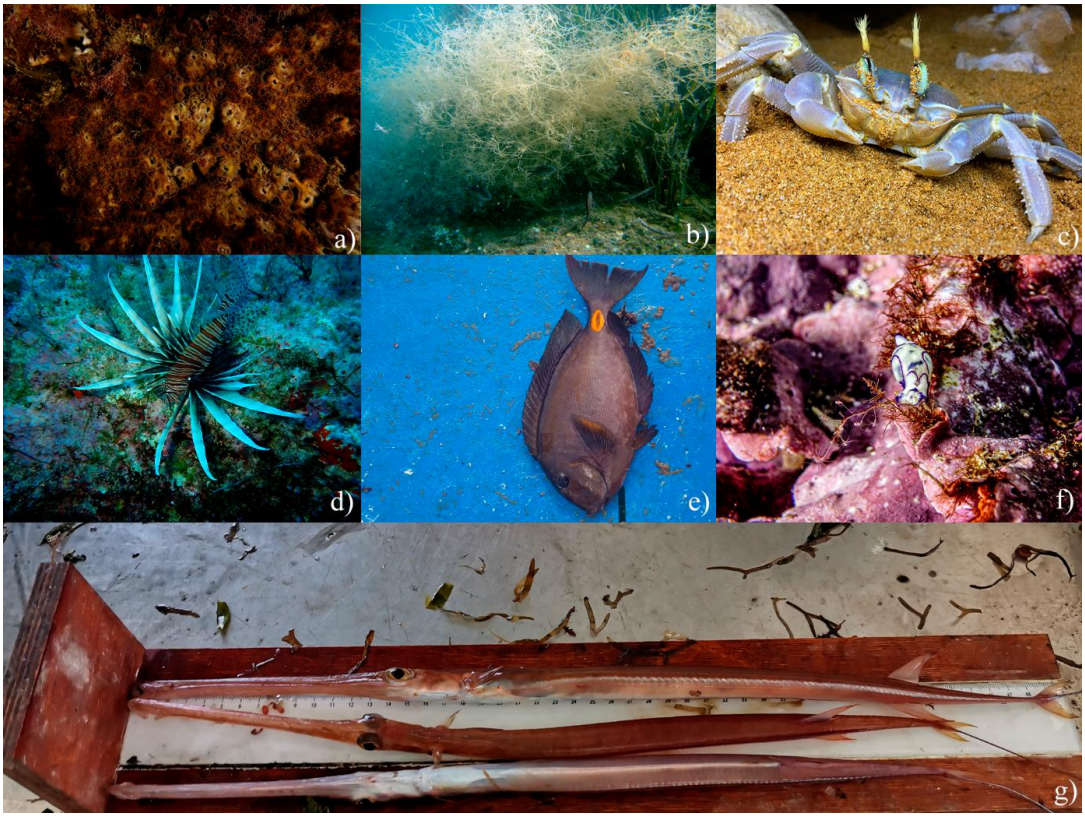

Fig. 10.5: Pictures of the target species included in the Google form by interviewees: a) the coral *Oculina patagonica*, Capo Negro, Tabarka, Tunisia, photo: Egidio Trainito; b) the bryozoan *Amathia verticillata*, Sestri Levante, Genova, Italy, photo: Marco Bertolino; c) the crab *Ocypode cursor*, Ramla l-Ħamra, Gozo, Malta, photo: Antonia Scicluna; d) the fish *Pterois miles*, Biševo Island, Croatia, photo: Tatjana Bakran-Petricioli; e) the fish *Acanthurus monroviae*, Cartagena, Spain, photo: Miguel Ángel Gallego; f) the nudibranch *Lamprohaminoea ovalis*, Tavolara, Sardinia, Italy, photo: Egidio Trainito; g) the fish *Fistularia petimba*, Cyprus, photo: Marios Papageorgiou.

The distribution map of *Oculina patagonica* (Fig. 10.6), first recorded in Italy in 1966 (Zibrowius, 1974), counts 683 occurrences, illustrating its widespread presence across various Mediterranean geographical sectors, with particularly high concentrations of records along the Spanish coasts. The species is also well-documented in Greece, Lebanon, Israel, and Italy, and, subordinately, in Syria, Egypt, Tunisia, and Algeria, reflecting its broad geographic range. Data from different sources reveal distinct trends: scientific literature confirms occurrences primarily in

Spain, southern Italy (Sicily), Greece, Syria, Lebanon, Israel, Egypt, Malta, Tunisia, and Algeria. Online records mainly feature sightings along the Spanish and French coasts, including Corsica, with isolated records in Israel, Tunisia and Morocco; in particular, OBIS data are concentrated primarily along the Spanish coasts. This localized geographic scope likely reflects a dataset-specific bias, where large-scale regional monitoring programs or specific research projects (e.g., those focused on the Western Mediterranean) have preferentially shared their records with the OBIS platform. Consequently, while OBIS provides high-resolution data for certain areas, it offers a less continuous representation of the species' Mediterranean distribution compared to other aggregated sources like GBIF. Local Ecological Knowledge and Citizen Science contributions for *O. patagonica*, report further occurrences in the same regions of other sources but are especially localized in regions lacking such records, such as Cyprus and especially peninsular Italy (on both the Tyrrhenian and Adriatic sides), as well areas around Sicily and the Sicily Channel besides some localities of eastern Adriatic along Croatia.

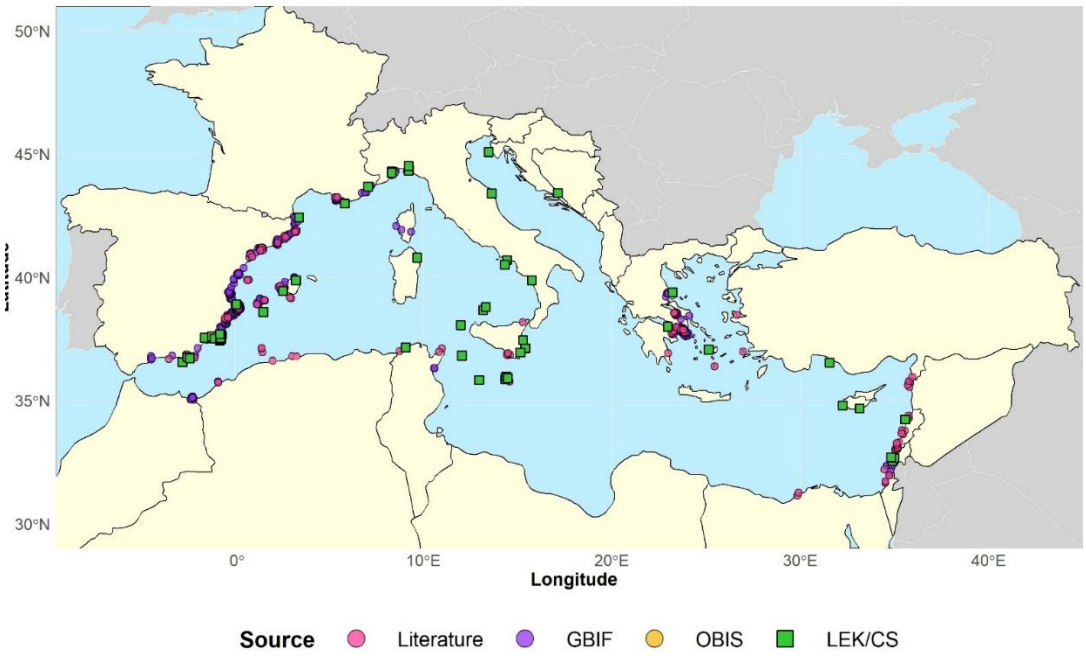

Fig. 10.6: Occurrences of the scleractinian *Oculina patagonica* in the Mediterranean Sea. Different colors and markers highlight the source of the records.

Amathia verticillata (Fig. 10.7) has 510 reported occurrences, confirming its wide presence across the Mediterranean, with major data densities in central, western and northern areas. The species is well-documented along the Spanish and French coasts, across Italy (including islands, particularly in the Tyrrhenian Sea), and the Greek islands. It also commonly occurs in Tunisia, while it is more sporadically reported in Egypt and along further North African coasts (Morocco, Algeria and Libya) as well as in Turkey, Cyprus and Israel. However, records from the different sources do not overlap completely and report occurrences for different sites. Scientific literature predominantly reports the species in Italy including the first occurrence provided by delle Chiaje (1822, from an unreported locality in the Kingdom of the Two Sicilies, an area covering almost all southern Italy) (delle Chiaje, 1821). Further records are reported in Slovenia, Malta, and Tunisia, with a few scattered records in Spain, Israel and Libya. For online sources, GBIF records are mostly concentrated along the French coast, with additional sightings in Italy, Spain, Greece, Egypt, and Morocco; OBIS data are mainly located in central Italy and Greece. Local Ecological Knowledge contributions report further occurrences than traditional sources, particularly in southern Italy, along the French and Spanish coasts, and extending to Croatia, Turkey and Cyprus, with this last area almost only covered by LEK and CS data. Social network sources provide a single record, located in central Italy.

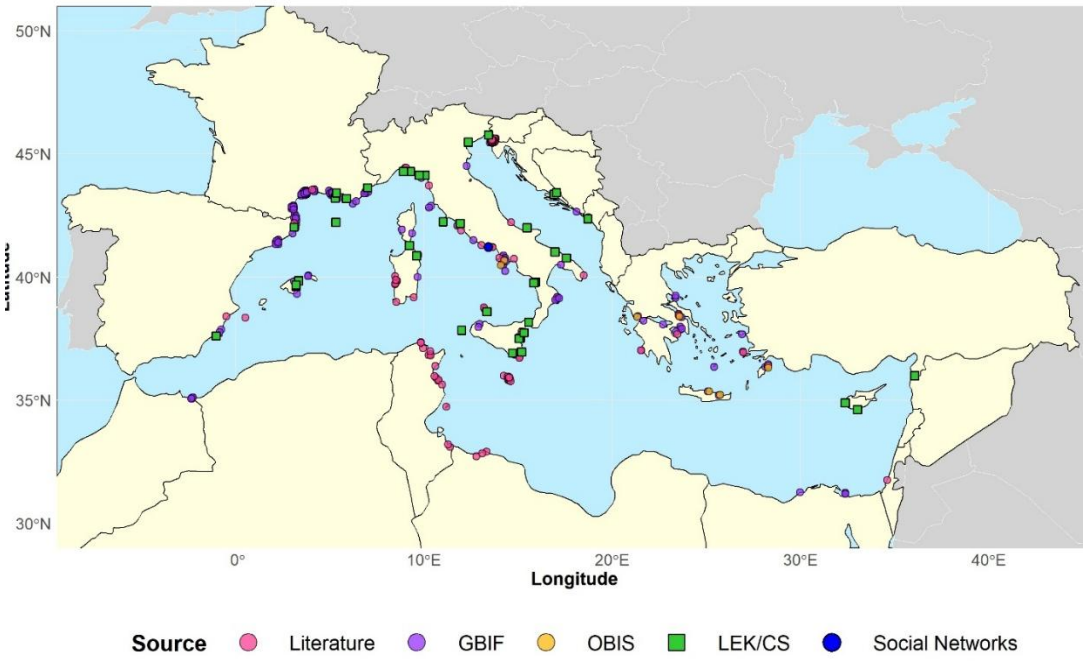

Fig 10.7: Occurrences of bryozoan *Amathia verticillata* in the Mediterranean Sea. Different colors and markers highlight the source of the records.

Lamprohaminoea ovalis, was first reported in the Mediterranean from Greece in 2001 (Zenetos et al., 2003) and counts a total of 155 records (Table 10.1). This species seems predominantly distributed in western Mediterranean (Fig. 10.8), with many records concentrated along the coasts of Spain, France, and Italy, especially in the Tyrrhenian Sea. The species is also present in the Sicily Channel, covering Lampedusa, Linosa as well as the Malta Archipelago, and along the Ionian coasts of Sicily with few reported records in Croatia, Greece, and Cyprus. Literature locates the occurrences between the Tyrrhenian coast of Italy and Spain, reinforcing a strong western Mediterranean presence, but also in the Sicily Channel, Malta, the Ionian coast of Sicily and the Strait of Messina, with occasional occurrences in Croatia, Greece and Libya. Online databases provide only GBIF records displaying a more distributed pattern across the Mediterranean, with sightings in Spain, Italy, Malta, and Greece. Local Ecological Knowledge and Citizen Science contributions confirm sightings along the Italian Tyrrhenian coast, Corsica, Malta and Greece, while also significantly add wide areas in the Tyrrhenian Sea and reports from Cyprus. Social network occurrences align partially with other sources, reporting

sightings in Spain, France, the Italian Tyrrhenian and Ionian coast (Sicily), and Croatia.

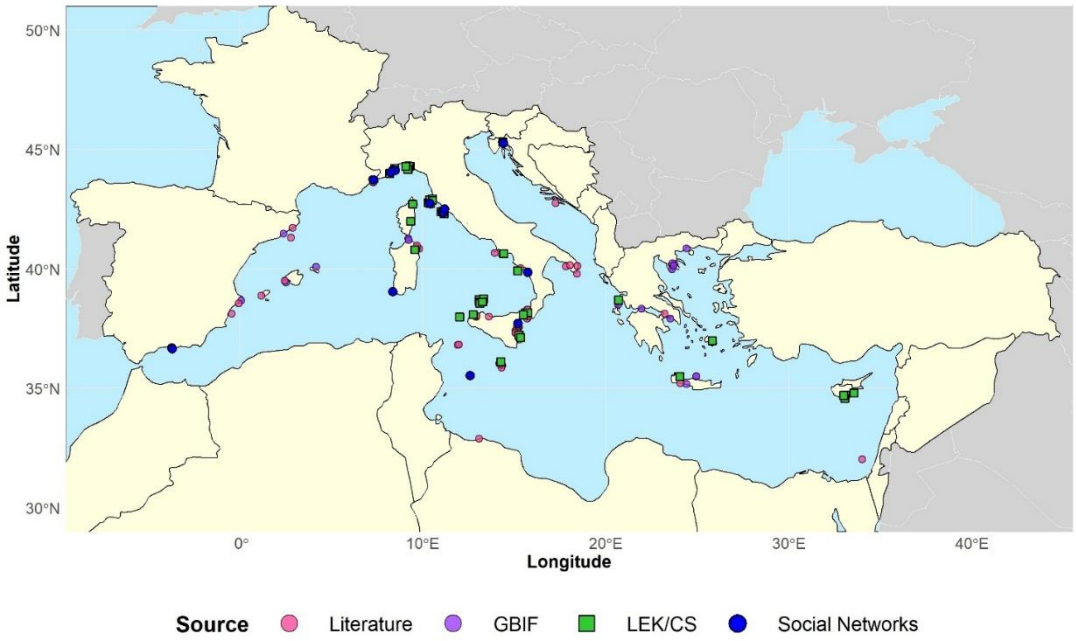

Fig. 10.8: Occurrences of the nudibranch *Lamprohaminoea ovalis* in the Mediterranean Sea. Different colors and markers highlight the source of the records.

Ocypode cursor (Fig. 10.9, Table 10.1) counts 505 occurrences, especially in the southeastern Mediterranean, where this species was historically observed in Egypt in 1933 (Marchessaux et al., 2023), with numerous records in the Levantine Sea, as well as in the Aegean Sea, the Ionian coasts of Italy and Greece, and the Sicily Channel and few occasional occurrences in the western part of the Mediterranean. Literature provides occurrences mainly in southern Italy, both on the Ionian and Tyrrhenian coasts – where it was observed only in recent years (Bàez et al., 2025), Malta, Greece, Cyprus, Lebanon, and Israel, highlighting its preference for warm southern beaches (Tiralongo et al., 2020; Marchessaux et al., 2024). GBIF records closely align with this pattern, while also adding reports from Greece, Turkey, Lebanon, Israel, Egypt and Tunisia. OBIS data are scarce and mainly focused in

Turkey. LEK contributions reinforce traditional distribution insights, concentrating in the same southeastern Mediterranean regions and especially along southern Sicily and Malta, but significantly add few records in the Adriatic and in the western Mediterranean. Social networks are mainly focused on southern Italy, especially in Sicily, along the Sicily Channel and southern Ionian Sea.

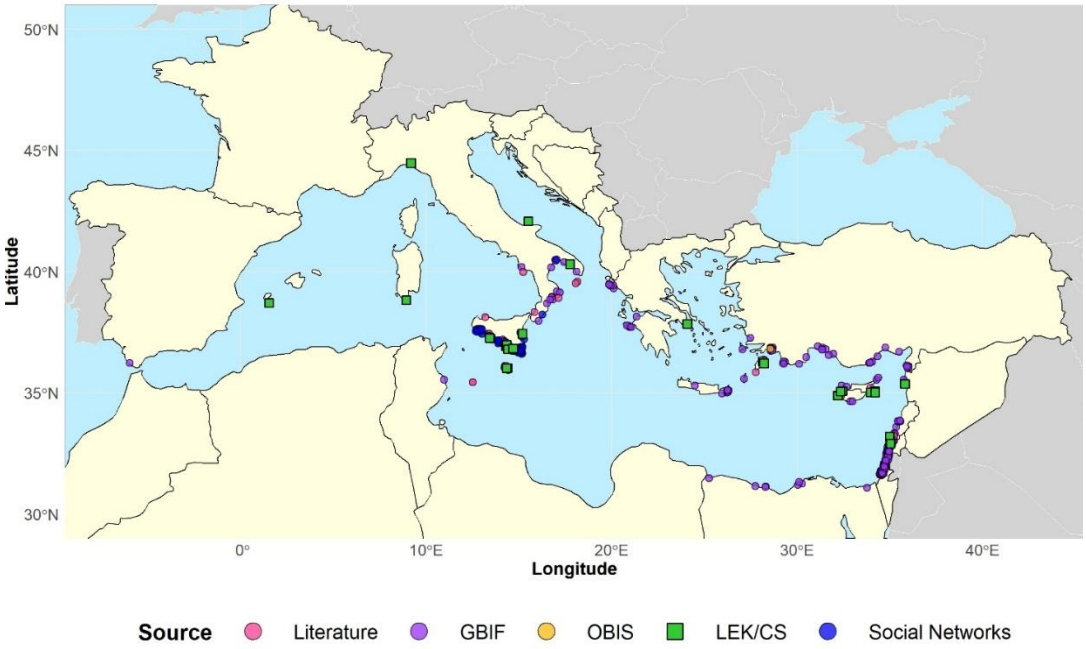

Fig. 10.9: Occurrences of the decapod *Ocypode cursor* in the Mediterranean Sea. Different colors and markers highlight the source of the records.

First observed near the Strait of Gibraltar in 1981 (Crespo et al., 1987), *Acanthurus monroviae* is the least reported species among those analyzed, with only 37 occurrences across the Mediterranean (Fig. 10.10, Table 10.1). However, unlike other target species, a relatively higher number of records originated from North African coasts, particularly from Algeria and Libya. The scarcity of records makes it particularly challenging to assess its distribution, though available data suggest some apparent concentrations of records in specific regions. Scientific literature provides records in Spain, Algeria, Tunisia, Libya, and Malta, with evidence

confirming the occurrence of a population in Maltese waters (Dulčić et al., 2025), but also occurrences in Israel, Greece and Croatia. LEK questionnaire data confirms the presence in Malta, while adding new reports from Greece and Croatia, in regions lacking records from other sources. Online data provide only only one GBIF occurrence, close to the Spanish-French border, further supporting its limited presence.

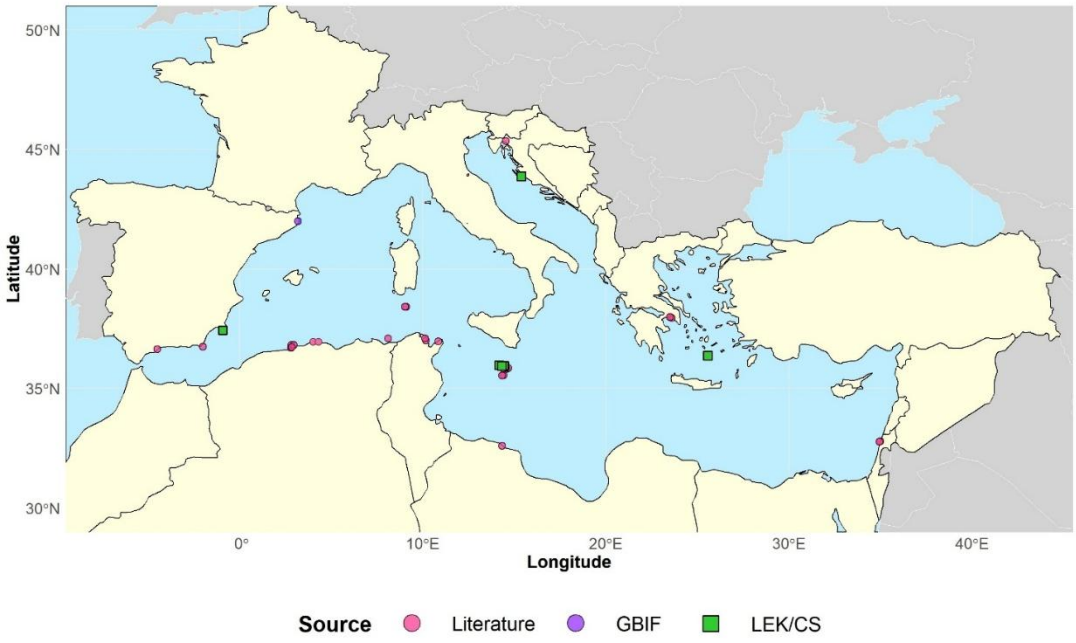

Fig. 10.10: Occurrences of the fish *Acanthurus monroviae* in the Mediterranean Sea. Different colors and markers highlight the source of the records.

Fistularia petimba has its first Mediterranean occurrence documented in Spain 1996 by Càrdenas et al. (1997). The distribution map (Fig. 10.11, Table 10.1), with 119 records, confirms that *F. petimba* predominantly occurs in the eastern Mediterranean, with a strong concentration of records reported in the Levantine Basin (from Israel to Turkey, including also Lebanon and Syria and several sites in Cyprus) and the Aegean Sea (Greece). While literature and online data primarily report sightings along Israeli waters, with limited occurrences in Greece, Cyprus, and Turkey, other sources suggest a wider distribution. LEK questionnaire results confirm some occurrences along Turkey's border with Syria, Cyprus, and Greece, while also reporting records in Malta, in the Sicily Channel (with records in

Lampedusa and Linosa), and eastern Sicily (Ionian coast). Further information by LEK also add sightings in previously undocumented areas in central Italy, with one report on the Tyrrhenian coast (Campania) and another in the Adriatic Sea (Apulia).

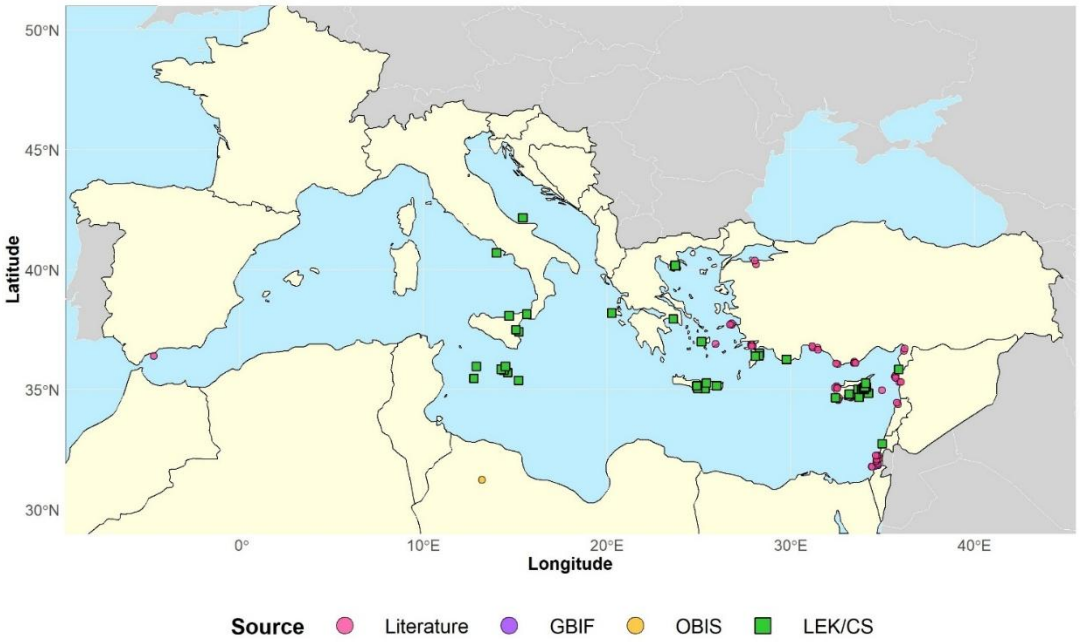

Fig. 10.11: Occurrences of the fish *Fistularia petimba* in the Mediterranean Sea. Different colors and markers highlight the source of the records.

Pterois miles, fist observed in Israel in 1991 (Golani and Sonin, 1992), is the most reported species among those analyzed, with 3203 occurrences and a widespread presence across the eastern Mediterranean and only few records reported in the western Mediterranean, between Algeria, Tunisia and Sardinia (Italy) (Fig. 10.12; Table 10.1). Literature sources overwhelmingly document its wide presence in the Aegean Sea and the Levantine Sea, covering Greece, Turkey, Cyprus, Syria, Lebanon, and Israel. Fewer records originate from Egypt, Libya, Tunisia, Algeria and Italy, especially along the Ionian Sea, from Apulia to Sicily. Online data cover the same areas, reinforcing the prevalence in Greece, Turkey, Cyprus, Syria, Lebanon, Israel, and Egypt while extending also to Albania and Croatia; OBIS records, however, primarily concentrate along the Greek coasts and related islands,

emphasizing a common presence of this species in the Aegean Sea. Social networks highlight occurrences in Italy, particularly in southern Sardinia, Strait of Messina, Apulia and Calabria and in western Mediterranean waters. LEK questionnaire data provide crucial insights hat complement existing datasets, offering updated contemporary records in key transitional zones, especially in the northern and central Adriatic Sea, including Albania, Montenegro, and Croatia.

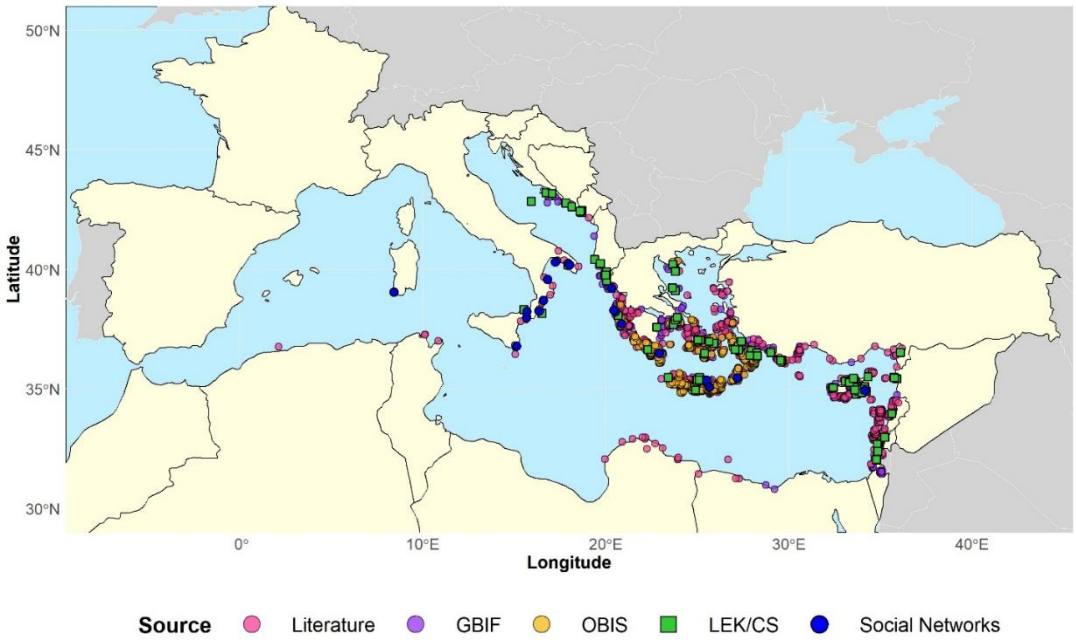

Fig. 10.12: Occurrences of the fish *Pterois miles* in the Mediterranean Sea. Different colors and markers highlight the source of the records.

10.5. DISCUSSION

This study aligns with a growing body of research that integrates information retrieved from traditional literature with modern, collaborative, and inclusive analytical approaches — most notably LEK and CS – and with emerging information sources such as social media data, an approach previously proven effective for tracking marine data in the Mediterranean (Giovos et al., 2019), which have only recently begun to be systematically employed in ecological research. Here, we

expand upon this framework by systematically applying it across multiple target species simultaneously to evaluate basin-wide patterns. The value of LEK in the Mediterranean context is widely demonstrated by recent studies (Azzurro et al., 2011, 2016, 2019; Barbato et al., 2021; Veneroni and Fernandes, 2021). Similarly, CS initiatives have been increasingly recognized as powerful tools to monitor biodiversity loss and habitat degradation in Mediterranean marine ecosystems (Bodilis et al., 2014; Bargnesi et al., 2020). However, such integrative approaches have generally been applied to single-species case studies, whereas the present analysis undertakes the more ambitious effort of extending this framework to multiple species simultaneously. This allows for direct comparison of outcomes across taxa and provides a broader perspective on ecological transformations and their potential drivers. Only after establishing this overarching rationale do we proceed to examine the specific differences and affinities among the data sources employed.

The contribution of each different source on the total number of occurrences for each species highlights different outcomes for each species.

While literature was the only reference until recently, it still plays a crucial role in collecting data on species distribution and occurrences representing the most important source, at least for some species, such as *A. monroviae* and *F. petimba*. Indeed, current research is widely focused on NIS trying to monitor their spreading and estimate their impact on native biota, especially for species that are perceived as threatening (Tarkan et al., 2021). On the other hand, for the other four investigated species distribution representation largely relies on other sources of information with only a lower number of occurrences reported by literature. The total trend highlights how online databases provide the most occurrences (53.54%) followed by literature, LEK/CS and social networks. Local Ecological Knowledge and Citizen Science are proven to be a necessary and effective tool, especially for easily recognizable species.

The predominance of occurrence records from the year 2000 onwards in this dataset is likely attributed to several synergistic factors. Over the last two decades, the scientific interest in biological invasions has grown exponentially as scientists have become more aware of the long-term ecological and economic effects of NIS (Pyšek et al., 2020; Ricciardi et al., 2017). Furthermore, the methodology of data collection has evolved; the formal integration of CS and LEK into biodiversity monitoring is a relatively recent development that has significantly boosted recording rates (Pocock et al., 2017). This shift is closely linked to the digital revolution: the ubiquity of smartphones and the rise of social media platforms have empowered non-experts

to document 'unusual' organisms. These platforms facilitate rapid expert identification and data sharing, effectively filling distributional gaps that traditional monitoring programs might miss (Daume; 2016).

Ocypode cursor, the only native thermophilic species analyzed, presents additional northernmost occurrence records in Liguria and Sardinia (September 2024) beyond its historically recognized distribution (Marchessaux et al., 2024; Báez et al., 2025). Local Ecological Knowledge and social media reports from the north western Mediterranean — e.g., the Tyrrhenian coast of Sicily, Sardinia and Liguria in 2024-2025 — indicate the presence of the ghost crab *O. cursor* in sectors characterized by lower average sea surface temperatures compared to its native Mediterranean range. This apparent contradiction suggests that the species' northward progression might not be driven solely by uniform basin-wide warming. Instead, it could be favored by the mitigation of extreme winter thermal minima in these northern sectors, or it may point toward a potential ecological plasticity and physiological adaptation of *O. cursor* to lower thermal regimes than previously documented. If substantiated, this complex dynamic would align with recent syntheses attributing the species' expansion to regional sea surface warming shifts, while highlighting that localized colonization might involve rapid adaptation processes consistent with earlier evidence of a rapid westward spread in the Mediterranean (Tiralongo et al., 2020). However, owing to the scantiness of such records, further research is needed to ascertain this spreading and to assess the ecological consequences of this expansion, including potential interactions with native coastal species.

Lamprohaminoea ovalis has a well-documented and seemingly rapid expansion in the Mediterranean in the last 20 years, with its first records in the Ligurian sea in 2021 (Azzola et al., 2022). Citizen-science and social media observations in the north western Mediterranean — particularly the Ligurian Sea and portions of the French coast (2021–2024) — may confirm the recent northward and westward expansion of *L. ovalis*. This is consistent with the first Ligurian record reported in 2022 and with a broader set of 13 new records documented across the Adriatic, Balearic, Ionian and Ligurian basins (2021–2024), as well as a westernmost Alboran Sea occurrence in autumn 2023. Recent analyses further corroborate this trend, linking the new northernmost and westernmost records of *L. ovalis* to documented increase in mean annual and minimum sea temperatures in the Ligurian and Provençal sectors during 2021–2024 (Azzola et al., 2025). Our findings, especially the ones coming from LEK and social networks relating to the last 5 years, provide new insights on the spread of this species, with many occurrences in the Ligurian Sea and in France, thus concentrated in northern regions.

Pterois miles, one of the most aggressively expanding alien species (Azzurro et al., 2017; Almabruk et al., 2020; Bottaccini et al., 2024), was initially restricted to the eastern Mediterranean. Social media and citizen-science reports provide new westernmost occurrence records for *P. miles*, filling historical distribution gaps and documenting its contemporary presence in some in the central sectors of the basin including Apulia, Calabria, the Strait of Messina and southern Sardinia. If confirmed, this trend could support the hypothesis that temperature anomalies are facilitating its invasion process—supported by recent ecological niche models under warming scenarios (Mitchell and Domínguez Almela, 2025) and field evidence of its expansion into lower-temperature waters (Bottaccini et al., 2024). Given the well-documented ecological impacts of lionfish in previously invaded areas (Kletou et al., 2016; 2022), its potential spreading would warrant proactive management strategies to mitigate consequences for native fish communities. Nevertheless, further targeted studies remain essential to fully understand and quantify the specific impacts of this invasion on Mediterranean biodiversity as the species moves westward (Bottaccini et al., 2024).

The distribution of *F. petimba* also raises concern about range shifts, particularly in light of new LEK reports from central Italy. While this species is traditionally associated with eastern Mediterranean waters (Stern et al., 2017; Papageorgiou et al., 2023), its presence in Campania, Apulia and Sicily may indicate dispersal events facilitated by warming sea surface temperatures. Despite sporadic records across the basin, it is still unclear whether these sightings represent established populations or isolated occurrences, highlighting a significant knowledge gap in its current expansion dynamics (Stern et al., 2017; Cerim et al., 2021; Ragheb, 2022). However, due to species misidentification risks, further confirmation is required to ensure that observations do not correspond to the congener F. commersoni.

The contribution of CS and LEK was evident across all target species, although the relative importance of these sources varied considerably in percentage terms. Interestingly, no clear relationship emerged between the degree of prior scientific documentation and the proportional contribution of LEK/CS records (calculated as the percentage of LEK/CS points relative to the total dataset of each species): both less-studied species (e.g., *A. monroviae*, *F. petimba*) and widely investigated taxa (e.g., *Pterois miles*) benefited from these complementary inputs. However, the data show that the results provided by LEK and CS are significantly higher for less-documented taxa. In some cases, LEK and CS reported occurrence records otherwise absent from formal datasets, while in others they contributed novel presence information from previously undocumented areas. Moreover, many of these records are among the most recent observations available, which may

represent preliminary evidence of ongoing range expansion—a hypothesis that warrants further verification and long-term monitoring. The reports from Greece, Malta and Croatia for *A. monroviae*, and central Italy for *F. petimba*, demonstrate that citizen science can give information about undocumented populations, underscoring the importance for future biodiversity monitoring initiatives. In this context, LEK has proven particularly effective in providing valuable observations for species not commonly monitored through conventional scientific methods, often compensating for the lack of formal data. This outcome highlights that for rare or understudied species, non-expert sightings are not merely supplementary but could represent a primary and essential source of information about the species presence. Although social network sources provided additional insights, their overall impact was more limited, reinforcing the central role of LEK in expanding species distribution records. Comparable evidence has been reported in the literature: for instance, fishermen' knowledge has been successfully used to reconstruct behavioral traits and conservation relevance of elasmobranchs in the Mediterranean (Barbato et al., 2021), to detect ecological decline across multiple taxa (Veneroni and Fernandes, 2021), and to assess risks for endangered large-bodied sharks (De Santis et al., 2025). Moreover, large-scale LEK initiatives have documented shifting distributions of Mediterranean fishes under climate change and biological invasions (Azzurro et al., 2019; Azzurro et al., 2024), highlighting the capacity of participatory knowledge to reveal range expansions and novel occurrences. These parallels reinforce the reliability of LEK as a complementary source of distributional data and suggest that the new records identified here may similarly reflect ongoing ecological transformations.

However, the accuracy of LEK data must be carefully evaluated, as certain species can be frequently misidentified in the field. For example, *O. patagonica* is occasionally confused with *C. caespitosa* (Linnaeus, 1758), a native Mediterranean coral, while *F. petimba* can be mistaken for *Fistularia commersonii* (Rüppel, 1838), a much more common and widespread NIS in the Mediterranean. When photographic evidence is lacking, verification challenges arise, requiring researchers to critically assess LEK reports before integrating them into formal distribution models. Hence, the high importance of these data for rare and understudied species calls for increased rigor in the validation process to ensure scientific accuracy. A standard approach that harmonizes data gathering and validation protocols is essential, as it enables researchers to fully employ the wide potential of LEK biodiversity monitoring.

Our multi source synthesis indicates the recent geographical records we document largely fall within the last two decades. This chronological pattern aligns with the

principal temporal coverage of our datasets (2000–2025) and with a well documented increase in Mediterranean Sea surface temperatures (SST), potentially suggesting climate-driven distribution shifts that would, however, require dedicated spatial analyses to be formally confirmed. This concordance strengthens the ecological plausibility that warming has facilitated the establishment and spread of thermophilic and NIS species now reported in previously cooler sectors (e.g., Ligurian–Provençal areas. To ensure a robust baseline, historical occurrence records from earlier decades were also incorporated, allowing us to contextualize recent sightings against the long-term warming trends documented in the region (Pisano et al., 2020; Garrabou et al., 2022). At the same time, the inclusion of LEK and CS has proven pivotal: these sources contributed recent, geographically complementary records—often supported by photographs—that fill gaps left by literature and global databases, particularly for under monitored taxa (Azzurro et al., 2019; Deidun et al., 2021). Notably, several of the northernmost and westernmost observations in our dataset derive from LEK/CS and social media, suggesting ongoing acclimatization and potential westward/northward expansion for specific taxa, while recognizing the need for continued validation and long term monitoring (Bottaccini et al., 2024; Poursanidis et al., 2022). Nevertheless, we caution that misidentification risk persists for look alike species (e.g., *O. patagonica* vs. *C. caespitosa*; *F. petimba* vs. *F. commersonii*), and that spatial blind spots may reflect uneven research capacity across countries. Consequently, the most robust interpretation is that integrated, participatory data streams—anchored to a climate relevant timeframe—could provide timely signals of distributional change that merit targeted surveys and model refinement to disentangle climate driven processes from introduction pathways and sampling bias.

This study underscores the importance of integrating multiple data sources—traditional literature, online biodiversity databases (GBIF, OBIS), LEK, CS, and social networks—to refine our understanding of species distributions. While databases offer valuable baselines, they often suffer from regional biases and gaps, especially for under-monitored species. Such gaps may arise because certain taxa are perceived as less economically relevant, less charismatic, or not associated with evident deleterious ecological effects or health riskes, leading to limited monitoring efforts compared to commercially important or conservation-priority species (e.g., large pelagic fishes, marine mammals). LEK and CS effectively help cover these spatial and temporal gaps, offering real-time, localized observations that complement traditional monitoring networks.

Despite sustained efforts to broaden participation through LEK and CS, substantial geographic blind spots persist—particularly in regions with limited research

infrastructure or lower socio-economic capacity—because biodiversity information is unevenly generated and shared across space, taxa, and communities. Global syntheses show that open biodiversity datasets (e.g., GBIF/OBIS) remain strongly biased toward high income countries and accessible locations (near roads, cities, shipping routes), leaving data poor but biodiversity rich areas underrepresented and constraining robust trend detection (Amano et al., 2021; Hughes et al., 2021). While participatory monitoring increases data volume and reach, it can replicate or introduce new biases (e.g., taxonomic and spatial skew, observer expertise, lack of absence and effort metadata), with contributions disproportionately concentrated in certain nations and taxa, and a marked underrepresentation of marine groups and invertebrates (Mandeville et al., 2023; Della Rocca et al., 2024). These imbalances have socio-political roots and macroeconomic correlates, shaping which regions and communities are “seen” by conservation science. Recent analyses demonstrate that data richness hotspots align with wealth and historical inequalities, reinforcing inequities in decision making unless explicitly corrected (Doll, 2025; Caldwell et al., 2024). Accordingly, addressing blind spots requires not only methodological innovation (e.g., semi-structured CS protocols, modeling effort and preferential sampling, integrating eDNA and standardized surveys) but also sustained capacity building investments and governance solutions to mobilize marine and coastal data where gaps are largest (Arazy and Malkinson, 2021; Tang et al., 2021; OBIS GBIF Joint Strategy, 2024). In this light, LEK/CS contributions in our dataset should be interpreted as timely, complementary signals rather than comprehensive baselines, and their integration with targeted sampling, training, and node level support (GBIF/OBIS) remains essential to reduce spatial biases and ensure that ecological knowledge is not constrained by national disparities in research output. Addressing these imbalances requires both methodological innovation—through inclusive approaches such as LEK and CS—and structural investment in capacity building to ensure that ecological knowledge is not constrained by national disparities in research output.

Given the rigorous selection and data extraction protocol applied in this study (see Materials and Methods), any potential residual redundancy within the final dataset is heavily minimized and considered negligible. Consequently, these minor overlapping residues are extremely limited and do not affect the overall reliability, geographical proportionality, or biological validity of the discussion.

In practical terms, this integrated approach has substantially increased occurrence data and refined species range delineation, providing a robust basis for targeted surveys and the exploration of correlations between distributional shifts and climatic trends, such as the sea-surface temperature anomalies detected by Copernicus.

This progress aligns with findings from analogous studies (Azzurro et al., 2019; Maggio et al., 2022; Perizia et al., 2023), which highlight shared operational challenges—including misidentification and the need for photographic validation—thereby reinforcing the necessity for standardized LEK protocols and hybrid monitoring frameworks.

The innovation introduced lies particularly in the valorization of non-conventional sources, such as local ecological knowledge and data derived from social media, which have been treated with equal dignity compared to academic and institutional sources. This approach has revealed how such contributions can enrich the information framework, while requiring more rigorous validation protocols. Moreover, the transformation of raw data into percentage impacts has made comparisons between sources more immediate, providing a useful tool to guide research and management priorities.

The results of this study support the evidence of the climate change actively reshaping Mediterranean biodiversity, facilitating the expansion of thermophilic and non-indigenous species into new habitats as also remarked by numerous recent papers among which Bindoff et al. (2019).

The Mediterranean remains an ever-changing ecosystem, continuously influenced by environmental shifts and anthropogenic pressures. Tracking biodiversity through a combination of interdisciplinary methodologies—integrating traditional scientific research with citizen science and LEK—will be fundamental to safeguarding marine communities and ensuring informed, proactive conservation efforts in the years to come.

10.6. REFERENCE LIST

Albano, P. G., Schultz, L., Wessely, J., Taviani, M., Dullinger, S., and Danise, S., 2024. The dawn of the tropical Atlantic invasion into the Mediterranean Sea. *Proceedings of the National Academy of Sciences*, 121(15), e2320687121.

Almabruk, S.A., Rizgalla, J., Giovos, I. and Bariche, M., 2020. Social media reveals the first records of the invasive lionfish *Pterois miles* (Bennett, 1828) and parrotfish *Scarus ghobban* Forsskål, 1775 from Egypt (Mediterranean Sea). *BioInvasions Records*, 9(3), pp.574-579. https://doi.org/10.3391/bir.2020.9.3.13

Amano, T., Lamming, J.D. and Sutherland, W.J., 2016. Spatial gaps in global biodiversity information and the role of citizen science. *Bioscience*, 66(5), pp.393-400. https://doi.org/10.1093/biosci/biw022

Arazy, O. and Malkinson, D., 2021. A framework of observer-based biases in citizen science biodiversity monitoring: Semi-structuring unstructured biodiversity monitoring protocols. *Frontiers in Ecology and Evolution*, 9, p.693602. https://doi.org/10.3389/fevo.2021.693602

Aurelle, D., Thomas, S., Albert, C., Bally, M., Bondeau, A., Boudouresque, C.F., Cahill, A.E., Carlotti, F., Chenuil, A., Cramer, W. and Davi, H., 2022. Biodiversity, climate change, and adaptation in the Mediterranean. *Ecosphere*, 13(4), p.e3915. https://doi.org/10.1002/ecs2.3915

Azzola, A., Merotto, L., Solca, M., Trainito, E., Enrichetti, F., Montefalcone, M. and Furfaro, G., 2025. Conquering the north: the recent expansion of a Lessepsian sea slug in the north-western Mediterranean Sea as a mirror of seawater warming. *BioInvasions Records*, 14(4), pp.953-968. https://doi.org/10.3391/bir.2025.14.4.16

Azzola, A., Furfaro, G., Trainito, E., Doneddu, M. and Montefalcone, M., 2022. Seawater warming favours the northward range expansion of Lessepsian species in the Mediterranean Sea: the cephalaspidean *Lamprohaminoea ovalis*. *Journal of the Marine Biological Association of the United Kingdom*, 102(3-4), pp.167-173.

Azzurro, E. and D'Amen, M., 2022. Climate change paves the way for a new inter-ocean fish interchange. *Frontiers in Ecology and the Environment*, 20(10), pp.558-563. https://doi.org/10.1002/fee.2459

Azzurro, E., D'Amen, M., Chiappi, M., Ferri, F., Grifoni, P., Napoli, E., Luna, G.M., Strafella, P., Smeraldo, S. and Biancone, N., 2024. ORMEF: a geospatial web platform for mapping and visualizing exotic fish records in the Mediterranean and

surrounding seas. *Management of Biological Invasions*, 15(4), pp.601-616. https://doi.org/10.3391/mbi.2024.15.4.09

Azzurro, E., Sbragaglia, V., Cerri, J., Bariche, M., Bolognini, L., Ben Souissi, J., Busoni, G., Coco, S., Chryssanthi, A., Fanelli, E. and Ghanem, R., Garrabou , J., Gianni, F., Grati, G., Kolitari, J., Letterio, G., Lipej, L., Mazzoldi, C., Milone, N., Pannacciulli, F., Pešić, A., Samuel-Rhoads, Y., Saponari, L., Tomanic, J., Topçu, N. E., Vargiu, G., Moschella, P., 2019. Climate change, biological invasions, and the shifting distribution of Mediterranean fishes: A large-scale survey based on local ecological knowledge. *Global Change Biology*, 25(8), pp.2779-2792. https://doi.org/10.1111/gcb.

Azzurro, E., Stancanelli, B., Di Martino, V. and Bariche, M., 2017. Range expansion of the common lionfish *Pterois miles* (Bennett, 1828) in the Mediterranean Sea: an unwanted new guest for Italian waters. *BioInvasions Records*, 6(2), pp.95-98. https://doi.org/10.3391/bir.2017.6.2.01

Azzurro, E., Moschella, P. and Maynou, F., 2011. Tracking signals of change in Mediterranean fish diversity based on local ecological knowledge. *PLOS One*, 6(9), p.e24885. https://doi.org/10.1371/journal.pone.0024885

Baez, J.C., Akyol, O., Azzurro, E., Battaglia, P., Belmonte-Gallegos, A., Christidis, G., Crocetta, F., Dalyan, C., Gönül, Y., Grati, F. and Greco, S., 2025. New records of rarely reported species in the Mediterranean Sea (March 2025). *Mediterranean Marine Science*, 26(1), pp.256-276. https://doi.org/10.12681/mms.40675

Barbato, M., Barria, C., Bellodi, A., Bonomi, S., Borme, D., Cetkovic, I., Colloca, F., Colmenero, A.I., Crocetta, F., De Carlo, F. and Demir, E., 2021. The use of fishers' Local Ecological Knowledge to reconstruct fish behavioral traits and fishers' perception of conservation relevance of elasmobranchs in the Mediterranean Sea. *Mediterranean Marine Science*, 22(3), pp.603-622. https://dx.doi.org/10.12681/mms.25306

Bargnesi, F., Lucrezi, S. and Ferretti, F., 2020. Opportunities from citizen science for shark conservation, with a focus on the Mediterranean Sea. *The European Zoological Journal*, 87(1), pp.20-34. https://doi.org/10.1080/24750263.2019.1709574

Bastari, A., Mascarell, Y., Ortega, M. and Coll, M., 2022. Local fishers experience can contribute to a better knowledge of marine resources in the Western Mediterranean Sea. *Fisheries Research*, 248, p.106222. https://doi.org/10.1016/j.fishres.2021.106222

Bélisle, A.C., Asselin, H., LeBlanc, P. and Gauthier, S., 2018. Local knowledge in ecological modeling. *Ecology and Society*, 23(2), 14. https://www.jstor.org/stable/26799118

Bianchi, C.N., 2007. Biodiversity issues for the forthcoming tropical Mediterranean Sea. *Hydrobiologia*, 580(1), pp.7-21.

Bindoff, N.L., Cheung, W.W., Kairo, J.G., Arístegui, J., Guinder, V.A., Hallberg, R., Hilmi, N., Jiao, N., Karim, S., Levin, L. and O'Dongue, S., 2019. Changing ocean, marine ecosystems, and dependent communities. https://doi.org/10.1017/9781009157964

Bindoff, N.L., Cheung, W.W.L., Kairo, J.G., Arístegui, J., Guinder, V.A., Hallberg, R., Hilmi, N., Jiao, N., Karim M.S., Levin, L., O'Donoghue, S., Purca Cuicapusa, S.R., Rinkevich, B., Suga, T., Tagliabue, A. and Williamson, P. 2022. Changing ocean, marine ecosystems, and dependent communities. In Pörtner, H.-O. et al. (Eds) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate Cambridge University Press, Cambridge, UK and New York, NY, USA, (2019) pp. 447-587. https://doi.org/10.1017/9781009157964.007.

Bodilis, P., Louisy, P., Draman, M., Arceo, H.O. and Francour, P., 2014. Can citizen science survey non-indigenous fish species in the eastern Mediterranean Sea? *Environmental Management*, 53(1), pp.172-180. https://doi.org/10.1007/s00267-013-0171-0

Boero, F., Féral, J.P., Azzurro, E., Cardin, V., Riedel, B., Despalatovic, M., Munda, I., Moschella, P., Zaouali, J., Fonda Umani, S., Theocharis, A., Wiltshire, K. and Briand, F., 2008. I–Executive Summary of CIESM workshop climate warming and related changes in Mediterranean marine biota. In CIESM workshop monographs (Vol. 35, pp. 5-21). Bd de Suisse Monaco.

Bonebrake, T.C., Brown, C.J., Bell, J.D., Blanchard, J.L., Chauvenet, A., Champion, C., Chen, I.C., Clark, T.D., Colwell, R.K., Danielsen, F. Dell, A.I., Donelson, J.M., Evengård, B., Ferrier, S., Frusher, S., Garcia, R.A., Griffis, R.B., Hobday, A.J., Jarzyna, M.A., Lee, E., Lenoir, J., Linnetved, H., Martin, V.Y., Mccormack, P.C., Mcdonald, J., Mcdonald-Madden, E., Mitchell, N., Mustonen, T., Pandolfi, J.M., Pettorelli, N., Possingham, H., Pulsifer, P., Reynolds, M., Scheffers, B.R., Sorte, C.J.B., Strugnell, J.M., Tuanmu, M.N., Twiname, S., Vergés, A., Villanueva, C., Wapstra, E., Wernberg, T. and Pecl, G.T., 2018. Managing consequences of climate-driven species redistribution requires integration of ecology, conservation and social science. *Biological Reviews*, 93(1), pp.284-305. https://doi.org/10.1111/brv.12344

Bonn, A., Brink, W., Hecker, S., Herrmann, T.M., Liedtke, C., Premke-Kraus, M., Voigt-Heucke, S., Gönner, J.V., Altmann, C., Bauhus, W. and Bengtsson, L., Brandt, M., Bruckermann, T., Büermann, A., Dietrich, P., Dörler, D., Eich-Brod, R., Eichinger, M., Ferschinger, L., Freyberg, L., Grützner, A., Hammel, G., Heigl, F., Heyen, N. B., Hölker, F., Johannsen, C., Kiefer, S., Klan, F., Kluß, T., Kluttig, T., Knapp, V., Knobloch, J., Koop, M., Lorke, J., Munke, M., Mortega, K. G., Pathe, C., Richter, A., Schumann, A., Soßdorf, A., Stämpfli, T., Sturm, U., Thiel, C., Tönsmann, S., van den Bogaert, V., Valentin, A., Wagenknecht, K., Wegener, R., Woll, S., 2022. White paper citizen science strategy 2030 for Germany. Helmholtz Association, Leibniz Association, Fraunhofer Society, universities and non-academic institutions, Leipzig, Berlin. https://doi.org/10.5281/zenodo.7117771.

Bottacini, D., Pollux, B.J., Nijland, R., Jansen, P.A., Naguib, M. and Kotrschal, A., 2024. Lionfish (*Pterois miles*) in the Mediterranean Sea: a review of the available knowledge with an update on the invasion front. *NeoBiota*, 92, pp.233-257. https://doi.org/10.3897/neobiota.92.110442

Brierley, A.S. and Kingsford, M.J., 2009. Impacts of climate change on marine organisms and ecosystems. *Current Biology*, 19(14), pp.R602-R614. https://doi.org/10.1016/j.cub.2009.05.046

Caldwell, I.R., Hobbs, J.P.A., Bowen, B.W., Cowman, P.F., DiBattista, J.D., Whitney, J.L., Ahti, P.A., Belderok, R., Canfield, S., Coleman, R.R. Iacchei, M., Johnston, E.C., Knapp, I., Nalley, E.M., Staeudle, T.M., Làruson, A.J., 2024. Global trends and biases in biodiversity conservation research. *Cell Reports Sustainability,* 1(5), p.100082. https://doi.org/10.1016/j.crsus.2024.100082

Cárdenas, S., Berastegui, D.A. and Ortiz, J., 1997. First record of *Fistularia petimba* Lacepéde, 1803 (Pisces, Fistulariidae) off the coast of Cadiz (southern Iberian Peninsula). *Boletín Instituto Español de Oceanografía*, 13(1), pp.83-86.

Cerim, H., Yapıcı, S., Gülşahin, A., Soykan, O. and Bilge, G., 2021. The first record of the red Cornetfısh (*Fistularia petimba* Lacepède, 1803) in the Aegean Sea*. Duzce University Journal of Science and Technology*, 9(2), pp.607-615.

Cooley, S., Schoeman, D., Bopp, L., Boyd, P., Donner, S., Kiessling, W., Martinetto, P., Ojea, E., Racault, M.F., Rost, B. and Skern-Mauritzen, M., 2023. Oceans and coastal ecosystems and their services. In Pörtner H.-O. et al. (Eds) Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change []. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 379–550, https://doi.org/10.1017/9781009325844.005

Coppari, M., Roveta, C., Di Camillo, C., Garrabou, J., Lucrezi, S., Pulido Mantas, T., and Cerrano, C., 2024. The pillars of the sea: strategies to achieve successful marine citizen science programs in the Mediterranean area. *Ecology and Evolution,* 24(1), 100.

Crespo, J., Rey, J.C. and Garcia, A., 1987. Primera cita de *Acanthurus monrovae* Steindachner, 1876 y de *Diodon eydouxii* Brissout de Barneville, 1846 para la ictioma europea. *Miscellània Zoològica*, 11, pp.271-275.

Daume, S., 2016. Mining Twitter to monitor invasive alien species — An analytical framework and sample information topologies. *Ecological Informatics*, 31, pp.70-82.

Deidun, A., Insacco, G., Galdies, J., Balistreri, P. and Zava, B., 2021. Tapping into hard-to-get information: the contribution of citizen science campaigns for updating knowledge on range-expanding, introduced and rare native marine species in the Malta-Sicily Channel. *BioInvasions Records*, 10(2), pp.257-269. https://doi.org/10.%0b3391/bir.2021.10.2.03

Deidun, A., Crocetta, F., Sciberras, A., Sciberras, J., Insacco, G. and Zava, B., 2017. The protected taxon *Ocypode cursor* (Linnaeus, 1758)(Crustacea: Decapoda: Ocypodidae)–documenting its well-established presence in the central Mediterranean. *The European Zoological Journal*, 84(1), pp.96-103. https://doi.org/10.1080/11250003.2017.1281355

Della Rocca, F., Musiani, M., Galaverni, M. and Milanesi, P., 2024. Improving online citizen science platforms for biodiversity monitoring. *Journal of Biogeography*, 51(12), pp.2412-2423. https://doi.org/10.1111/jbi.15000

delle Chiaie, S., 1828. Memorie sulla storia e notomia degli animali senza vertebre del regno di Napoli (Vol. 3). Dalla stamperia della Sociéta tipografica.

De Santis, L.J., Bonanomi, S., Li Veli, D., Bottaro, M. and Lucchetti, A., 2025. Fishers' knowledge and risk assessment: a combined approach to studying endangered large-bodied sharks in the central Mediterranean. *Reviews in Fish Biology and Fisheries*, 35(2), pp.733-753.

Doll, P.C., 2025. Addressing disparities in global biodiversity data: Conservation. *Nature Reviews Biodiversity*, 1(8), pp.495-495. https://doi.org/10.1038/s44358-025-00072-7

Dulčić, J., Ugarković, P., Miočić-Stošić, J., and Tutman, P., 2025. First record of the Monrovia doctorfish *Acanthurus monroviae* Steindachner, 1876 (Perciformes:

Acanthuridae) in the Adriatic Sea (Croatian waters). *BioInvasions Records*, 14(2), pp.449-456. https://doi.org/10.3391/bir.2025.14.2.12

Evans, J., Tonna, R. and Schembri, P.J., 2017. A bevy of surgeons: first record of *Acanthurus chirurgus* (Bloch, 1787) from the central Mediterranean, with notes on other Acanthuridae recorded in the region. *BioInvasions Records*, 6(2), pp.105-109. https://doi.org/10.3391/bir.2017.6.2.03

Fianchini, M., 2025. Towards an integrated ecological modelling framework to assess the risk of Alien Species spread in the Mediterranean Sea: *Caulerpa cylindracea* as a case study. PhD thesis, University of Trieste.

Finger, L., van den Bogaert, V., Schmidt, L., Fleischer, J., Stadtler, M., Sommer, K. and Wirth, J., 2023, August. The science of citizen science: a systematic literature review on educational and scientific outcomes. *Frontiers in Education,* 8, p. 1226529.

Fraisl, D., Haklay, M., Hager, G., When, U., See, L., Hecker, S., Tzovaras, B. G., Gold, M., Ceccaroni, L., Kieslinger, B., Woods, S., Nold, C., Balázs, B., Mazzonetto, M., Rüfenacht, S., Shanley, L. A., Motion, A., Sforzi, A., Dörler, D., Heigl, F, Vohland, K., Wagenknecht, K., Schaefer, T., Riemenschneider, D., Lindner, A.B., Weißpflug, M., Mačiulienė, M., 2026. Delineating the contours of citizen science: Development of the ECSA characteristics of citizen science. *Open Research Europe*, *5*, 128. https://doi.org/10.12688/openreseurope.19411.4

Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., Hallett, J.G., Eisenberg, C., Guariguata, M.R., Liu, J. and Hua, F., 2019. International principles and standards for the practice of ecological restoration. *Restoration Ecology*. 27(S1), pp.S1-S46.

Garcia-Bustos, V., 2025, Conservation attitudes and perceived biodiversity among divers on the 201panish mediterranean coast: insights from local ecological knowledge. *Oceans*, 6 (1), 4. https://doi.org/10.3390/oceans6010004

Garrabou, J., Gómez-Gras, D., Medrano, A., Cerrano, C., Ponti, M., Schlegel, R., Bensoussan, N., Turicchia, E., Sini, M., Gerovasileiou, V. and Teixido, N., 2022. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Global Change Biology*, 28(19), pp.5708-5725. https://doi.org/10.1111/gcb.16301

Garrabou, J., Coma, R., Bensoussan, N., Bally, M., Chevaldonné, P., Cigliano, M., Díaz, D., Harmelin, J.G., Gambi, M.C., Kersting, D.K. and Ledoux, J.B., 2009. Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the

2003 heat wave. *Global Change Biology*, 15(5), pp.1090-1103. https://doi.org/10.1111/j.1365-2486.2008.01823.x

Giangrande, A., Pierri, C., Del Pasqua, M., Gravili, C., Gambi, M.C. and Gravina, M.F., 2020. The Mediterranean in check: Biological invasions in a changing sea. *Marine Ecology*, 41(2), p.e12583. https://doi.org/10.1111/maec.12583

Gitay, A. and Glazer, A., 1979. Biological fouling in Israel power stations and in a proposed intersea conduit. *Israel Journal of Zoology*, 28(1), p.61.

Giovos, I., Stoilas, V. O., Al-Mabruk, S. A., Doumpas, N., Marakis, P., Maximiadi, M., Moutopoulos, D., Kleitou, P., Tiralongo, F., de Maddalena, A., 2019. Integrating local ecological knowledge, citizen science and long-term historical data for endangered species conservation: Additional records of angel sharks (Chondrichthyes: Squatinidae) in the Mediterranean Sea. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 29(6), 881-890. https://doi.org/10.1002/aqc.3089

Golani, D. and Sonin, O., 1992. New records of the Red Sea fishes, *Pterois miles* (Scorpaenidae) and *Pteragogus pelycus* (Labridae) from the eastern Mediterranean Sea. *Japanese Journal of Ichthyology*, 39(2), pp.167-169.

Haklay, M., Dörler, D., Heigl, Dörler, D., Heigl, F.,Manzoni, M., Hecker, S., Vohland, K., 2021. What is citizen science? The challenges of definition. In Vohland, K.,Land-Zandstra, A., Ceccaroni, L., Lemmens, R., Perellò, J., Ponti, M., Samson, R. and Wagenknecht, K., 2021.. The science of citizen science, 13(1), pp.34-51. https://doi.org/10.1007/978-3-030-58278-4

Harris, L.G. and Tyrrell, M.C., 2001. Changing community states in the Gulf of Maine: synergism between invaders, overfishing and climate change. *Biological Invasions*, 3(1), pp.9-21. https://doi.org/10.1023/A:1011487219735

Harvell, C.D., Kim, K., Burkholder, J.M., Colwell, R.R., Epstein, P.R., Grimes, D.J., Hofmann, E.E., Lipp, E.K., Osterhaus, A.D.M.E., Overstreet, R.M. and Porter, J.W., 1999. Emerging marine diseases—climate links and anthropogenic factors. *Science*, 285(5433), pp.1505-1510.

Hijmans, R.J., 2018. Raster: Geographic data analysis and modeling. R package version, 2, p.8. https://rspatial.org/raster/

Hijmans, R.J., Phillips, S., Leathwick, J. and Elith, J., 2010. Dismo: Species distribution modeling. CRAN: Contributed Packages. https://cran.r-project.org/web/packages/dismo/index.html

Hughes, A.C., Orr, M.C., Ma, K., Costello, M.J., Waller, J., Provoost, P., Yang, Q., Zhu, C. and Qiao, H., 2021. Sampling biases shape our view of the natural world. *Ecography*, 44(9), pp.1259-1269. https://doi.org/10.1111/ecog.05926

Kleitou, P., Moutopoulos, D.K., Giovos, I., Kletou, D., Savva, I., Cai, L.L., Hall-Spencer, J.M., Charitou, A., Elia, M., Katselis, G. and Rees, S., 2022. Conflicting interests and growing importance of non-indigenous species in commercial and recreational fisheries of the Mediterranean Sea. *Fisheries Management and Ecology*, 29(2), pp.169-182. https://doi.org/10.1111/fme.12531

Kleitou, P., Hall-Spencer, J.M., Savva, I., Kletou, D., Hadjistylli, M., Azzurro, E., Katsanevakis, S., Antoniou, C., Hadjioannou, L., Chartosia, N. and Christou, M., 2021. The case of lionfish (*Pterois miles*) in the Mediterranean Sea demonstrates limitations in EU legislation to address marine biological invasions. *Journal of Marine Science and Engineering*, 9(3), p.325. https://doi.org/10.1186/s41200-016-0065-y

Kletou, D., Hall-Spencer, J.M. and Kleitou, P., 2016. A lionfish (*Pterois miles*) invasion has begun in the Mediterranean Sea. *Marine Biodiversity Records*, 9(1), p.46.

Maggio, T., Perzia, P., Falautano, M., Visconti, G. and Castriota, L., 2022. From LEK to LAB: The case of the blue crab *Portunus segnis* in the Pelagie Islands Marine Protected Area, central Mediterranean Sea. *Ocean & Coastal Management*, 219, p.106043. https://doi.org/10.1016/j.ocecoaman.2022.106043

Mancinelli, G., Belmonte, F., Carlino, P., Potenza, L. and Belmonte, G., 2019. The tufted ghost crab *Ocypode cursor* in the Mediterranean Sea: an updated overview of its distribution. In 54th European Marine Biology Simposium Book of Abstract.

Mandeville, C.P., Nilsen, E.B., Herfindal, I. and Finstad, A.G., 2023. Participatory monitoring drives biodiversity knowledge in global protected areas. *Communications Earth & Environment*, 4(1), p.240. https://doi.org/10.1038/s43247-023-00906-2

Marchessaux, G., Gjoni, V., Tantillo, M.F., Bejean, T. and Sarà, G., 2024. The expansion of the Atlantic–Mediterranean ghost crab *Ocypode cursor* (Linnaeus, 1758): Distribution, environmental niches and future perspectives. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 34(3), p.e4119. https://doi.org/10.1002/aqc.4119

Marchini, A., Ferrario, J. And Minchin, D., 2015. Marinas may act as hubs for the spread of the pseudo-indigenous bryozoan *Amathia verticillata* (Delle Chiaje, 1822) and its associates. *Scientia Marina*, 79(3), pp.355-365.

Massicotte, P., South, A. and Hufkens, K., 2023. Rnaturalearth: World map data from natural earth. R package version, 1(1).

Mitchell, E. and Dominguez Almela, V., 2025. Modelling the rise of invasive lionfish in the Mediterranean. *Marine Biology*, 172(1), p.18. https://doi.org/10.1007/s00227-024-04580-6

Molinari, A., Bavestrello, G., Canessa, M., Cosma, A., 2026. Co-Occurrence of Shallow Scleractinians *Cladocora caespitosa* (Linnaeus, 1767) and *Oculina patagonica* De Angelis D'Ossat, 1908 in the Ligurian Sea. *Water*, 18(9), 998.

Moullec, F., Barrier, N., Guilhaumon, F., Peck, M.A., Ulses, C. and Shin, Y.J., 2023. Rebuilding Mediterranean marine resources under climate change. *Marine Ecology Progress Series*, 708, pp.1-20. https://doi.org/10.3354/meps14269

Noto, L.V., Cipolla, G., Pumo, D. and Francipane, A., 2023. Climate change in the Mediterranean Basin (Part II): a review of challenges and uncertainties in climate change modeling and impact analyses. *Water Resources Management*, 37(6), pp.2307-2323. https://doi.org/10.1007/s11269-023-03444-w

OBIS & GBIF (2024) OBIS-GBIF 2024 Joint Action Plan for Marine Biodiversity Data. Copenhagen: GBIF Secretariat. https://doi.org/10.35035/doc-e52v-5875

Occhipinti-Ambrogi, A. and Galil, B., 2010. Marine alien species as an aspect of global change. *Advances in Oceanography and Limnology*, 1(1), pp.199-218. https://doi.org/10.1080/19475721003743876

Papageorgiou, M., Resaikos, V. and Petrou, A., 2023. A preliminary assessment of *Fistularia petimba* (Lacepède, 1803) migration in the Mediterranean Sea: historical and new data from Cyprus (Levantine Sea) with biological notes. *Mediterranean Marine Science*, 24(2), pp.446-453. https://doi.org/10.12681/mms.29027

Pebesma, E. and Bivand, R., 2023. Spatial data science: with applications in R. Chapman and Hall/CRC.

Perzia, P., Cillari, T., Crociata, G., Deidun, A., Falautano, M., Franzitta, G., Galdies, J., Maggio, T., Vivona, P. and Castriota, L., 2023. Using local ecological knowledge to search for non-native species in Natura 2000 sites in the central Mediterranean Sea: An approach to identify new arrivals and hotspot areas. *Biology*, 12(9), p.1158. https://doi.org/10.3390/biology12091158

Pisano, A., Marullo, S., Artale, V., Falcini, F., Yang, C., Leonelli, F.E., Santoleri, R. and Buongiorno Nardelli, B., 2020. New evidence of Mediterranean climate change

and variability from sea surface temperature observations. *Remote Sensing*, 12(1), p.132. https://doi.org/10.3390/rs12010132

Pistevos, J.C.A., Zenetos, A., Stranga, Y., Teaca, A., Begun, T., Trkov, D., Langeneck, J., Muresan, M., Comas-González, R., Sempere-Valverde, J., Toso, A., Chebaane, S., Navarro-Barranco, C., Rosso, A., Png-Gonzalez, L., Giakoumi, S., Vázquez-Luis, M., Cañizares-González, J.M., Siddiolo, C., Donato, G.M.E., Giacobbe, S., Carbonell, A., Zakhama-Sraieb, R., Di Martino, E., Ammar, I.A., Cosentino, A., Mnasri Afifi, I., Sanfilippo, R., Bitar, G., Kytinou, E., Tari, G., Huseyinoglu, M.F., Gerakaris, V., Issaris, Y., Polytimi-Ioli Lardi, Oikonomidis, G., Salomidi, M., Tsirintanis, K., Kleitou, P., Constantinou, G., Michail, C., Bariche, M., Deidun, A., Marrone, A., Ragkousis, M., Falautano, M., Castriota, L., Morri, C., Bianchi, C.N., Skouradakis, G., Fiona Tomas Nash, Digenis, M., Mancini, E., Stefanova, E.S., Vella, A., Vella, N., Vasileva Mihneva, V., Papadimitriou, E., Skolka, M., Stefanova, K., Fortič, A., Garcia, M., Dailianis, T., Tamburello, L., Victor Surugiu[37], Stancanelli, B., Di Martino, V., Bosmali, A., Mavrič, B., Gerovasileiou, V., Kletou, D., Crocetta, F., Rallis, J., Evans, J., Altamirano Jeschke, M., Leda Liyue Cai, Taşkın, E., Franzitta, G., Ramzi Sghaier, Y., Kennedy, A., Bartolo, A.G., Küpper, F.C., Rousou, M., Víctor Orenes-Salazar, Bonifazi, A., Hadjioannou, L., Vlantaridis, Z., El Shaer, H., Mülkibar Çiftçioğlu, Cerim, H., Lipej, L., Grech, D., Zotou, M., Azzurro, E., Schembri, P.J., Tiralongo, F., Chatzigeorgiou, G., Di Lorenzo, M., Vigo Fernandez, M., Di Franco, A., Orlando-Bonaca, M, Calò, A., Malefaki, C., García-Charton, J.A., Papadakis, O., Yapıcı, S., Tanduo, V., D'Aniello, I., Munari, M., Kampouris, T.E., Putignano, M., Virgili, R., Agius Darmanin, S., Bilgiç, F., Sardo, G., Calabrò, M., Nikolaou, T., Erga, Z., Zogheib, A., Balistreri, P., Çağlar, S., Yalgın, F., Osca, D., Gratsia, E., Aglieri, G., Çinar, M.E., Mutalipassi, M., Coco, S., Gkoulia, A., Ramos-Esplá, A.A., Mannino, A.M., Dimichele, D., Spinelli, S., Arroyo Martínez, E., Tursi, A., Capasso, A., Borut Mavrič, Christidis, G., Solca, M., Rifi, M., Radhouan Belgacem El Zrelli, Ramla Bouhlel, Scalera, R., Bandi, A., Reboa, A., Mazaris, A., Bazairi, H., Bertolino, M., Selfati, M., Sirchia, B., Georgiadis, C.G., Petricioli, D., Macaluso, E., D'aniello, E., Fotiadis, N., Tezel, R., Slavica Petović, Bakran-Petricioli, T., Pitacco, V., Colletti, A., Bensari, B., Bahbah, L., D'aniello, S., Psailas, S., Kalogirou, S., Kaikai, T., Forcada, A., Manfredonia, A., Bottalico, A., Valle, C., Bedoret, C., Damalas, D., Sacco, D., Mollo, E., Iatrou, F., Cerqueira, F., Viard, F., Villani, G., Foulquié, M., Geraci, M.C., Šiško, M., Ocaña, O., Renaud Dupuy De La Grandrive, Vitale, S., Rossi, T., Samaha, Z., Aguilar, R., Alvarez, H., Menabit, S., Pavel, A.B., Azzola, A., Bos, A.R., Anastasiadis, A., Blanco, J., Lejeusne, C., Coppola, D., Davoult, D., Faget, D., Scannella, D., Keppel, E., Falsone, F., Fortunato Palma Esposito, García, S., Furfaro, G., Zibrowius, H., Iziani, I., Anastasopoulou, I.,

Kavakakis, K., Scavino, L., Merotto, L., Yankova, M., Montefalcone, M., Leban, N., Ungaro, N., Mariottini, P., Perry, A.L., Stavrou, P., Mazzella, V., Raykov, V., Ferrario, J., Stamouli, C., Siapatis, A., Vernadou, E. and Katsanevakis, S. 2026. Unpublished Mediterranean and Black Sea records of marine alien, cryptogenic, and neonative species. *BioInvasions Records*, 15 (in press).

Pocock, M.J., Tweddle, J.C., Savage, J., Robinson, L.D. and Roy, H.E., 2017. The diversity and evolution of ecological and environmental citizen science. *PLOS One*, 12(4), p.e0172579.

Poursanidis, D., Kougioumoutzis, K., Minasidis, V., Chartosia, N., Kletou, D. and Kalogirou, S., 2022. Uncertainty in marine species distribution modelling: trying to locate invasion hotspots for *Pterois miles* in the eastern mediterranean sea. *Journal of Marine Science and Engineering*, 10(6), p.729. https://doi.org/10.3390/jmse10060729

Provoost, P., Bosch, S. and Appeltans, W., 2022. Robis: Ocean Biodiversity Information System (OBIS) client. R package version, 2(3), p.9, https://CRAN.R-project.org/package=robis.

Pyšek, P., Hulme, P.E., Simberloff, D., Bacher, S., Blackburn, T.M., Carlton, J.T., Dawson, W., Essl, F., Foxcroft, L.C., Genovesi, P. and Jeschke, J.M., 2020. Scientists' warning on invasive alien species. *Biological Reviews*, 95(6), pp.1511-1534.

Ragheb, E., 2022. Morphometric and meristic characteristics of the first record *Fistularia petimba* (Lacepède, 1803) and *Fistularia commersonii* (Rüppell, 1838)(Piscès: Fistulariidae) from the Egyptian Mediterranean waters (West Alexandria). *Egyptian Journal of Aquatic Research*, 48(2), pp.143-150. https://doi.org/10.1016/j.ejar.2022.01.003

Raitsos, D.E., Beaugrand, G., Georgopoulos, D., Zenetos, A., Pancucci-Papadopoulou, A.M., Theocharis, A. and Papathanassiou, E., 2010. Global climate change amplifies the entry of tropical species into the Eastern Mediterranean Sea. *Limnology and Oceanography*, 55(4), pp.1478-1484. https://doi.org/10.4319/lo.2010.55.4.1478

Ricciardi, A., Blackburn, T.M., Carlton, J.T., Dick, J.T., Hulme, P.E., Iacarella, J.C., Jeschke, J.M., Liebhold, A.M., Lockwood, J.L., MacIsaac, H.J. and Pyšek, P., 2017. Invasion science: a horizon scan of emerging challenges and opportunities. *Trends in Ecology & Evolution*, 32(6), pp.464-474. https://doi.org/10.1016/j.crsus.2024.100082

Rivetti, I., Fraschetti, S., Lionello, P., Zambianchi, E. and Boero, F., 2014. Global warming and mass mortalities of benthic invertebrates in the Mediterranean Sea. *PLOS One*, 9(12), p.e115655. https://doi.org/10.1371/journal.pone.0115655

Rosenzweig, C., Casassa, G., Karoly, D.J., Imeson, A., Liu, C., Menzel, A., Rawlins, S., Root, T.L., Seguin, B., Tryjanowski, P. and Parry, M.L., 2007. Assessment of observed changes and responses in natural and managed systems. In Parry, M.L., Canziani, O.F., Palutikof, J.P., Van der Linden, P.J. and Hanson, C.E., . (Eds) Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, UK: Cambridge University Press, 79-131.

Serrano, E., Coma, R., Ribes, M., Weitzmann, B., Garcia, M. and Ballesteros, E., 2013. Rapid northward spread of a zooxanthellate coral enhanced by artificial structures and sea warming in the western Mediterranean. *PLOS One*, 8(1), p.e52739. https://doi.org/10.1371/journal.pone.0052739

Silva Lima, da J.A., Junqueira, A.B., de Oliveira, J.G.C., Mazzochini, G.G., de Oliveira Santos, A.P., de Oliveira Estevo, M., Batista, V.S. and Campos-Silva, J.V., 2025. Fishers' local ecological knowledge provides valuable insights into the impacts of environmental changes on coastal fishing resources. *Proceedings of the Royal Society B: Biological Sciences*, 292(2058): 20251836. https://doi.org/10.1098/rspb.2025.1836

Stern, N.I.R., Paz, G.U.Y., Yudkovsky, Y., Lubinevsky, H. and Rinkevich, B., 2017. The arrival of a second 'Lessepsian sprinter'? A first record of the red cornetfish *Fistularia petimba* in the Eastern Mediterranean. *Mediterranean Marine Science*, 18(3), pp.524-528. https://doi.org/10.12681/mms.14144

Tang, B., Clark, J.S. and Gelfand, A.E., 2021. Modeling spatially biased citizen science effort through the eBird database. *Environmental and Ecological Statistics*, 28(3), pp.609-630. https://doi.org/10.1007/s10651-021-00508-1

Tarkan, A.S., Tricarico, E., Vilizzi, L., Bilge, G., Ekmekçi, F.G., Filiz, H., Giannetto, D., İlhan, A., Killi, N., Kirankaya, Ş.G. and Koutsikos, N., 2021. Risk of invasiveness of non-native aquatic species in the eastern Mediterranean region under current and projected climate conditions. *The European Zoological Journal*, 88(1), pp.1130-1143. https://doi.org/10.1080/24750263.2021.1980624

Tiralongo, F., Messina, G., Marino, S., Bellomo, S., Vanadia, A., Borzì, L., Tibullo, D., Di Stefano, A. and Lombardo, B.M., 2020. Abundance, distribution and ecology of the tufted ghost crab *Ocypode cursor* (Linnaeus, 1758)(Crustacea: Ocypodidae)

from a recently colonized urban sandy beach, and new records from Sicily (central Mediterranean Sea). *Journal of Sea Research*, 156, p.101832. https://doi.org/10.1016/j.seares.2019.101832

Veneroni, B. and Fernandes, P.G., 2021. Fishers' knowledge detects ecological decay in the Mediterranean Sea. *Ambio*, 50(6), pp.1159-1171. https://doi.org/10.1007/s13280-020-01452-3

Weatherdon, L.V., Magnan, A.K., Rogers, A.D., Sumaila, U.R. and Cheung, W.W., 2016. Observed and projected impacts of climate change on marine fisheries, aquaculture, coastal tourism, and human health: an update. *Frontiers in Marine Science*, 3, p.48. https://doi.org/10.3389/fmars.2016.00048

Wickham, H., 2025. Bryan J. readxl: Read excel files. R package version 1.4. 3. 2023 [online]

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L.D.A., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J. and Kuhn, M., 2019. Welcome to the Tidyverse. *Journal of Open Source Software*, 4(43), p.1686. https://doi.org/10.21105/joss.01686

Wickham, H., 2016. Ggplot2. Elegant graphics for data analysis. Springer Nature, pp.260. https://link.springer.com/book/10.1007/978-3-319-24277-4

Zenetos, A., Gofas, S., Russo, G. and Templado, J., 2003. List of Exotic Molluscs Species in the Mediterranean. Volume 3. Molluscs. CIESM ATLAS of exotic species in the Mediterranean. http://www.ciesm.org/atlas/

Zibrowius H. 1974. *Oculina patagonica*, Scléractiniaire hermatypique introduit en Méditerranée. *Helgolander Wiss. Meeresunters*, 26, pp.153-173. https://doi.org/10.1007/BF01611381

Chapter 11



The Multisource Database

Note: A minor structural distinction should be highlighted regarding the categorization of global repositories across different sections of this thesis. In contrast to Chapter 10, where the unified database structure and final metadata tables group GBIF and OBIS records into a single combined category, this chapter treats the two repositories as separate entities. This choice stems from a fundamental difference in how the data are visualized. In Chapter 10, every target species is paired with a distribution map where data points from the two different sources are color-coded, making them instantly identifiable both geographically and numerically. However, since the comprehensive table in Chapter 11 encompasses several species that are not visually represented through maps, maintaining GBIF and OBIS as standalone columns was necessary to preserve data granularity and ensure unambiguous traceability for all listed taxa.

11 The Multisource Database

11.1. Introduction

The architectural framework of this research is rooted in the critical need to address the geographical and temporal gaps regarding traditional scientific literature and its limitations. To overcome these constraints, a multisource approach was adopted, integrating bibliographic data with other information streams, including institutional databases such as GBIF and OBIS, Local Ecological Knowledge (LEK), Citizen Science (CS), and Social Network data. In the present chapter we extended to a discrete number of species the multisource approach first applied to only some iconic species (see Chapter 10: Siddiolo et al., in press). As demonstrated in that paper, this synergy of sources aims to build a comprehensive and high-resolution database for each of the selected species, providing a solid baseline for mapping the rapid biogeographical changes in their current distribution in the Mediterranean basin.

11.2. Materials and Methods

The methodological core of this research is a multisource integration approach, designed to summaryze different information streams into a unified biogeographical framework (see Chapters 2 and 10). Rather than relying on a single data source, this strategy harmonizes bibliographic records with Local Ecological Knowledge (LEK), Citizen Science (CS), and Digital Mining (Social Media and online databases such as GBIF and OBIS). This synergy allows for a comprehensive assessment of Mediterranean biological shifts, capturing both established trends and emerging "early warning" signals.

The complete database, which represents the baseline for this thesis, is available in the Supplementary Materials (https://doi.org/10.5281/zenodo.18554596). For each taxon, a specific reference date is indicated, marking the formal conclusion of the data collection phase. This date primarily corresponds to the final systematic access to global repositories such as GBIF and OBIS. While the bibliographic research aimed to align strictly with these temporal boundaries to maintain consistency, a dynamic update protocol was applied: the literature review was extended whenever highly relevant or

groundbreaking studies were published prior to the finalization of the thesis.

Given the extensive number of species included in the database - many of which are subjects of intense scientific production - achieving a 100% exhaustive coverage of all existing literature is an inherent challenge. Nevertheless, a rigorous effort was made to reach the highest possible level of bibliographic saturation. A thorough review of scientific publications was carried out using SCOPUS, Google Scholar, and ResearchGate. Using keywords such as 'distribution', 'Mediterranean', and 'occurrence' for each species ensured a broad retrieval of relevant studies. This approach enabled the collection of historical and peer-reviewed accounts of species presence in various regions. This research focused on prioritizing primary records, first occurrences, and significant range expansions to ensure that the dataset provides a highly accurate and representative reflection of each species' current distribution and ecological status in the Mediterranean basin.

11.3. STRUCTURAL ANALYSIS OF THE MULTISOURCE DATABASE

The development of the multisource database resulted in the collection of a total of 49.890 occurrence records for the selected target species. This significant data volume is the concrete outcome of a methodological strategy designed to overcome the structural limitations of conventional monitoring systems, thereby enhancing scientific suitability to the rapid biogeographical change currently affecting the Mediterranean Sea. The structure of the dataset reflects a robust integration of heterogeneous data streams:

Indexed Literature: With 6.647 records, peer-reviewed literature offers the necessary scientific context to calibrate and ground-truth more recent observations.
Online Repositories: The largest percentage of data is obtained from the GBIF (25.064 records) and OBIS (17.625 records) databases, which provide most of the historical and validated backbone of the database.
Local Ecological Knowledge and Citizen Science (LEK/CS): Provided 353 records, highlighting the importance of the experience of professional stakeholders, such as fishermen and divers. These data are crucial in providing a long-term temporal perspective and detecting rare or cryptic species that are often underrepresented in standardized surveys.

Social Networks Data: With 201 records, the monitoring of digital platforms enabled the acquisition of real-time georeferenced data on a basin scale. This source proved particularly effective for "charismatic" and easily detectable species.

Species	Literature	gbif	OBIS	LEK/CS	Social Networks	TOTAL
Amphistegina lobifera	51	10	30	0	0	91
Amathia gracilis	26	2	1	0	0	29
Amathia gracillima	4	0	0	0	0	4
Amathia verticillata	201	289	7	39	1	537
Bugula neritina	97	332	21	0	0	450
Bugulina stolonifera	16	76	10	0	0	102
Tricellaria inopinata	65	56	2	0	0	123
Cassiopea andromeda	151	16	111	3	3	284
Cladocora caespitosa	43	2850	1472	0	0	4365
Eunicella cavolini	256	6127	1556	0	3	7942
Eunicella verrucosa	19	475	347	0	0	841
Paramuricea clavata	203	6258	1915	0	12	8388
Oculina patagonica	185	477	1	54	0	717
Lamprohaminoea ovalis	70	41	0	42	16	169
Pinctada radiata	414	261	217	1	1	894
Callinectes sapidus	514	1618	417	14	19	2582
Ocypode cursor	47	393	4	26	34	504
Percnon gibbesi	450	866	482	46	27	1871
Portunus segnis	394	14	24	0	4	436
Acanthurus monroviae	31	1	0	6	0	38
Aetomylaeus bovinus	33	64	26	0	16	139
Fistularia petimba	73	6	1	39	0	119
Lagocephalus sceleratus	195	96	326	4	4	625
Pomadasys incisus	30	358	98	0	23	509
Pterois miles	1820	868	528	82	20	3318
Seriola fasciata	19	5	2	0	6	32
Siganus luridus	543	1237	1053	6	10	2849
Siganus rivulatus	640	595	7661	0	0	8896
Sparisoma cretense	57	1673	1314	0	22	3066
TOTAL	6647	25064	17625	353	201	49890

Table 11.1: Total number of records for each of the target species, divided by source.

Table 11.1 summaryzes the distribution of records for each target species across the considered sources, establishing the analytical baseline for the distributional patterns discussed in subsequent sections.

11.4. Main results and comments on Native Thermophilic Species

The most substantial volume of data within the native group corresponds to Anthozoans, specifically long-lived gorgonians and scleractinian corals. While these records allow for the construction of a high-resolution map of species presence, it is important to emphasize that distribution data alone do not necessarily reflect the health status or physiological condition of the individuals or the associated benthic communities: *Paramuricea clavata* (8,388 records), *Eunicella cavolini* (7,942 records), and *Cladocora caespitosa* (4,365 records) represent the most record-dense taxa in the database, with most of the records obtained from online sources such as GBIF and OBIS. *Eunicella verrucosa* (841 records) further strengthens the baseline for understanding the current distribution of native gorgonians across the basin.

Species such as the bull ray *Aetomylaeus bovinus* (139 records) and the ghost crab *Ocypode cursor* (504 records) exhibit low sighting frequencies in formal scientific literature. For this reason, every validated report becomes fundamental. The contribution of Social Networks (16 records for *A. bovinus* and 34 for *O. cursor*) is crucial for mapping their distribution and identifying new occurrence sites that might otherwise remain undocumented for years, especially considering that they are both underrepresented in literature (Baéz et al., 2025). The parrotfish *Sparisoma cretense* (3,066 records) and the bastard grunt *Pomadasys incisus* (509 records) show a significant presence in the database. While both species are mostly represented in online databases, *P. incisus* benefits from 23 social network reports.

To better understand the importance of a multisource approach, the distribution map of *A. bovinus* and *P. incisus* are displayed in Fig. 11.1 and 11.2. Although *A. bovinus* exhibits low sighting frequencies in formal scientific literature, the multisource dataset reveals a broad distribution, particularly within the western Mediterranean. A key finding emerging from the multisource approach is the remarkably low spatial overlap among data sources and their high geographical complementarity. Rather than providing redundant information, each source contributed unique occurrence records from different sectors of the Mediterranean, substantially expanding the overall known distribution of *Aetomylaeus bovinus*. This result highlights the added

value of integrating heterogeneous data streams, because reliance on any single source would have produced a markedly incomplete representation of the species' distributionLiterature records are primarily localized in Turkey, the Central Adriatic, and Southern Italy. Conversely, GBIF data are concentrated along the coasts of Spain, France, northern Italy, and the Northern Adriatic. This demonstrate as the contribution of Social Networks is crucial for filling geographical gaps in Italy, Spain, and Croatia, while OBIS provides essential complementary data for Tunisia, Turkey, Croatia, and Spain. This mosaic of records shows that for rare megafauna like the bull ray, every validated report - regardless of the source - is fundamental for mapping a distribution that would otherwise remain fragmented and partially documented for years.

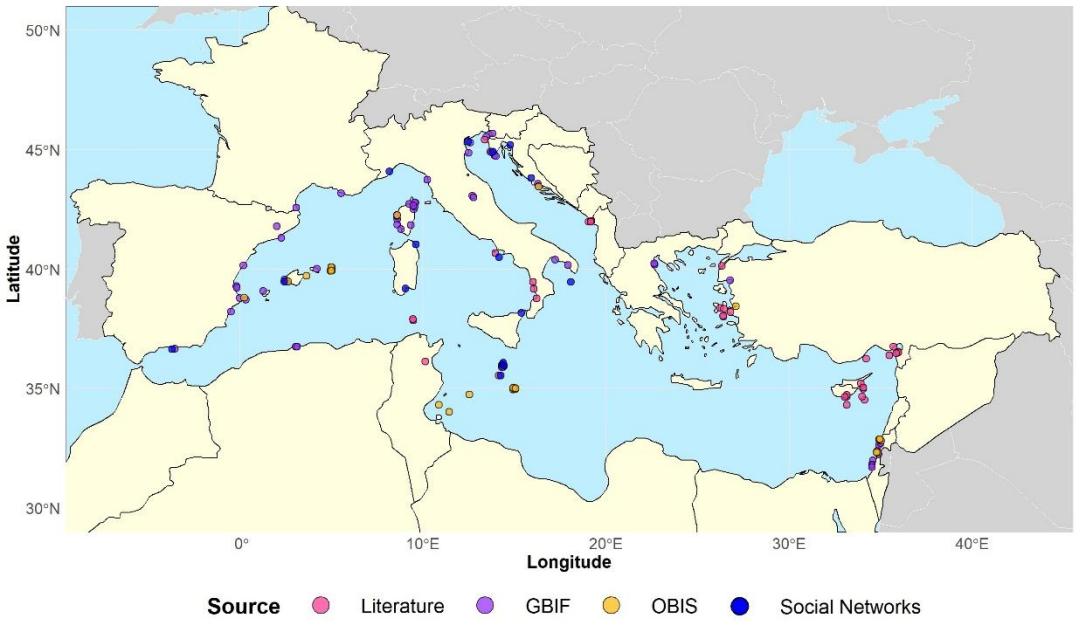

Figure 11.1: Distribution map of *Aetomylaeus bovinus* in the Mediterranean.

The distribution of the bastard grunt (*P. incisus*) shows an equally coherent pattern of source-driven complementarity. While the species is widespread across the Western Mediterranean, several occurrences are reported for the eastern basin.

Literature reports cover a wide range, including Morocco, Italy, Croatia, Greece, and sporadic sightings in Egypt and Lebanon. GBIF data shows a high density of records almost exclusively clustered along the Spanish and French coasts and North-Central Italy, with only occasional reports in the Levantine Sea (Greece, Turkey, and Egypt). OBIS further enriches the dataset with significant records in France and Greece, while providing data for Algeria, Tunisia, and Israel. Finally, the Social Network reports complete the spatial framework by documenting the species' presence along the Italian Tyrrhenian coast, Southern Italy, Tyrrhenian Sicily, and the Ionian Sea.

In these cases, the integration of unconventional sources is particularly significant for species that are traditionally underreported in standardized surveys.

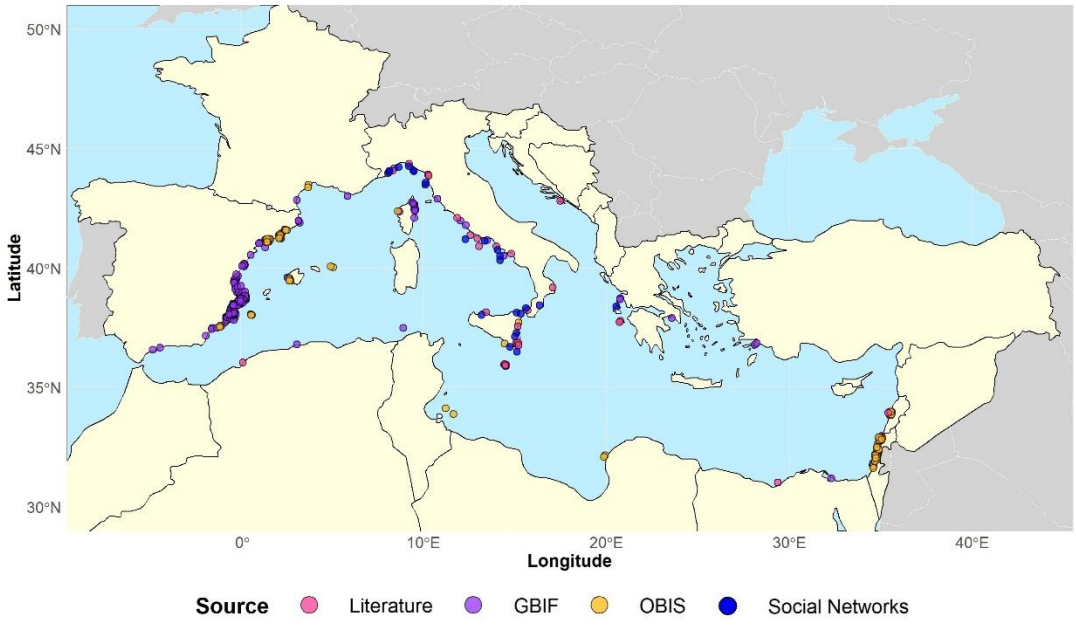

Figure 11.2: Distribution map of *Pomadasys incisus* in the Mediterranean.

11.5. Main results and comments on NIS and Cryptogenic Species

The database provides a high number of records for non-indigenous taxa, highlighting their successful colonization of Mediterranean potential new ranges.

This group benefits significantly from the integration of participatory sources, which often track the high-velocity spread of these organisms more effectively than traditional surveys, especially when large-sized or iconic taxa are involved.

Siganus rivulatus (8,896 records) and *Siganus luridus* (2,849 records) are the most abundant NIS fish in the database. Notably, *S. rivulatus* shows a massive concentration of data within the OBIS node (7,661 records), indicating a well-documented presence in online databases. The lionfish *Pterois miles* (3,318 records) has the highest number of records in indexed literature (1,820). Additionally, the 82 records from LEK/CS and 20 from Social Networks underscore its charismatic nature, making it a primary target for citizen science reporting. The Atlantic blue crab *Callinectes sapidus* (2,582 records) and the blue swimming crab *Portunus segnis* (436 records) are key indicators of active invasion fronts. For *C. sapidus*, the synergy between GBIF (1,618 records) and participatory data (33 records combined from LEK and Social) has been essential for mapping its rapid expansion into coastal lagoons and estuaries.

The dataset includes the cryptogenic, *Bugula neritina* (450 records), and the NIS bryozoan (also recently included within cryptogenics) *Amathia verticillata* (537 records). While these are largely represented in GBIF, the inclusion of 39 LEK/CS records for *A. verticillata* demonstrates the value of stakeholder observations for macro-epibionts. For microscopic and less visible taxa, the targeted sampling of floating plastics was instrumental in expanding their known Mediterranean range. This is evidenced by the records for *Tricellaria inopinata* (123 records), *Bugulina stolonifera* (102 records), *Amathia gracilis* (29 records) and *Amathia gracillima* (4 records). Despite being less "charismatic" than fish, these species show a notable presence in the literature (65 records for *T. inopinata* and 26 for *A. gracilis*). Other species such as *Amphistegina lobifera* (91 records) further illustrate the diversity of the dataset, where data from OBIS (30 records) and GBIF (10 records) are complemented by 51 records from indexed literature (Guastella et al., 2023, and references therein).

11.6. Discussion

The results presented in this chapter demonstrate that the integration of heterogeneous data sources is not merely a quantitative exercise but a qualitative tool for modern Mediterranean biogeography. The only caveat is that data originating from non-traditional sources must be opportunely verified by expert taxonomists. However, the global decline in taxonomic expertise represents an important challenge for the long-term validation of these expanding data streams. To counter

this trend, there is an urgent need for institutional support to ensure academic turnover and a substantial increase in professional taxonomist positions. This highlights the need for collaborative validation networks, increased use of photographic evidence, and the development of complementary digital tools capable of supporting, although not replacing, expert taxonomic assessment. By aggregating 49,890 records, this database provides a high-resolution snapshot of a basin in transition, effectively addressing the primary knowledge gaps identified in Chapter 2. The inclusion of 353 LEK/CS and 201 Social Network records was pivotal for mapping the peripheral edges of expansion for species like *Ocypode cursor* and *Aetomylaeus bovinus*, as shown in Fig. 11.1 and Fig. 10.8.

One of the most significant findings is the role of participatory data in reducing the temporal time lag between field observation and formal documentation. For invasive species such as *Pterois miles* and *Callinectes sapidus*, the continuous stream of data from fishers and digital platforms provided near real-time tracking of their ongoing range expansion and invasion fronts (Siddiolo et al., 2025a; Siddiolo et al. – in press). Furthermore, the implementation of expert validation and photographic identification – especially for data provided by social networks and LEK/CS – ensured that the inclusion of sources such as social media data did not compromise the dataset's scientific rigor. In the specific case of Anthozoans, the presence of photos in digital streams offered a unique additional advantage: photos may provide ecological information beyond simple species occurrence: while institutional databases typically store presence records and associated spatial coordinates, photographic evidence can offer a preliminary assessment of colony condition, including signs of bleaching, necrosis, or partial mortality. Consequently, these records may contribute not only to species distribution mapping but also to the early detection of ecological changes and health-related impacts that are generally not captured by traditional biodiversity catalogues. In fact, unlike literature records, which often represent a "frozen" moment in the past, the continuous flow of digital data allows for the verification of a species' persistence in a specific area. By comparing recent photographic evidence with historical records from the same general locality, it is possible to obtain a preliminary indication of changes in species occurrence, colony size and condition, or local abundance. Although precise relocation of the same colonies or organisms is often not feasible using LEK/CS records alone, these observations can provide timely information on emerging ecological changes and potential impacts. In other words, leveraging LEK and CS is akin to deploying widespread teams of witnesses constantly present across the territory. This approach effectively overcomes the inherent spatial and temporal limitations of traditional monitoring programs, which are strictly constrained by the

limited number of professional researchers (zoologists, botanists, and ecologists) available for field data collection. The possibility to document contemporary conditions at sites of known occurrence makes LEK an important complementary tool for tracking the effects of heatwaves, pollution, and other anthropogenic pressures, providing information that may become available more rapidly than through traditional monitoring programmes This ability to update the "present state" of a site makes LEK an essential tool for tracking the immediate impacts of heatwaves, pollution and other human activities providing a level of temporal resolution that traditional monitoring, often limited by funding and/or multi-year publication lags, cannot achieve.

In conclusion, the strategic involvement of participatory sources has transformed this database from a static historical collection into a possible continuously updated tool as new records become available. This evolved dataset provides the empirical foundation necessary for the Species Distribution Models (SDMs) analyzed in the previous chapters, offering a systemic perspective on the ecological reorganization triggered by the ongoing climate crisis.

11.7. REFERENCE LIST

Guastella, R., Evans, J., Mancin, N., Caruso, A. and Marchini, A., 2023. Assessing the effect of *Amphistegina lobifera* invasion on infralittoral benthic foraminiferal assemblages in the Sicily Channel (Central Mediterranean). *Marine Environmental Research*, 192, p.106247.

Siddiolo, C., Palummo, V., Milisenda, G., Pipitone, C., Rosso, A. and Chemello, R., 2025a. Assessing Habitat Suitability and Distribution Patterns of the Invasive Brachyuran Crabs Callinectes sapidus and Portunus segnis in the Mediterranean Basin. *Mediterranean Marine Science*, 26(3), 428-439. https://doi.org/10.12681/mms.38715

Siddiolo C., Chemello R. and Rosso A., 2026. Complementary Data Sources for Mapping Target Mediterranean Non-Native and Cryptogenic Species: The Role of Local Knowledge and Citizen Science *Regional Studies in Marine Science* (in press).

Chapter 12



Conclusions and Future Perspectives

12 Conclusions and Future Perspectives

12.1. Connecting Methodological Innovation and Ecological Findings

The primary objective of this doctoral research was to develop, test, and apply a multisource framework for improving the detection, monitoring, and interpretation of marine biodiversity changes in the Mediterranean Sea. The broader scientific ambition underlying this objective was to overcome the limitations of traditional monitoring approaches and explore how heterogeneous data sources can be integrated to capture the rapid ecological transformations currently affecting the basin. The Mediterranean Sea is currently a global "hotspot" for both climate change and biological invasions (Mannino et al., 2017). The results summarized in the Multisource Database (Chapter 11), including nearly 50,000 records, confirm that the "tropicalization" and "southernization" of the basin are no longer future projections but ongoing realities.

The integration of LEK, CS, and Social Media data extraction (Chapters 10 and 11) proved to be the crucial ingredient in overcoming the gaps given by traditional data gathering (Reyes-Garcia et al., 2020; Fraisl et al., 2022). While online databases like GBIF and OBIS provided the historical and current backbone of species occurrence data, participatory sources were capable of identifying emerging expansion fronts in near real-time, revealing previously undocumented occurrences, range-edge populations, and geographical areas that remain underrepresented in conventional monitoring programmes. This synergy was not just a data-gathering exercise; it was a fundamental shift in how we observe the sea, moving from a static and outdated approach to a dynamic, predictive monitoring system. Importantly, the operational relevance of this shift depends on its capacity to be embedded within existing and continuously maintained observation infrastructures. In this regard, the proposed framework is designed to be fully compatible with established marine data ecosystems, including global biodiversity repositories (e.g., GBIF, OBIS) and European marine monitoring infrastructures.

The adoption of interoperable data standards and reproducible analytical workflows ensures that both structured scientific datasets and unstructured participatory inputs (e.g., Local Ecological Knowledge, Citizen Science observations, and social media-derived records) can be systematically integrated and updated over time.

Rather than constituting an isolated analytical exercise, the framework is intended to function as an evolving monitoring layer that can be maintained through

institutional stewardship and sustained data streams. This includes potential integration with regional environmental agencies, research consortia, and operational programs supporting marine biodiversity assessment and climate change monitoring in the Mediterranean Basin.

In this perspective, sustainability is achieved not through the permanence of a single analytical implementation, but through the reproducibility of the workflow and its adaptability to continuously incoming heterogeneous data sources.

12.2. RANGE VARIATION AND MECHANISMS OF DISPERSAL

A significant section of this research was dedicated to understanding the mechanisms of dispersal, with a specific focus on the often-overlooked group of Bryozoans. This choice is directly aligned with the core ambition of the thesis, as Bryozoans represent an ecologically informative but frequently under-sampled taxonomic group, particularly sensitive to changes in environmental conditions and dispersal dynamics. Their life-history traits, including sessility and the capacity for both natural and anthropogenic dispersal, make them a relevant model for investigating early signals of biogeographical shifts.

Rather than constituting a taxon-specific deviation from the main framework, their inclusion serves as a targeted validation case for the proposed multisource monitoring approach, testing its effectiveness in detecting cryptic or underreported components of marine biodiversity change. In this way, the analysis of Bryozoans complements and strengthens the overarching objective of the thesis by demonstrating the applicability of the framework beyond well-studied and easily detectable taxa.

The discovery of *Microporella hastingsae* as a possible new Lessepsian migrant (Chapter 3; Rosso and Siddiolo, 2024) served as a preliminary indicator of how "invisible" species can spread over long distances exploiting anthropogenic waste for rafting wide Mediterranean sectors and possibly to become established far from their native ranges often unnoticed. This topic was further exploited in Chapter 4 (Rosso et al., 2025), where the analysis of stranded plastic debris concerning *M. hastingsae* and *M. browni*, provides empirical evidence that anthropogenic litter facilitates the passive westward transport of non-indigenous species. Furthermore, the taxonomic and ecological revision of the genus *Fenestrulina* (Chapter 5; Rosso et al., 2025) offered a critical counter-narrative. the presence of *F. communis* on drift debris underscores that dispersal potential is not the limiting factor for their

distribution, but rather the availability of suitable environmental "windows" for settlement.

12.3. Species Distribution Models (SDMs): Mapping Invasions and Climate-Driven Shifts

A key objective of this research was to translate static occurrence data into predictive insights. The implementation of Species Distribution Models (SDMs) using the MaxEnt model allowed for a quantitative assessment of habitat suitability for both invasive and native species under climate stress.

The taxonomic and ecological revision of the genus *Fenestrulina* (Chapter 5) provides a critical counter-narrative to the expansion of invaders. By noting the genus's absence in the warmer Levantine Sea, this study identifies Sea Surface Temperature (SST) as a hard physiological barrier for "cold-temperate" taxa. This establishes a baseline for monitoring the retreat of native species (Stuart-Smith et al., 2017) as thermal niches contract. Importantly, this perspective shifts the analytical focus from species introductions alone to a bidirectional understanding of biogeographic change, where both range expansions and range contractions are treated as complementary signals of ecosystem reorganization.

In this framework, the absence of cold-temperate taxa from increasingly warm regions such as the Levantine Basin is not interpreted as a static distributional gap, but as a dynamic indicator of ongoing thermal filtering processes and habitat suitability loss. As sea surface temperatures continue to rise, such baseline distributions become essential reference points for detecting early warning signals of biodiversity decline, particularly for taxa occupying the trailing edge of their climatic niches.

Therefore, the *Fenestrulina* case contributes not only to understanding physiological constraints on distribution, but also to establishing a methodological baseline against which future contraction patterns of native biodiversity can be quantitatively assessed.

The findings in Chapter 6 (Siddiolo et al., 2025a) represent the analytical climax of the multisource data strategy, shifting the focus from historical recording to spatial forecasting. By modeling the habitat suitability of *Callinectes sapidus* and *Portunus segnis*, this study provides the tentative evidence required to link the specific

environmental variables of climate change with the large-scale reorganization of Mediterranean biodiversity. Taken together, these results can be interpreted within a single unifying framework in which sea surface temperature acts as the primary structuring force of biogeographical change across taxa. Within this perspective, the patterns described in Chapter 1 and the “southernization” documented in Chapter 11 are not independent observations, but expressions of the same underlying process of thermal reconfiguration of the basin. This finding connects directly to the biogeographical patterns discussed in Chapter 1 and the "southernization" documented in Chapter 11. It suggests that the northern expansion of Lessepsian migrants is physically constrained by thermal thresholds and other environmental variables, which are currently being breached due to global warming (Khalil et al., 2025).

However, the Mediterranean's ecological reorganization follows a consistent thermal logic, regardless of whether the species is a recent invader or a long-standing native inhabitant. The transition from the modeling of invasive crabs (Chapter 6, Siddiolo et al., 2025a) to the study of the loggerhead sea turtle, *Caretta caretta* (Chapter 7) (Siddiolo et al., 2025b), highlights a fundamental shift in the basin's "habitability map." In Chapter 7, the Mean Temperature of the Coldest Quarter (Bio11) was identified as the most significant predictor for nesting suitability, contributing 89% to the model. This mirrors the findings in Chapter 6, where SST was the primary driver (64.6%) for the Lessepsian crab *P. segnis*. Beyond the taxonomic differences, this convergence highlights a consistent macroecological signal in which thermal constraints emerge as the dominant predictor of species redistribution across marine taxa in the Mediterranean Basin. While the crabs are guided by marine parameters, the sea turtle's northward shift is dictated by the thermal stability of the coastal environment. The comparison between the Copernicus (1979–2018) and WorldClim (1979–2000) datasets proves that as the "coldest quarter" becomes warmer, beaches along the Tyrrhenian coast of Sicily—previously unsuitable—have now crossed the thermal threshold for successful incubation.

From this integrated perspective, the northward shift observed across taxa emerges as a coherent macroecological response to the breakdown of historical thermal barriers, rather than as a set of independent species-specific phenomena.

The data synthesized in this thesis suggests that the "Northward Shift" is a cross-taxa phenomenon:

1. Invasive Pioneers: *Callinectes sapidus* exploiting warming northern lagoons (Chapter 6, Siddiolo et al., 2025a).

2. Native Expansion: *Caretta caretta* establishing regular nesting sites on Northern Sicilian and Tyrrhenian beaches (Chapter 7: Siddiolo et al., 2025b).
3. Thermophilic Colonizers: The ghost crab *Ocypode cursor* reaching Northern Sicily (Chapter 8: Pipitone and Siddiolo in: Báez et al. 2025), following a thermal pattern nearly identical to that of the loggerhead turtle.
4. Retreat of temperate species distribution from hottest south-eastern Mediterranean sectors (Chapter 5, Rosso et al. 2025).

Together, these processes indicate that “tropicalization” and “meridionalization” are not separate phenomena, but two complementary expressions of a single, basin-wide reorganization driven by the progressive erosion of historical thermal constraints.

12.4. New Framework for Mediterranean Marine Biodiversity Monitoring: Integrating Multi-source Data and Climate-Driven Patterns

The cumulative evidence introduced in this thesis leads to a fundamental conclusion: the Mediterranean Sea has entered a state of permanent ecological transition. The historical stability of Mediterranean biogeography is being replaced by a dynamic "shifting baseline," where the boundaries between native, neonative, and invasive species are increasingly blurred (Martìnez et al., 2023). However, this process should not be interpreted as a uniform or continuously accelerating transition. Instead, biogeographical change in the Mediterranean - particularly in highly dynamic regions such as the Levantine Basin - exhibits a non-linear structure characterized by alternating phases of rapid reorganization and periods of relative short-term stability (typically spanning 2–3 years).

Within this framework, the concept of a shifting baseline reflects not only long-term directional change, but also the episodic nature of ecological turnover, in which abrupt shifts (e.g., invasion pulses or range expansions) are interspersed with intervals of comparatively reduced compositional change.

In this context, the research demonstrates that traditional monitoring, while essential, is no longer sufficient when used in isolation to capture the full spatiotemporal complexity of contemporary biogeographical change. The success of this work lies in the conceptualization of a multisource "detecting network". By

treating Local Ecological Knowledge (LEK), Citizen Science (CS), and Social Media (Chapters 10, 11) as legitimate scientific sensors, we have moved beyond the gaps given by incomplete approaches.

A major contribution of this thesis is the transition from descriptive mapping to predictive and actionable science. The parallel application of Species Distribution Models (SDMs) to both high-impact invaders (*C. sapidus*, *P. segnis* - Chapter 6) and protected megafauna (*C. caretta* - Chapter 7) reveals a shared climate-driven logic (Turan, 2020; Solanou et al., 2023).

In conclusion, the Mediterranean "tropicalization" and "southernization" are complex, multi-scale processes that require an adaptive scientific approach. We have shown that the arrival of a microscopic bryozoan on a piece of plastic (Chapter 4) and the relocation of the nest of a 100 kg sea turtle (Chapter 7) are symptoms of the same global phenomenon: the breach of the Mediterranean's historical thermal barriers. The pattern proposed here - integrating multisource data, predictive modeling, and vector analysis - provides a strong framework for the future of Mediterranean marine research.

However, the utility of these high-resolution maps and databases extends far beyond academic interest. They are designed as strategic decision-support tools for stakeholders and policymakers. In an era where climate change keeps outpacing traditional legislative updates, the dynamic distribution maps generated in this study offer empirical evidence to support applied marine management.

The potential implementation of these tools, however, must be contextualized within existing legal, administrative, and institutional frameworks, which operate on time scales that are often slower and more discontinuous than ecological change itself. As a result, their adoption is expected to follow a phased trajectory rather than an immediate operational transition.

- **Short-term (1–2 years):** primary use within research environments and pilot initiatives, including EU-funded projects and collaborations between academic institutions and environmental agencies, where SDM outputs and multisource datasets can be tested as experimental decision-support tools.
- **Medium-term (3–5 years):** partial integration into regional monitoring and advisory systems, such as Marine Protected Areas and national environmental agencies. However, implementation is likely to remain heterogeneous, depending on institutional capacity, data interoperability, and governance priorities.

- **Long-term (EU program scale, >5 years):** potential incorporation into structured policy cycles such as the Marine Strategy Framework Directive (MSFD) and Natura 2000 adaptive management processes, where dynamic biodiversity models may contribute to periodic revisions of conservation planning.

Within this framework, examples of partial success (e.g., increasing use of citizen science data in biodiversity monitoring), structural limitations (slow uptake of predictive models in spatial planning), and persistent gaps between early warning signals and policy response illustrate the uneven nature of science-to-policy translation in marine ecosystems.

- **Implement Adaptive Conservation:** informing the redesign of Marine Protected Areas (MPAs) and Natura 2000 sites to include emerging "climate shelters" and new nesting fronts (Albano et al., 2026).
- **Guide Socio-Economic Planning:** assisting local authorities and the fishing industry in managing the expansion of invasive species (e.g., blue crabs) or the protection of flagship species that drive eco-tourism.
- **Support Transnational Biosecurity:** providing a standardized dataset that can be integrated into European and Mediterranean-wide directives for more effective coastal management.

To safeguard the ecological integrity and the socio-economic stability of the basin, we must embrace a science that is as interconnected, transnational, and rapid as the changes we are witnessing. The "new" Mediterranean is already here; our monitoring systems—and the policies that rely on them—must now evolve to meet it. Crucially, such evolution must occur on very short time scales, often shorter than standard political and administrative decision-making cycles. This implies that the challenge is not only technological or scientific, but also institutional, requiring a level of responsiveness that exceeds the temporal horizon of typical political mandates and governance structures.

In this sense, the main constraint to adaptation lies not in the absence of knowledge, but in the speed at which such knowledge can be translated into actionable policy within existing institutional frameworks.

12.5. REFERENCE LIST

Albano, P.G., Noè, S., Steger, J., Bussard, S., Chiappi, M., Huseyinoglu, M.F., Papatheodoulou, M., Resaikos, V., Hua, Q., Kaufman, D.S. and Olivé, I., 2026. Upwelling generates a unique refugium from climate change in the fast warming Eastern Mediterranean Sea. *Biodiversity and Conservation*, *35*(1), p.32. https://doi.org/10.1007/s10531-025-03228-1

Fraisl, D., Hager, G., Bedessem, B., Gold, M., Hsing, P.Y., Danielsen, F., Hitchcock, C.B., Hulbert, J.M., Piera, J., Spiers, H. and Thiel, M., 2022. Citizen science in environmental and ecological sciences. *Nature reviews methods primers*, *2*(1), p.64.

Khalil, M.T., Mostafa, A.B. and El-Naggar, M.M., 2025. Climate Change and Lessepsian Migration to the Mediterranean Sea. In *Climate Changes Impacts on Aquatic Environment: Assessment, Adaptation, Mitigation, and Road Map for Sustainable Development* (pp. 85-118). Cham: Springer Nature Switzerland.

Mannino, A.M., Balistreri, P. and Deidun, A., 2017. The marine biodiversity of the Mediterranean Sea in a changing climate: the impact of biological invasions. *Mediterranean identities-environment, society, culture*, pp.101-127.

Martínez, J., Leonelli, F.E., García-Ladona, E., Garrabou, J., Kersting, D.K., Bensoussan, N. and Pisano, A., 2023. Evolution of marine heatwaves in warming seas: the Mediterranean Sea case study. *Frontiers in Marine Science*, *10*, p.1193164.

Pipitone, C. and Siddiolo, C., 2025. First record of the tufted ghost crab *Ocypode cursor* in northern Sicily (Tyrrhenian Sea). In Báez, J.C., Akyol, O., Azzurro, E., Battaglia, P., Belmonte-Gallegos, A., Christidis, G., Crocetta, F., Dalyan, C., Gönül, Y., Grati, F., Greco, S., Gubili C., Kesici, N.B., Lipej, L., Mancini, E., Mavrič, B., Orenes-Salazar, V., Ortega Ceacero, J.A., Pipitone, C., Poursanidis, D., Romeo, T., Sánchez- Tocino, L., Siddiolo C., Skarvelis, K., Spinelli, A., Tanduo, V., Tiralongo, F., Trkov, D., Ünal, V., Yücedağ Bakir, E. and Zamuda, L.L. 2025. New records of rarely reported species in the Mediterranean Sea (March 2025). *Mediterranean Marine Science*, 26(1), 256–276. https://doi.org/10.12681/mms.40675.

Pistevos, J.C.A., Zenetos, A., Stranga, Y., Teaca, A., Begun, T., Trkov, D., Langeneck, J., Muresan, M., Comas-González, R., Sempere-Valverde, J., Toso, A., Chebaane, S., Navarro-Barranco, C., Rosso, A., Png-Gonzalez, L., Giakoumi, S., Vázquez-Luis, M., Cañizares-González, J.M., Siddiolo, C., Donato, G.M.E., Giacobbe, S., Carbonell, A., Zakhama-Sraieb, R., Di Martino, E., Ammar, I.A., Cosentino, A., Mnasri Afifi, I., Sanfilippo, R., Bitar, G., Kytinou, E., Tari, G.,

Huseyinoglu, M.F., Gerakaris, V., Issaris, Y., Polytimi-Ioli Lardi, Oikonomidis, G., Salomidi, M., Tsirintanis, K., Kleitou, P., Constantinou, G., Michail, C., Bariche, M., Deidun, A., Marrone, A., Ragkousis, M., Falautano, M., Castriota, L., Morri, C., Bianchi, C.N., Skouradakis, G., Fiona Tomas Nash, Digenis, M., Mancini, E., Stefanova, E.S., Vella, A., Vella, N., Vasileva Mihneva, V., Papadimitriou, E., Skolka, M., Stefanova, K., Fortič, A., Garcia, M., Dailianis, T., Tamburello, L., Victor Surugiu[37], Stancanelli, B., Di Martino, V., Bosmali, A., Mavrič, B., Gerovasileiou, V., Kletou, D., Crocetta, F., Rallis, J., Evans, J., Altamirano Jeschke, M., Leda Liyue Cai, Taşkın, E., Franzitta, G., Ramzi Sghaier, Y., Kennedy, A., Bartolo, A.G., Küpper, F.C., Rousou, M., Víctor Orenes-Salazar, Bonifazi, A., Hadjioannou, L., Vlantaridis, Z., El Shaer, H., Mülkibar Çiftçioğlu, Cerim, H., Lipej, L., Grech, D., Zotou, M., Azzurro, E., Schembri, P.J., Tiralongo, F., Chatzigeorgiou, G., Di Lorenzo, M., Vigo Fernandez, M., Di Franco, A., Orlando-Bonaca, M, Calò, A., Malefaki, C., García-Charton, J.A., Papadakis, O., Yapıcı, S., Tanduo, V., D'Aniello, I., Munari, M., Kampouris, T.E., Putignano, M., Virgili, R., Agius Darmanin, S., Bilgiç, F., Sardo, G., Calabrò, M., Nikolaou, T., Erga, Z., Zogheib, A., Balistreri, P., Çağlar, S., Yalgın, F., Osca, D., Gratsia, E., Aglieri, G., Çinar, M.E., Mutalipassi, M., Coco, S., Gkoulia, A., Ramos-Esplá, A.A., Mannino, A.M., Dimichele, D., Spinelli, S., Arroyo Martínez, E., Tursi, A., Capasso, A., Borut Mavrič, Christidis, G., Solca, M., Rifi, M., Radhouan Belgacem El Zrelli, Ramla Bouhlel, Scalera, R., Bandi, A., Reboa, A., Mazaris, A., Bazairi, H., Bertolino, M., Selfati, M., Sirchia, B., Georgiadis, C.G., Petricioli, D., Macaluso, E., D'aniello, E., Fotiadis, N., Tezel, R., Slavica Petović, Bakran-Petricioli, T., Pitacco, V., Colletti, A., Bensari, B., Bahbah, L., D'aniello, S., Psailas, S., Kalogirou, S., Kaikai, T., Forcada, A., Manfredonia, A., Bottalico, A., Valle, C., Bedoret, C., Damalas, D., Sacco, D., Mollo, E., Iatrou, F., Cerqueira, F., Viard, F., Villani, G., Foulquié, M., Geraci, M.C., Šiško, M., Ocaña, O., Renaud Dupuy De La Grandrive, Vitale, S., Rossi, T., Samaha, Z., Aguilar, R., Alvarez, H., Menabit, S., Pavel, A.B., Azzola, A., Bos, A.R., Anastasiadis, A., Blanco, J., Lejeusne, C., Coppola, D., Davoult, D., Faget, D., Scannella, D., Keppel, E., Falsone, F., Fortunato Palma Esposito, García, S., Furfaro, G., Zibrowius, H., Iziani, I., Anastasopoulou, I., Kavakakis, K., Scavino, L., Merotto, L., Yankova, M., Montefalcone, M., Leban, N., Ungaro, N., Mariottini, P., Perry, A.L., Stavrou, P., Mazzella, V., Raykov, V., Ferrario, J., Stamouli, C., Siapatis, A., Vernadou, E. and Katsanevakis, S. 2026. Unpublished Mediterranean and Black Sea records of marine alien, cryptogenic, and neonative species. *BioInvasions Records*, 15 (in press).

Reyes-García, V., Fernández-Llamazares, Á., García-del-Amo, D. and Cabeza, M., 2020. Operationalizing local ecological knowledge in climate change research:

Challenges and opportunities of citizen science. *Changing climate, changing worlds: local knowledge and the challenges of social and ecological change*, pp.183-197.

Rosso, A. and Siddiolo, C., 2024. *Microporella hastingsae* Harmelin, Ostrovsky, Cáceres-Chamizo and Sanner, 2011 (Bryozoa, Cheilostomatida): a possible new Lessepsian species in the Mediterranean Sea? *Mediterranean Marine Science*, *25*(1), pp.73-83.

Rosso, A., Di Martino, E. and Siddiolo, C., 2025. Going west: the spread of non-native *Microporella* (Bryozoa) species on drift plastic debris. *Mediterranean Marine Science*, *26*(1), pp.71-89.

Rosso, A., Di Martino, E., Donato, G., Figuerola, B., Gerovasileiou, V., Siddiolo, C., Sinagra, A., Sanfilippo, R. and Sciuto, F., 2025. Unlocking Mediterranean bryozoan diversity: seven new species unveiled after fixing a neotype for *Fenestrulina malusii* (Audouin & Savigny, 1826) (Cheilostomatida, Fenestrulinidae). *ZooKeys*, *1254*, p.1.

Siddiolo, C., Palummo, V., Milisenda, G., Pipitone, C., Rosso, A. and Chemello, R., 2025a. Assessing Habitat Suitability and Distribution Patterns of the Invasive Brachyuran Crabs *Callinectes sapidus* and *Portunus segnis* in the Mediterranean Basin. *Mediterranean Marine Science*, 26(3), 428–439. https://doi.org/10.12681/mms.38715.

Siddiolo, C., Rosso, A., Orecchio, G. and Lo Valvo, M., 2025b. Heat Nests: The impact of climate change on loggerhead turtle (*Caretta caretta*) nesting distribution in Sicily (Italy). *Ecology and Evolution*, *15*(4), p.e71177.

Siddiolo, C., Chemello, R. and Rosso, A. 2026. Complementary Data Sources for Mapping Target Mediterranean Non-Native and Cryptogenic Species: The Role of Local Knowledge and Citizen Science. *Regional Studies in Marine Science.* (in press).

Solanou, M., Valavanis, V.D., Karachle, P.K. and Giannoulaki, M., 2023. Looking at the Expansion of Three Demersal Lessepsian Fish Immigrants in the Greek Seas: What Can We Get from Spatial Distribution Modeling? *Diversity*, *15*(6), p.776.

Stuart-Smith, R.D., Edgar, G.J. and Bates, A.E., 2017. Thermal limits to the geographic distributions of shallow-water marine species. *Nature Ecology & Evolution*, 1(12), pp.1846-1852.

Turan, C., 2020. Species distribution modelling of invasive alien species*; Pterois miles* for current distribution and future suitable habitats. *Global Journal of Environmental Science and Management*, 6(4), 429-440.