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CITIZEN SCIENCE FOR BIODIVERSITY ON MARINE-COASTAL AREAS: AN APPLICATION ON THE CENTRAL ADRIATIC IN ITALY

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Abstract

This thesis explores the role of *Citizen Science* (CS) in biodiversity monitoring, focusing on its integration into long-term ecological research programs and its application in marine-coastal systems, particularly along the Central Adriatic coast. The ongoing biodiversity crisis necessitates innovative tools to enhance large-scale data collection over extended spatial and temporal scales. In this context, CS has emerged as a promising approach, bridging the gap between science and society and enabling large-scale biodiversity assessments through the active involvement of citizens and volunteers. During the first section of the thesis, a preliminary bibliographic review on CS applications for coastal biodiversity monitoring revealed a growing expansion of CS initiatives, with a significant increase in publications since 2020. Italy stands out for the number of studies conducted, supported by well-established research networks and institutions such as the National Research Council of Italy (CNR) and the Citizen Science Italia ETS association (CSI). The reviewed studies show that CS was applied on marine environments and multi-species projects, while observations related to plant species remain less frequent. However, the need for more advanced analytical approaches and data validation strategies has emerged to enhance the reliability and applicability of findings for conservation purposes. To address these challenges, in the following steps of this research we developed a semi-opportunistic CS project for biodiversity monitoring supported by iNaturalist platform, Wild Coast Adriatic (WCA), implemented in a set of CS campaigns carried out along the Central Adriatic coast over four years. The implementation of WCA provided valuable insights into both ecological and methodological aspects, offering evidence on how CS and the digital platforms such as iNaturalist can enhance the spatial and temporal coverage of observations, facilitate the identification of threatened species and those characteristic of habitats of European interest as defined by the Habitat Directive (92/43/EEC, 1992), and serve as an early warning tool for the detection of invasive alien species. However, to ensure the reliability of collected data, CS-based monitoring requires rigorous validation procedures, supported by verification protocols conducted by experts present on the platforms, and advanced technologies such as artificial intelligence for automatic species identification available on platforms like iNaturalist. A key aspect of this study was the collaboration with LTER-IT (Long-Term Ecological Research - Italy), the Italian national network for Long-Term Ecological Research, which studies terrestrial, freshwater, marine, and transitional ecosystems through an integrated and multidisciplinary approach. This partnership enabled the expansion of the participatory approach to a broader variety of ecosystems. The ecological diversity of the monitored sites allowed for comparative analyses of ecological dynamics and anthropogenic pressures, supporting the development of tailored management strategies for each habitat type. Furthermore, the integration of CS data with traditional scientific monitoring datasets contributed to a deeper

understanding of environmental dynamics over extended temporal scales. This thesis highlights the growing relevance of CS as a fundamental tool for ecosystem monitoring, demonstrating its ability to integrate scientific research, education, and public participation. Strengthening how collaborative and resilient monitoring networks are essential to addressing the challenges posed by climate change and biodiversity loss, while fostering sustainable and effective conservation strategies. Establishing synergies between science, local communities, and institutions is crucial for promoting conservation actions that are both scientifically robust and socially inclusive, ensuring a broader impact at both local and global scales.

Introduction

The ongoing biodiversity crisis calls for innovative tools capable of collecting ever-increasing volumes of monitoring data across extensive areas and among these, *Citizen Science* (CS) has emerged as a promising approach, making significant contributions to addressing this urgent challenge.

CS is a collaborative or participatory approach to scientific research that actively involves non-experts in the collection and analysis of scientific data. This methodology contributes to bridge the gap between scientists and the public, enabling the acquisition of multiple-scale and time-sensitive data that would be impractical to collect through traditional scientific methods.

Over the past two decades, CS has emerged as a transformative force in ecology and the environmental sciences, actively involving the public in the production of scientific knowledge. This innovative paradigm has reshaped both the practice and the conceptualization of scientific inquiry, enhanced knowledge-generation processes and amplified the societal impact of science (Bonney et al., 2009; Silvertown, 2009).

The significance of CS lies in its capacity to mobilize large numbers of participants, enabling the monitoring of environmental phenomena, the collection of ecosystem data, and the detection of changes over time. These contributions may be crucial for enhancing our understanding of the natural world and supporting sustainable resource management. Beyond its scientific value, CS fosters active public engagement, raising awareness and interest in environmental issues. By leveraging collective participation, it bridges the gap between science and society, making scientific advancements more accessible and meaningful for diverse audiences.

Although forms of public participation in scientific processes date back to the time of Linnaeus - when amateur naturalists contributed to biodiversity cataloguing (Miller-Rushing et al., 2012) it is only in the last few decades, with the advent of digital technologies, that CS has attained a truly global and strategically significant dimension (Newman et al., 2012). Defined as the direct participation of non-academically trained citizens in the collection, validation, analysis, and interpretation of scientific data, CS began to consolidate in the 1990s and has experienced noteworthy quantitative and qualitative growth since the early 2000s (Dickinson et al., 2010; Wiggins & Crowston, 2011).

Many efforts have been made to define CS in ways that capture the plurality and complexity of the concept. According to researchers at the Oxford English Dictionary (OED), the first documented use of the term CS in its current sense dates back three decades. The term appeared in a January 1989 issue of the MIT Technology Review in an article entitled “Lab for the Environment” - Kerson, 1989. Over time, various definitions have been proposed. The Green Paper Citizen Science Strategy 2020 for Germany (2016) describes CS as a “*process of generating knowledge through various*

participatory formats. Participation can range from the short-term collection of data to the intensive use of leisure time to delve deeper into a research topic together with scientists and/or other volunteers, to ask questions, and to get involved in some or all phases of the research process". Meanwhile, the European Union (2019) emphasizes that "*more and more Europeans hold higher education degrees. Enabled by digitalisation and knowledge, citizens are today prosumers capable of shaping the innovation process and bypassing restrictive practices of established sectors and governments. This goes well beyond citizen science and covers the entire research and innovation process*". In the United States, Citizenscience.gov defines *CS* as a process in which "*the public participates voluntarily in the scientific process, addressing real-world problems in ways that may include formulating research questions, conducting scientific experiments, collecting and analysing data, interpreting results, making discoveries, developing technologies and applications, and solving complex problems*."

Overall, these definitions emphasize the need for an open and inclusive perspective of the different research practices and participatory activities that arise when individuals outside formal research roles actively contribute to scientific endeavours (Vohland et al., 2021). This plurality of definitions is crucial for the advancement of CS enabling it to address the varied needs across its many fields of application. As a result, defining CS with a single, universal concept is a challenging task, given the broad range of topics and issues it encompasses.

In 2015, the European Citizen Science Association (ECSA, https://www.ecsa.ngo) defined CS as a "*flexible*" concept applicable across disciplines and contexts. To establish a standardized framework for this approach, ECSA published the 10 principles of Citizen Science (ECSA, 2015), outlining key practices considered as the basis for ensuring high-quality and comparable CS initiatives. These principles offer the basis for implementing an inclusive and collaborative approach to scientific research by the active involvement of citizens in scientific projects (Bonney et al., 2009). Such CS projects not only generate new knowledge but also deliver tangible scientific results that may aid the development of conservation strategies and environmental policies.

CS represents an innovative approach to scientific research, extending beyond the mere involvement of citizens in data collection. While participatory contributions enhance the spatial and temporal coverage of observations, CS is increasingly recognized as an interdisciplinary tool with objectives ranging from the production of new scientific knowledge to the development of more effective environmental management strategies (Gentili et al., 2021; McKinley et al., 2017). One of its most significant aspects is its capacity to support large-scale and long-term monitoring, particularly in fields where data collection requires substantial resources and continuity over time, such as in the study of climate change (Dawson et al., 2020), biodiversity monitoring, and the dynamics of evolving

ecosystems (Compagnone et al., 2023). Beyond its practical value, CS plays a key role in scientific education, enhancing public understanding of environmental processes and raising awareness of global challenges (Vohland et al., 2021). Active participation in research fosters the development of analytical and critical thinking skills, increasing engagement in science and promoting a more responsible approach to environmental issues. CS is also strategically relevant in policy-making and governance support. Citizen-generated data can complement official datasets, contributing to the development of evidence-based management strategies. This approach is particularly valuable in air quality monitoring (Constant, 2018), water pollution assessment (Ramírez et al., 2023), environmental contamination studies (Nelms et al., 2022), and in the monitoring of terrestrial and marine ecosystems (Compagnone et al., 2023). The involvement of the public provides valuable insights that can influence policy decisions and environmental planning. Furthermore, CS fosters a direct dialogue between the public, scientific institutions, and policymakers, raising awareness of local and global environmental issues while actively engaging researchers in shaping management plans and conservation strategies (Vohland et al., 2021). A key aspect of CS is its ability to create global networks for scientific collaboration, facilitating the exchange of data and knowledge between researchers and citizens at the international level. This synergy enables a more inclusive and participatory approach addressing global environmental challenges, supporting the principles of Open Science and ensuring that scientific research remains accessible and transparent. While CS is most widely applied in biological and ecological sciences, it also plays an important role in political science, social sciences, humanities, and computational technologies. At both national and international levels, numerous projects promote the integration of CS across multiple research fields, demonstrating its interdisciplinary potential. For instance, the "Agenzia per la Promozione della Ricerca Europea" (APRE) actively supports CS initiatives aimed at bridging the gap between science and society (www.apre.it - APREmagazine n. 21). In the humanities and social sciences, CS has gained increasing relevance through initiatives such as the Bentham Project (https://www.ucl.ac.uk/bentham-project/transcribe-bentham), which engages the public in the online transcription of Jeremy Bentham's original manuscripts and correspondence. This project not only improves accessibility to historical documents but also demonstrates how CS can contribute to the digitalization and preservation of cultural heritage. In more technical fields, CS is widely used in distributed computing, leveraging the processing power of thousands of volunteers to address complex biomedical and scientific problems. A notable example is FOLDING@HOME (https://foldingathome.org), which allows participants to contribute their computing resources to support research on COVID-19, Alzheimer's disease, and cancer. This initiative highlights how CS can provide tangible contributions to biomedical research, accelerating protein modeling and drug

discovery. Despite its broad interdisciplinary applications, CS is most extensively used in environmental sciences. Projects developed in this domain vary widely, but to ensure that collected data are scientifically valid and applicable, it is essential to adhere to rigorous methodological standards, employing standardized protocols and robust validation strategies.

Concerning CS in our country, Italy has been a pioneer in Europe, being among the first countries to establish an Italian Citizen Science Association, known as Citizen Science Italia ETS (CSI), which held its first national meeting in November 2021. This ETS conference served as the starting point for a national discussion that laid the groundwork for the official establishment of the association (https://www.citizenscience.it). CSI is dedicated to promoting collaborative research between volunteers and scientists, fostering the generation of scientific knowledge through active citizen participation. This process of participatory science is designed to be inclusive and to contribute to sustainable development by providing valuable data and information that can aid the definition of environmental and social policies. Additionally, the association seeks to establish robust collaboration networks at both national and international levels, engaging with similar organizations worldwide.

The ever-increasing spread of CS is certainly linked to several factors as the emergence of numerous associations and projects, the advancements in technology and the widespread availability of the Internet (Newman et al., 2012). These factors have significantly facilitated its expansion, visibility, potential for remote collaboration, and diversification of areas of implementation.

Specifically, a CS project consists of several key phases, each of which plays a crucial role in determining the success of the initiative and the quality of the collected data. The first and most fundamental step is the definition of a clear scientific question, grounded in solid background knowledge (Bonney et al., 2009). This initial phase is critical to ensuring that both scientists and participants share a clear understanding of the project's common objectives and scientific significance. Developing an interdisciplinary research team is another key element (Bonney et al., 2009). A successful CS project requires specialists from various fields, each contributing expertise in project design, implementation, and data analysis. A crucial challenge in CS is ensuring data quality (Hochmair et al., 2020). This depends on three main factors, the clearly defined data collection protocols, the structured and user-friendly data submission formats, and the adequate training for participants(Bonney et al., 2009). Even with these safeguards, some concepts and methodologies may require special attention and specific training to ensure data reliability. Inconsistent or erroneous data may be excluded from analyses without compromising the overall integrity of the project. Thus, the development of standardized protocols is fundamental in CS projects. Data collection must follow precise guidelines to ensure uniformity and comparability across multiple participants and locations. To be effective, these protocols must be easy to follow, clearly explained, and engaging for volunteers

(Sullivan et al., 2014). Educational materials play a crucial role in participant recruitment and training. Once participants are selected, they must receive comprehensive instructional materials and support to ensure they can operate autonomously and accurately. These materials can be provided via digital platforms, video tutorials, and downloadable manuals, while training workshops have proven particularly effective in enhancing data quality and fostering a sense of community among participants (Bonney et al., 2009). An interesting aspect of CS is that participants can also be involved in data analysis and interpretation, providing an educational opportunity that helps them understand the scientific process in its entirety and promotes awareness of research and biodiversity conservation (Kobori et al., 2016). Data collected through CS can reveal emerging ecological phenomena or large-scale trends that require further targeted studies. Many CS projects, in fact, are not limited to data collection, but also aim to publish the results, both in technical reports and scientific articles, thus ensuring their validity and usability in the scientific community (Bonney et al., 2009). The dissemination of data and discoveries obtained is essential for the success of a CS project and for its contribution to ecological knowledge, also and above all with the community that participated in the previous phases of the study.

Before the massive spread of the Internet, CS manifested itself in a more limited and fragmented way. For example, one of the first manifestations of CS was in the USA where ornithology enthusiasts have been contributing to bird counts for decades (such as the National Audubon Society's famous Christmas Bird Count, which began in the early 1900s - https://www.audubon.org/community-science/christmas-bird-count). Such collaborations were typically coordinated by scientific or nature conservation organizations using traditional methods such as mailings, printed bulletins, periodic conferences, and, at most, telephone calls.

With the ever-increasing diffusion of the Internet between the late 1990s and 2000s, new possibilities for CS opened. The possibility of creating dedicated websites and online platforms, through which volunteers from all over the world began to participate in data collection, analysis and sharing projects (Newman et al., 2012; Pocock et al., 2024), exponentially favoured its diffusion in Europe and the world. Another factor that played a fundamental role in the diffusion of CS was the rapid sharing of information, as the Internet, drastically reducing communication times, allowed the data collected by citizens to be sent in almost real-time to researchers who can validate them, process them and return results to the citizens, thus encouraging participants to continue. Furthermore, before the Internet, participation was often limited to a limited territory, today, however, a citizen can collaborate in an environmental monitoring project on the other side of the globe simply by sending observations via apps or web portals. All this has been possible thanks to the ever-increasing diffusion of smartphones,

tablets, low-cost sensors and measuring instruments connected to the Internet, which has revolutionized data collection (Newman et al., 2012).

In this context, to facilitate the active engagement of participants in CS projects, the use of dedicated digital platforms is a key element, allowing data collection, sharing, and validation in an accessible and standardized manner (Newman et al., 2012). Among the most widely used platforms at the international level are Zooniverse, eBird, PlantNet, and iNaturalist, which have revolutionized the way citizens and researchers collaborate in documenting biodiversity. Zooniverse (https://www.zooniverse.org) exploit collective intelligence for the analysis of astronomical, zoological or environmental images (López-Guillén et al., 2024; Simpson et al., 2014; Sullivan et al., 2014). eBird, developed by the Cornell Lab of Ornithology (https://www.birds.cornell.edu), is a global platform for bird monitoring that enables users to report bird sightings, contributing to the creation of databases on species distribution and population trends (Sullivan et al., 2014). It is widely used in academic research (https://ebird.org) to analyze avian migration patterns, assess population changes, and evaluate the effects of climate change on bird communities. Pl@ntNet (https://identify.plantnet.org/it), on the other hand, is an application designed for the identification and cataloging of plant species. Based on an image recognition system, it allows users to photograph a plant and receive an identification suggestion from an extensive botanical database, supporting both enthusiasts and researchers in the study of plant diversity and the monitoring of floristic composition in various ecosystems.

In this study, iNaturalist (https://www.inaturalist.org) was adopted for the collection and management of data on marine-coastal biodiversity. The choice of iNaturalist was motivated by its ability to integrate an artificial intelligence-based species recognition system, by the active involvement of a large scientific and amateur community, and by the possibility of validating observations through a collaborative process (Baker et al., 2024). This platform enables the collection of georeferenced data on target species, providing fundamental support for biodiversity analysis and monitoring ecological variations (Di Cecco et al., 2021). The decision to use a digital tool such as iNaturalist was made not only to facilitate public participation but also because of its ability to generate high-quality datasets, which are valuable for scientific studies and can be integrated into long-term monitoring systems. Its application thus represents a strategic opportunity to bridge the gap between science and society, making research more accessible and participatory. However, despite its numerous advantages, the use of iNaturalist presents some critical aspects remain related to the quality and validity of data (Del Vecchio et al., 2019; Hochmair et al., 2020; Kosmala et al., 2016).

One of the main limitations concerns data quality and identification reliability, as observations are initially classified by users and only later validated by the scientific community (Hochmair et al., 2020). This process may lead to misidentifications, particularly for taxa that are difficult to distinguish visually or for lesser-known taxonomic groups. However, this limitation can be mitigated by high-quality images and by the active correction of misidentifications by expert users within the iNaturalist scientific community. Another challenge is the geographic distribution of observations, which is often biased toward densely populated areas, resulting in fewer records from remote or less accessible regions. For this reason, CS activities are often strategically organized in data-deficient areas to enhance geographic coverage. Furthermore, the platform does not implement a strict standardization of data collection protocols, as observations are uploaded opportunistically and do not always follow predefined systematic procedures. Despite these limitations, the value of the platform remains significant, provided that data validation is carefully managed (Hochmair et al., 2020).

For this reason, in this study, iNaturalist data were analyzed rigorously, assessing their reliability and integrating them, where possible, with additional data sources to improve the robustness of ecological analyses. If properly controlled, the use of this platform significantly enhances biodiversity monitoring capabilities. The operational framework of iNaturalist is structured to ensure the reliability of collected observations. Users, via the website or mobile application, can upload photographs or audio recordings of organisms encountered in nature. Each observation is automatically georeferenced and linked to temporal information regarding the date of the sighting.

One of the defining features of iNaturalist is its artificial intelligence (AI) system, which aids in species identification by analyzing the uploaded images or audio files and providing suggestions based on pre-existing datasets in the iNaturalist database. However, automated identification is only a preliminary step: the validation process, known as data quality assessment (DQA) (Hochmair et al., 2020), requires active involvement from the scientific community and expert naturalists. Each observation initially remains in “Needs ID” status until at least two independent users confirm the species identification. When an observation receives at least two concordant confirmations from experienced users with recognized expertise in the specific taxonomy, it attains “Research Grade” status (Aristeidou et al., 2021). Only observations that reach this level are considered reliable and are automatically shared with the Global Biodiversity Information Facility (GBIF) (https://www.gbif.org), one of the world’s largest biodiversity databases, ensuring their availability for scientific research and conservation planning.

CS for biodiversity is characterized by a multiplicity of methodological approaches and a notable heterogeneity of objectives. It can range from long-term wildlife monitoring projects (e.g. Cornell Lab of Ornithology’s “eBird”;) to initiatives for mapping marine habitats (e.g. “Reef Check” -

https://www.reefcheck.org), up to environmental data collection activities such as temperatures and chemical-physical parameters of water (Dickinson et al., 2010) o Environmental DNA (eDNA - Kvalheim et al., 2024).

The integration of advanced information technologies - such as artificial intelligence tools for automatic data validation and data mining applications - has allowed an increase in the reliability and analysis capacity of large datasets generated by participants (Newman et al., 2012; Wiggins & Crowston, 2011). This, in turn, has made CS an increasingly attractive and sustainable option for professional researchers, allowing them to overcome some of the traditional limitations, such as the heterogeneity of the data collected or the difficulty of standardization (Kosmala et al., 2016). Indeed, it should always be kept in mind that, despite its great potential, CS presents some critical issues that need to be addressed systematically. First of all, the quality of data can be variable, as participants have different levels of skills and experience (Kosmala et al., 2016). This requires, in many cases, the adoption of standardization protocols, training sessions, data verification systems and the use of robust methods for validating the information collected (Dickinson et al., 2010). Furthermore, the management of large datasets requires adequate infrastructures, processing capacity and advanced analytical skills (Wiggins & Crowston, 2011). Another limiting factor concerns the motivation and loyalty of volunteers, who need timely feedback, recognition of their contribution and a clear perception of the impact of their efforts. Without a long-term engagement strategy, based on transparency of objectives, sharing of results and the possibility of interacting with researchers, the risk is that of losing the availability of citizens over time (Bergami et al., 2023; Newman et al., 2012)

To maximize the benefits of CS, the active involvement of stakeholders is crucial, that is, all those subjects - government institutions, natural resource management bodies, NGOs, industries, and local communities - that have a direct or indirect interest in environmental protection and natural resource management. Stakeholders can help define research questions, establish intervention priorities, ensure logistical and economic support for projects, as well as promote the implementation of scientific results in public policies and management practices (Kobori et al., 2016).

The value of CS is, therefore, manifested not only at a cognitive level but also at a strategic level. The collected data can be integrated into predictive models, adaptive management plans or targeted conservation measures, contributing to a more solid, informed and inclusive environmental governance. This potential to influence environmental policies and decisions represents one of the most innovative and promising aspects of CS, which thus becomes a bridge between pure research and its applications on the social, economic and regulatory levels (Vohland et al., 2021).

In this framework, this thesis seeks to explore and give evidence on how an innovative CS approach, based on the use of digital tools and robust scientific principles, can enhance ecological monitoring. By enabling the coverage of large study areas in shorter timeframes and across seasons, CS helps to generate new research opportunities, informs improved conservation strategies and fosters broader public participation in protecting the marine-coastal environment. The overarching goal is to contribute to the development and consolidation of a more inclusive, effective and resilient model of environmental investigation and management, equipped to address the complex ecological challenges of the 21st century.

By a set of study cases, the thesis explored the potential of Semi-Opportunistic CS Projects, supported by digital platforms such as iNaturalist, for biodiversity monitoring on marine-coastal systems with a specific focus on the Central Adriatic coast in Italy. In this context, the "Wild Coast Adriatic" (WCA) project (https://sites.google.com/view/wild-coast-adriatic/home?authuser=0) was launched as an experimental initiative to gather observations made by citizens and refine their application on academic research. The study cases were implemented on the Central Adriatic coastal system of Abruzzo and Molise, characterized by a shallow continental shelf with sandy and mixed seabeds transitioning into sandy and pebbly coastal systems. These coastal systems serve as natural barriers against erosion and host diverse habitats and species of conservation concern, including *Ammophila arenaria* (L.) Link, *Eryngium maritimum* L. (on the emerged dune sectors), and *Cymodocea nodosa (Ucria) Asch* (in the seabed near the coastline). The conservation of overall coastal sea-inland systems assures several ecosystem services. However, this ecosystem faces challenges from coastal erosion due to climate change, habitat fragmentation from urbanization, overfishing, pollution, and the introduction of invasive species impinging ecosystem resilience and compromising biodiversity (de Francesco et al., 2019; Di Febbraro et al., 2021; Varricchione, 2019).

Despite these threats, the high natural value, the presence of several protected areas, its representativeness of Mediterranean coastal systems (Stanisci et al., 2014), and the intense human activity make the coastal systems of the Central Adriatic an excellent setting for implementing a CS project and testing its potential.

The project's approach extends beyond the simple collection of information; it employs a rigorous framework where data provided by volunteers undergo validation and analysis to ensure a robust information base. Validated and checked observations support ecological interpretations useful for aiding updated management strategies.

Furthermore, during this project, we obtained evidence of the potential of CS, as a valuable bridge between pure research and its applications in social, educational and management contexts.

Collaboration with organizations such as Ambiente Basso Molise (http://ambientebassomolise.blogspot.com) and protected areas like the Torre del Cerrano Marine Protected Area (https://www.torredelcerrano.it) enabled activities such as inspections or educational activities. These efforts aided the creation of citizen monitoring networks for protected species, including *Caretta caretta* (Linnaeus, 1758) and *Kentish plover* (Linnaeus, 1758), present in the area under study.

The research applications instead, focused on three main groups of species of conservation concern, each of relevance for biodiversity management. Specifically, the research includes: a) species of conservation concern listed on the IUCN Red List and in the annexes of the Habitats Directive (HD). Monitoring these species besides being claimed by environmental regulations, is needed for the assessment of their levels of threat and for guiding priority protection measures; b) plant species that are "diagnostic" of the presence of habitats of conservation interest at the European level. The periodical assessment of diagnostic species enables the evaluation of changes in the conservation status of natural and semi-natural ecosystems and helps to identify areas requiring conservation actions; c) Alien species, including invasive taxa, are listed as particularly worrying in the European Union. Revealing the presence and distribution of those species is essential for implementing Early Detection and Rapid Response strategies, for curtailing potential impacts on native biodiversity.

The in-depth study of these aspects has led to two scientific contributions (Compagnone et al., 2023, 2024), suggesting the usefulness of CS for biodiversity analysis within coastal systems. These contributions underscore the validity of the adopted approach and highlight the relevance, after thorough verification by experts, of the data generated through active citizen participation.

This PhD thesis is structured into 5 chapters. Following the introduction, Chapter 1 offers a preliminary literature review that contextualizes the state of the art in CS for monitoring marine-coastal biodiversity over the last years. This analysis provides a valuable framework for assessing the effectiveness of the strategies adopted so far and identifying prospects for more comprehensive and sustainable monitoring efforts.

The subsequent two chapters focus on scientific research supported by biodiversity data collected by CS volunteers. Specifically, Chapter 2 ("*Coastal Biodiversity Assessment Aided by Citizen Science Volunteers: A Look at the Italian Central Adriatic*") highlights how collaboration with volunteers can provide essential biodiversity data for analyzing the conservation status of marine-coastal biodiversity by leveraging the potential of a Semi-Opportunistic *Citizen Science* project. The study (Compagnone et al., 2023) investigates the role of CS in monitoring marine-coastal biodiversity, using the "Wild Coast Adriatic" (WCA – ex CASCADE) project, as a case study. The WCA project,

developed through the iNaturalist platform, focuses on the Central Adriatic coast of Italy. The study focuses on three taxonomic groups of conservation interest: threatened species listed in the IUCN Red List and in the annexes of the Habitats Directive (HD); plant species that are diagnostic of habitats of conservation concern according to the Habitats Directive (HD) and non-native species. The research is based on data collected between 2020 and 2023 by citizens that totalizes 3,784 observations covering 742 species, of which 81% achieved the status of "Research Grade" underscoring the value of the data generated through active citizen participation. The results highlight the key role of CS in detecting priority species and habitats of interest, enhancing knowledge of their spatial distribution, and monitoring threatened species such as *Pinna nobilis* (Linnaeus 1758 - CR in Red List of IUCN) and *Caretta caretta* (VU in Red List of IUCN). Additionally, the implementation of the WCA project supported the identification of habitats of European concern according to the Habitats Directive (e.g. habitat 1110: "*Sandbanks which are slightly covered by sea water all the time*"), thereby informing management priorities for conservation. The study also demonstrates the effectiveness of CS in detecting invasive alien species, including *Acacia saligna* (Labill.) H.L. Wendl and *Ailanthus altissima* (Mill.) Swingle, provides crucial data for early detection and rapid intervention systems.

This study offers new evidence on how citizen-collected data can contribute to biodiversity values and threats monitoring in complex and dynamic systems as coastal transitions, orienting conservation efforts and their sustainable management. By combining public education with scientific research, our work highlights the value of CS in addressing knowledge gaps and presents itself as a replicable and scalable model for similar contexts. The analysis showed that citizen participation not only enriches scientific databases with valuable and real-time information but also promotes broad awareness and direct engagement in environmental conservation by creating a certain fidelity in participation in the project.

Chapter 3 ("*Exploring the Contribution of a Generalist Citizen Science Project for Alien Species Detection and Monitoring in Coastal Areas. A Case Study on the Adriatic of Central Italy*") focuses on the role of CS in detecting and monitoring alien species (a critical issue of integrated marine-coastal ecosystems management). The study (Compagnone et al., 2024) explores the potential of CS for documenting and monitoring alien species in marine-coastal systems on the Central Adriatic of Italy. The research is based on 2.194 "Research Grade" observations collected between 2020 and 2023 through the generalist CS project Wild Coast Adriatic (WCA), developed on the iNaturalist platform. We revealed 139 occurrences of 50 alien species. Notably, five of these species are listed in the European Regulation on Invasive Species (Regulation (EU) 1143/2014 EEC), highlighting the effectiveness of CS as a tool for early detection and monitoring of invasive species. The work assessed

the seasonal dynamics of reports, highlighting peaks of observations in summer and autumn, and explored the geographical origin of the species, mainly from the Americas. The spatial distribution of alien species shows a greater concentration outside protected areas, but a significant number were also reported within Natura 2000 sites and Long-Term Ecological Research (LTER). The study demonstrates how CS can contribute to improving monitoring and management strategies, facilitating the understanding of the spatial and temporal distribution of invasive species and supporting the implementation of targeted conservation actions in marine-coastal systems. The work identified ways in which the collected data can be used to develop effective response strategies, highlighting the ability of CS to act as a valid tool to support conservation and biological control policies.

Chapter 4 presents other activities, and methodological in-depth interventions conducted on coastal areas during the doctorate, thus offering a glimpse of the skills acquired and the broader framework of scientific collaboration in which the research is inserted. Finally, Chapter 5 discusses future perspectives, highlighting the potential of synergies with long-term monitoring networks such as LTER (https://lternet.edu).

LTER is a global network engaged in research on ecosystems, the critical zone, and socio-ecology, operating across terrestrial, freshwater, transitional, and marine environments. It comprises 44 national networks, 700 LTER sites, and 80 LTSER (Long-Term Socio-Ecological Research) platforms dedicated to socio-ecological research (Mirtl et al., 2018; Wohner et al., 2021).

Within LTER network there is ILTER (International Long-Term Ecological Research) that serves as the international counterpart for local network of LTER such as eLTER (European Long-Term Ecological Research - https://elter-ri.eu/ilter). LTER-Europe acts as an umbrella organization that coordinates 30 national LTER networks, and provides significant contributions to the international network, such as maintaining DEIMS-SDR (Dynamic Ecological Information Management System - Site and Dataset Registry - https://deims.org), the metadata portal that collects information on LTER sites (Bergami et al., 2023).

The primary objective of LTER is to study long-term ecosystem changes by adopting an integrated approach to analyze the interactions between environmental and social factors, while monitoring both gradual transformations and extreme events (Mirtl et al., 2018). The network provides a globally distributed research infrastructure that supports studies in ecosystem ecology, biodiversity, and socio-ecological research, ensuring high-quality interoperable services in close collaboration with research infrastructures at different levels.

LTER represents an interdisciplinary scientific community, engaging multiple institutions, thousands of scientists, and a broad range of disciplines. Socio-ecological research, particularly within LTSER platforms, aims to involve stakeholders in environmental monitoring, co-design of research

methodologies, and defining research priorities (Haberl et al., 2006; Mauz et al., 2012). This approach requires a strong commitment from scientists to operate within an interdisciplinary framework that integrates natural, social, and human sciences, as well as a willingness to actively collaborate with communities and stakeholders, including CS initiatives. As reported by Bergami et al. (2023), LTER hosts various CS initiatives, each addressing different aspects of long-term ecological research. Recently, the LTER-IT network launched an initiative on iNaturalist, aimed at strengthening the relationship between citizens and researchers and promoting long-term collection of biodiversity data within the LTER network, which could further improve the use of CS data and could foster the integration between science, civil society and environmental policies.

Chapter 1 – *Citizen science* for coastal Biodiversity: Innovations, Insights, and Future Pathways

1.1 *Introduction*

In recent decades, *Citizen Science* (CS) has taken an increasingly central role in biodiversity monitoring, offering a valuable resource for enhancing scientific data collection, raising public awareness, and fostering active participation in environmental research (Aristeidou, Herodotou, Ballard, Young, et al., 2021; Silvertown, 2009). This collaborative approach, which engages citizens without formal academic training, has proven particularly effective in marine-coastal contexts, characterized by an ecological complexity and a geographical distribution that makes constant monitoring exclusively entrusted to professional researchers difficult (Vohland et al., 2021).

Marine-coastal areas, host highly dynamic habitats rich in biodiversity, but at the same time fragile and threatened by human activities, climate change and the introduction of alien species. In this context, *Citizen Science* may contribute not only to the monitoring of local biodiversity but also to the early detection of critical phenomena, such as the increase in invasive species or episodes of anomalous fauna mortality (Compagnone et al., 2024; Pocock et al., 2024).

This chapter presents a brief exploration and preliminary results on the evolution and contributions of CS to biodiversity studies in marine-coastal ecosystems by analyzing scientific literature and looking for its applications in supporting decision-making processes and biodiversity conservation efforts.

The bibliographic search seeks to provide a comprehensive overview of key *Citizen Science* initiatives in monitoring marine-coastal environments, illustrating how this approach is becoming increasingly useful for monitoring, understanding and preserving these ecosystems. It also briefly explores the recent developments and technological innovations favouring the growth of this field of research on coastal areas, including the use of digital platforms, mobile applications and geolocalized reporting systems (Newman et al., 2012).

1.2 *Material and Method*

Literature Search

We conducted an extensive literature search using the Scopus database, which allows for in-depth exploration of peer-reviewed journal articles. The keywords chosen for the search were "citizen science", "biodiversity", "plants", "animals", "flora", "fauna", "vegetation" "coasts", "coast",

"coastal", "dunes", "dune". The keywords were selected using a participatory approach involving a team of researchers with experience in coastal systems monitoring, biodiversity and *Citizen Science*. The results of the initial search and the download of the articles involved a period of 15 years, from 2009 to 2024. We chose this time frame to provide a comprehensive overview of the evolution and diffusion of *Citizen Science* and its increasingly growing use in coastal ecosystems. From the total number of records retrieved from Scopus (n = 244), based on the selected keywords, the search was limited only to manuscripts written in English, only Papers and Reviews were selected, not including books, conference papers, notes and preprint articles. All articles from these searches were first screened by examining title, abstract and keywords to exclude articles with information not relevant to the research objectives (N = 124; Figure 1).

The preliminary analysis of selected papers (period 2009-2024) reveals a significant increase over time in the utilization of *Citizen Science* for monitoring marine-coastal biodiversity. This chapter focuses on papers published during the last 5 years (2020-2024), a period when CS demonstrated the most significant impact. A comprehensive analysis covering the entire period will be conducted in the near future for publication.

The selected articles underwent a filtering process based on pre-established criteria, retaining only those focused on marine-coastal biodiversity monitoring and analysis.

After a review of titles, abstracts and keywords, and the selection of some specific years, 78 articles were considered suitable for the final analysis. Figure 1 illustrates the flow of the selection phases, and the metadata used for categorization. The extracted metadata has been divided into five main categories: A) Geographical Parameters and Protection Constraints; B) Time Parameters; C) Type of Biological data; D) Methodology for data collection; and E) Methodology for analysis.

From these categories, sub-categories were then identified for the classification of articles shown in Figure 1; an exploratory analysis of the selected research was therefore carried out on papers published from 2020 to 31 October 2024.

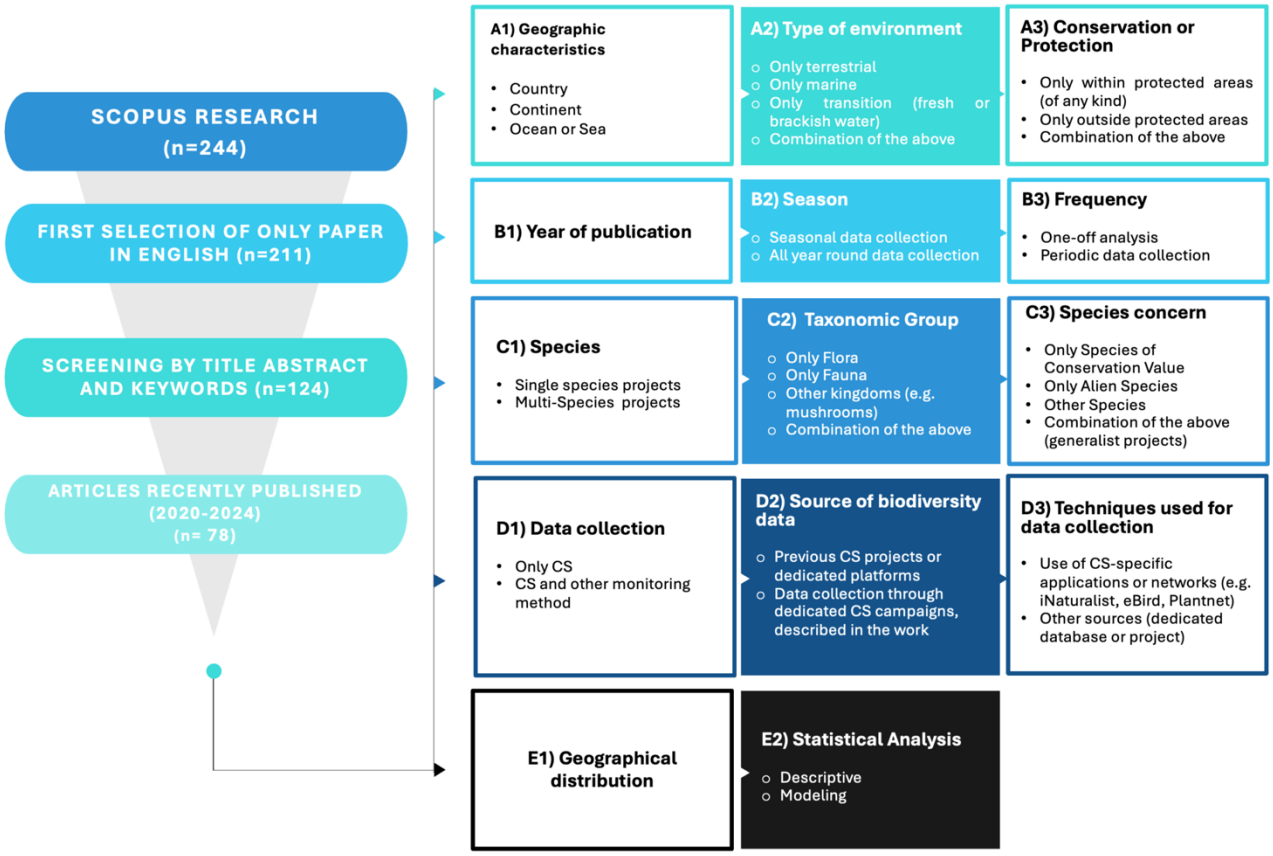


Figure 1. Article selection process and metadata used for bibliographic analysis. The diagram illustrates the selection phases of *Citizen Science* articles for monitoring marine-coastal biodiversity. The selected metadata correspond to the categories: **Geographical Parameters and Protection Constraints**, A (1,2,3); **Time Parameters**, B (1,2,3); **Type of Biological data**, C (1,2,3); **Methodology for data collection**, D (1,2,3); **Methodology for analysis**, E (1,2).

1.3 *Preliminary Results*

The first parameters observed were geographical ones; observing the distribution it was found that the continent most represented is Europe (30), followed by America (27), with a concentration in South America (14 - Figure 2; Table 1). Africa and Asia, on the other hand, have only 5 and 10 studies respectively, while Oceania is represented by 9 articles (Table 1). This geographical distribution shows a greater presence of CS projects in areas with well-established research networks and a tradition of participatory monitoring.

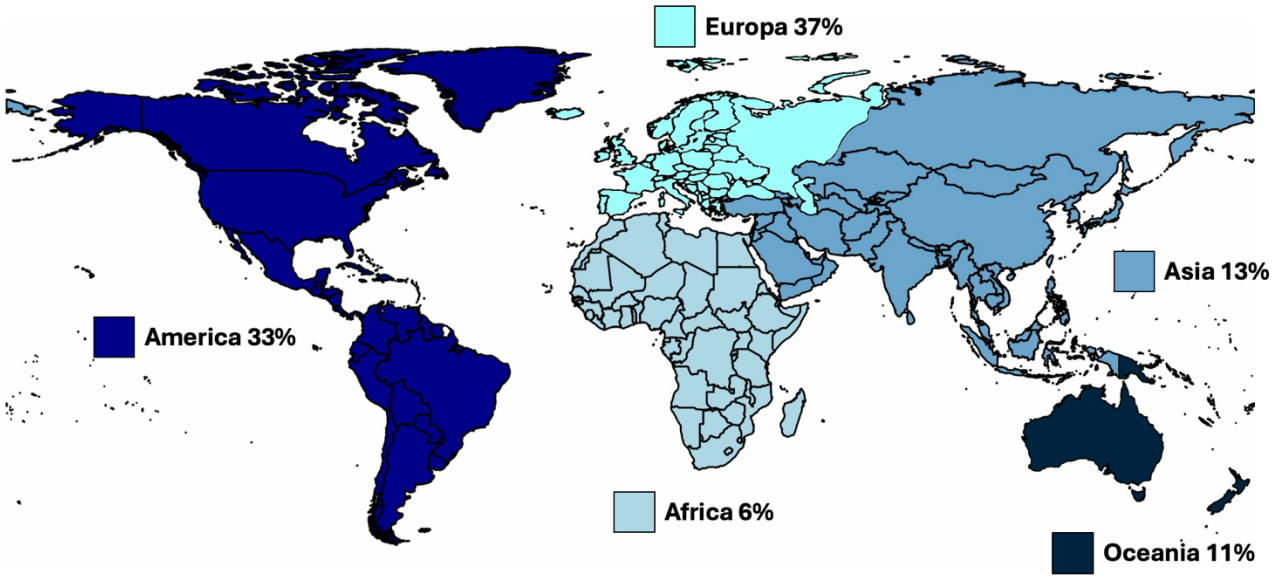


Figure 2. Percentage of publications per continent.

The distribution of studies by marine area also reflects this trend: 28% of the studies were conducted in the Atlantic Ocean (35 studies), followed by the Pacific with 20% (25 studies). The Mediterranean Sea accounts for 11% (13 studies), while the North Sea covers 7%. This prevalence of ocean areas over closed seas suggests a greater focus on open waters, although the Mediterranean remains one of the most studied regions for its biodiversity and strong anthropogenic pressures.

A more in-depth analysis allowed us to observe the countries where the work took place. Not all papers have a very detailed description of the study area, which is why the degree of provenance, based on the country, can be different. However, it turned out that the country with the highest number of publications related to the monitoring of marine coastal biodiversity using CS is Italy (Figure 3) and this can be attributed to several factors. First of all, the geographical conformation of Italy, with a large peninsula and numerous islands, offers a variety of marine and coastal habitats that require monitoring and conservation. The growing environmental awareness and the commitment of local communities have further encouraged citizens' participation in the collection of scientific data. Furthermore, the support of institutions and universities has played a crucial role. In fact, the National Research Council of Italy (CNR) has promoted CS initiatives, recognizing the importance of citizen involvement in scientific research by establishing the "*Premio CNR per la Citizen Science: Biblioteca Guglielmo Marconi*", which held its second edition this year, promoting also projects that deal with coastal monitoring as one of the two winning projects "Seaty Lab - Citizen science per il censimento e caratterizzazione della biodiversità marina lungo la costa urbana". Participatory research projects dedicated to biodiversity, highlighting the Italian commitment to this sector (https://www.cnr.it/it/premio-citizen-science). These activities, together with the Citizen Science

Italia ETS association that promotes the development of CS in Italy, operate in an open science perspective, collaborating closely with other international networks to build inclusive tools and solutions, placing Italy among the first nations in the use of CS for coastal marine biodiversity monitoring. These elements have allowed Italy to overtake nations with larger territorial extensions, demonstrating the effectiveness of an integrated approach to scientific research and environmental conservation.

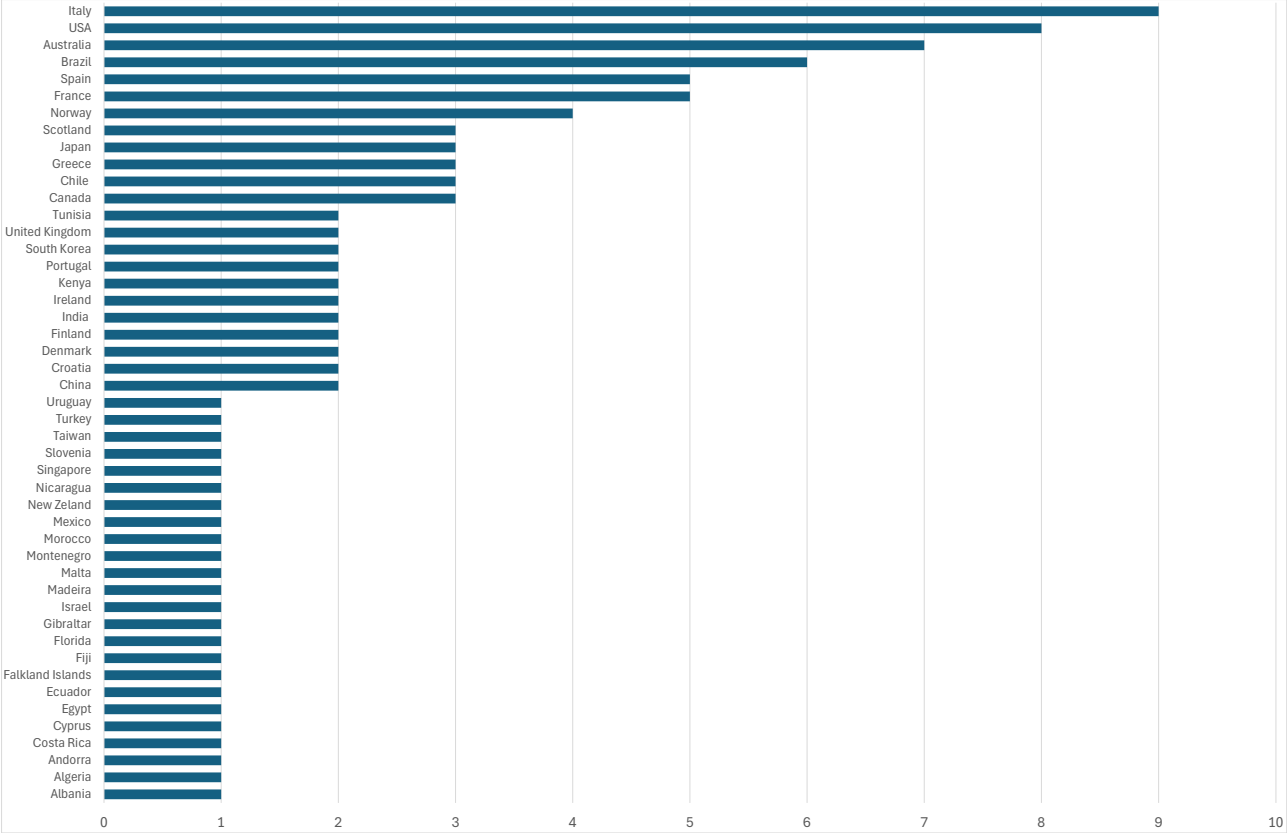


Figure 3. Number of publications on CS for monitoring coastal marine biodiversity per country.

Regarding the monitored environment, 66% of the studies exclusively concerned marine environments, underlining the centrality of *Citizen Science* in projects that require large spatial coverage and significant resources. Studies that combine the monitoring of marine and coastal environments represent 18%, highlighting the interest in transitional ecosystems (Armitage et al., 2021 – Table 1).

An important aspect of the analysis is the distribution of studies in relation to the protection regime (Table 1). 43% of the studies were conducted outside protected areas, while 36% covered both within and outside protected areas (Young et al., 2021). Only 13% have analyzed biodiverse exclusively inside protected areas, such as Marine Protected Areas (AMP - de Zwaan et al., 2024).

This result confirms the ability of *Citizen Science* to effectively monitor even areas that are difficult to reach or not a priority for research institutions.

The temporal analysis highlighted a significant growth in the number of publications starting from 2020. In particular, 2021 was the year with the highest number of publications 24%, followed by 2023 and 2024 with 20% each. 2020 represented 14% of the publications analyzed (Table 2).

From the point of view of seasonality and frequency of monitoring, most of the studies adopted a continuous approach, with campaigns carried out periodically throughout the year, to ensure sufficient temporal coverage to detect seasonal variations and long-term ecological phenomena.

For the monitored species, 65% of studies were multi-species projects, while 35% focused on single species, often alien or threatened (Compagnone et al., 2023; Grattarola et al., 2024). Studies dedicated to monitoring specific categories show a greater interest for protected or threatened species listed in the IUCN Red List 36% (28 papers - Hodgins et al., 2024), while only 5 papers (6%) have monitored alien species (Grattarola et al., 2024- Figure 4; Table 3). This shows that *Citizen Science* is being used not only for large scale projects but also for initiatives targeting vulnerable species (Hodgins et al., 2024).

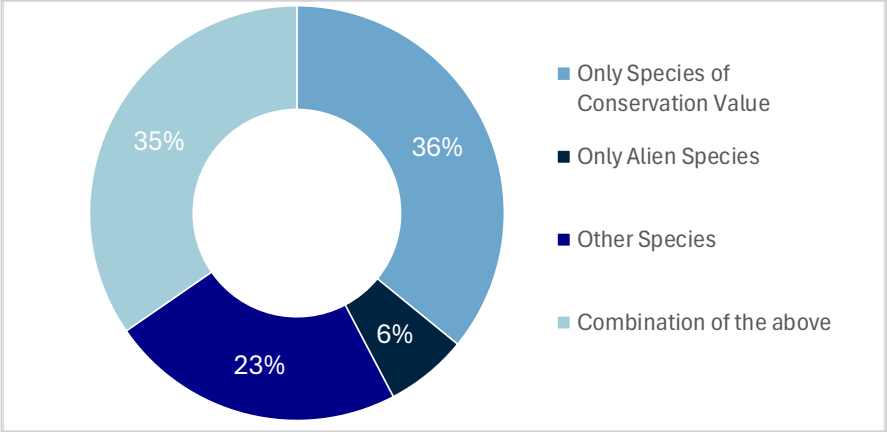


Figure 4. Percentage of research accounting of species of conservation concern (threatened or alien), other species or a combination thereof.

Analyzing the taxonomic groups of collected data by CS, it emerged that most studies concern animal species (59 articles), while only 4 studies focused exclusively on plant species, with 14 works monitoring flora and fauna together (Table 3). This imbalance can be explained by the ecological and cultural relevance of some animal species, such as cetaceans and seabirds, often used as indicators of the health status of ecosystems (Lodi et al., 2023; Rojas-Barrantes & Sandoval, 2024).

Regarding data collection approaches, almost 60% of the studies used only data collected through *Citizen Science* projects, while 40% integrated traditional methods. Furthermore, 25 studies exploited dedicated digital platforms, such as iNaturalist (https://www.inaturalist.org), eBird (https://ebird.org)

and PlantNet (https://identify.plantnet.org/it), which make data collection more accessible and precise thanks to geolocalization and species recognition features (Table 4).

Finally, the analysis of statistical methods used for analyzing CS data shows that 65% of the studies rely on descriptive analyses, while 35% use modelling approaches, such as species distribution models (SDM), which allow to predict the distribution of species based on environmental data (Table 5). This highlights a growing use of advanced methodologies to draw more accurate inferences from data collected through *Citizen Science*.

Summary tables of the preliminary analysis of papers published on CS and biodiversity in coastal areas in the period 2020-2024:

Table 1. Number of papers classified by Geographical metadata: continent, type of environment and protection regime.

A1 – Continent	n.	**A2) Type of environment**	n.	**A3) Protection constraints**	n.
Africa	5	Only terrestrial	11	Only within protected areas	10
Asia	10	Only marine	52	Only outside protected areas	34
Europa	30	Only transition (fresh or brackish water)	1	Combination of the above	28
North America	12	Combination of the above	14	NA	6
Central America	1				
South America	14				
Oceania	9				

Table 2. Number of papers considering temporal Parameters: year of publication, seasonality, frequency of data collection.

B1) Year	n.	**B2) Season**	n.	**B3) Frequency**	n.
2024	16	Seasonal	20	One-off analysis	19
2023	16	All year round	58	Periodic	59
2022	17				
2021	19				
2020	10				

Table 3. Number of papers classified by main biodiversity targets of CS data collection.

C1) Species	n.	C2) Taxonomic Group	n.	C3) Type of Category per species	n.
Single species	27	Only Flora	4	Only species of Conservation Value	28
Multi-Species	51	Only Fauna	59	Only Alien Species	5
		Other kingdoms	1	Other Species	18
		Combination of the above	14	Combination of the above	27

Table 4. Number of papers classified by the data collection characteristics: approach, source and tools.

D1) Collection approach	n.	D2) Source of CS data	n.	D3) CS data collection tools	n.
Only CS	46	Data collection from previous CS projects or dedicated platforms	20	Use of CS applications or networks (e.g. iNaturalist, eBird, Plantnet)	25
CS and other monitoring method	32	Data collection through dedicated CS campaigns, described in the work	40	Other sources	52
		Data collection through dedicated CS campaigns, described in the work	18	NA	1

Table 5. Number of papers classified by the methodology of data analysis.

E1) Geographic distribution	n.	E2) Statistic analysis	n.
SI	61	Descriptive	51
NO	17	Modeling	27

1.4 *Conclusion*

This chapter, presenting a preliminary bibliographic analysis of *Citizen Science* (CS) for monitoring marine-coastal biodiversity, has highlighted the crucial role of this participatory approach in ecological research. The results confirm that CS not only expands the capacity to monitor large and complex areas, often difficult to reach with traditional means but also contributes to improving the environmental awareness of local communities.

From a geographical point of view, Europe and the Americas represent the main research hubs, thanks to the presence of solid collaboration networks and infrastructures dedicated to *Citizen Science*.

Furthermore, ocean areas and some closed seas, such as the Mediterranean, continue to be central to marine biodiversity monitoring. The most studied environments are exclusively marine ones, confirming the need for participatory observations in complex and expensive ecosystems to monitor with traditional methodologies.

The temporal analysis has highlighted a significant growth in the number of publications starting from 2020, a sign of an increasingly widespread adoption of CS. This expansion reflects the evolution of the role of CS from an experimental method to a recognized and integrated tool in environmental monitoring programs.

Citizen science has proven to be particularly effective for monitoring animal species, often considered ecological indicators. Digital platforms, such as iNaturalist, eBird and PlantNet, have played a key role, in making monitoring more accessible and facilitating accurate and georeferenced data collection.

Despite progress, some methodological challenges remain. Most studies are limited to a descriptive analysis of the collected data, while a minority uses advanced modelling approaches. The adoption of more sophisticated techniques represents a promising direction to improve data interpretation and support more effective management decisions.

In summary, *Citizen Science* is now a fundamental pillar of marine-coastal monitoring, thanks to its ability to integrate research, education and community engagement. However, to ensure further growth and greater scientific accuracy, it will be necessary to invest in innovative technologies, global collaborative projects and training programs for *Citizen Scientists*. These efforts could contribute not only to the protection of biodiversity but also to the creation of a widespread culture of environmental responsibility.

Chapter 2 - Coastal Biodiversity Assessment Aided by *Citizen Science* Volunteers: A Look at the Italian Central Adriatic

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Article

Coastal Biodiversity Assessment Aided by Citizen Science Volunteers: A Look at the Italian Central Adriatic

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Abstract: Coastal ecosystems, encompassing land and marine environments and hosting substantial biodiversity, are among the most threatened worldwide. The European Habitats Directive prioritises coastal habitats and species, requiring legislative, direct protection, monitoring, and informational measures. Accurate habitat and species monitoring is crucial to conservation efforts, yet biodiversity research in complex, ever-changing environments like coastal areas is difficult. Citizen Science may bridge biodiversity assessment and eco-friendly monitoring by incorporating non-scientists into the data collection for scientists and stakeholders. A Citizen Science approach supported by a dedicated iNaturalist project (called Wild Coast CASCADE) was implemented to obtain a complete monitoring framework that includes observations of many taxa in terrestrial, aquatic, and transitional dynamic coastal environments in the Central Italian Adriatic coast. We explored data gathered focusing on the IUCN Red List species, the species and habitats of European conservation concern, and the non-native species. Between 2020 and 2023, we collected 3784 records covering 742 species, with 81% meeting the "research grade criteria", and these were retained for subsequent research. Citizen Science volunteers have collected 291 georeferenced animal records from the global IUCN Red List, 51 plant species from 14 species that are indicators of the presence of habitats of European Conservation Concern, and 44 non-native plants and animals. Our results provide evidence that citizen research projects can effectively assist in monitoring coastal–marine habitats and species. They also underline the potential of Citizen Science for biodiversity conservation and emphasize the importance of public engagement in conservation efforts.

Keywords: cross taxa monitoring; iNaturalist; Habitats Directive; European regulation on alien species; IUCN Red List; Long-Term Ecological Research sites

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1. Introduction

Coastal ecosystems are characterised by dynamic transitional zones between terrestrial and marine environments, exhibiting significant levels of specialised biodiversity [1,2]. Not only do they possess significant quantities of unique flora and fauna, but they also offer a multitude of benefits to society and ecosystem services [3,4]. Simultaneously, coastal areas are ranked as one of the most at risk in the world [5,6], with the Mediterranean region being particularly vulnerable [7,8]. To mitigate the ongoing deterioration of these imperilled habitats, they are subject to conservation restrictions that have been imposed at

both the global and regional level. The Convention on Biological Diversity [9] underscores the importance of allocating focused attention and financial resources to the preservation of biodiversity in coastal areas. The Member States of the European Union have collectively embraced the Council Directive 92/43/EEC, more often known as the Habitats Directive (HD). This legislation represents an important step forward in the development of a European approach to nature conservation. The HD designates numerous coastal ecosystems as habitats that require conservation efforts. These habitats are specifically mentioned in Annex I of the directive. Additionally, the HD identifies certain coastal species of flora and fauna that are of conservation importance. These species are included in Annexes II, IV, and V of the Habitats Directive, deserving either direct (the species) or indirect (their habitat) protection. Art. 17 of the directive impose all member states to monitor and report every six years on the distribution and conservation status of all species and habitats listed in Annexes I, II, IV and V. Furthermore, it establishes a comprehensive network of biologically significant areas referred to as the Natura 2000 network, aiming to preserve these ecosystems and species in a state of "good conservation status". Each Natura 2000 site is obligated to develop and implement the essential measures and actions required to guarantee the enduring preservation of the designated species and habitats as stipulated by HD. These measures must encompass regulatory, direct protection, monitoring, and information-based strategies. The importance of precise monitoring of habitats and species is widely acknowledged as a crucial element of successful conservation strategies [10,11]. However, conducting periodic biodiversity assessments in complex and ever-changing environments such as coastal transitions can be problematic. This difficulty stems from a variety of factors, including the high costs involved [12,13], poor accessibility to specific sampling locations [14], and the intricate nature of organising field campaigns that require frequent and regular intervals [15].

Citizen Science (CS) is a potential solution for bridging the divide between biodiversity assessment and the implementation of efficient and economical monitoring practises [16]. Citizen Science encompasses the participation of non-professional citizens in many scientific activities, including data collection and analysis, technology development, species occurrence assessment, and the dissemination of these endeavours [16]. The continuous expansion of online platforms and the introduction of novel digital technologies are facilitating a significant increase in the engagement of CS activities [16,17]. Volunteer participation in environmental data collection fosters their connection to research subjects, while also raising public awareness about pressing issues such as biodiversity loss, climate change, environmental contamination, and the spread of invasive species [18]. Furthermore, CS efforts have shown favourable improvements in citizen behaviour, encouraging a more environmentally concerned and scientifically engaged citizenry [19]. At the same time, there is empirical support for the impact of data acquired by CS endeavours in the surveillance of distinct ecological systems, such as forests or savannas [20–22]. CS may also contribute to increasing public awareness in long-term monitoring areas [23,24]. Certain studies have specifically focused on investigating the application of CS in the monitoring of fauna, e.g., [25,26], or flora [27]. Additionally, there are studies that have explored the use of CS for monitoring specific domains, such as water or land [28,29]. CS initiatives are frequently aimed at specific tasks, such as implementing environmental education for youth [30–32], studying the presence of rare or less attractive species [33,34], or even monitoring biological invasions [35,36]. Yet, the studies that simultaneously analyse organisms belonging to distinct kingdoms are still scarce [37–39]. Moreover, the use of CS to support the implementation of a comprehensive observation framework, which includes observations of many taxa in various terrestrial, aquatic, and transitional dynamic systems in coastal regions, has not been attempted thus far, and it is necessary to enhance our comprehension of how CS can function in such a context.

iNaturalist [40] is a social networking platform that was founded in 2008 to facilitate the collaboration of individuals from various scientific backgrounds, including professionals and laypeople, to collectively document and disseminate discoveries related to

biodiversity [40]. This platform is well recognised as an efficient networking service for the purpose of observing biodiversity and preserving associated data within the realm of CS activities. iNaturalist relies on a substantial user base of over six million registered participants, serving as a hub for scientists, naturalists, biologists, and citizens alike who are interested in advancing online CS endeavours and facilitating the gathering of biodiversity data [40]. The collection consists of more than 160 million verifiable observations, with a continuous growth rate, and each observation is accompanied by details, including the geographic location and date of observation. The dataset excludes observations of organisms that are held in captivity or those that have been cultivated. Notably, around 100 million of these observations have achieved the designation of "research grade", indicating their credibility and suitability for scientific applications (as of 10 October 2023). The iNaturalist programme has been recognised as a key tool for collecting biodiversity data in multiple nations globally [41]. Moreover, it has gained significant popularity as a social platform for consolidating nature-related data [12]. According to [42], the platform has the capacity to significantly contribute to the implementation of conservation strategies by providing useful data to many stakeholders, including research initiatives, land managers, environmental organisations, and the wider public.

Within this framework, the current study aims to examine the capacity of CS initiatives facilitated by the iNaturalist platform in monitoring biodiversity in coastal–marine regions, with a specific focus on the Central Adriatic Italian coast as a designated experimental site. For this purpose, we established a specialised iNaturalist project known as the "Wild Coast CASCADE" (WCC) and subsequently investigated critical questions pertaining to the preservation of biodiversity within these regions by means of CS. Subsequently, we focused our attention on those data pertaining to taxonomic groups that are of conservation significance. These groups include (a) species that are listed in the IUCN red book and are also present in the annexes of HD, (b) plant species that serve as indicators for the occurrence of habitats that are of conservation concern in Europe (HD), and (c) non-native species. Focusing on these three species groups can meet different needs in conservation biology. Firstly, the updated distribution of vulnerable species might potentially enhance devoted monitoring and conservation efforts. Secondly, investigating the occurrence of plant species that serve as indicators of European habitats may allow us to propose specific management priorities for the analysed coasts. Finally, the inclusion of current and accurate data regarding the occurrence of alien organisms can enhance the effectiveness of the early detection systems for invasive species.

2. Materials and Methods

2.1. Study Area

Biodiversity data were gathered from the coastal areas of the Abruzzo and Molise regions in Central Italy, along the Italian Central Adriatic coast. The study area, spanning a total distance of roughly 166 km and encompassing a landward extent of 300 m and a seaward extent of 500 m, exhibits a Mediterranean climate. This stretch of coast is distinguished by expanses of sandy or gravelly/pebbly beaches that are occasionally interrupted by rocky promontories and interspersed with the mouths of rivers. Previous studies evidenced the high ecological significance of the analysed coasts [43,44]. The southern sector is characterised by seashores mostly composed of gravel and pebbles (Abruzzo), while the southern tract (Molise) is predominantly characterised by low dunes. As far as bathymetry is concerned, the entire study area is characterised by very shallow depths, with the depths sloping gently from the coast towards the open sea [45].

The study area comprises a total of eleven areas under differ types of protection, including 1 marine protected area, 3 regional reserve sites, and 7 Natura 2000 sites (Figure 1), all requiring biodiversity monitoring activities, as mandated national and international regulations. In addition, the area includes two sites of the Long-Term Ecological Research Network (LTER), specifically referred to as "Foce Saccione-Bonifica Ramitelli" (IT20-003-T)

and "Foce Trigno-Marina di Petacciato" (IT20-002-T; [46]; https://deims.org/6d7ffd99-40e1-4f0d-ad26-6904581dbe9b (accessed on 1 August 2023)).

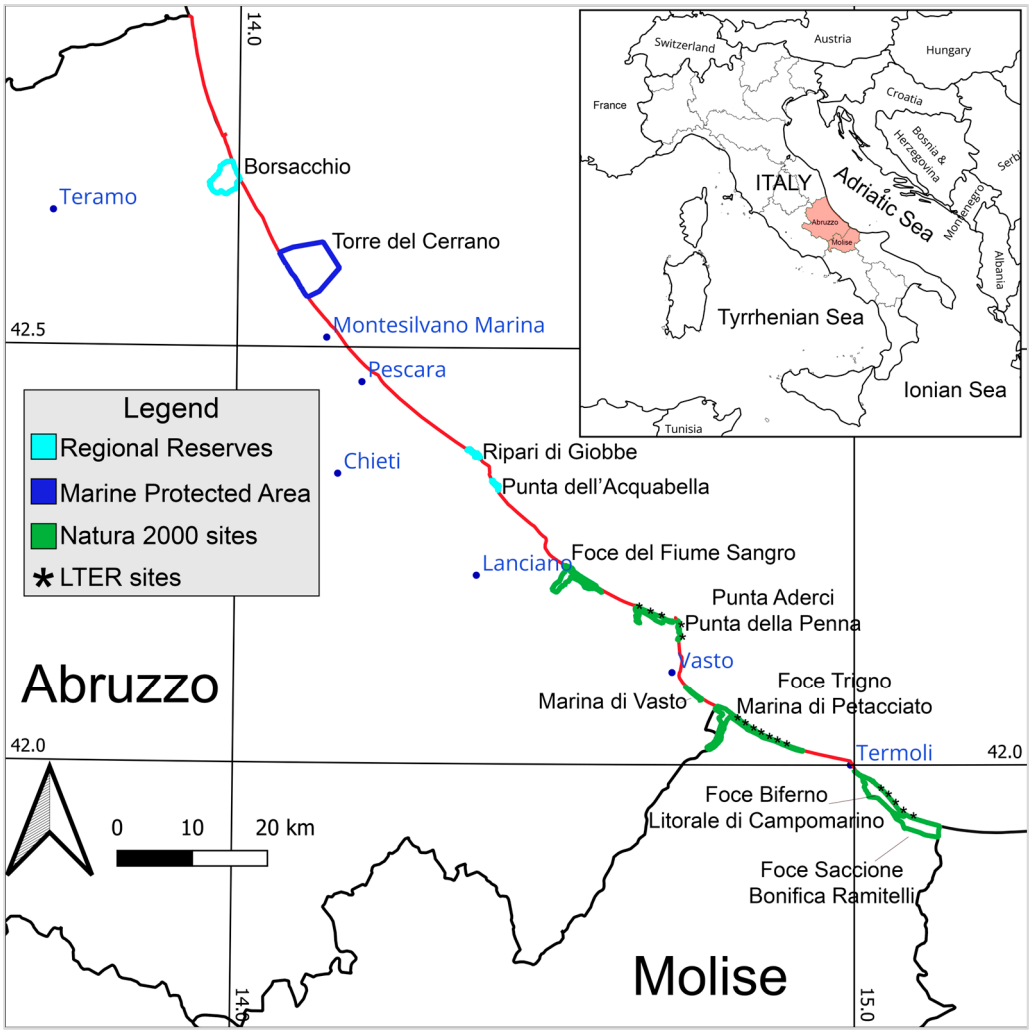


Figure 1. Central Adriatic coast of the Abruzzo and Molise Region (Italy). Protected areas are reported in different colours, with the Natura 2000 sites in green (IT7140107-Lecceta litoranea di Torino di Sangro e foce del Fiume Sangro; IT7140108-Punta Aderci—Punta della Penna; IT7140109-Marina di Vasto; IT7228221-Foce Trigno—Marina di Petacciato; IT7222216-Foce Biferno—Litorale di Campomarino; and IT7222217-Foce Saccione—Bonifica Ramitelli), regional reserves in cyan (Riserva naturale del Borsacchio; Ripari di Giobbe-Foce Fiume Moro; Punta dell'Acquabella), and the Marine Protected Area in blue (Torre del Cerrano, annexing on emerged dunes a Natura 2000 site IT7120215). Asterisks indicate the LTER sites (IT20-002-T in the north and IT20-003-T in the south). The name of the main cities (with more than 30,000 residents) are reported in blue text as the analysed seashore (Abruzzo and Molise Regions) is indicated with a red line.

2.2. Data Collection

Data were collected through CS initiatives, which included active engagement in public outreach and educational activities that began in August 2020 (for details, see Figure 2). We sent invitations to a diverse group of people, requesting their cooperation and participation in the process of collecting data on the presence of wild species in both natural and semi-natural sites. From 2020 to 2022, a total of 12 CS initiatives along the Central Adriatic coast were coordinated and implemented in collaboration with local NGO's, such as "Ambiente Basso Molise" (http://ambientebassomolise.blogspot.com/ (accessed on 1 August 2023)) and the Abruzzo Institution for Protected Areas (IAAP, https://www.iaap.it/

(accessed on 1 August 2023)), along with protected area management bodies such as the Marine Protected Area "Torre del Cerrano" and the Special Area of Conservation Punta Aderci–Punta della Penna (IT7140108). Our initiative was partially supported by the INTERREG Italy–Croatia CASCADE project (https://www.italy-croatia.eu/web/cascade (accessed on 1 August 2023)) and the LIFE17 NAT/IT/000565 CALLIOPE project (https://lifecalliope.eu/ (accessed on 1 August 2023)).

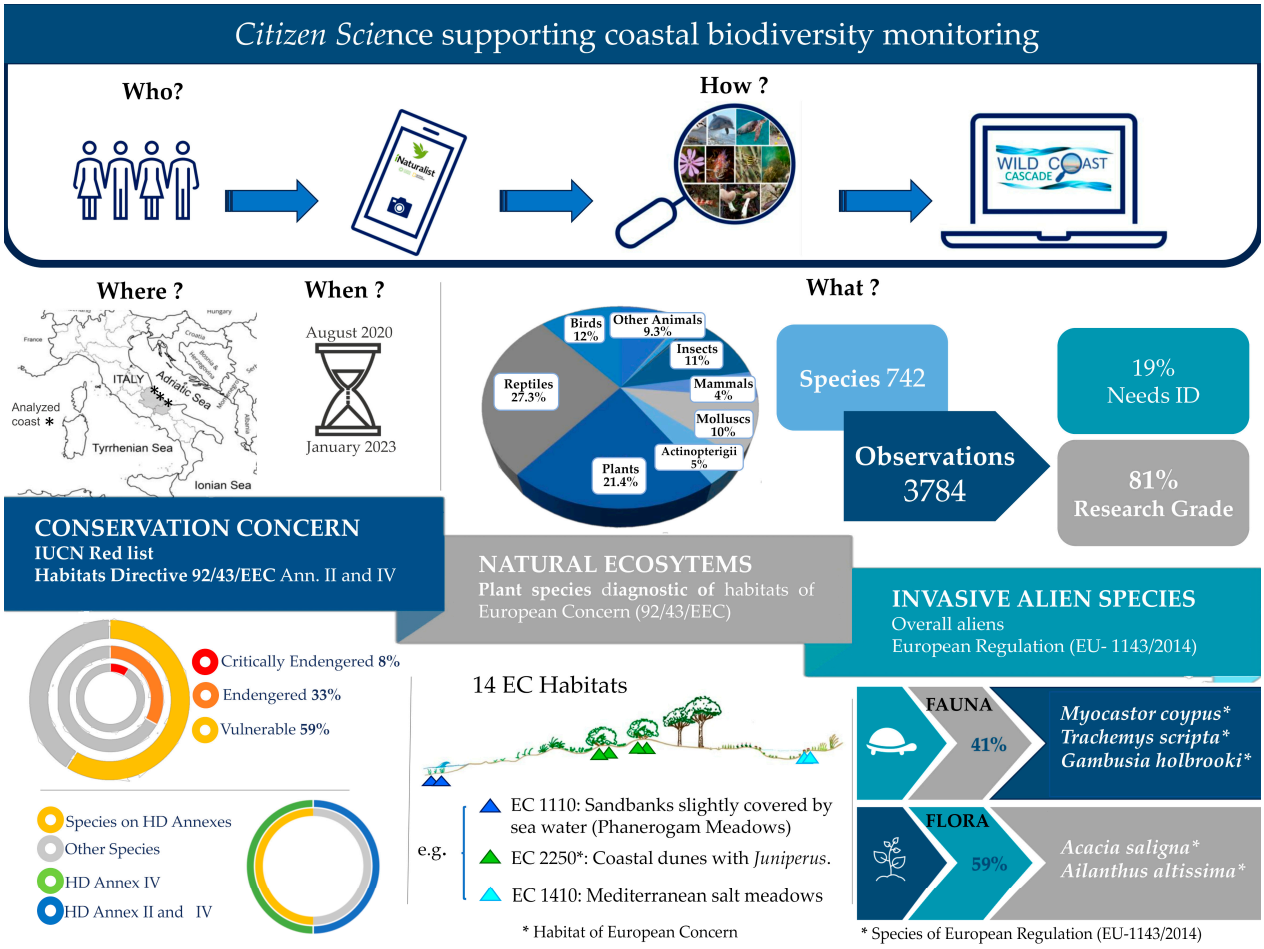


Figure 2. Flowchart depicting a synthetic overview of the adopted approach.

2.3. Data Storage and Organization

The WCC records were obtained from a diverse range of sources, including organised CS events and the independent leisure activities of individuals. These records were collected from the beginning of August 2020 to the end of January 2023 and involved the participation of hundreds of observers (Figure 2). Data were systematically collected within a dedicated iNaturalist project known as the "Wild Coast CASCADE" (WCC) (https://www.inaturalist.org/projects/wild-coast-cascade (accessed on 1 August 2023)). Each individual observation submitted to the WCC project consisted of one or more field photographs, precise geographic coordinates, and a proposed taxonomic identification provided by the iNaturalist criteria (for the full explanation of how iNaturalist works, please refer to https://www.inaturalist.org/pages/help#general3 (accessed on 1 August 2023)). In addition to the iNaturalist platform, we established a specialised Facebook webpage that offered people with low computer experience the chance to submit observations that the managers of the WCC will then upload to iNaturalist on their behalf.

The comprehensive evaluation of the quality of each observation involved an initial classification of the newly submitted entry as "Needs ID", indicating the requirement for

verification and potential correction by members of the iNaturalist community who possess expertise in the relevant taxonomic categories.

After achieving a consensus among a majority of specialists (i.e., more than two-thirds) who verified the identification of the organism at the species level, the observation was subsequently elevated to the category of "research grade". This categorization enhances the suitability of the data for scientific utilisation (Figure 2). The data collected consisted of a wide range of living organisms, representing different taxonomic levels. The aforementioned observations were categorised according to the 13 taxonomic groups acknowledged by iNaturalist, namely Actinopterygii, amphibians, arachnids, birds, chromists, fungi and lichens, insects, mammals, molluscs, plants, protozoa, reptiles, and other animals [40].

2.4. Data Extraction and Analysis

We first classified data on iNaturalist taxonomic groups and evaluated the reliability of the observations collected, keeping for further analysis the records that had reached the "research grade".

The number of threatened species (Figure 2) collected within the WCC project was assessed by relying on the global [47] and Italian [48] IUCN Red Lists. Additionally, the conservation concern level of these species in Europe was determined by referring to the annexes of the HD. The IUCN Red List provides a comprehensive and up-to-date assessment of the conservation status and risk of extinction for various biological species. These species are classified into nine categories, and, among these, we focused on critically endangered (CR), endangered (EN), vulnerable (VU), and near threatened (NT). The annexes of the HD consist of a list of species that member states of the European Union have agreed to safeguard and regulate through a range of measures. These measures include the designation of Areas of Special Conservation Interest (Annex II), the establishment of stringent protection rules (Annex IV), and the development of national management plans (Annex V).

As for the analysis on plant species that represent "diagnostic taxa" (Figure 2) according to the HD, we followed the nomenclature recommended in the updated checklist of "Flora d'Italia" [49]. These species are of outmost importance in influencing the composition and operation of these habitats. Because of their importance to the general functionality and survival of the ecosystem, they are also known as "focal species" [50]. The identification of diagnostic species was based on the "Italian Vegetation Prodrome" [51] and the European Union's Habitat Interpretation Manual [52].

Subsequently, we shifted our attention towards an analysis of alien and invasive species (IAS; Figure 2) that are included in the European regulation known as "on the prevention and management of the introduction and spread of invasive alien species" (Regulation (EU) No. 1143/2014, hereafter referred to as the IAS Regulation). The IAS Regulation delineates a catalogue of invasive alien species categorised as being of "Union concern". These species pose a threat to biodiversity and ecosystem services, necessitating coordinated efforts at the European Union level [53]. The determination of the origin of non-native species was also established by Galasso et al. [54] and Loy et al. [55]. In our analysis of plant species, we incorporated the research conducted by Galasso et al. [54] and its subsequent revisions [56,57]. Regarding the fauna, we conducted a thorough examination of the data provided by the Global Biodiversity Information Facility (GBIF) platform (https://www.gbif.org (accessed on 1 August 2023)). Additionally, we conducted a quick analysis of the plant species that are poisonous to humans based on information from the iNaturalist platform and consulting some of the relevant literature (e.g., [58]).

3. Results and Discussion

As of 31 January 2023, the WCC project has documented a total of 3,784 observations by 250 distinct users pertaining to 742 species across diverse ecosystems (terrestrial and aquatic; Table 1). The research has acquired a large number of observations collected systematically through time and across diverse coastal ecosystems (terrestrial and aquatic).

These observations provide compelling evidence of the efficacy of the dedicated CS activities, as well as the valuable contributions made by people during their leisure activities. During the summer season, the coastal regions under study attract a significant number of tourists. However, during the winter and fall seasons, these sites are frequented by schools and local people [4]. Scaling with the study area extent, our collection of data showed figures that are comparable to previous studies conducted in various regions, such as California, Scandinavia, South America, and North Asia [59]. Our findings also align with the research conducted by international institutions, including natural history museums [30].

Table 1. Number of observations that are "research grade" and species per iNaturalist taxa, along with the respective percentages.

iNaturalist Macro-Categories	Number of Observations	% of Observations	Number of Species	% of Species
Actinopterygii	168	5%	53	7%
Amphibians	10	<1%	3	<1%
Arachnids	50	1%	18	3%
Birds	434	12%	82	11%
Chromists	8	<1%	2	<1%
Fungi and lichens	11	<1%	2	<1%
Insects	415	11%	161	22%
Mammals	162	4%	8	1%
Molluscs	358	10%	79	11%
Other animals	350	9%	94	13%
Plants	784	21%	230	31%
Reptiles	1034	27%	10	1%
Total	3784		742	

As for the number of records per taxonomic group, reptiles account for 27% of total records, making it the most observed group, followed by plants (21%), birds (12%), and insects (11%). The less represented categories (with less than 1%), include amphibians, fungi and lichens, and chromists (Table 1). A substantial percentage of species is also present among the category of other animals, i.e., 13%. On iNaturalist, this macro-category collects a series of taxonomic categories, such as Cnidaria, Arthropoda, and Chordata, without any distinction and in which we have identified species of considerable importance.

The high number of reptile observations is mainly attributed to records of *Caretta caretta*. In recent years, this species has been recolonising and returning to historical nesting sites along the coasts of Spain, France, and Western Italy [60], with the WCC project providing evidence of this ongoing process also in the Adriatic.

Plants was the most diverse taxonomic category, with 236 species recorded (31%), followed by insects (163 species; 22%). Birds are another taxonomic group that has a significant number of reports and species (82 species, 11%). In this case, it is highly probable that this pattern is associated with the sea–land ecotone, which provides a diverse range of trophic niches [61].

Conversely, the lowest represented taxonomic groups, each comprising less than 1% of the total, were fungi and lichens (two taxa), chromists (two taxa), and amphibians (three taxa) (Table 1). Such a distribution of reports is congruent with earlier iNaturalist studies that have identified plants and insects as the most often observed groups [59]. Plants and insects in the studied area showed a great species diversity, which is indicative of the extensive ecological mosaic influenced by a pronounced environmental sea–land ecotone. This ecotone, found within relatively narrow coastal strips, facilitates substantial turnover rates of plant species [62] and arthropods [63].

The "research grade" status achievement, indicating species that have undergone thorough review, was observed in 81% of the cases (Figure 3). The "research grade" was reached according to iNaturalist criteria of at least 2/3 of users agreeing on an identification,

and, in our case, most of the observations (81%) reached "research grade", with 1 or 2 users in agreement with the submitting user. Less than 1% of the "research grade" observations showed any remaining disagreement among users on the determination of the specimen. This highlights the significant potential of CS activities in involving a high number of well-trained citizens who are able to improve collected data reliability, thus confirming the usefulness of the iNaturalist platform in the context of future research and conservation endeavours, despite some research highlighting limitations and biases in the iNaturalist approach [64–66], including errors or undersampling in less known and charismatic taxa, while well-known taxa or charismatic species might be oversampled. Accordingly, it is worth mentioning that both amphibians and reptiles have attained a "research grade" status of 100% for all their recorded observations (Figure 3). The higher quality of these observations can be primarily attributed to the number of records related to a few easily recognizable species. For example, the abundance of reptile observations at the "research grade" is mainly due to the loggerhead turtle (*Caretta caretta*) and the Italian wall lizard (*Podarcis siculus*) records, while for amphibians, it includes several observations of the Balearic green toad (*Bufotes balearicus*) and the marsh frog (*Pelophylax ridibundus*).

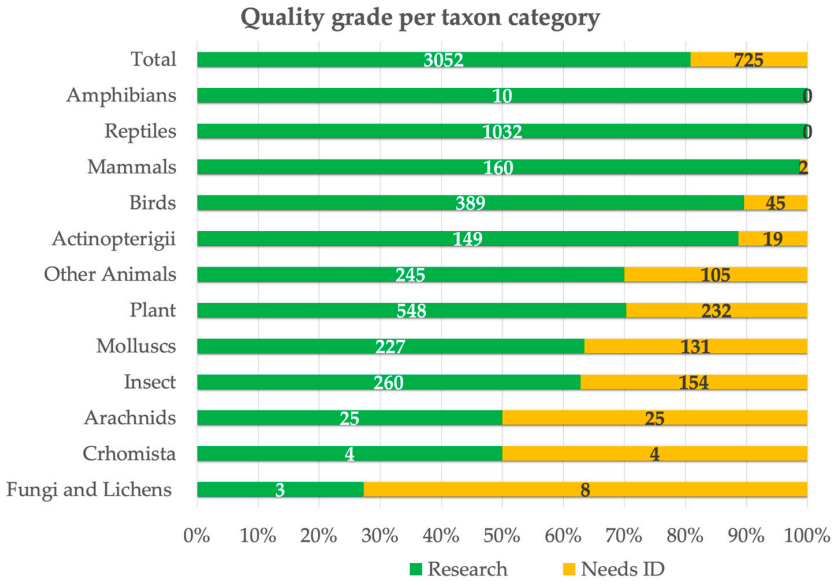


Figure 3. Number and percentage of observations at research level and on need of ID for each iNaturalist macro-category.

Among the other macro-categories, most taxonomic groups reached the "research grade" for at least the 50% of the records. Only fungi and lichens had less than 30% of their observations at the "research grade" (Figure 3). As observed by Barbato et al. [34] in regard to marine environments, most of the reports that did not reach the "research grade" (19% requiring identification) are not readily identifiable and classifiable by photographic evidence. The 30% of plant records that have not achieved the research status can be ascribed to the phenology and seasonal variability of species features (e.g., flowers and fruits), which enable identification only within a short time frame [26].

3.1. Species of Conservation Concern

The WCC has documented a total of 291 observations (Table 2) of species that fall within the global IUCN Red List [47]. These observations pertain to 17 species that have been classified as critically endangered (CR—5.9%), endangered (EN—17.7%), vulnerable (VU—47.0%), or near threatened (NT—29.4%). Among the most threatened taxa, we documented the occurrence of one critically endangered species (Fan Mussel—*Pinna nobilis*) and three endangered (EN) species (namely *Testudo hermanni*, *Cladocora caespitosa*, and *Chelonia mydas*).

The critically endangered Fan Mussel (*Pinna nobilis* Linnaeus, 1758), the largest long-lived endemic bivalve species in the Mediterranean Sea [67], has faced a significant decline since 2016, primarily attributed to infections caused by pathogens. This infection likely heightened the species' susceptibility to changes in water temperature, resulting in sporadic occurrences around the Adriatic seashore [68]. The reported occurrence of *Pinna nobilis* within the WCC project can help enhance scientific research and guide future monitoring efforts. The occurrence areas of *Pinna nobilis* can serve as pilot sites for implementing reinforcement actions aimed at boosting the population of the species [69]. Moreover, they can guide habitat restoration plans and facilitate the implementation of protection actions required by the HD for species listed on Annex IV.

The Hermann's tortoise (*Testudo hermanni* Gmelin, 1789) is an endangered terrestrial Testudinidae that is native to the northern coastal region of the Mediterranean and occurs in Italy with a fragmented distribution [70]. The Hermann's tortoise exhibits a preference for well-preserved coastal dune mosaics throughout the Adriatic coast that consist of many habitats that are of conservation concern [71]. Being highly susceptible to habitat deterioration [72], its occurrence underscores the high conservation status of certain coastal tracts in the Central Adriatic.

Updated data on the presence of Annex II species outside the Natura 2000 network can also help us organise monitoring campaigns targeted at expanding the network. The occurrence data collected within protected areas can aid in the implementation of targeted conservation measures for species listed on Annex IV of the HD.

The WCC also documented the presence of the endangered green sea turtle (*Chelonia mydas* Linnaeus, 1758), which has a preferential distribution on tropical and subtropical waters and a reduced presence in temperate regions [73]. The green turtle population in the Mediterranean Sea is highly susceptible to the effects of climate change and human activities, which have a detrimental impact on all stages of its life cycle, from eggs to adult individuals [74]. The significance of our observations is heightened by recent research that highlights the strategic importance of the Adriatic basin for the conservation of green turtle populations [60]. Furthermore, the new data on green sea turtle's occurrence in the Adriatic coastal area provide valuable insights for planning additional monitoring campaigns and developing specific protection measures, as mandated by the European Union for species listed on Annex IV (HD).

Table 2. Status of threatened species registered on the WCC iNaturalist according to the global and the Italian IUCN Red Lists [48,75] along with their inclusion in HD Annexes II and IV. The number of observations and the iNaturalist taxonomic category are also reported. CR, critically endangered; EN, endangered; VU, vulnerable; NT, near threatened; LC, least concern; NE, not evaluated.

Species	GLOBAL IUCN	Italian IUCN	HD Ann.	No. of Obs.	iNaturalist Category
Pinna nobilis	CR	CR	IV	3	Mollusks
Cladocora caespitosa	EN	LC		9	Other animals
Chelonia mydas	EN	NE	IV	3	Reptiles
Testudo hermanni	EN	EN	II; IV	8	Reptiles
Caretta caretta	VU	EN	II; IV	239	Reptiles
Passer italiae	VU	VU		8	Birds
Streptopelia turtur	VU	LC		5	Birds
Palinurus elephas	VU	NE		2	Other animals
Balaenoptera physalus	VU	EN	IV	1	Mammals
Epinephelus marginatus	VU	EN		2	Fishes
Aythya ferina	VU	VU		1	Birds
Cerambyx cerdo	VU	LC	II; IV	1	Insects
Haematopus ostralegus	NT	VU		3	Birds
Calidris ferruginea	NT	NE		2	Birds
Aythya nyroca	NT	EN		1	Birds
Raja asterias	NT	NE		2	Other animals
Sciaena umbra	NT	VU		1	Fishes

The Mediterranean Pillow Coral (*Cladocora caespitosa* Linnaeus, 1767) is an endangered long-lived reef-building species indigenous to the Mediterranean Sea, where it forms scattered colonies, beds, or vast banks [76,77]. *Cladocora caespitosa* is declining in the Adriatic Sea due to its great sensitivity to pollution [78], invasive algae [79], eutrophication [80], trawling, dredging [81], and climate change. *Cladocora caespitosa* was discovered in the setting of infra-littoral algal biocenosis, providing additional evidence of the presence of the Habitat of European Concern 1170 "Reefs" on several coastal tracts where the habitat had not previously been documented. Moreover, the WCC's new knowledge may enable future scientific campaigns to adequately record and map the Reef EU habitat, updating its distribution range in the Central Adriatic area and extending the execution of necessary conservation actions [77].

The loggerhead sea turtle (*Caretta caretta* Linnaeus, 1758) has a broad distribution in the Mediterranean Sea [11]. The Italian breeding population of *Caretta caretta* plays a crucial role in preserving the genetic diversity of the species [82]. The species is classified in the national Red List as endangered [48], as it suffered a serious decline in Italy that were caused by multiple threats, such as urban expansion, human trampling, and pollution [83]. The recorded occurrences and nesting sites for *Caretta caretta* in the WWC database fill the information gap concerning the Central Adriatic coast, where, until about ten years ago, there was a lack of recorded nesting sites [84]. Furthermore, the current distribution data can be instrumental in guiding scientific research and the development of suitable conservation measures for Italian populations, as advocated for species listed on Annexes II and IV of the Habitats Directive (42/93/EEC).

The investigation of the WCC database, with a focus on endangered species, demonstrates how CS can be used to monitor various types of wildlife in need of conservation. This indicates an essential issue that necessitates additional research [85]. The abundance of georeferenced recordings of species listed on the IUCN Red List and in the HD annexes allows us to generate a comprehensive picture of the priority areas of the Central Adriatic coast that require concerted conservation efforts. Our findings highlight the potential of CS for biodiversity monitoring, a task that is frequently performed for a single taxon. The biodiversity data acquired in these broad areas can play a critical role in the development of integrated coastal management strategies. These strategies should successfully include the conservation needs of each taxon or group of taxa within the geographical framework offered by protected area networks such as the Natura 2000 network and regional/national protected areas.

3.2. EU Habitats

In WCC, we recorded 51 plant species which are diagnostic of 14 habitats of European Conservation Concern (Table 3). Our results reveal the presence of the typical ecosystems of dune zonation from the halo-nitrophilous formations on the drift-line to the fore dune woody formations (e.g., 1210: Annual vegetation of drift lines; 2110: Embryonic shifting dunes; 2120: Shifting dunes with *Ammophila arenaria*; 2130 *: Fixed coastal dunes with herbaceous vegetation; 2230: Malcolmietalia dune grasslands; 2250 *: Coastal dunes with *Juniperus* spp.; 2260: Cisto-Lavanduletalia dune sclerophyllous scrubs; and 2270 *: Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*), some cliff formations (1240: Vegetated sea cliffs of the Mediterranean coasts with endemic *Limonium* spp.), a rich and heterogeneous salt marsh mosaic (1410: Mediterranean salt meadows *Juncetalia maritimi*; 1420: Mediterranean and thermo-Atlantic halophilous scrubs *Sarcocornietea fruticosi*; 3170*: Mediterranean temporary ponds; and 6420: Mediterranean tall humid herb grasslands of the *Molinio-Holoschoenion*), and few river (3250: Constantly flowing Mediterranean rivers with *Glaucium flavum*) and marine habitats (1110: Sandbanks slightly covered by seawater).

The data acquired validates earlier research indicating the great diversity and well-preserved dune mosaic characterising the Molise coast [86], which, in accordance with HD, is in large part included in the Natura 2000 network [4]. It also points to the necessity

of restoration efforts along the Abruzzo coastal dunes, where natural ecosystems are fragmented and poorly covered by European protection areas [87]. Conservation actions aimed at reinforcing populations of dune-building perennial grasses (e.g., *Ammophila arenaria* and *Elymus farctus*) and reducing trampling pressure, for example, may play a critical role in dune consolidation, ensuring both biodiversity values and ecological functions [88].

Table 3. List of the recorded diagnostic plant species of habitats of European Conservation Concern, along with the respective habitat code and name [89]. * Priority habitats.

Species	Habitat Code and Name
Cymodocea nodosa (Ucria) Asch.	1110: Sandbanks which are slightly covered by seawater all the time
Cakile maritima Scop. subsp. *Maritima* *Salsola kali* L. *Salsola soda* L.	1210: Annual vegetation of drift lines
Crithmum maritimum L.	1240: Vegetated Sea cliffs of the Mediterranean coasts with endemic *Limonium* spp.
Calystegia soldanella (L.) R. Br. *Elymus farctus* (Viv.) Runemark ex Melderis *Eryngium maritimum* L. *Euphorbia paralias* L. *Euphorbia peplis* L. *Lotus creticus* L. *Medicago marina* L. *Polygonum maritimum* L.	2110: Embryonic shifting dunes
Achillea maritima (L.) Ehrend. et Y.P. Guo *Ammophila arenaria* LK. *Anthemis maritima* L. *Cyperus capitatus* Vand. *Echinophora spinosa* L. *Eryngium maritimum* L. *Lotus creticus* L. *Pancratium maritimum* L. *Sixalix atropurpurea* (L.) Greuter and Burdet	2120: Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes)
Glaucium flavum Crantz	3250: Constantly flowing Mediterranean rivers with *Glaucium flavum*
Euphorbia terracina L. *Verbascum niveum* subsp. *garganicum* (Ten.) Murb.	2130 *: Fixed coastal dunes with herbaceous vegetation (grey dunes)
Artemisia campestris L. *Erodium laciniatum* (Cav.) Willd. *Lagurus ovatus* L. *Malcolmia ramosissima* (Desf.) Thell. *Matthiola incana* (L.) R. Br. *Ononis variegata* L. *Silene colorata* Poir. *Verbascum niveum* subsp. *garganicum* (Ten.) Murb.	2230: *Malcolmietalia* dune grasslands
Asparagus acutifolius L. *Juniperus macrocarpa* Sm. *Myrtus communis* L. *Phillyrea angustifolia* L. *Pistacia lentiscus* L. *Rhamnus alaternus* L. *Smilax aspera* L.	2250 *: Coastal dunes with *Juniperus* spp.
Asparagus acutifolius L. *Cistus creticus* L. *Cistus salviifolius* L. *Phillyrea angustifolia* L. *Pistacia lentiscus* L. *Rhamnus alaternus* L. *Rosmarinus officinalis* L. *Smilax aspera* L.	2260: *Cisto-Lavanduletalia* dune sclerophyllous scrubs
Phillyrea angustifolia L. *Pinus halepensis* Mill. *Pinus pinea* L. *Pistacia lentiscus* L.	2270 *: Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*

Table 3. *Cont.*

Species	Habitat Code and Name
Atriplex prostrata Boucher ex DC. *Blackstonia perfoliata* (L.) Huds. *Juncus acutus* L. *Limbarda crithmoides* (L.) Dumort.	1410: Mediterranean salt meadows (*Juncetalia maritimi*)
Sarcocornia fruticosa (L.) A.J. Scott	1420: Mediterranean and thermo-Atlantic halophilous scrubs (*Sarcocornietea fruticosi*)
Schoenus nigricans L. *Scirpoides holoschoenus* (L.) Soják *Tripidium ravennae* (L.) H. Scholz	6420: Mediterranean tall humid herb grasslands of the Molinio-Holoschoenion

The coastal dunes with *Juniperus* spp. form a priority habitat characterised by a distinctive *Juniperus* scrub which is mainly threatened by urban expansion, tourist pressure [90], and invasive alien plants [91]. These dune juniper thickets, which reach the northern limit of their geographical range in Molise [86], are included in a Natura 2000 site, where they provide suitable habitats for several species of fauna of conservation concern, such as the Hermann tortoise [71].

The recorded salt meadows (*Juncetalia maritimi*) are characteristic of well-preserved back-dune depressions that are periodically flooded by brackish water. Unfortunately, as with most salt meadows, they are impinged by land reclamation, changes in water regimes, urbanization, invasive species, and coastal erosion [92]. The observed habitat, which represents one of the few remaining coastal wetlands in the Mediterranean [93], is encompassed within a Natura 2000 site. These meadows may play a pivotal role in biodiversity conservation, serving as essential habitats for both resident and migratory avian species, as well as various aquatic organisms, like fish and arthropods [94].

We also have detected the presence of *Cymodocea nodosa* (Ucria) Ascherson formations on the Central Adriatic coastal seabed. *Cymodocea* meadows may play a crucial role in supporting fish populations by offering refuge to schools, facilitating the establishment of trophic niches, and serving as nursery sites [95]. Additionally, these meadows have a significant function in safeguarding coastal areas from various environmental impacts [96]. The areas of occurrence, all identified outside the Natura 2000 network, warrant dedicated field campaigns to verify and map the presence of *Cymodocea nodosa* meadows.

The record of species that are diagnostic of habitats of European concern has enabled their identification on the Central Adriatic coast. Despite the partial degradation of coastal areas, these habitats remain valuable components, serving as important seed banks for the recolonization of degraded areas and providing the natural support for their recovery. Our findings highlight the potential of CS for vegetation monitoring, a task that, in line with the Habitat Directive, is typically scheduled every 5 years. However, this time interval may be inadequate for studying highly dynamic ecosystems like dunes [97]. Citizen Science could also help indirectly to monitor the anthropogenic pressures that most affect habitat and species of conservation concern, providing essential information for their proper management.

3.3. Alien Species

We registered 109 records of 44 non-native species (Tables 4 and 5). We specifically reported the presence of 25 alien plants (57%) and 19 species of non-native fauna (43%). It is worth noting that six of the alien plants belong to the taxonomic family *Asteraceae*, which is distinguished by its mostly anemophilous dispersal mechanism, making them particularly effective in the processes of expansion and colonization. The substantial number of *Asteraceae* species aligns well with the overall composition of alien flora in Italy [54] and Europe [98]. Instead, the number of *Poaceae* records appears relatively low in comparison to Italy's alien flora. This is likely due to the difficulty in identifying these

species, which poses a challenge for both regular citizens in the field and professionals who rely solely on uploaded photos.

In terms of life forms, we found a significantly higher number of perennial plants, including herbs, shrubs, and trees, than the national average [99]. This is most likely due to their extensive and long-lasting vegetative structures, which allow them to be identified all year. In contrast, we have documented fewer annuals than the national list of non-native plants [54], which can be attributed to the limited season observational window of annuals.

Two of the alien plants, namely *Acacia saligna* and *Ailanthus altissima*, have been identified as invasive species of European Union concern [53]. For these two species, the Italian government is required to undertake monitoring, management, and control measures. *Acacia saligna* is among the most invasive taxa in Italy and Europe, and in the Central Adriatic coast, it mostly colonises back dune habitats, impinging several habitats of conservation concern (e.g., coastal dunes with *Juniperus* spp., dunes with sclerophyllous vegetation of Cisto-Lavanduletalia, and wooded dunes with *Pinus pinea* and/or *Pinus pinaster*). This information is supported by the studies conducted by Marzialetti et al. [100]. *Ailanthus altissima*, commonly known as the Tree of Heaven, is a highly invasive plant that is present on every continent except Antarctica. Its primary distribution in its invasive range includes urban areas, from where it has expanded into neighbouring natural and semi-natural environments [101]. *Ailanthus altissima* provides significant negative impacts on biodiversity by altering the vegetation structure, degrading soil properties, and threatening ecosystem stability [102]. The WCC has identified the existence of several invasive species of European Union concern within the Adriatic coast's network of protected areas. These occurrence data can be used to lead future dedicated field investigations targeted at detecting and mapping alien plants, which are required for the implementation of control or eradication methods outlined in European legislation.

Table 4. List of non-native species, along with the number of reports, taxonomic family, and life form: "Tree" (phanerophytes); "Shrub" (nano-phanerophytes and woody climbers); "Dwarf" (chamaephytes); "Herb" (hemicryptophytes and geophytes); "Annual" (therophytes) (Sensu [103]) and geographic origin. Bold font highlights invasive alien species of European Union concern [53]. Superscript letters: NI, invasive neophytes; NC, casual neophytes; NN, naturalised neophytes; (Sensu [54]); TX, toxic.

Species	No.	Family	Life Form	Origin
Xanthium orientale subsp. *italicum* (Moretti) Greuter^{NI}	11	*Asteraceae*	Annual	North America
***Acacia saligna* (*Labill.*) *H.L. Wendl.*^{NI}**	9	*Fabaceae*	Tree	Western Australia
Oxalis pes-caprae L.^{NI}	7	*Oxalidaceae*	Herb	South Africa
Carpobrotus acinaciformis (L.) L. Bolus^{NI}	5	*Aizoaceae*	Dwarf	South Africa
Carpobrotus edulis (L.) N.E. Br.^{NI}	5	*Aizoaceae*	Dwarf	South Africa
Erigeron bonariensis L.^{NI}	3	*Asteraceae*	Annual	South America
Opuntia stricta (Haw.) Haw.^{NI}	3	*Cactaceae*	Shrub	Central America
Robinia pseudoacacia L.^{NI}	3	*Fabaceae*	Tree	North America
Symphyotrichum squamatum (Spreng.) G.L. Nesom^{NI}	3	*Asteraceae*	Annual	South America
***Ailanthus altissima* (Mill.) Swingle^{NI}**	2	*Simaroubaceae*	Tree	China
Datura stramonium L.$^{NI-TX}$	2	*Solanaceae*	Annual	Central/North Am.
Euphorbia maculata L.^{NI}	2	*Euphorbiaceae*	Annual	North America
Oxalis articulata Savigny^{NI}	2	*Oxalidaceae*	Herb	South America
Agave americana L.^{NI}	1	*Asparagaceae*	Shrub	Central/North Am.
Amorpha fruticosa L.^{NI}	1	*Fabaceae*	Shrub	North America
Erigeron canadensis L.^{NI}	1	*Asteraceae*	Annual	North America
Helianthus annuus L.^{NC}	1	*Asteraceae*	Annual	North America
Mirabilis jalapa L.^{NI}	1	*Nyctaginaceae*	Herb	South America
Nicotiana glauca Graham^{NI-TX}	1	*Solanaceae*	Shrub	South America
Oenothera glazioviana Micheli^{NI}	1	*Onagraceae*	Herb	North America
Opuntia ficus-indica (L.) Mill.^{NI}	1	*Cactaceae*	Shrub	Central America
Paspalum dilatatum Poir.^{NI}	1	*Poaceae*	Herb	South America
Pittosporum tobira (Thunb.) W.T. Aiton^{NN}	1	*Pittosporaceae*	Shrub	Eastern Asia
Senecio inaequidens DC^{NI-TX}	1	*Asteraceae*	Herb	South Africa
Yucca gloriosa L.^{NI}	1	*Asparagaceae*	Shrub	North America

It is also worth noting the existence of some toxic alien plants (e.g., *Datura stramonium*, *Senecio inaequidens*, and *Nicotiana glauca*) [58] that pose an additional threat to human health. Following the CS approach, special campaigns for their identification might be organised, raising people's knowledge of the risks connected with their ingestion, usage, or exposure.

The WCC recorded 40 observations of 19 alien species of fauna (Table 5). *Myocastor coypus* was the most recorded species, followed by *Trachemys scripta*. It is noteworthy that these two species, in addition to *Gambusia holbrooki*, are widely recognised as being highly invasive in Europe, thus warranting their inclusion in the European regulation [53].

Table 5. List of non-native species, along with the relative number of reports (40 for fauna), taxonomic category (taxon), and geographic origin (origin). Bold font highlights invasive alien species of European Union concern [53].

Species	No.	iNaturalist Taxon	Origin
Myocastor coypus (Molina, 1782)	13	Mammals	South America
Trachemys scripta (Schoepff, 1792)	4	Reptiles	North America
Hystrix cristata (Linnaeus, 1758)	2	Mammals	Africa
Magallana gigas (Thunberg, 1793)	2	Molluscs	Asia
Paysandisia archon (Burmeister, 1880)	2	Insects	South America
Rapana venosa (Valenciennes, 1846)	2	Molluscs	Asia
Sceliphron caementarium (Drury, 1773)	2	Insects	North America
Threskiornis aethiopicus (Latham, 1790)	2	Birds	Africa; Asia
Anadara transversa (Say, 1822)	1	Molluscs	North America
Blatta orientalis (Linnaeus, 1758)	1	Insects	Asia; Africa
Cairina moschata (Linnaeus, 1758)	1	Birds	South America
Complex *Pelophylax ridibundus* (Pallas, 1771)	1	Amphibians	Europe; Asia
Gambusia holbrooki (Girard, 1859)	1	Actinopterygii	North America
Harmonia axyridis (Pallas, 1773)	1	Insects	Asia
Isodontia mexicana (de Saussure, 1867)	1	Insects	North America
Leptoglossus occidentalis (Heidemann, 1910)	1	Insects	North America
Rhynchophorus ferrugineus (Olivier, 1790)	1	Insects	Asia
Steatoda nobilis (Thorell, 1875)	1	Arachnids	Macaronesia
Trichopoda pictipennis (Fabricius, 1781)	1	Insects	South America

The coypu (*Myocastor coypus*) is an aquatic rodent that is native to South America and was imported to Italy for fur farming [104]. The escaped individuals tend to establish themselves preferentially along riverbanks and in wetlands, leading to detrimental effects on biological diversity, ecosystems, crops, and irrigation systems. Given the severity of this invasion and the high ecological value of the studied coasts, our data underscore the urgent need to implement control and eradication measures. A management and restriction strategy for the coypu should be implemented following a thorough assessment of its current distribution along the Central Adriatic coast [104].

The pond slider (*Trachemis scripta*) is a tortoise native to North America that was introduced through the pet trade. Mostly sold as small hatchlings, they are often released by owners into natural systems during their adulthood. The pond slider can establish breeding populations and competes with native species for food resources and basking sites, also exerting strong predation pressure on the biodiversity of invaded water bodies [105]. Considering this, a deeper field evaluation aiming at better defining and comprehending the ongoing invasion became critical [106]. Such updated data could be utilised to identify the proper control mechanisms claimed by the European Union and the Italian management plan [106].

4. Conclusions

Citizen Science data from the WCC project showed the promise of this strategy, which directly engages citizens in biodiversity monitoring. Citizen research projects that are supported by the iNaturalist platform have shown that they can monitor habitats and

species in complex and ever-changing landscapes, like coastal–marine transitions. Existing and archived data, as well as prospective data from the next phase of the project, may give biodiversity study and management opportunities. The WCC is a pioneering programme that collects multi-taxa and multi-domain data, which may be useful for integrated biodiversity monitoring, especially in long-term observation sites like the LTER network [23] in the examined area.

The WCC submitted new and amended spatial data on various IUCN red book or HD annex species. The simultaneous analysis of the spatial distribution and consistency of several conservation-important species across the coastal gradient can help determine comprehensive habitat restoration strategies and implement specific protective measures claimed by international agreements and policies like the Convention on Biological Diversity [9] and the HD. The high number of species on the WCC, indicating the presence of multiple European habitats of conservation concern (HD), showed a wide range of ecosystems along the Central Adriatic coast, some of which are new to the area. In line with previous research by Drius et al. [4], the WCC's coastal transition mosaic is still largely intact.

The citizen research strategy using iNaturalist has also been helpful in catching alien species across large areas at a cheap expense. Our findings suggested that CS can help implement targeted monitoring and control actions against invasive alien species, as required by European law [53]. The WCC may help identify foreign plant and animal species, thus enabling early detection and eradication. Additionally, it may help monitor invasive taxa's regional expansion and population dynamics to ensure effective control. Lozano et al. [107] and Di Febbraro et al. [108] emphasise that the data derived from CS can improve predictions of the spread of invasive alien species, especially when used in nationwide projects.

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Chapter 3 - Exploring the contribution of a generalist *Citizen Science* project for alien species detection and monitoring in coastal areas. A case study on the Adriatic of Central Italy

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Exploring the Contribution of a Generalist *Citizen Science* Project for Alien Species Detection and Monitoring in Coastal Areas. A Case Study on the Adriatic of Central Italy

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Abstract: Coastal areas are biodiversity hotspots, providing essential ecosystem services, yet they are among the most threatened systems, particularly by alien species invasion. The European regulation on invasive alien species (IAS) highlights early detection as a key prerequisite for effective containment or eradication strategies. Traditional monitoring methods are costly and time-consuming, and *Citizen Science* (CS) may be a promising alternative. We assessed the contribution of the generalist CS project "Wild Coast Adriatic" (WCA) developed on the iNaturalist platform to the detection of alien species (AS) along the Central Adriatic coast. Using WCA, we extracted alien occurrences and explored AS seasonal patterns, geographic origins, dangers (EU regulation), and distributions inside protected areas (Natura 2000 and LTER sites). Between 2020 and 2023, WCA gathered 2194 research-grade observations of 687 species, including 139 records of 50 AS, five of which are of European concern. *Asteraceae* and *Fabaceae* (plants) as well as insects and mollusks (fauna) were the most abundant aliens. The observations increased over time, with more records concentrated in autumn and summer. Most AS come from the Americas and occurred outside the protected areas. Our results underline the contribution of CS data for detecting AS in coastal ecosystems, offering a valid support for early warning, monitoring, and management strategies.

Keywords: iNaturalist; Natura2000; LTER; marine–coastal ecosystems; European regulation on alien species

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1. Introduction

The dynamic interface between terrestrial and marine environments in coastal areas supports high levels of specialized biodiversity [1]. Coastal zones are among the most threatened ecosystems globally [2], with the Mediterranean region being particularly vulnerable to environmental and anthropogenic pressures [3]. Coastal landscapes, composed of a mosaic of habitats, are particularly fragile and vulnerable to biodiversity loss, with the invasion of alien species (AS) being one of the major threats [4,5]. The invasion of coastal areas by alien species is amplified by anthropogenic disturbances, such as urbanization, pollution, agriculture [6–9], and tourism pressure [10]. Additionally, the fragmentation of coastal mosaics intensifies the adverse effects of climate change, further increasing susceptibility to alien invasions [11,12]. AS pose a significant threat to biodiversity [13], leading to changes in species composition, degradation of habitats, and the loss of crucial ecosystem processes (e.g., productivity, nutrient cycle, and soil characteristics) [14,15] and the related ecosystem services [16,17].

The detrimental effects of AS on natural communities and ecosystems have been documented worldwide [18–20]. Numerous studies have highlighted the impact of IAPs (invasive alien plants) on native biodiversity, particularly on focal species composition and cover [15], as well as the consequent alteration of ecosystem functioning [21–23]. Studies on IAAs (invasive alien animals) also evidenced consistent negative effects on the ecological balance, hydraulic dynamics and economic sustainability of invaded aquatic ecosystems [24,25]. Biological invasions are a major concern in the Mediterranean, posing a significant threat to biodiversity conservation [26,27], with the Adriatic coast being particularly affected [28]. As with most research on invasive alien species in other ecosystems [29], studies in this region typically focus on individual habitats or sites and are often limited to one or a few species. Notably, some research has concentrated on alien vascular plants [22,30,31], while studies on alien fauna remain scarce [32]. Conserving coastal mosaics would benefit from a comprehensive overview of both flora and fauna across the landscape. Innovative and cost-effective tools, such as *Citizen Science* (CS), may offer valuable support for this initial data collection, helping professionals in prioritizing monitoring areas [33].

Biological invasions are a key concern in environmental policy [34], leading the European Union to adopt the IAS (invasive alien species) Regulation in 2014 (Regulation (EU) no. 1143/2014; hereafter referred as IAS Regulation). This regulation addresses the threat posed by invasive alien species to biodiversity and ecosystem services, listing species of "Union concern". It mandates coordinated actions among European countries for monitoring, early warning, and managing these species to mitigate their impact on biodiversity and ecosystem functioning [27,35]. The economic limitations for biodiversity management restrict the possibilities of implementing monitoring programs based on large-scale fieldwork [36]. Furthermore, systematically surveying and monitoring complex and dynamic ecosystems (e.g., coastal dunes or riverbanks) using conventional biodiversity field campaigns might not be possible due to high costs [37].

Protected areas, widely recognized as essential for biodiversity conservation and as critical barriers against the introduction, establishment, and spread of invasive alien species (IAS) [38], are increasingly threatened by IAS invasions worldwide. Managing IAS poses significant challenges for protected area managers [39]. In European protected areas, plant invasions are particularly concerning, ranking as the second most significant biodiversity threat after habitat fragmentation [40]. The prevention of IAS introduction and establishment, alongside early warning, rapid detection, and swift intervention, is widely regarded as the most effective strategy [41]. In this context, *Citizen Science* (CS) could play a valuable role in supporting proactive management through early warning and monitoring systems [42].

Given the substantial threat posed by alien species in coastal landscapes [5] and within protected areas networks [43], there is a pressing need for rapid and effective monitoring tools, and *Citizen Science* (CS) could be the optimal solution [33,36]. *Citizen Science*, by engaging public participants, enables the generation of extensive datasets across broad spatial scales and long time periods, contributing valuable knowledge to support IAS management actions. This collaborative approach produces valuable insights that can inform timely and effective management actions to mitigate invasions. Furthermore, public participation through *Citizen Science* plays a crucial role in raising awareness [44], creating learning opportunities, fostering civic engagement, and influencing policy development [45]. It also contributes to environmental management for IAS, helping to reduce their establishment, spread, and impact. The early detection of invasive alien species (IAS) is a fundamental prerequisite for any effective containment or eradication strategy [46–49], as well as for modeling future invasion risks [50,51], both claimed by the European regulation. Traditional IAS detection usually involves intensive field investigations, which can be time-consuming and costly [52]. Nowadays, the use of CS enables the acquisition of data on biodiversity and its threats in wider areas with higher visitation frequency and has expanded the range of applications in the field of IAS detection [53,54]. Moreover, CS is a

worthwhile and valid tool for the early detection of invasive alien species [55] and for the long-term monitoring of their spread [56]. Specific applications have been developed for monitoring alien species through dedicated campaigns [36,57–60] in various environments such as forests [61] and grasslands [62]. However, further research is needed to assess the effectiveness of a generalist multi-taxa *Citizen Science* project for the monitoring of invasive alien species in coastal ecosystems [42,60].

One of the most widely used platforms in CS studies is iNaturalist, a global platform that enables users worldwide to share biodiversity observations, making it a vital tool for biodiversity monitoring on an international scale [63]. iNaturalist is accessible globally, allowing users to share biodiversity data from anywhere at any time, though uploads. The platform provides open access to all data, enabling users to freely download and utilize the information for research, conservation, and educational purposes [64]. Among the methods used to gather and share biodiversity data on iNaturalist, Bioblitzes are well recognized events held in parks, natural habitats, and urban areas. These events facilitate rapid biodiversity assessments within specific geographic locations over short time frames, involving local communities and policymakers, thereby fostering a broader understanding and appreciation of environmental biodiversity [65].

While *Citizen Science* offers a powerful tool for large-scale data collection, it is subject to some limitations. Spatial biases often arise due to human population density, as areas with a higher number of inhabitants or higher visitation rates are more likely to be monitored [54]. Temporal biases also affect data quality, with higher observation rates during daylight hours and favorable weather conditions, which leads to limited data on nocturnal species and increased reporting during the summer month.

Nevertheless, the utilization of *Citizen Science* can significantly contribute by reporting new species occurrences or unobserved behaviors in local fauna and flora [66,67]. This enhanced data acquisition provides essential information for conservation and environmental management. For instance, the number of observations recorded by CS can vary considerably over time and across seasons, offering valuable insights into seasonal invasion patterns. Recent studies have shown peaks in observation activity corresponding to periods of biological activity [67], as is the case for annual plants that are visible during the growing season and can be underestimated if monitored during a single period of the year. On the other hand, many alien plant species exhibit phenological patterns that differ from those of native species (e.g., [30]), allowing them to be observed by citizens during periods when experts typically do not schedule monitoring or data collection campaigns.

In this context, the present work sets out to explore the contribution of a generalist multi-taxa *Citizen Science* project, "Wild Coast Adriatic" (WCA), developed on the iNaturalist platform, for monitoring and documenting alien species occurrences in marine–coastal ecosystems of the Central Adriatic Sea in Italy. Through this research, we aim to highlight the potential of *Citizen Science* in tackling the challenges related to monitoring alien species. Specifically, we explore how *Citizen Science* can aid in monitoring IAS within complex ecosystems, such as coastal dunes, where traditional field surveys tend to be expensive and often provide incomplete data. A generalist multi-taxa CS project like WCA, which provides a comprehensive overview of both flora and fauna across different habitats in the landscape, throughout the year, may be valuable for collecting baseline initial data and guiding the prioritization of monitoring efforts.

2. Materials and Methods

2.1. Study Area

The study area, located on the Italian Central Adriatic coast, covers approximately 166 km (Molise and Abruzzo Regions), extends 300 m inland and 500 m seaward, and is characterized by a Mediterranean climate [68,69] (Figure 1). The mean annual temperature reaches 16 °C with a yearly precipitation of 385.8 mm (data available at https://scia.isprambiente.it/, accessed on 15 June 2024) [69]. Thermo types in the area range from

meso-Mediterranean to thermo-Mediterranean, while ombro types vary from dry to humid-subhumid conditions [70].

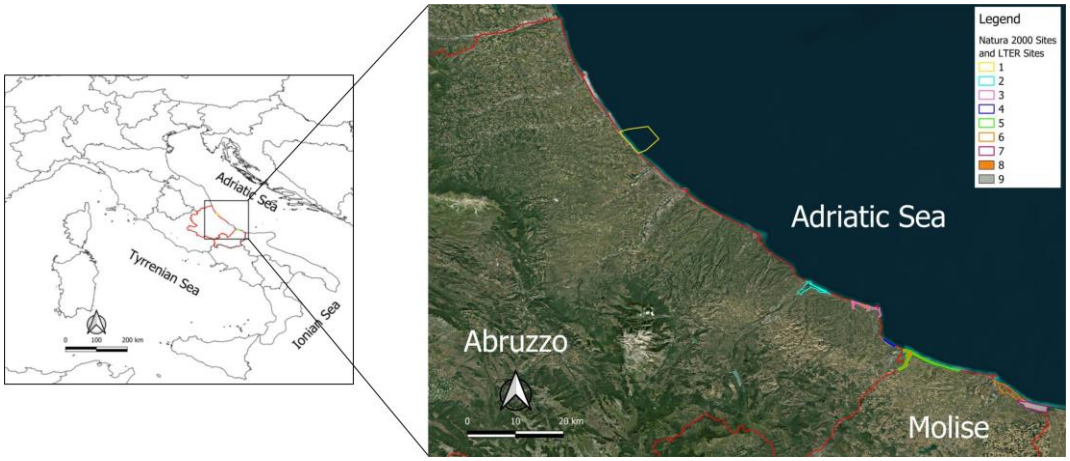


Figure 1. Study area along the Central Adriatic coast, with the boundaries of the regions highlighted in red, including seven Natura 2000 sites (1: Torre del Cerrano; 2: Lecceta litoranea di Torino di Sangro e foce del Fiume Sangro; 3: Punta Aderci—Punta della Penna; 4: Marina di Vasto; 5: Foce Trigno—Marina di Petacciato; 6: Foce Biferno—Litorale di Campomarino; and 7: Foce Saccione—Bonifica Ramitelli) and two LTER sites (8: LTER Foce Trigno–Marina di Petacciato and 9: LTER Foce Saccione-Bonifica Ramitelli).

The analyzed seashore is characterized by sandy or gravelly/pebbly beaches, occasionally interrupted by rocky promontories and river mouths. Previous research has highlighted the ecological significance of this area [71–74] that, despite anthropogenic pressure, still host several habitats that, according to the Habitats directive of the European Union (Council Directive 92/43/EEC; hereafter HD), are of conservation concern (e.g., 1210: Annual vegetation of drift lines; 2110: Embryonic shifting dunes; 2120: Shifting dunes with *Ammophila arenaria*; 2130*: Fixed coastal dunes with herbaceous vegetation; 2230: *Malcolmietalia* dune grasslands; 2250*: Coastal dunes with *Juniperus* spp.; 2260: *Cisto-Lavanduletalia* dune sclerophyllous scrubs; 2270*: Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*; 9340: *Quercus ilex* and *Quercus rotundifolia* forests; 1240: Vegetated sea cliffs of the Mediterranean coasts with endemic *Limonium* spp.; 1410: Mediterranean salt meadows *Juncetalia maritimi*; 1420: Mediterranean and thermo-Atlantic halophilous scrubs (*Sarcocornietea fruticosi*); 1510*: Mediterranean salt steppes; 1150*: Coastal lagoons (*Limonietalia*); 3170*: Mediterranean temporary ponds; 6420: Mediterranean tall humid herb grasslands of the *Molinio-Holoschoenion*; 3250: Constantly flowing Mediterranean rivers with *Glaucium flavum*; 1110: Sandbanks slightly covered by seawater; 1130: Estuaries; 1160: Large shallow inlets and bays; and 1170: Reefs).

Moreover, the study area includes seven Natura 2000 sites (Figure 1, IT7120215—Torre del Cerrano; IT7140107—Lecceta Litoranea di Torino di Sangro e Foce del Fiume Sangro; IT7140108—Punta Aderci—Punta della Penna; IT7140109—Marina di Vasto; IT7228221—Foce Trigno—Marina di Petacciato; IT722216—Foce Biferno Litorale di Campomarino; and IT722217—Foce Saccione—Bonifica Ramitelli) and two nodes of the Long-Term Ecological Research Network (LTER—IT20-003-T—Foce Saccione-Bonifica Ramitelli and IT20-002-T—Foce Trigno—Marina di Petacciato) (Figure 1).

Regarding the presence of alien species along the analyzed coast, some local studies have evidenced the occurrence of some alien plants, such as *Acacia saligna* (Labill.) H.L.Wendl. and *Oenothera stucchii* Soldano [22,30,31], while fewer studies have highlighted alien fauna, such as *Anadara transversa* (Say, 1822) and *Rapana venosa* (Valenciennes, 1846) [32].

2.2. Data Download

We extracted the observations of alien species collected from 2020 to 2023 stored in the generalist multi-taxa *Citizen Science* project "Wild Coast Adriatic" (WCA- https://www.inaturalist.org/projects/wild-coast-adriatic; accessed on 27 March 2024), which gathers biodiversity records [75] on the iNaturalist platform (https://www.inaturalist.org/; accessed on 27 March 2024). As in previous research (e.g., [60,76,77]), we retained only research-grade observations. Records of alien species were carefully reviewed and blindly verified through consultation with five experts, which validated all identifications made by the platform, before proceeding with the analysis.

The WCA project was developed on the iNaturalist platform (Figure 2), as it is both useful and reliable for supporting biodiversity research and data collection [78,79]. The platform's diffusion is further enhanced by the increasing use of mobile devices such as phones and tablets, which enable accurate data collection [60]. Each WCA record included a photo or audio file, the geographic coordinates, the date, and an attempt of identification. The thorough assessment of each observation's quality begins with categorizing newly submitted entries as "needs ID" (NI). This indicates that the entry requires verification and potential correction by iNaturalist community members who specialize in the relevant taxonomic categories. After verification, several observations were upgraded to the category of "research grade" (RG). Observations that were uploaded without evidence of the organism, for example a date or location, or those that were marked as "captive/cultivated" were automatically given as "casual" [78]. The organisms referable to different taxonomic levels were assigned by iNaturalist to the following coarse categories: Actinopterygii, Amphibians, Arachnids, Aves, Chromists, Fungi and Lichens, Insects, Mammals, Mollusks, Plants, Protozoa, Reptiles, and Other Animals (http://www.inaturalist.org; accessed on 27 March 2024). Data collection for WCA was promoted through the implementation of various CS initiatives, in collaboration with local associations and protected areas. These initiatives saw active participation from the public in collecting of data, including the presence of alien species in natural and semi-natural coastal environments over the four years between 2020 and 2023.

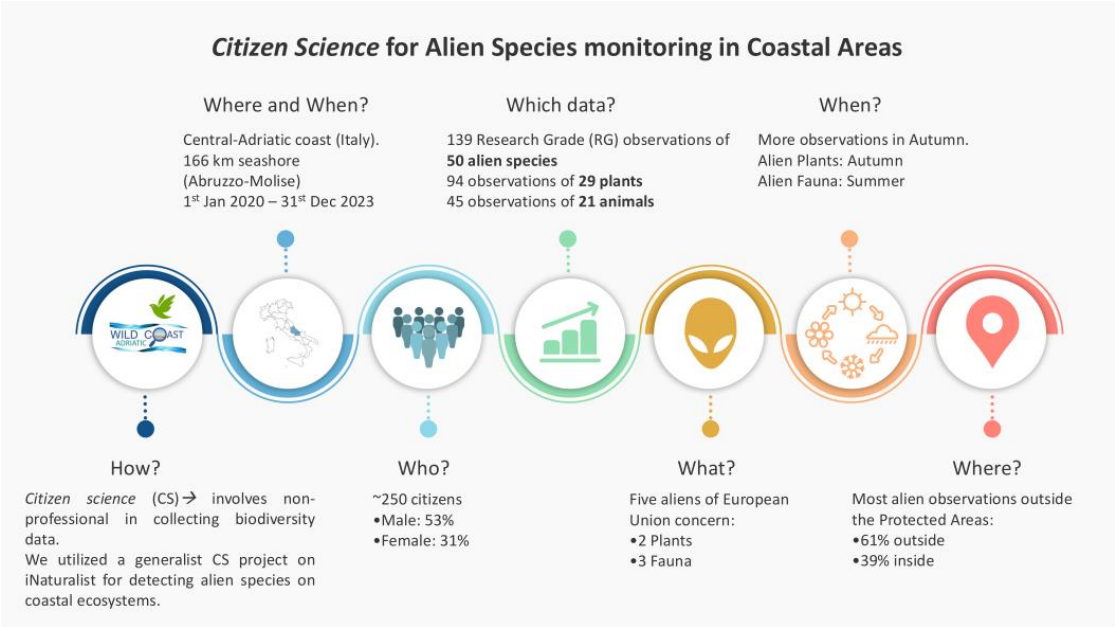


Figure 2. A flowchart that provides a synthetic view of the adopted approach.

2.3. Data Characterization and Analysis

After a brief description of the observations gathered in the WCA project, we analyzed alien species, both terrestrial and aquatic.

Following the iNaturalist categorization of WCA observations into alien and native species, we calculated the percentage of observations and the proportion of species classified as 'alien taxa' for all species, as well as separately for flora and fauna. The iNaturalist assignments were checked by consulting Galasso et al. [80] and Bartolucci et al. [81,82] for the flora and Loy et al. [83] and GBIF [84] for the fauna. The few casual records (in captivity or planted) were excluded from the analysis. We checked whether they are listed as species of European concern in the IAS Regulation (Regulation (EU) No. 1143/2014), which mandates monitoring, prevention, and management, and explored their abundance and distribution.

Then, we explored the following:

- The temporal trends in record collection by quantifying the number of observations of alien species per year and season, as it could facilitate the monitoring of expansion dynamics and the identification of risk factors;
- The alien species continent of origin, as it could be useful to understand invasion routes and facilitate management plans;
- The spatial distribution of alien species observations across the study area and quantification of the presence of the records both inside and outside the protected areas such as Natura 2000 sites (https://www.mase.gov.it/pagina/regione-molise-0; accessed on 11 April 2024) and LTER network (https://deims.org/6d7ffd99-40e1-4f0d-ad26-6904581dbe9b; accessed on 11 April 2024), which has important implications for biodiversity management and conservation [43].

All analyses were performed with R Statistical Software [85] using the "ggplot2" package [86].

2.4. Participants and Settings

WCA includes observations recorded by approximately 250 citizens, aged between 16 and 65 years. Nearly half of the contributors to the WCA project are male (n = 134), while one-third are female (n = 78), and 16% did not declare their gender. The project, initially supported by the Interreg Italy-Croatia CASCADE program, was implemented through a series of *Citizen Science* activities, primarily of two types: Bioblitz and observation campaigns led by local experts. Two one-day Bioblitz events were implemented with a total of 52 participants. One event was held at Abruzzo at the Marina di Vasto Regional Nature Reserve (SAC IT7140109—Marina di Vasto), and the other was held at Molise at the Fantine Communal Nature Reserve in Campomarino (SAC IT222217/eLTER IT20-003-T—Foce Scaccione—Bonifica Ramitelli). Participants for the Bioblitz were recruited through direct communication and the dissemination of posters via social media, official websites, emails, and physical flyers. Additionally, 10 observation campaigns, each lasting a few hours, were led by local experts and naturalistic guides with similar participant recruitment approaches. Most participants in these campaigns were students and ordinary citizens of various ages, including children and adults. These activities took place inside and outside different protected areas of the two regions, such as the Torre del Cerrano Marine Protected Area in Abruzzo (IT7120215—Torre del Cerrano) and the Mouth of Biferno river in Molise (IT722216—Foce Biferno Litorale di Campomarino). Interestingly, numerous reports were registered outside the scheduled initiatives by several participants who, after the activities, remained interested in collaborating.

3. Results

During the considered years (2020–23), the WCA project documented a total of 2933 observations, 74.5% of which (2194) obtained research-grade status, referring to 687 species. Among the research-grade observations, 139 (6.3%) are relative to alien records, referring to 50 different alien species (Table 1). In total, 120 observations are of alien plant (AP) species, 78.3% of which (94) obtained research-grade status, with a total of 29 species belonging to 15 taxonomic families (Table 1). Two of these species, *Acacia saligna* (with 11 records) and *Ailanthus altissima* (Mill.) Swingle (with 4 records) are of European concern.

Regarding the taxonomic families of the AP species, *Asteraceae* and *Fabaceae* accounted for 38% (28% and 10%, respectively, Figure 3) of the total, followed by *Aizoaceae* (7%), *Cactaceae* (7%), *Caprifoliaceae* (7%), *Onagraceae* (7%), *Oxalidaceae* (7%), and *Solanaceae* (7%) (Figure 3, Appendix A, Table A1).

Table 1. Number of records and species recorded in the Wild Coast Adriatic project (WCA), along with the number of aliens (overall, flora and fauna) and the relative numbers reaching the research grade or in Needs ID.

		Total	Research Grade	Needs ID
Records	WCA (overall)	2933	2194	739
	Aliens	170	139	31
	Alien Flora	120	94	26
	Alien Fauna	50	45	5
Species	WCA (overall)	786	687	190
	Aliens	58	50	14
	Alien Flora	34	29	11
	Alien Fauna	24	21	3

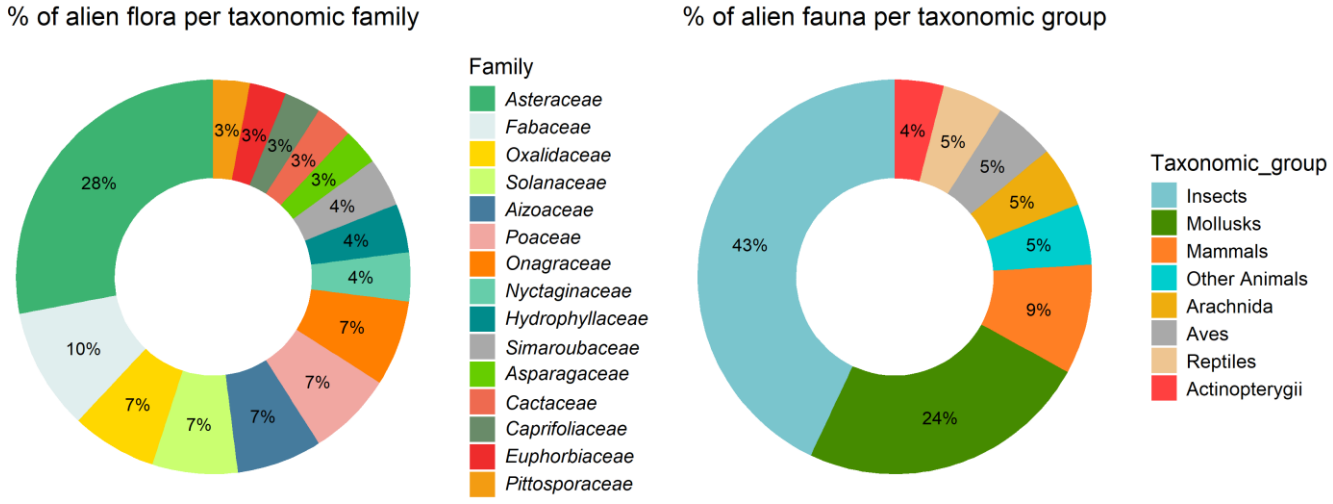


Figure 3. Percent of WCA alien species per floristic taxonomic family [87] and fauna taxonomic group (classes are defined according to iNaturalist classification scheme: https://www.inaturalist.org; accessed 27 March 2024).

Regarding alien fauna, a total of 50 observations were reported in the WCA project, 90% of which (45) obtained research-grade status, encompassing 21 species, and belonging to 8 iNaturalist categories. Insect species are the most abundant, representing 43% of the total, followed by Mollusks (24%) and Mammals (9%) (Figure 3). Three species of alien fauna are included in the IAS Regulation: *Myocastor coypus* (Molina 1782) (12 records), *Trachemys scripta* (Thunberg in Schoepff, 1792) (4 records), and *Gambusia holbrooki* (Girard, 1859) (1 record) (Appendix A, Table A2).

Concerning the origin of alien species, most of them come from the Americas (Figure 4). This pattern holds even when the data are disaggregated, with both alien flora and fauna showing the highest numbers coming from the American continent. In terms of total species, the Americas are closely followed by Asia, which exhibits a greater number of fauna species compared to flora. Africa follows, with a similar number of plant and animal species (Figure 4).

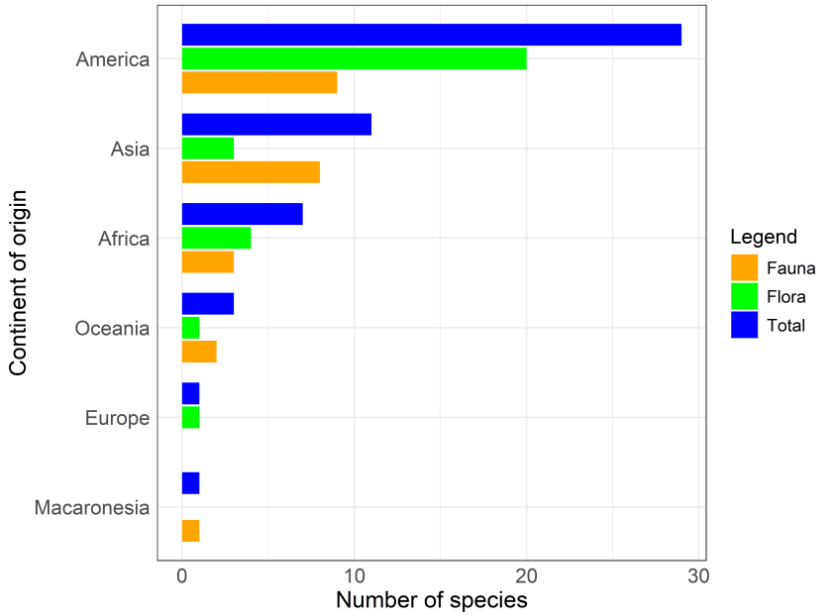


Figure 4. Origin of alien species.

The number of observations per year tends to increase over time for overall taxa, as well as when considering either plants or animals (Figure 5). The number of observations increases steadily from 2020 to 2023, with a slight dip in the year 2022. An exception to this trend is fauna, which had the highest number of observations in 2021 (Figure 5).

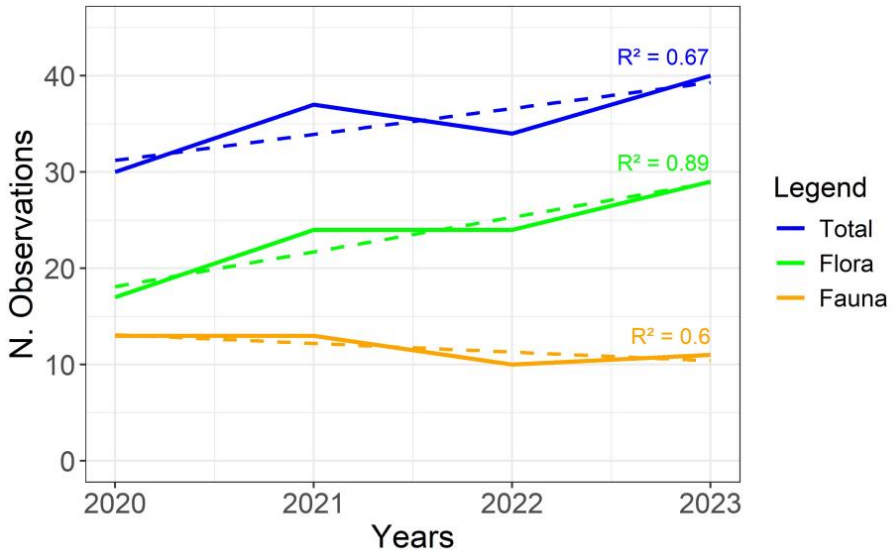


Figure 5. Number of alien research-grade (RG) observations per year. The trend lines are shown as dashed lines.

The number of observations varied across seasons with higher numbers in summer (41) and autumn (43). The number of observations for alien plants consistently surpasses those for animals, with the peak occurring in autumn (33) for flora and in summer (18) for fauna (Figure 6).

The geographic distribution of alien species records for both flora and fauna revealed a heterogeneous pattern of occurrences, with a higher concentration in the Southern sector of the Abruzzo region (Figure 7).

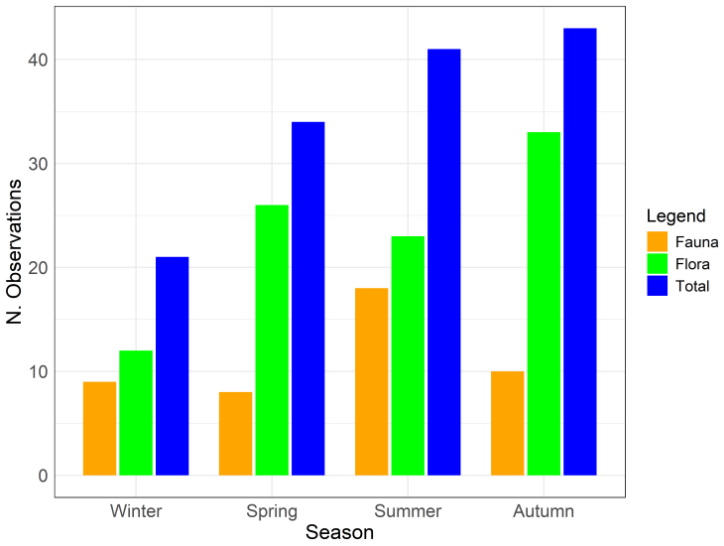


Figure 6. Number of alien observations per season. Winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and autumn (September, October, and November).

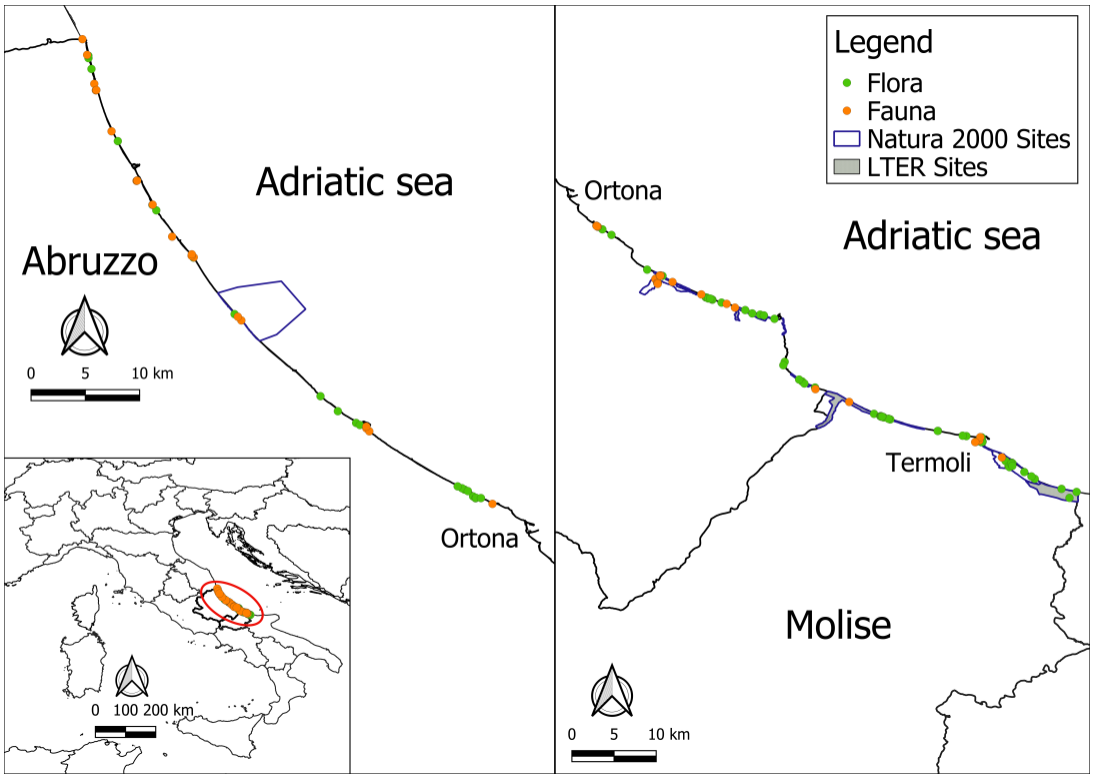


Figure 7. Distributions of alien species observations along the study area (highlighted in the red oval).

Most observations (60%) were recorded outside protected areas, while only 55 records of alien species were documented within Natura 2000 sites and LTER sites (Figure 7, Appendix A, Tables A1 and A2). Specifically, both alien flora and fauna were more frequently found outside protected areas. However, alien plants had a higher proportion of occurrences within protected areas (42.5%) compared to alien fauna (33.3%) (Figure 7, Appendix A, Tables A1 and A2).

4. Discussion

The present study identified a significant number of exotic species widely distributed across the Italian Central Adriatic coastal area. Consistent with findings from other *Citizen Science* initiatives [59,78], we observed a predominance of alien plant species over animal ones. This trend may be attributed to differences in mobility and the relative ease of detecting plant species. Sessile plants, being stationary, are more easily observable and accessible, while mobile and often elusive animals tend to avoid human presence, making them less likely to be observed (https://extension.umaine.edu/signs-of-the-seasons/volunteers-field-guide/how-to-observe/; accessed on 10 July 2024) [88]. Additionally, many animals exhibit annual patterns in presence and detectability, giving the impression of being absent when, in reality, they are not [89].

The increasing number of observations over time, coupled with the consistent number of observations across seasons, suggest the effectiveness of *Citizen Science* (CS) campaigns. WCA initiatives have successfully engaged and motivated volunteers to continue collecting data independently, even in the absence of expert-led campaigns.

The registered presence of alien species represents a further warning sign about the ecological integrity of the Italian Central Adriatic coast [90]. The improved knowledge of their composition and distribution may be crucial for the conservation of biodiversity and the management of alien invasions in these marine–coastal ecosystems. Concerning the alien flora, the substantial number of *Asteraceae* and *Fabaceae* species found with WCA project in our study area aligns well with the overall composition of alien flora in Italy and Europe [80,91]. The relatively low number of *Poaceae* species compared to the overall alien flora in Italy [80] is likely due to the difficulty in identifying these species. Both amateur enthusiasts and professional botanists often encounter difficulties when relying solely on photos for *Poaceae* species identification [92]. As for alien fauna, insects were the taxonomic group with the most species observed. Plant–insect interactions can sometimes be surprising [93], and these arthropods can even thrive in harsh environments characterized by highly specialized flora, such as coastal areas [94]. Furthermore, the planting of alien ornamental plants in gardens and bathing establishments, such as Palms, has promoted the spread of other phytophagous insects, such as the red palm weevil (*Rhynchophorus ferrugineus*), which we have recorded in semi-natural areas.

This species, being a major problem in the Mediterranean region and responsible for the loss of over 100,000 palm trees with estimated annual costs of several hundred million EUR since their introduction into Europe, has specific European-level strategies for the eradication and containment (see for details https://cordis.europa.eu/project/id/289566/reporting; accessed on 10 July 2024). The presence of this invasive pest, revealed by our CS campaigns, was reported to the health authorities, who in turn must implement a specific control and eradication strategy. The second most frequently observed taxonomic group of alien fauna was mollusks, consistent with previous research [95,96] that identified mollusks as one of the primary phyla in the marine–coastal fauna, both in general and as alien species [97,98]. Moreover, WCA revealed a significant presence of mammals (9%) along the Italian Central Adriatic coast. Mammals frequently venture into man-made environments in search of food, which increases their likelihood of being detected and reported by citizens [99]. The WCA project reported five alien species of European concern (Regulation (EU) No. 1143/2014), including two plants, *Acacia saligna* and *Ailanthus altissima*, and three animals, *Myocastor coypus*, *Trachemys scripta*, and *Gambusia holbrooki*. These records confirm and improve the distribution data of these species along the Central Adriatic coast and require immediate control and monitoring actions by local health authorities, coordinated by national authorities [14]. Among the alien plants, *Acacia saligna* is one of the most invasive taxa [100] in Italy and Europe [101]. Native to Australia, it was introduced in the Mediterranean basin and Italy in the 1950s for reforestation, dune stabilization, and ornamental purposes [18,102–105]. Along the analyzed coast, it mainly invades back dune habitats [31,106] causing multiple negative effects on biodiversity (e.g., decline of native and diagnostic species) [18,21,31,104] and altering soils features, nutrient cycles, and

microclimatic conditions [107]. Furthermore, together with *Oenothera stucchii*, *A. saligna* has been documented for the first time in the Abruzzo region, thanks to the contributions of the WCA project.

Regarding alien fauna species of European concern, the most frequently observed is *Myocastor coypus*, a large semi-aquatic rodent native to South America, introduced in the early 20th century for commercial breeding purposes (mainly for fur production) [108]. The presence of coypu in the national territory poses both ecological and economic challenges [108], as it can be very damaging to the environment [109]. In this context, it is crucial to urgently implement the management and containment strategy developed by the Ministry of the Environment in collaboration with the National Wildlife Fund Institute, outlined in the "Guidelines for the control of coypu (*Myocastor coypus*) [108]", following a thorough assessment of its current distribution along the Central Adriatic coast.

The largest number of alien species comes from America, with 20 species of flora and 9 species of fauna, followed by Asia and Africa. The notable prevalence of American species may be attributed to the expansive and diverse ecosystems present in America [110], which offer a rich assortment of taxa that have discovered analogous habitats in Europe [111,112]. Moreover, this observed trend could potentially signify a long-standing history of commerce and interaction spanning multiple centuries among various geographical areas [113].

In line with the growing popularity of *Citizen Science* [114,115] and iNaturalist as a biodiversity data collection platform [116], WCA recorded an increase in the number of observations per year across all alien taxa as well as when considering plants or animals separately. In our case, the intensity of survey activities has grown as more people have engaged in *Citizen Science* in recent years, leading to the increased accumulation of observational data [60]. Furthermore, over time, more individuals began using CS tools independently after the organized activities, and WCA also saw an increase in the number of observations in the last year, even without formal CS initiatives. Such results underscore the importance and contribution of *Citizen Science* initiatives and the iNaturalist platform for monitoring and studying alien species spread [59].

Alien species occurrences have been reported in all seasons, but predominantly in the summer (41), when the presence of more people and tourists increases observation rates [88]. Warmer weather and extended daylight hours make summer more appealing for recreational activities [54], leading to increased public data collection. A secondary peak in observations is registered in autumn (43), during the blooming period of most alien plants, while native plants have already completed their life cycles [22]. This shifted blooming period makes alien plants more visible in autumn [30], attracting greater attention from citizens. The observed seasonal detection of alien species provides a basis for tailoring coastal monitoring activities and concentrating efforts during specific periods that reflect the phenological behavior and detectability of these species.

Regarding the invasion of protected areas such as coastal Natura 2000 sites and long-term ecological research (LTER) sites, we recorded a lower presence of alien species compared to unprotected areas. This suggests that, while alien species may still colonize these zones, their invasion rate is likely curtailed due to the presence of effective conservation measures, biotic filters (e.g., high biodiversity and ecosystem function), and relatively lower anthropogenic pressures, including reduced propagule pressure from infrastructures and less frequent human disturbances [43,117]. Indeed, conservation actions and biodiversity management strategies enhance ecosystem resilience and help protect them from the significant threat posed by alien species [81]. Continuous monitoring and research at Natura 2000 and LTER sites are crucial for refining management strategies and assessing the effectiveness of current conservation measures. This targeted approach improves the control of alien species and contributes to the overall health and stability of ecosystems. Additionally, the collected data can be used to develop distribution models for alien species, identify invasion hotspots, and focus attention and control measures on invaded coasts [117].

5. Conclusions

Our study highlights the value of *Citizen Science* (CS) as a valuable tool for detecting and monitoring alien species (AS) in marine–coastal ecosystems. The Wild Coast Adriatic (WCA) project successfully used the iNaturalist platform to document the presence of AS along the Italian Central Adriatic coast, also within protected areas. CS sampling enabled the recording of a significant number of alien species across the study area, with some taxa recorded for the first time in specific coastal areas. This underscores the potential of *Citizen Science* as a cost-effective surveillance, early warning and monitoring tool that complements expert efforts while reducing the need of extensive fieldwork. Among the different families (flora) and taxonomic categories (fauna) observed, there are some species of Union concern, that are regulated at the European level and for which management and eradication plans are required. The presence of these species was reported to the management authorities, who in turn implement a specific monitoring or eradication actions. The number of observations and citizen scientists increased over time, highlighting the growing potential of *Citizen Science* for alien species early detection and support for implementing effective containment and management strategies.

Monitoring and studying the spatial and temporal distribution patterns of alien species is essential for developing effective management and conservation policies. Additionally, the year-round distribution of IAS records underscores the critical need for continuous monitoring efforts to achieve a comprehensive understanding of their temporal behavior and spread in within local ecosystems and PAs. Our results revealed that alien species are distributed heterogeneously inside and outside the protected areas (Natura 2000 and LTER sites), suggesting the effectiveness of protected areas in preserving natural ecosystems. Moreover, our results suggest that generalist multi-taxa *Citizen Science* projects such as Wild Coast Adriatic can serve as valuable tools for alien species monitoring, helping in biodiversity conservation and management of alien invasions in marine–coastal ecosystems. The increasing recruitment of citizen scientists underline the growing public awareness on the importance of alien species monitoring, prevention, and control in Italian coastal ecosystems.

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Data Availability Statement: Data are available on iNaturalist platform (https://www.inaturalist.org/projects/wild-coast-adriatic—accessed on 16 October 2024).

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. List of Alien Species with "Research-Grade" (RG) Status Collected from 2020 to 2023, in the Generalist Multi-Taxa Citizen Science (CS) Project "Wild Coast Adriatic" (WCA)

Table A1. List of alien plant species along with the taxonomic family status [80]. Life Growth: "CH suffr" (suffruticose chamaephytes); "G bulb" (bulbous geophytes); "G rhiz" (rhizomatous geophytes); "H bienn" (biennial hemicryptophytes); "H caesp" (caespitose hemicryptophytes); "NP" (nanophanerophytes); "P caesp" (caespitose phanerophytes); "P lian" (lianose phanerophytes); "P scap" (scapose phanerophytes); "T rept" (reptans therophytes); and "T scap" (scapose therophytes) [87]. Geographic origin and numbers of observations: Total, Inside PA, and Outside PA (Protected Areas—Natura 2000 sites and LTER sites). Bold font highlights invasive alien species of European Union concern [35].

					N. Observations		
Species	**Family**	**Status**	**Life Growth**	**Origin**	**Total**	**Inside PA**	**Outside PA**
Acacia saligna (Labill.) H.L.Wendl.	*Fabaceae*	Invasive Neophyte	P scap	Oceania	11	7	4
Agave americana L. subsp. *americana*	*Asparagaceae*	Invasive Neophyte	P caesp	America	3	0	3
Ailanthus altissima (Mill.) Swingle	*Simaroubaceae*	Invasive Neophyte	P scap	Asia	4	0	4
Ambrosia psilostachya DC.	*Asteraceae*	Invasive Neophyte	G rhiz	America	2	2	0
Amorpha fruticosa L.	*Fabaceae*	Invasive Neophyte	P caesp	America	3	0	3
Bidens subalternans DC.	*Asteraceae*	Invasive Neophyte	T scap	America	2	2	0
Carpobrotus acinaciformis (L.) L.Bolus	*Aizoaceae*	Invasive Neophyte	Ch suffr	Africa	6	1	5
Carpobrotus edulis (L.) N.E.Br.	*Aizoaceae*	Invasive Neophyte	Ch suffr	Africa	5	2	3
Datura stramonium L.	*Solanaceae*	Invasive Neophyte	T scap	America	3	2	1
Erigeron bonariensis L.	*Asteraceae*	Invasive Neophyte	T scap	America	3	1	2
Erigeron canadensis L.	*Asteraceae*	Invasive Neophyte	T scap	America	1	1	0
Euphorbia maculata L.	*Euphorbiaceae*	Invasive Neophyte	T rept	America	2	1	1
Helianthus annuus L. subsp. *annuus*	*Asteraceae*	Casual Neophyte	T scap	America	1	0	1
Lonicera japonica Thunb.	*Caprifoliaceae*	Invasive Neophyte	P lian	Asia	1	0	1
Mirabilis jalapa L.	*Nyctaginaceae*	Invasive Neophyte	G bulb	America	1	0	1
Nicotiana glauca Graham	*Solanaceae*	Invasive Neophyte	NP	America	1	0	1
Oenothera glazioviana Micheli	*Onagraceae*	Invasive Neophyte	H bienn	America	1	0	1
Oenothera stucchii Soldano	*Onagraceae*	Invasive Neophyte	H bienn	Europa	12	9	3
Opuntia ficus-indica (L.) Mill.	*Cactaceae*	Invasive Neophyte	P succ	America	1	0	1
Opuntia stricta (Haw.) Haw.	*Cactaceae*	Invasive Neophyte	P succ	America	2	0	2
Oxalis articulata Savigny	*Oxalidaceae*	Invasive Neophyte	G bulb	America	2	2	0
Oxalis pes-caprae L.	*Oxalidaceae*	Invasive Neophyte	G bulb	Africa	7	1	6
Paspalum dilatatum Poir.	*Poaceae*	Invasive Neophyte	H caesp	America	1	0	1
Phacelia tanacetifolia Benth.	*Hydrophyllaceae*	Naturalized Neophyte	T scap	America	1	0	1
Pittosporum tobira (Thunb.) W.T.Aiton	*Pittosporaceae*	Naturalized Neophyte	P caesp	Asia	1	0	1
Robinia pseudoacacia L	*Fabaceae*	Invasive Neophyte	P scap	America	3	1	2
Senecio inaequidens DC.	*Asteraceae*	Invasive Neophyte	Ch suffr	Africa	1	0	1
Symphyotrichum squamatum (Spreng.) G.L.Nesom	*Asteraceae*	Invasive Neophyte	T scap	America	4	3	1
Xanthium orientale subsp. *italicum* (Moretti) Greuter	*Asteraceae*	Invasive Neophyte	T scap	America	9	5	4
					94	40	54

Table A2. List of alien fauna species, along with the taxonomic group, taxonomic family, geographic origin, and numbers of observations: Total, Inside PA and Outside PA (Protected Areas—Natura 2000 sites and LTER sites). Bold font highlights invasive alien species of European Union concern [35].

Species	Taxonomic Group	Family	Origin	N. Observations		
				Total	Inside PA	Outside PA
Gambusia holbrooki (Girard, 1859)	Actinopterygii	*Poeciliidae*	America	1	1	0
Steatoda nobilis (Thorell, 1875)	Arachnida	*Theridiidae*	Macaronesia	1	0	1
Threskiornis aethiopicus (Latham, 1790)	Aves	*Threskiornithidae*	Africa; Asia	2	1	1
Blatta orientalis (Linnaeus, 1758)	Insects	*Blattidae*	Africa; Asia	1	0	1
Halyomorpha halys (Stål, 1855)	Insects	*Pentatomidae*	Asia	1	0	1
Harmonia axyridis (Pallas, 1773)	Insects	*Coccinellidae*	Asia	1	0	1
Icerya purchasi (Maskell, 1878)	Insects	*Margarodidae*	Oceania	1	0	1
Isodontia mexicana (de Saussure, 1867)	Insects	*Sphecidae*	America	1	0	1
Paysandisia archon (Burmeister, 1880)	Insects	*Castniidae*	America	1	0	1
Rhynchophorus ferrugineus (Olivier, 1790)	Insects	*Dryophthoridae*	Asia	2	0	2
Sceliphron caementarium (Drury, 1773)	Insects	*Sphecidae*	America	2	1	1
Trichopoda pictipennis (Fabricius, 1781)	Insects	*Tachinidae*	America	1	0	1
Hystrix cristata (Linnaeus, 1758)	Mammals	*Hystricidae*	Africa	1	0	1
Myocastor coypus (Molina, 1782)	Mammals	*Myocastoridae*	America	12	6	6
Anadara kagoshimensis (Tokunaga, 1906)	Mollusks	*Arcidae*	Asia	2	0	2
Anadara transversa (Say, 1822)	Mollusks	*Arcidae*	America	4	0	4
Magallana gigas (Thunberg, 1793)	Mollusks	*Ostreidae*	Asia	1	0	1
Potamopyrgus antipodarum (J. E. Gray, 1843)	Mollusks	*Tateidae*	Oceania	1	0	1
Rapana venosa (Valenciennes, 1846)	Mollusks	*Muricidae*	Asia	1	0	1
Callinectes sapidus (Rathbun, 1896)	Other Animals	*Portunidae*	America	4	2	2
Trachemys scripta (Thunberg in Schoepff, 1792)	Reptiles	*Emydidae*	America	4	4	0
				45	15	30

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Chapter 4 - Other contributions on biodiversity in the Central Adriatic Coast

In this chapter, we provide a comprehensive overview of the research activities, data collection efforts, and in-depth methodological interventions carried out in the Adriatic coastal areas in Central Italy during the PhD. This work not only highlights the skills developed throughout the research but also contextualizes it within the broader framework of scientific collaboration. To enrich the understanding of biodiversity across various ecosystems along the Central Adriatic coast, we: a) explored sections of the seabed to identify the presence of marine habitats (*Notulae* on *Cymodocea nodosa* (Ucria) Asch); b) sampled and analyzed the biotic and abiotic characteristics of the Biferno estuary; c) investigated the spatial and temporal patterns of stranded cetaceans.

4.1 *Notulae on the presence of Cymodocea nodosa (Ucria) Asch in the seabed along the Molise coast*

In this doctoral project, an initial exploratory data collection was conducted to study the seabed along the Molise coast. During this survey, the marine seagrass *Cymodocea nodosa* (Ucria) Asch. was detected and sampled and a dedicated floristic *Notulae* was submitted and published (Peruzzi et al., 2023). This species, of the family Cymodoceaceae, is widely distributed along the Atlantic coasts of Europe and Africa and is also spread in the Mediterranean and Black Sea (https://www.isprambiente.gov.it/it/banche-dati/atlante-delle-specie-marine-protette/vegetali/cymodocea-nodosa-ucria-ascherson-1870). *Cymodocea nodosa* thrives in sandy and muddy seabed with shallow waters, typically at depths up to 30 meters, where sufficient light support photosynthesis (Máñez-Crespo et al., 2020). Meadows of *Cymodocea nodosa* often coexist with other marine seagrasses, such as *Posidonia oceanica* (L.) Delile and *Zostera marina* L. (Buia & Marzocchi, 1995; Infantes et al., 2011). These meadows form complex ecosystem mosaics that play a crucial role in substrate stabilization and enhancing biodiversity in coastal environments (Buia et al., 2003; Infantes et al., 2011).

Cymodocea nodosa is notable for its remarkable adaptability to fluctuating environmental conditions, including variations in salinity, nutrient availability, and sediment composition. This marked plasticity makes it a key component assuring coastal ecosystems resilience (Garrido et al., 2013; Piro et al., 2015). The *Cymodocea nodosa* meadows play a crucial role in protecting coastal marine transitions by stabilizing sediments, curtailing wave energy and mitigating coastal erosion (Koch et al., 2009). Their extensive roots form a natural network that consolidates the seabed, reducing the impact of waves and currents. This natural barrier is particularly useful in areas subject to high anthropogenic pressure, where it helps counteract erosive processes (Koch et al., 2009). From an

ecological perspective, *Cymodocea nodosa* meadows provide critical habitats for a wide range of marine species. They offer refuge, feeding area, and breeding site, particularly for fishes, which benefit from the protection from predators and favorable conditions for development among the seagrass leaves (Casas et al., 2021). Moreover, these meadows support a rich community of invertebrates, crustaceans, and mollusks, significantly contributing to the overall biodiversity of coastal marine systems. Another crucial aspect of *Cymodocea nodosa* is its contribution to the carbon cycle and climate change mitigation (Egea et al., 2018; M. Koch et al., 2013). Seagrass meadows, including this species, can capture and store large amounts of organic carbon in their tissues and the underlying sediments. This process plays a significant role in counteracting the accumulation of greenhouse gases in the atmosphere and global oceanography, making *Cymodocea nodosa* an ecologically important resource in the fight against climate change (Fourqurean et al., 2012).

Cymodocea nodosa meadows also improve the quality of coastal waters by acting as natural filters that reduce nutrient and suspended sediment loads, thereby enhancing water transparency and the health of surrounding ecosystems (Boutahar et al., 2022). These characteristics make the species an important ecological indicator for monitoring the health of coastal environments. Despite its resilience, *Cymodocea nodosa* is threatened by various anthropogenic and environmental factors, which can damage or destroy entire meadows (Konstantinidis et al., 2022; Najdek et al., 2020). Additionally, climate change, with rising water temperatures and ocean acidification, poses an increasing challenge to its survival (Egea et al., 2018; Konstantinidis et al., 2022). Nutrient pollution and eutrophication promote the proliferation of epiphytic algae, which can compete with *Cymodocea nodosa* for light and nutrients, compromising its growth and vitality (Tsioli et al., 2021).

The conservation of *Cymodocea nodosa* is supported by European regulations such as the Habitat Directive (92/43/EEC - vnr.unipg.it), which recognizes seagrass meadows as priority habitats (HD 1110: *Sandbanks which are slightly covered by sea water all the time*). However, ensuring its long-term protection requires adopting integrated management strategies that include regular monitoring, regulation of human activities in sensitive areas, and restoration of degraded habitats. *Cymodocea nodosa* meadows not only represent an essential element for biodiversity and the health of coastal ecosystems but also play a fundamental role in protecting coastlines, mitigating climate change, and promoting coastal water quality.

The species was collected during dives and beach patrols in correspondence with the Molise LTER sites: IT20-002-T “Foce Trigno-Marina di Petacciato” and IT20-003-T “Foce Saccione-Bonifica Ramitelli” (www.lteritalia.it; https://deims.org) and adjacent areas such as Natura 2000 sites. The identification of the species allowed for the publication of a *Notulae* in the Bulletin of the Italian Botanical Society in the section “Nuove Segnalazioni Floristiche Italiane 14. Flora Vascolare (121 –

137), pages 2 and 3, *Notula* 132." The data on *Cymodocea nodosa* was included in the reference dataset of the study (Peruzzi et al., 2023).

These new observations of *Cymodocea nodosa* formations along the Central Adriatic coasts are of considerable ecological and conservation importance. With further assessments, these findings could provide the basis for newly mapping a directive habitat on the surveyed coasts (EC Habitat 1110: *Sandbanks which are slightly covered by sea water all the time* – EUNIS code: A5.5 - *Sublittoral macrophyte-dominated sediment*). This information could support the seaward expansion of the N2K network, contributing to the enlargement of existing marine protected areas and aligning with the Marine Directive's (*Habitat Direttive 92/43/EEC*, 1992) mandate to increase protected areas across Europe.

Nuove segnalazioni floristiche italiane 14. Flora vascolare (121–137)

L. Peruzzi, E. Meneguzzo, N.M.G. Ardenghi, E. Banfi, G. Galasso, F. Compagnone, T. Pagliani, S. Zignone, G. Michelutti, G. Tavilla, S. Biondolillo, S. Sciandrello, L. Lastrucci, L. Bernardo, F. Roma-Marzio

121. ***Allium pallens*** L. (Amaryllidaceae)
CAL: Saracena (Cosenza), presso il torrente Garga (WGS84: 39.803007 N, 16.137033 E), prato umido, 830 m s.l.m., 24 agosto 2022, *L. Peruzzi* (FI). – Specie di nuova segnalazione per il Sottodistretto argentino.
La segnalazione più vicina al presente ritrovamento è relativa a Castrovillari (Cosenza) (Terracciano 1891), comunque collocata nel Sottodistretto sibarite (Bernardo et al. 2011).

Lorenzo Peruzzi

122. ***Rosa spinosissima*** L. (Rosaceae)
CAL: San Donato di Ninea (Cosenza), loc. Frida (WGS84: 39.711904 N, 16.007438 E), su substrato calcareo a margine bosco, 1250 m s.l.m., 13 agosto 2022, *L. Peruzzi* (FI). – Terza segnalazione per la Calabria.
La specie è segnalata con dubbio per la Calabria da Lattanzi (2012). Successivamente, la stessa autrice (in Bartolucci et al. 2018) considera certa la presenza nella regione, sulla base di raccolte d'erbario inedite in CLU da lei determinate (L. Bernardo, *com. pers*.). Si tratta di due campioni, provenienti da due diverse località distanti circa un paio di chilometri in linea d'aria dal presente ritrovamento: Monte Mula, lungo la strada che porta in cima, alla fine della faggeta, San Donato di Ninea, prov. Cosenza, Calabria (WGS84: 39.70008 N, 15.973361 E), prato sassoso margine sentiero, 1850 m s.l.m., 28 luglio 2006, *L. Bernardo, D. Gargano, C. Maiolo* (CLU); Monte Mula, lungo la strada che porta in cima, poco dopo il Campo, San Donato di Ninea, prov. Cosenza, Calabria (WGS84: 39.696436 N, 15.977355 E), margine sentiero su pendio sassoso, 1650 m s.l.m., 28 luglio 2006, *L. Bernardo, D. Gargano, C. Maiolo* (CLU).

Lorenzo Peruzzi

123. ***Silene catholica*** (L.) W.T.Aiton (Caryophyllaceae)
CAL: San Sosti (Cosenza), loc. Castagneto (WGS84: 39.661717 N, 16.013666 E), margine strada, 600 m s.l.m., 15 agosto 2022, *L. Peruzzi* (FI, PI nr. 061813). – Terza segnalazione per la Calabria.
La specie era nota finora in Calabria solo per due località nel comune di Papasidero (Cosenza) (Di Marco, Peruzzi 2009, Di Marco et al. 2013).

Lorenzo Peruzzi

124. ***Cardamine occulta*** Hornem. (Brassicaceae)
(NAT) **LOM**: Sesto Calende (Varese), Via Remo Barbieri (WGS84: 45.724407 N, 8.625425 E), sponda del fiume Ticino, 195 m s.l.m., 9 agosto 2022, *E. Meneguzzo* (FI, Herb. *E. Meneguzzo*). – Prima segnalazione di specie esotica naturalizzata per la provincia di Varese.

Enzo Meneguzzo, Nicola M. G. Ardenghi

125. ***Glebionis segetum*** (L.) Fourr. (Asteraceae)
(CAS) **LOM**: Sesto Calende (Varese), loc. Oriano Ticino, Via Candiani (WGS84: 45.737684 N, 8.652557 E), ambiente ruderale, 260 m s.l.m., 23 maggio 2010, *E. Meneguzzo* (FI, *Herb. E. Meneguzzo*). – Prima segnalazione di specie esotica casuale per la provincia di Varese.
Entità rarissima e occasionale nel nord della penisola, *Glebionis segetum* è una specie steno-mediterraneo-turanica divenuta euri-mediterranea (Bartolucci et al. 2018, Pignatti et al. 2018).

Enzo Meneguzzo, Nicola M. G. Ardenghi

126. ***Oloptum miliaceum*** (L.) Röser & H.R.Hamasha (Poaceae)
LOM: Sesto Calende (Varese), loc. Sorgenti della Capricciosa (WGS84: 45.745139 N, 8.621692 E), prato umido per risorgiva, 295 m s.l.m., 16 maggio 2020, *E. Meneguzzo* (FI, *Herb. E. Meneguzzo*). – Prima segnalazione per la provincia di Varese.
Entità rara ma in espansione al nord della penisola, *Oloptum miliaceum* è una specie di origine mediterranea (Pignatti et al. 2017, Bartolucci et al. 2018).

Enzo Meneguzzo, Nicola M. G. Ardenghi

127. ***Vicia cordata*** Wulfen ex Hoppe (Fabaceae)
LOM: Besozzo (Varese), Via Trieste 110 (WGS84: 45.865298 N, 8.668860 E), verde mantenuto, 235 m s.l.m., 27 aprile 2013, *E. Meneguzzo* (FI, *Herb. E. Meneguzzo*). Sesto Calende (Varese), loc. Oriano Ticino, Via Candiani (WGS84: 45.738366 N, 8.652618 E), bordo carrareccia, 260 m s.l.m., 17 aprile 2017, *E. Meneguzzo* (FI, *Herb. E. Meneguzzo*). – Prima segnalazione per la provincia di Varese.

Enzo Meneguzzo, Nicola M. G. Ardenghi

128. ***Carex demissa*** Hornem. subsp. ***demissa*** (Cyperaceae)
LOM: Sesto Calende (Varese), loc. Cocquo (WGS84: 45.743903 N, 8.610529 E), prato umido, 330 m s.l.m., 5 maggio 2020, *E. Meneguzzo* (FI, *Herb. E. Meneguzzo*). – Conferma per la provincia di Varese.
Esiste una precedente segnalazione considerata dubbia (sub *Carex tumidicarpa* Andersson) presso la Palude Brabbia (Macchi 2005). Altre due stazioni sono presenti nel territorio comunale sestese a quote inferiori. Entità rara, *Carex demissa* è una specie di origine euro-americana (anfi-atlantica) (Pignatti et al. 2017).

Enzo Meneguzzo, Nicola M. G. Ardenghi, Enrico Banfi, Gabriele Galasso

129. ***Festuca danthonii*** Asch. & Graebn. subsp. ***danthonii*** (Poaceae)
LOM: Sesto Calende (Varese), Via Capricciosa (WGS84: 45.729830 N, 8.629293 E), cotica erbosa arida, 205 m s.l.m., 9 giugno 2016, *E. Meneguzzo* (FI, *Herb. E. Meneguzzo*). – Prima segnalazione per la provincia di Varese.

Enzo Meneguzzo, Nicola M. G. Ardenghi, Enrico Banfi, Gabriele Galasso

130. ***Fumaria parviflora*** Lam. (Papaveraceae)
LOM: Albizzate (Varese), Via Montello (WGS84: 45.720731 N, 8.795863 E), scarpata erbosa a bordo strada, 326 m s.l.m., 8 maggio 2015, *E. Meneguzzo* (FI, *Herb. E. Meneguzzo*). – Prima segnalazione per la provincia di Varese.

Enzo Meneguzzo, Nicola M. G. Ardenghi, Enrico Banfi, Gabriele Galasso

131. ***Verbena rigida*** Spreng. (Verbenaceae)
(CAS) **LOM**: Sesto Calende (Varese), Via Tortorino (WGS84: 45.728014 N, 8.628670 E), incolto arido, 196 m s.l.m., luglio 2008, *E. Meneguzzo* (FI, *Herb. E. Meneguzzo*). – Prima segnalazione di specie esotica casuale per la provincia di Varese.
Verbena rigida è stata segnalata per la prima volta in Italia come casuale in Lombardia da Galasso et al. (2018) senza alcuna specifica della località; qui vengono indicati i dati di raccolta. La specie è stata osservata nuovamente nel giugno dell'anno successivo, è stata raccolta e invasata per preservarla da lavori di riqualificazione dell'area: da allora si hanno nuovi polloni e relative fioriture. Neofita casuale, *V. rigida* è una specie di origine sud-americana (Pignatti et al. 2018).

Enzo Meneguzzo, Nicola M. G. Ardenghi, Enrico Banfi, Gabriele Galasso

132. ***Cymodocea nodosa*** (Ucria) Asch. (Cymodoceaceae)
MOL: Termoli, località Marinelle, fondale prospiciente la spiaggia di Rio Vivo compreso fra la battigia e le scogliere frangiflutti (WGS84: 41.989790 N, 15.009026 E), 1 m, 17 luglio 2022, *T. Pagliani, F. Compagnone* (FI). –

Seconda segnalazione per il Molise.
Cymodocea nodosa è stata rinvenuta per la prima volta in Molise nel 2010 nel porto di Termoli (Olivieri 2010). La nuova stazione qui segnalata, distante oltre due chilometri dalla prima segnalata per la regione, è localizzata lungo il litorale prospiciente la Zona Speciale di Conservazione "Foce Biferno – Litorale di Campomarino" (IT7222216) dove risulta abbondante e frequente nell'alleanza *Zosterion marinae* Christiansen 1934, tipica dell'habitat 1110 "Banchi di sabbia a debole copertura permanente di acqua marina" della Direttiva Europea 92/43/EEC.

Federica Compagnone, Tommaso Pagliani

133. ***Leonurus cardiaca*** L. (Lamiaceae)
(CAS) **LOM**: Sesto Calende (Varese), loc. San Giorgio, Via San Giorgio (WGS84: 45.736812 N, 8.642356 E), ambiente ruderale, 248 m s.l.m., 12 giugno 2011, *G. Michelutti* (FI, *Herb. G. Michelutti*). – Prima segnalazione di specie esotica casuale per la provincia di Varese.

Enzo Meneguzzo, Sandro Zignone, Gianpaolo Michelutti, Nicola M. G. Ardenghi

134. ***Petunia atkinsiana*** (Sweet) D.Don ex W.H.Baxter (Solanaceae)
(CAS) **SIC**: Catania, lungo il bordo strada, 15 m s.l.m. (WGS84: 37.506542 N, 15.090850 E), 25 luglio 2022, *G. Tavilla, S. Biondolillo, S. Sciandrello* (FI, CAT). – Seconda segnalazione per la Sicilia e prima segnalazione per la provincia di Catania.
In Sicilia *Petunia atkinsiana* risulta segnalata solo per l'isola di Linosa (Domina et al. 2012). La nuova stazione qui riportata è formata da pochi individui che crescono lungo il margine stradale.

Gianmarco Tavilla, Sandra Biondolillo, Saverio Sciandrello

135. ***Potamogeton berchtoldii*** Fieber (Potamogetonaceae)
LOM: Ternate (Varese), Via per Ternate SP33 (WGS84: 45.776609 N, 8.683275 E), fosso in pratone da sfalcio umido, 272 m s.l.m., 5 ottobre 2014, *E. Meneguzzo* (FI, *Herb. E. Meneguzzo*). – Prima segnalazione per la provincia di Varese.
Potamogeton berchtoldii è una specie subcosmopolita rara in Italia (Pignatti et al. 2017, Bartolucci et al. 2018).

Enzo Meneguzzo, Nicola M. G. Ardenghi, Enrico Banfi, Gabriele Galasso, Lorenzo Lastrucci

136. ***Prospero autumnale*** (L.) Speta (Asparagaceae)
CAL: Oriolo (Cosenza), sopra la cappella della Madonna della Neve sul versante SE del T.ne Cineco presso Acqua Carbonara, bosco misto mesofilo con prevalenza di *Quercus frainetto* Ten., 980 m s.l.m. (WGS84: 39.970387 N, 16.447411 E), 26 agosto 2022, *F. Roma-Marzio, L. Bernardo, L. Peruzzi* (PI nr. 061712). – Specie di nuova segnalazione per l'Alto Ionio Cosentino.
Specie nota in Calabria per diverse località, ma tutte fuori dall'unità territoriale ambientale dell'Alto Ionio cosentino (Bernardo et al. 2011).

Liliana Bernardo, Lorenzo Peruzzi, Francesco Roma-Marzio

137. ***Sesleria autumnalis*** (Scop.) F.W.Schultz (Poaceae)
CAL: Oriolo (Cosenza), sopra la cappella della Madonna della Neve sul versante SE del T.ne Cineco presso Acqua Carbonara, bosco misto mesofilo con prevalenza di *Quercus frainetto* Ten., 980 m s.l.m. (WGS84: 39.970387 N, 16.447411 E), 26 agosto 2022, *F. Roma-Marzio, L. Bernardo, L. Peruzzi* (PI nr. 061714). – Specie di nuova segnalazione per l'Alto Ionio Cosentino.
Specie nota in Calabria per diverse località, ma tutte fuori dall'unità territoriale ambientale dell'Alto Ionio cosentino (Bernardo et al. 2011).

Liliana Bernardo, Lorenzo Peruzzi, Francesco Roma-Marzio

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4.2 *Ecological assessment of the Biferno river estuary (benthos communities and water quality)*

To assess the ecological status of estuarine ecosystems at the Biferno mouth (Molise coast), we analyzed benthic communities. These organisms are excellent indicators of environmental conditions due to their sensitivity to both natural and anthropogenic changes. Their persistence, allows these biocenoses to provide an integrated view of the spatial-temporal variations in ecosystem characteristics, acting as the "biological memory" of the environment (Damiani et al., 1998).

The structure of macrobenthic communities is closely linked to abiotic factors and is particularly sensitive to pollutants. For this reason, the macrobenthos are an excellent indicator of environmental conditions, including the presence and concentration of pollutants (La Mesa et al., 2019). For these reasons, benthic macroinvertebrates living on mobile substrates have been selected as bio-indicators of environmental quality within the framework of Directive 2000/60/EC. Their assessment plays a crucial role in defining the ecological and conservation status of coastal marine ecosystems.

As part of this thesis project, biological and ecological investigations were conducted along the coast facing the ZSC IT7222216 – "Foce Biferno – Litorale di Campomarino" to characterize the macrozoobenthic communities of sandy seabeds. In particular, the study focused on the estuary of the Biferno river to determine whether these communities could be classified as typically marine or brackish. The term "macrozoobenthos" refers to organisms larger than one millimetre that live in close contact with the seabed, either on its surface (epifauna) or buried within the upper layers of sediment (infauna) (La Mesa et al., 2019). The study of benthos is particularly significant as the composition and distribution of these communities provide insights into the condition of aquatic environments (Borisov et al., 2016; Harahap et al., 2018). Benthic communities change in response to environmental alterations caused by natural or anthropogenic disturbances, but these changes occur gradually. This makes benthos a reliable indicator of environmental conditions over time, characterized by a form of "biological memory" (Zuschin & Stachowitsch, 2009).

Sampling activities were carried out on the morning of June 3, 2022, led by Dr. Tommaso Pagliano with contributions from the Department of Biosciences and Territory and logistical support from the Guidotti Ships company in Termoli.

River mouths, such as that of the Biferno river, represent transitional environments where continuous and gradual salinity variations from approximately 3‰ in freshwater to around 35‰ in marine water determine the presence of specialized taxa distributed along the ecotonal gradient (Carroll & Thorp, 2014). These environments are natural transition zones between marine and continental ecosystems (Tagliapietra et al., 2014). Organisms typical of these habitats may either tolerate a wide salinity range or prefer a narrower range that is higher than freshwater levels. Other physico-chemical parameters, such as dissolved oxygen, also influence species distribution and presence.

The main taxonomic groups (Figure 1) characterizing these habitats include Polychaetes (e.g., Nereids), Crustaceans (Amphipods, Isopods, Palaemonids, Portunids), Mollusks (Bivalves and Gastropods), Cnidarians (sessile Anthozoans), and Echinoderms (Asteroids), view Table 1.

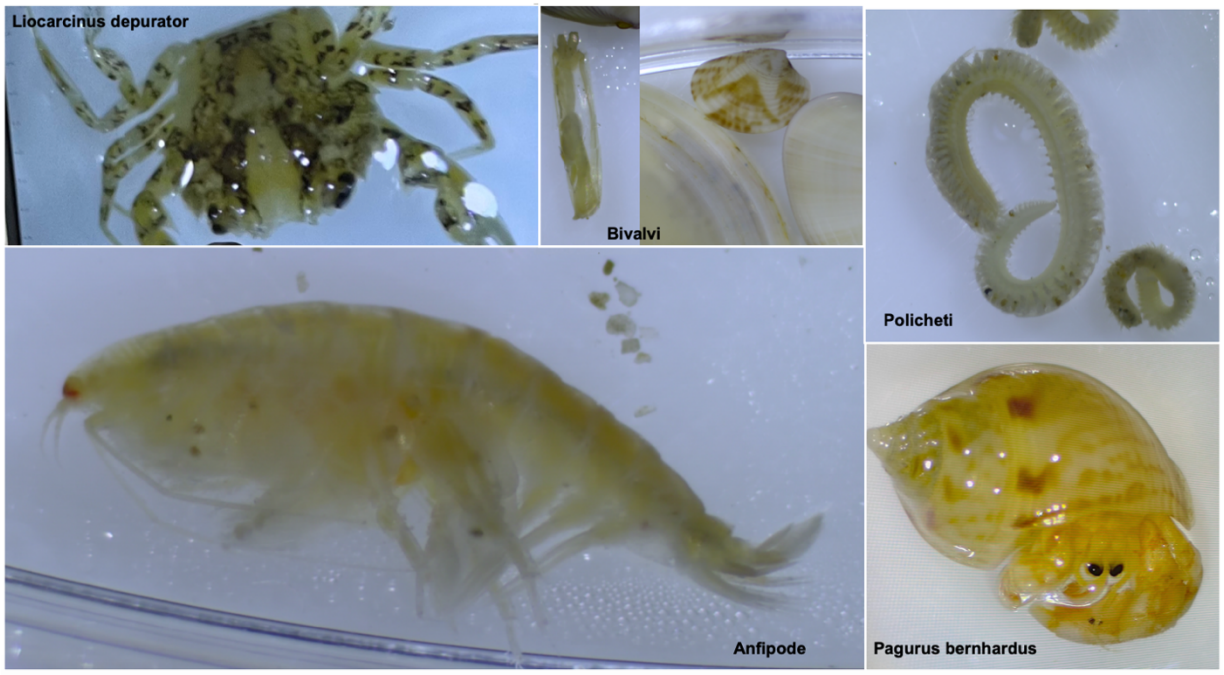


Figure 1. Images of some macrozoobenthos taxa collected on the Biferno estuary.

Table 1. Summary table of the first macrozoobenthos analyses. The number of specimens identified for each taxonomic category at each sampling point for three replicates is shown.

Repliche	Policheti	Bivalvi	Anfipodi	Isopodi	*Pagurus bernhardus*	*Liocarcinus depurator*	Arenicole	*Echinocardium cordatum*	Indet.	*Philocheras*	n indiv/plot	mean indiv/plot	total indiv/punto	sp per plot	media sp/plot	totale sp
1A	3	2									5	26	**78**	2	4	**12**
1B	29	9	1								39			4		
1C	26	5	1		1	1					34			6		
2A	4	8			1						13	7,7	**23**	3	2,3	**7**
2B	3	4									7			2		
2C	3										3			2		
3A	8	5	1								14	9,7	**29**	4	3,3	**10**
3B	2	4	3								9			4		
3C	3	3									6			2		
4A	3									1	4	5	**15**	2	2,7	**8**
4B	1	1						1			3			3		
4C	1	6							1		8			3		
5A	2	1									3	4	**12**	3	2,3	**7**
5B	1	3									4			2		
5C	1	4									5			2		
6A	0						82				82	28,3	**85**	1	1,0	**3**
6B	2	1									3			2		

Repliche	Policheti	Bivalvi	Anfipodi	Isopodi	*Pagurus bernhardus*	*Liocarcinus depurator*	Arenicole	*Echinocardium cordatum*	Indet.	*Philocheras*	n indiv/plot	mean indiv/plot	total indiv/punto	sp per plot	media sp/plot	totale sp
6C	0										0			0		
7A	1	1									2	1,7	**5**	2	1,7	**5**
7B	0										0			0		
7C	0	1	1		1						3			3		
8A	0	1	4		1						6	3,3	**10**	3	1,7	**5**
8B	0		3			1					4			2		
8C	0										0			0		
9A	0		1			1					2	2,7	**8**	2	2,0	**6**
9B	0			2		2					4			2		
9C	0		1			1					2			2		
10A	0		1								1	0,3	**1**	1	0,3	**1**
10B	0										0			0		
10C	0										0			0		
11A	0		2								2	1	**3**	1	0,7	**2**
11B	0										0			0		
11C	0	1									1			1		
12A	0	3	1								4	1,3	**4**	2	0,7	**2**
12B	0										0			0		
12C	0										0			0		

Macrozoobenthos sampling at the Biferno river mouth, corresponding to the 1130 "*Estuaries*" habitat, followed the ISPRA "Scheda Metodologica per il Campionamento del Macrozoobenthos di Fondi Mobili" (https://www.isprambiente.gov.it/files/icram/macrozoo.pdf). Initially, 13 sampling stations were identified, located in homogeneous seabed areas according to a systematic design, starting from the outermost part of the river mouth and moving toward its inner reaches (see Figure 2). Sampling at station 13 was not possible due to the shallow seabed and safety concerns related to the boat's operation in this area.

Sampling was conducted using a small boat. Sediment collection was performed with a Van Veen grab sampler with a 5-litre internal volume and a sampling surface area of 400 cm². Each station was sampled three times in slightly different locations to avoid disturbing previously sampled areas. The collected samples were washed at sea using a 1-mm mesh sieve and then preserved in polyethylene bags containing approximately 50 cc of 70% ethanol. Each bag was labeled with a code identifying the station (1 to 12) and the replicate (A, B, or C). Key physico-chemical parameters of the water were recorded using a multiparameter probe (Figure 2).

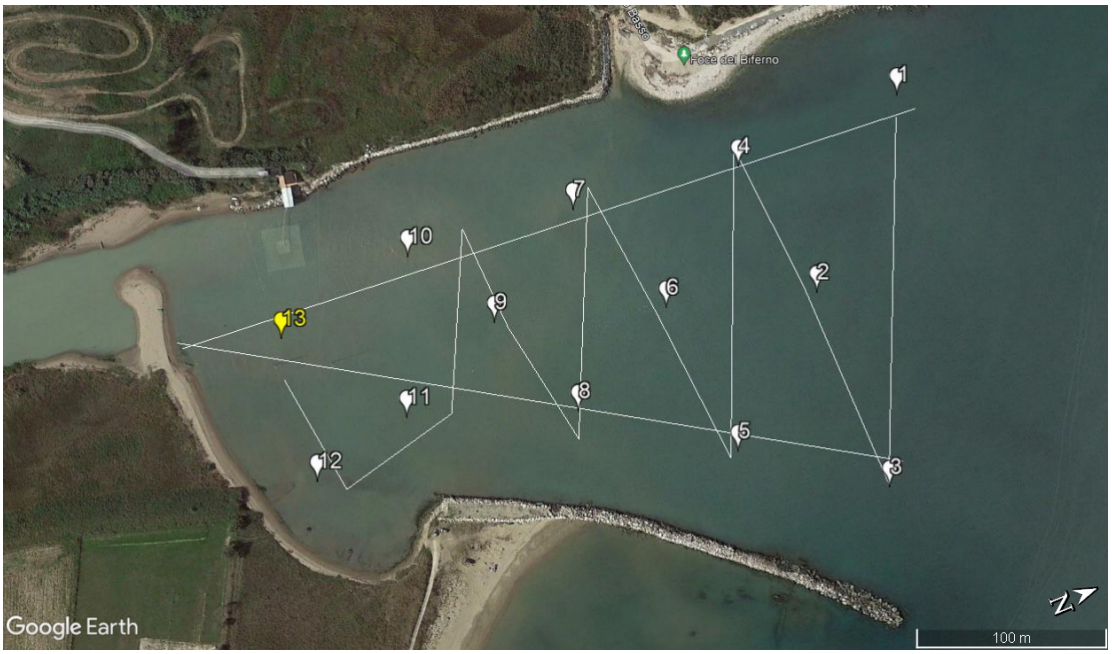


Figure 2. Sampling points of Macrozoobenthos near the mouth of the Biferno.

In the laboratory, organism identification was conducted with a high-definition video-equipped stereomicroscope (Figure 1), using taxonomic guides such as "Flora e Fauna del Mediterraneo" by Riedl (2005). The samples were sorted into taxonomic groups and preserved for further analysis. Preliminary results revealed a consistently high salinity (always above 31‰, with an average of 34.08‰) and a low abundance of individuals, all belonging to taxa typically associated with sandy and muddy marine substrates. No freshwater or brackish species were detected, indicating that the 1130 "*Estuaries*" habitat at the Biferno river mouth is currently limited in terms of its expected aquatic components.

This study highlights the importance of benthic communities as reliable indicators of environmental conditions, particularly in transitional ecosystems like river mouths. The findings at the Biferno river estuary revealed a consistently high salinity and a low diversity of macrozoobenthic taxa, all associated with marine habitats. The absence of freshwater or brackish species suggests a limited functionality of the 1130 "*Estuaries*" habitat in this area, emphasizing the need for further investigation.

Future research should focus on seasonal variability and incorporate additional environmental parameters to provide a more comprehensive understanding of the estuarine habitat's dynamics. Such studies are crucial for assessing the ecological status of the estuary and informing management strategies for its conservation. By characterizing the macrozoobenthic communities and identifying their responses to abiotic factors, this research contributes to a broader understanding of coastal-

marine ecosystems and underscores the value of preserving transitional zones like the Biferno estuary for biodiversity and ecosystem services.

4.3 *Cetacean Stranding Analysis*

During the initial exploratory phase of this doctoral project, and to gain a preliminary understanding of the Central Adriatic coastal system, we consulted and explored a biodiversity database developed and shared by the Centro Studi Cetacei (https://www.centrostudicetacei.it) and the GeoCetus project (www.geocetus.it). Based on this database, reporting sightings and strandings of marine mammals and reptiles we carried out a preliminary analysis on Cetacean strandings along the Central Adriatic coast. This analysis included examining the temporal distribution of strandings over the years and, with reference to the study by Benvegnù, (2013), investigating the distribution of age classes.
Cetaceans are an order of marine mammals divided into two main suborders: Mysticetes and Odontocetes (Cagnolaro et al., 2015). Mysticetes, such as the blue whale and the humpback whale, are characterized by the presence of baleen plates keratinous structures in place of teeth that filter water, retaining small organisms such as krill and plankton (Cagnolaro et al., 2015). Odontocetes, on the other hand, are predators equipped with smaller-sized teeth (Notarbartolo di Sciara & Demma, 2004). Among the most widespread Odontocetes in the Adriatic Sea, the family Delphinidae is the most numerous and includes charismatic species such as the bottlenose dolphin (*Tursiops truncatus*, Montagu, 1821) present throughout the Mediterranean Sea and subject to numerous ecological studies (Figure 1).

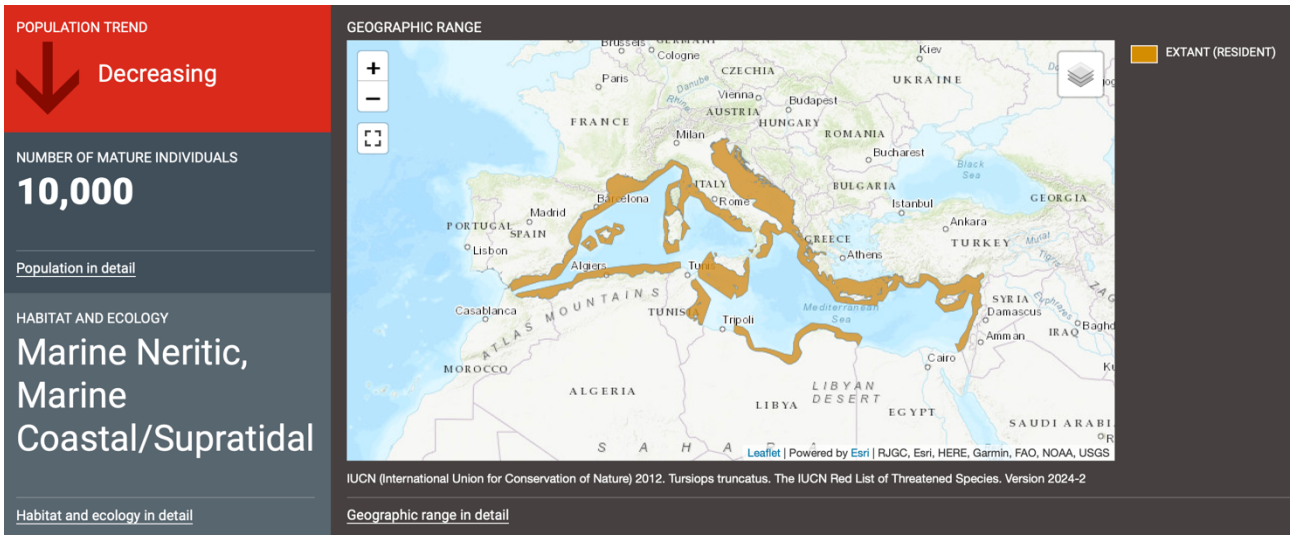


Figure 1. *Tursiops truncatus* distribution is second on the Red List of IUCN (https://www.iucnredlist.org/species/22563/2782611).

The bottlenose dolphin (*Tursiops truncatus*, Montagu, 1821) is one of the most well-known dolphin species in the world due to its intelligence, sociability, and cosmopolitan distribution. This animal can reach a length of 2–3 meters, with males being larger than females. It has a powerful and muscular body, with a short and stubby rostrum (Bearzi et al., 2009; Cagnolaro et al., 2015). The coloration is generally grey with lighter shades on the belly, which provides a camouflage effect to protect itself from predators. *Tursiops truncatus* is widely distributed in all temperate and tropical oceans, including the coastal waters of the Mediterranean (Bearzi et al., 2009).

From an ecological point of view, both species play a crucial role in regulating marine trophic dynamics. *Tursiops truncatus* is an opportunistic predator that feeds on benthic and demersal fish, such as mullets, red mullets, and cuttlefish, as well as cephalopods like octopuses and squid (Notarbartolo di Sciara & Demma, 2004).

More than 66% of Cetacean species are negatively affected by marine litter, so their monitoring is important to define the impact of marine plastic pollution on them and the surrounding environment (Fossi et al., 2018). This makes them excellent bioindicators of the health of the marine environment (www.lifedelfi.eu). Monitoring Cetacean populations is therefore fundamental to understanding ecological dynamics and evaluating the impact of anthropogenic activities on marine ecosystems (Fossi et al., 2018). The methodologies included for the monitoring are, for example, Capture-Mark-Recapture (CMR) systems using photographic images, acoustic recordings through hydrophones, and satellite techniques to track individual movements. In recent years, *Citizen Science* has played an important role in monitoring Cetaceans, thanks to dedicated projects such as "Argonauta" (https://www.centroricercacetacei.org/it/progetto-argonautica) or "CONCEPTU Mari" (https://www.lifeconceptu.eu). These initiatives involve volunteers, recreational boaters, and fishermen in collecting data on sightings, increasing the spatial and temporal coverage of observations and raising public awareness of the importance of marine biodiversity conservation (Alessi et al., 2019).

The main threats to *Tursiops truncatus* include acoustic pollution, accidental capture in fishing nets, collisions with boats, and habitat loss (Natoli et al., 2022). Acoustic pollution can interfere with their echolocation and communication abilities, causing disorientation and strandings (Notarbartolo di Sciara & Demma, 2004). Accidental capture in fishing nets is one of the main causes of mortality for these species, as they often become trapped and drown due to the inability to surface to breathe. The study of strandings provides valuable information on the causes of mortality and the health conditions of populations. Each stranding event is documented through photographic surveys and necropsy analyses, which can reveal the presence of infections, parasites, traumatic injuries, and contaminant

accumulation (Cagnolaro et al., 2015). *Citizen Science* contributes to the monitoring of strandings, with timely reports allowing the competent authorities to intervene promptly (De Weerdt et al., 2021). Monitoring the bottlenose dolphin is crucial given the protection plans in which it is included. The species is listed in Annexes II and IV of the Habitats Directive (Direttiva 92/43/CEE) and Annex II of the Bern Convention (https://www.coe.int/en/web/bern-convention), in Annex II of the SPA/BIO Protocol of the Barcelona Convention (http://data.europa.eu/eli/convention/1977/585/oj), and Annex II of the Bonn Convention (http://data.europa.eu/eli/convention/1982/461/oj). The species is included in the CITES Convention (https://cites.org/eng) and the ACCOBAMS Agreement (https://accobams.org/?option=com_content&view=article&id=1079:agreement-purpose&catid=68:presentation&Itemid=1). Moreover, the species is present in the IUCN Red Lists with a conservation status of "Vulnerable" (Bearzi et al., 2021).

During an exploratory phase of this doctoral project, we carried out a preliminary analysis of marine mammals and strandings along the coasts of Abruzzo and Molise from 2006 to 2021. The analysis utilized private databases from the Centro Studi Cetacei (https://www.centrostudicetacei.it) and the GeoCetus project (www.geocetus.it), which document sightings and strandings. It focused on the temporal distribution of strandings over the years and included an examination of age class distribution, following the methodology outlined by Benvegnù (2013).

The temporal distribution of strandings (Figure 2) highlighted an increase in findings starting from 2014. This temporal increase may depend on a combination of factors such as the spread of diseases or parasites (Cagnolaro L. et al., 2015) or changes in habitat conditions, in previous years (Natoli et al., 2022), which endanger the survival of this species. Furthermore, technological advances, in recent years, have facilitated greater data collection (*Citizen Science* - Alessi et al., 2019; Natoli et al., 2022).

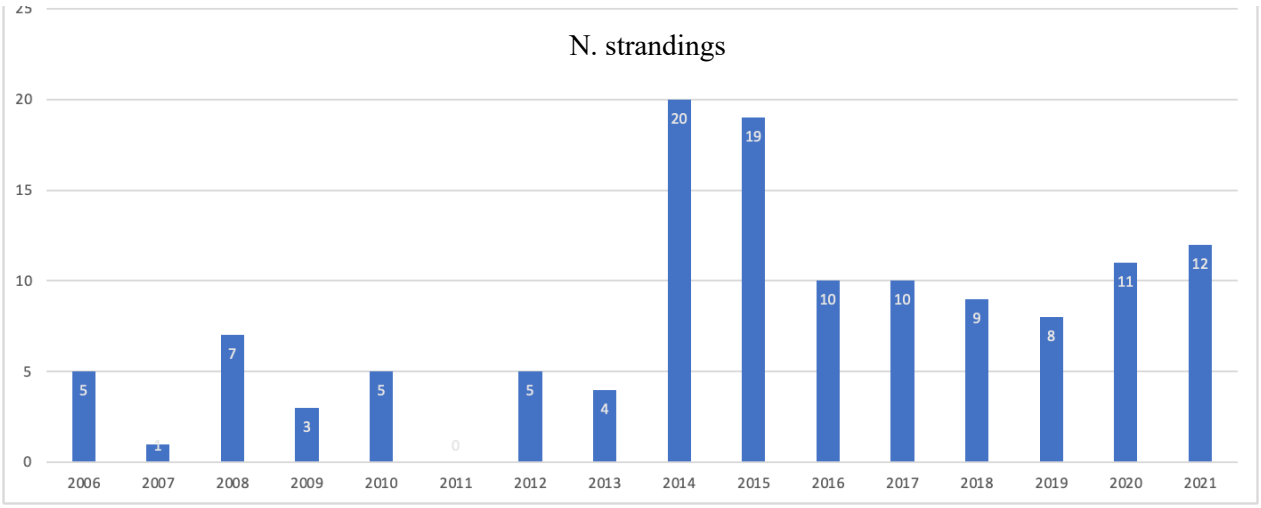


Figure 2. Number of strandings per year.

By correlating the size of each specimen with its sex, it was also possible to classify the stranded individuals into age classes, where possible: *newborns* (0 - 75 days), *calves* (75 days - 4 years), *juveniles* (females 5 - 9 years, males 5 - 11 years), *adults* (females 10 - 57 years, males 12 - 48 years; Benvegnù, 2013). The seasonal distribution of stranded individuals classified by sex and age was also analyzed (Figure 3).

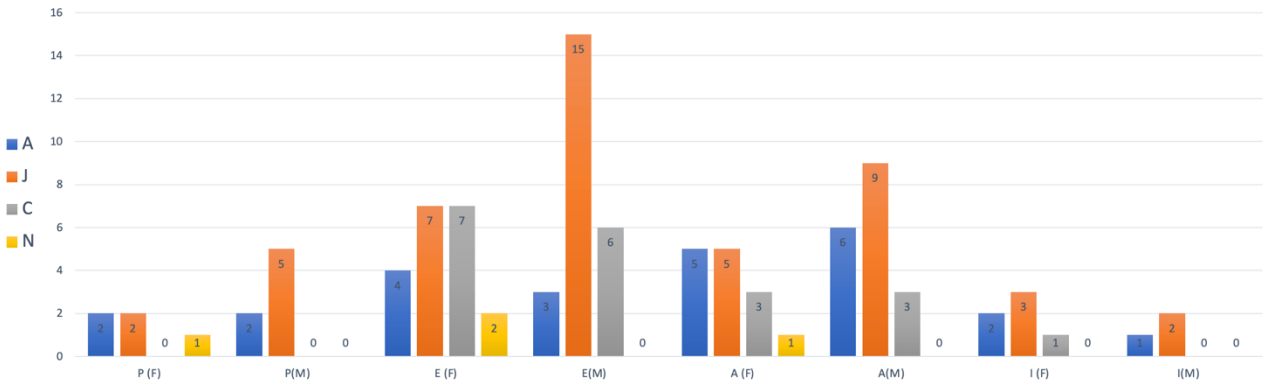


Figure 3. Number of strandings by age classes: **A**: *adult*-blue, **J**: *juveniles*-red, **C**: *calves*-grey, **N**: *newborn*-yellow, seasons: **P**: Spring, **E**: Summer, **A**: Autumn, **I**: Winter and, sex: **(F)**: females, **(M)**: males.

The most vulnerable class turns out to be male *juveniles*, who strand most frequently in the summer (Figure 3). While the increase in summer observations may be due to the greater presence of people on the beaches (tourism, sports, leisure, etc.) and, in part, to temporal variations in anthropogenic pressure and disturbance (Nowacek et al., 2007), the greater vulnerability of *juveniles* could be due to behavioral reasons, such as maternal separation during dispersion towards small sub-adult groups (Wells et al., 1987), which are less efficient at gathering food or defending themselves from potential threats (Benvegnù, 2013).

The information obtained from strandings is important but still very limited and could be improved if integrated with standardized monitoring systems such as photo-identification and line transect (La Mesa et al., 2019).

From the analysis of detection forms and necropsy certificates (made available by the CSC), it was possible to study and characterize the conditions of the specimens. On the carcasses of over 60% of the specimens (Figure 4), traces of anthropogenic impact (such as injuries from sharp objects) were present. In about 50%, plastic residues or other material, mostly ingested, were detected (marine litter - Fossi et al., 2018).

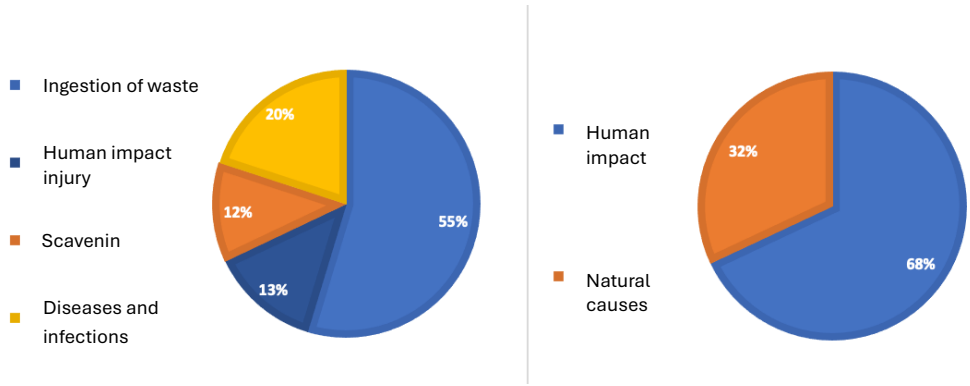


Figure 4. Summary diagrams of the conditions and impacts of Bottlenose dolphins when found.

This initial exploration highlights the presence of threats due to anthropogenic pressure and confirms the need to conduct further studies on stranded specimens to deepen knowledge about the health conditions of bottlenose dolphins in the Central Adriatic.

Tursiops truncatus is therefore a key species for studying marine biodiversity and monitoring the health of ecosystems. Strengthening monitoring networks and promoting cooperation between scientific institutions, environmental associations, and citizens is essential to developing effective conservation strategies and ensuring a sustainable future for marine ecosystems.

Chapter 5 - Future Developments

Finally, Chapter 5 discusses future perspectives, emphasizing the potential for synergies with Long-Term Monitoring Networks such as LTER (Long-Term Ecological Research). These collaborations could significantly enhance the use of *Citizen Science* (CS) data and foster greater integration between science, civil society, and environmental policies.

The overarching goal is to deepen our understanding of ecological dynamics and threats in fragile environments, thereby making a substantial contribution to conservation and management strategies. This ongoing collaboration opens new avenues for CS in biodiversity monitoring, extending its applicability across a wide range of ecosystems, including both marine and terrestrial environments identified within the selected LTER sites in Italy.

The experience matured on CS applications in coastal Adriatic areas will be extended to other LTER sites in Italy in which it can complement traditional research methods by increasing the quantity and spatial coverage of collected data. As observed in coastal areas, particular attention will be needed for the assessment of data quality, the temporal continuity of observations, and their integration into decision-making processes (Hochmair et al., 2020; López-Guillén et al., 2024).

By analyzing the extensive CS experience implemented in the network of LTER sites we aim to consolidate the results achieved and promote stronger synergies between existing monitoring networks, emerging technologies, and civil society to support effective and sustainable management strategies.

Collaborations with long-term ecological research networks, such as LTER (Long-Term Ecological Research - https://elter-ri.eu), will play a crucial role in advancing our understanding of the ecological dynamics and processes that shape these environments. The integration of citizen-collected data with long-term monitoring datasets will not only enrich existing databases but also enhance the ability to address global challenges such as climate change, pollution, and habitat loss (Peter et al., 2019).

Long-term monitoring networks, such as LTER, are fundamental for understanding ecosystem dynamics across temporal and spatial scales. The LTER network, based on continuous standardized data collection across different sites, allows the identification of long-term trends and robust analysis of ecological responses to critical events. The integration of CS data with LTER monitoring platforms can:

• Extend the temporal and spatial coverage of data thanks to citizen contributions;

• Validate citizen-collected data by comparing it with consolidated datasets, thereby increasing its reliability;

• Improve predictive capabilities through ecological models that combine historical time series with recent and distributed observations.

A promising development in marine-coastal biodiversity monitoring lies, in particular, in the collaboration established with the LTER-IT (Italian Long-Term Ecological Research - https://www.lteritalia.it) network. This network has launched an ambitious project to assess the potential and limitations of CS within a long-term monitoring framework. Dedicated projects have been set up for each LTER site within the Italian network on the iNaturalist platform, which serves as a primary tool for selecting sites to participate in the initiative. This collaboration aims to leverage the strengths of CS while addressing challenges, ultimately enhancing the effectiveness of long-term ecological research and conservation efforts.

The collaboration with the LTER-IT network represents a significant opportunity to integrate the *Citizen Science* approach within a long-term monitoring framework encompassing a wide range of heterogeneous ecosystems. This ecological diversity adds considerable value to the comparative analysis of environmental dynamics and anthropogenic pressures, providing a broader perspective on the threats facing different habitats. In particular, the selection of monitored sites reflects this heterogeneity. Among the selected sites are transitional ecosystems, such as lagoons; coastal areas, including our site “Foce Trigno - Marina di Petacciato” (IT20-002-T), which exemplifies marine-coastal monitoring in a high-biodiversity area; lakes, such as Lake Maggiore, a nationally significant freshwater ecosystem; high-altitude mountain parks that host emblematic alpine species; Mediterranean ecosystems characterized by forests and wetlands; and proglacial zones, fragile environments that reflect the direct consequences of glacier retreat. The application of the CS approach within such a diversified network of ecosystems will enable the enhancement of data on species of conservation interest, threatened species, and invasive alien species, providing a comprehensive overview of ecological conditions and pressures acting on each habitat. Comparing these ecologically distinct contexts will allow for the identification of not only the primary threats but also the underlying drivers, offering valuable insights for the development of tailored management strategies for each habitat type. A participatory approach applied to such complex monitoring systems may also highlight methodological limitations, such as the challenge of standardizing data collection protocols across different habitats. However, these challenges can be addressed through the use of innovative technologies, aimed at improving the quality of data collected by citizen scientists (Newman et al., 2012).

The integration of data collected represents a step forward in achieving a deeper understanding of ecological dynamics on a broader scale and the factors influencing biodiversity in such heterogeneous habitats. This project has the potential to become a reference model for long-term monitoring networks, fostering greater synergy between science, local communities, and conservation policies.

In our case, the “Foce Trigno - Marina di Petacciato” site was chosen, which currently counts over 750 observations collected thanks to the contribution of citizens, volunteers, and researchers. This collaboration represents a significant opportunity for growth, not only to strengthen data collection through participatory approaches but also to integrate CS data with those collected through traditional methodologies. The synergy between *Citizen Science* and long-term monitoring networks such as LTER can significantly improve the understanding of ecological dynamics and support sustainable management strategies. Furthermore, the collaborative approach strengthens the relationship between science, local communities, and policy makers, fostering a more inclusive and informed environmental management. This initiative holds great potential for the future as it further enhances citizen observations and broadens public participation in scientific research, even within international networks such as LTER. Investing in such projects means not only improving the effectiveness of environmental monitoring but also contributing to the dissemination of a scientific culture that raises awareness about biodiversity conservation (Kobori et al., 2016).

In the future, it will be essential to promote the development and implementation of projects that can support even non-expert users in collecting accurate data. The increasing and conscious use of AI could improve automatic image analysis and species recognition, thereby increasing monitoring efficiency and reducing human errors. Educational projects and awareness campaigns should also be promoted to raise citizen awareness of the importance of biodiversity and environmental threats. The training of qualified “citizen scientists” can improve the quality of collected data and foster a sense of belonging and responsibility towards the protection of marine-coastal ecosystems.

Collaboration with schools, universities, and local associations can foster the creation of a robust monitoring network in which citizens are not only observers but also active participants in the conservation of natural habitats. The interaction between science, civil society, and institutions can strengthen environmental policies and promote a participatory approach to resource management, enhancing the effectiveness of conservation measures.

The future of *Citizen Science* for marine-coastal biodiversity monitoring lies in the integration with long-term monitoring networks, the adoption of innovative technologies, and the active involvement of civil society. Synergies with programs such as LTER represent a unique opportunity to transform data collection from a simple observation tool into a cornerstone of global conservation strategies.

The combination of scientific data and citizen contributions can foster a deeper understanding of ecological dynamics and threats, contributing to the formulation of more effective policies and the protection of marine-coastal ecosystems. Investing in these perspectives means promoting sustainable and participatory management of natural environments, ensuring biodiversity conservation for future generations.

Conclusion

The present research, dealing with biodiversity assessment on particularly dynamic systems as coastal transitions, explored the potential and implemented the *Citizen Science* (CS) approach (a rapidly expanding set of methods and tools, in which citizens actively collaborate with researchers and institutions). This participatory model, which has gained significant relevance in the ecological field, resulted particularly effective in monitoring species and habitats in coastal areas. It enhances the understanding of environmental changes and offers updated information useful for supporting effective conservation measures.

Among the numerous platforms available that gained widespread popularity following the advent of the Internet (e.g. iNaturalist, eBird, PlantNet) we chose iNaturalist, which has proven to be a large-scale investigative tool, with growing potential for academic research and sustainable ecosystem management.

The development of a generalist CS project for monitoring biodiversity in dynamic ecosystems, using the Central Adriatic coast as a training ground (called Wild Coast Adriatic - WCA), effectively enabled the collection of valuable data, enhanced long-term knowledge of the region, and facilitated multi-taxa observations. This included species listed in Red Lists of IUCN or international directives and the identification of potentially invasive alien species and their distribution. Between 2020 and 2023, the WCA iNaturalist project, used as the primary reporting tool, facilitated the collection of thousands of observations on different taxonomic groups like marine organisms of high conservation value.

The WCA initiative was presented during the first National Conference Citizen Science Italia ETS in 2023, which promoted the establishment of participatory research networks aligned with the principles of inclusivity and directives set by the European Citizen Science Association (ECSA). WCA has contributed to the collection of reliable data and its subsequent analysis for both scientific research and management purposes. In this study, CS proved invaluable for monitoring marine-coastal ecosystems, which are increasing impinged by direct anthropogenic pressures, climate change, and the introduction of alien species (AS).

The adoption of a “semi-opportunistic” *Citizen Science* approach has extended the sampling range and actively involved volunteers and biodiversity enthusiasts. This approach has led to a significant increase in available data while simultaneously reducing the costs and time typically required for surveys conducted exclusively by specialized personnel.

The integration of digital technologies and cross-validation systems has improved the reliability of observations, minimized classification errors, and ensured an adequate level of scientific rigour.

From an environmental management perspective, the identification of threatened species and directive-listed habitats, along with the detection of invasive alien species, provides operational guidance for conservation efforts. This up-to-date information aligns with the goals of European regulations (e.g., the Habitat Directive - 92/43/EEC) and international agreements (Convention on Biological Diversity - https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A21993A1213%2801%29). Moreover, the data collected may offer opportunities to more effectively address the need for targeted interventions, such as the control and eradication of invasive alien species or the restoration of degraded habitats, enhancing the effectiveness of conservation strategies.

Simultaneously, citizen involvement in WCA initiatives has also had a positive socio-cultural impact, fostering increased awareness and collective responsibility toward environmental issues in the analyzed coastal areas. The two-way communication between scientists and volunteers - facilitated by simple digital tools - not only enhanced the quality of monitoring but also drives a paradigm shift in the perception of research, making it more accessible and integrated within the community. CS thus transcended its role as a data collection method, conforming a bridge between the scientific community and civil society, capable of generating shared strategies for the protection and enhancement of natural heritage. Despite its potential, some challenges remain, particularly concerning variability in quality. However, the application of standardized sampling protocols, the integration of artificial intelligence (IA), and expert validation significantly mitigate these issues. Another critical factor is the need for reliable and continuously updated technological platforms - such as iNaturalist - to ensure an efficient and sustainable flow of information. The findings of this research and the WCA project implementation have offered new evidence on the value of *Citizen Science* as a fundamental tool for detecting and monitoring biodiversity in marine-coastal ecosystems. As part of the Wild Coast Adriatic project, the iNaturalist platform was successfully used to document the presence of conservation-interest species and alien species along the Central Adriatic coast. This participatory approach enabled the collection of a significant number of observations, demonstrating the effectiveness of *Citizen Science* in gathering relevant ecological data in a relatively short time and at reduced costs.

In this context, the various chapters of the thesis enter into detail on specific aspects of this approach, outlining its practical application, challenges and future prospects. Specifically, the first chapter (**Chapter 1)** presents a preliminary bibliographic analysis, carried out with the support of the Scopus database. This analysis focuses on peer-reviewed articles published between 2020 to 2024. This analysis highlighted a growing diffusion of *Citizen Science* in monitoring marine-coastal biodiversity,

with a significant increase in publications starting from 2020. Italy stands out for its contribution to this field, driven by a combination of factors, including the high biodiversity, the variety of coastal habitats and the support of institutions such as the CNR and the activity of the Citizen Science Italia ETS that have strengthened the role of the country at an international level.
The analyzed papers primarily focus on marine environments and multi-species projects, while studies on plants are significantly fewer, and the digital platforms have played a pivotal role in facilitating data collection. However, most studies rely on descriptive analyses, with only a small proportion adopting advanced modelling techniques. This gap underscores the need for improving data analysis to support effective conservation strategies. Chapter 1 confirms that *Citizen Science* is a fundamental tool for marine-coastal monitoring, promoting an integrated approach that combines science, education, and public participation. To enhance data quality and support sustainable management of coastal ecosystems, investments in innovative technologies and global collaborations will be essential.

The WCA project (as illustrated in **Chapter 2**) has generated new spatial data and updates on several species listed in the IUCN Red List and the Habitat Directive (HD) annexes (II and IV), helping to fill important knowledge gaps. The observed species pinpoint the presence of numerous European habitats of community relevance along the Adriatic coast, some reported here for the first time in this area. As suggested by previous studies (e.g., Drius et al., 2019), the WCA findings confirm that the coastal transition mosaic in the Central Adriatic remains largely intact, underscoring its ecological and management value.
This information contributes significantly to scientific research because it provides detailed and updated georeferenced information on the distribution of threatened species and protected habitats, filling important knowledge gaps. In fact, the reports have allowed us to identify key areas for coastal conservation and management, which will certainly contribute to the planning of targeted measures for the protection of species and habitats of European interest. The observations have also highlighted the presence of human pressures and seasonal phenomena that influence biodiversity, underlining the importance of continuous monitoring to understand ecological dynamics. The WCA project has therefore demonstrated not only the effectiveness of *Citizen Science* in collecting relevant ecological data in a short time and at low costs but also its socio-cultural impact, promoting greater environmental awareness and active participation of local communities over time. The collaboration between citizens and researchers has helped fill important knowledge gaps, has strengthened the connection between science and society and suggested a replicable model for monitoring and conserving biodiversity in other coastal ecosystems. The joint assessment of the distribution and

coherence of species of interest along the coastal gradient provides a valuable resource for developing integrated management strategies and more effective environmental policies, in line with international guidelines and the Natura 2000 network.

Among the documented species (**Chapter 3**) are several alien taxa of community interest, regulated by the European Union, and subject to management and eradication plans. Data collected have been shared with competent authorities, providing concrete support for the implementation of specific monitoring, control, and eradication strategies. The progressive increase in observations and citizen scientist participation has highlighted the potential of *Citizen Science* for early detection of alien species, enabling timely interventions. This aspect is crucial for preventing the establishment and spread of invasive species, helping to mitigate associated ecological, economic, and social impacts.
The data collected have allowed the analysis of the spatial and temporal distribution of alien species, offering fundamental insights for the future development of targeted management and conservation policies. Additionally, the observation of seasonal variations in species presence has emphasized the importance of continuous monitoring efforts throughout the year, necessary to fully understand the ecological dynamics, behaviours, and dispersal patterns of alien species in local ecosystems.
The *Citizen Science* approach supported by the iNaturalist platform has proven useful not only for biodiversity but also for the early detection of invasive alien species, aiding in their eradication and control. The WCA project results suggest that the data collected can effectively track the regional spread of invasive species and their population dynamics, supporting a more efficient management strategy. Furthermore, a relevant aspect concerns the lower incidence of alien species in protected sites, such as Natura 2000 and LTER areas, compared to unprotected areas. This confirms the effectiveness of conservation measures but underlines the need for constant monitoring, which CS can offer, to strengthen ecological resilience. Finally, the study demonstrated the possibility of developing distribution models of alien species and identifying invasion hotspots, providing valuable indications to focus control actions on the most vulnerable areas.
As outlined in Chapters 2 and 3, studies highlight that *Citizen Science* data significantly improve predictions of the spread of invasive alien species, particularly when integrated into national-scale initiatives.

Chapter 4, instead, described the additional activities carried out within the project, including naturalistic notes, sampling activities in the Biferno river mouth, and the analysis of Cetacean strandings. These initiatives not only allowed for the reporting of species such as *Cymodocea nodosa* in new areas where it had never been recorded before but also integrated traditional monitoring

methodologies with a participatory approach, involving citizens, researchers, and volunteers. In particular, the monitoring at the Biferno mouth contributed to the collection of essential data on water quality and the biodiversity of a complex and sensitive transitional ecosystem. The analysis of Cetacean strandings, whose reports to the relevant authorities also occur through participatory approaches, highlighted the importance of a timely and coordinated reporting system to improve the management and conservation of vulnerable marine species. These activities demonstrated a complementarity with CS practices, providing a significant contribution to the protection of coastal ecosystems.

Finally, in **Chapter 5, t**he collaboration with the LTER network demonstrates the great potential of *Citizen Science* in expanding biodiversity monitoring to heterogeneous ecosystems, such as marine environments, lagoons, Mediterranean habitats, and mountainous and coastal areas. This diversity enables comparative analyses that could improve the understanding of ecological dynamics and anthropogenic pressures. The participatory approach represents a key strength as it integrates data collected by citizens and researchers, increasing the spatial and temporal coverage of observations and supporting the identification of major threats. Investigating such diverse contexts helps fill knowledge gaps, especially in complex and understudied habitats. The comparison of different ecosystems makes this initiative a reference model for global monitoring networks, promoting a more inclusive and participatory approach. Ultimately, investing in such collaborations can strengthen conservation strategies and support the development of resilient monitoring systems capable of responding to challenges related to climate change and biodiversity loss.

The results highlight the effectiveness of *Citizen Science* not only in detecting species of conservation interest and alien species but also in managing complex contexts such as transitional ecosystems and mountainous areas. The integration of data collected by citizens with those obtained through traditional methods, in collaboration with national and international networks such as the LTER network, can provide an innovative and interdisciplinary approach to understanding ecological dynamics at both local and global scales. However, challenges related to data quality and the standardization of protocols remain, particularly in ecologically heterogeneous ecosystems. These challenges can be addressed through training programs aimed at increasing participants' awareness and preparedness. CS thus emerges as a tool with immense potential for conservation strategies, promoting the sustainable and inclusive management of natural resources. Investing in collaborations between science, communities, and institutions can help build resilient monitoring networks capable

of addressing global challenges related to climate change and biodiversity loss, ensuring effective ecosystem protection for future generations.

Moreover, the success of the WCA project highlights the potential of *Citizen Science* as a strategic tool for addressing challenges in alien species management and biodiversity conservation within marine-coastal ecosystems. By actively involving citizens, the WCA project not only allowed the collection of valuable data but also enhanced local communities' awareness of environmental issues, promoting conscious and sustainable participation in protecting natural heritage.

The WCA project results showcase the transformative role of *Citizen Science* in supporting the management and conservation of marine-coastal biodiversity while raising societal awareness about environmental challenges. The data collected, analyzed, and archived throughout the project have bridged critical knowledge gaps and provided essential resources for future analyses, management strategies, and policy planning.

Ultimately, the Wild Coast Adriatic project represents a replicable model that integrates grassroots observations with specialized expertise to generate a deeper and more detailed understanding of ecological processes. *Citizen Science*, with its inclusive and participatory approach, continues to demonstrate its value as a powerful tool for addressing the environmental challenges. By fostering constructive dialogue between science and society and offering innovative solutions for biodiversity conservation, it embodies a model of participation and collective responsibility aligned with the United Nations Sustainable Development Goals (Agenda 2030 - https://unric.org/en/agenda-2030/).

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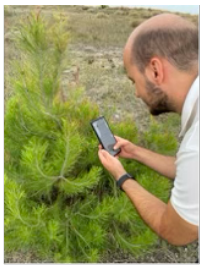
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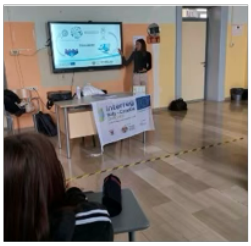





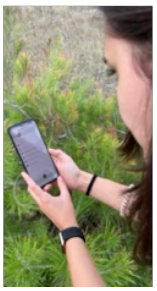








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