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Information Management

ORMEF: a geospatial web platform for mapping and visualizing exotic fish records in the Mediterranean and surrounding seas

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Abstract

ORMEF, accessible at https://www.ormef.eu, is a new interactive web platform that consolidates a vast historical repository of georeferenced records of exotic fishes, extracted from scientific literature. Covering observations spanning over a century, from 1896 to the present day, ORMEF incorporates 12,553 georeferenced occurrences distributed across 221 fish taxa, meticulously sourced from 805 scientific papers. This paper outlines the architecture of ORMEF and provides an insightful illustration of its tools and future developments. As an authoritative yet user-friendly reference, ORMEF has the potential to make a substantial impact across various initiatives. From advancing scientific research and supporting conservation efforts to engaging communities, ORMEF's outputs and data offer promising applications not only for marine bioinvasion research but also for informed decision-making at both the Mediterranean and EU levels.

Key words: non-indigenous species, biological invasions, occurrence records, decision support instrument, geoportal

Introduction

To tackle the escalating challenges posed by invasive species, which are persistently increasing on a global scale with no apparent signs of saturation (Seebens et al. 2017; IPBES 2023), dedicated information systems have been widely recognized as crucial by researchers and public bodies (Ricciardi et al. 2000; Saran et al. 2022). This need is particularly evident for the world's oceans (Bellard et al. 2016), especially in European and Mediterranean seas, where increasing efforts are dedicated to monitoring, updating, and refining Non-Indigenous Species (NIS) inventories (Galanidi et al. 2023). Fragmented and unstructured information on biodiversity typically hinders the analysis of species distribution (Whittaker et al. 2005). Specifically, structuring datasets in the NIS domain, with occurrence records scattered over large spatial and temporal scales, is an extremely challenging task.

However, advances in information technology unlock the enormous potential of these data in biodiversity science. The growing amount of georeferenced information, especially on non-indigenous fishes (Azzurro et al. 2022a), also highlights the need for available and up-to-date information on their occurrence and distribution.

Clearly, this information should be as accurate, well-documented, standardized, and openly accessible as possible to tackle NIS according to science-based strategies (Groom et al. 2017; Pagad et al. 2022). This need is well represented by the Kunming-Montreal Global biodiversity framework, TARGET 21 (CBD/COP/15/L25 https://www.cbdint/article/cop15-final-text-kunming-montreal-gbf-221222), quoting: *"Ensure that the best available data, information and knowledge, are accessible to decision-makers, practitioners and the public to guide effective and equitable governance, integrated and participatory management of biodiversity, and to strengthen communication, awareness-raising, education, monitoring, research and knowledge"*.

The same principles should be applied when assessing the health of the environment in the Mediterranean and European seas under European policies, particularly the EU Marine Strategy Framework Directive (MSFD) (2008/56/EC), with a descriptor (D2) dedicated to non-indigenous species introduced by human activities, and the EU Regulation No 1143/2014. This also concerns the Integrated Monitoring and Assessment Programme for the Mediterranean Region (IMAP), developed and adopted by the Contracting Parties to the Barcelona Convention (UNEP/MAP, 2017). Geoinformation and geoportals are also becoming central to Maritime Spatial Planning (MSP), the tool to manage the use of seas and oceans in the EU coherently and to ensure that human activities take place in an efficient, safe and sustainable way (Directive 2014/89/EU of the European Parliament), given that they have the promise of bringing together and integrating data from different sectors and sources, thus helping policy-makers to come to better decisions (Davret et al. 2024). Considering the importance of implementing the above-mentioned principles and the need to evaluate their effectiveness, now, more than ever, it is crucial to ensure that information regarding NIS in the Mediterranean and European Seas is not only accurate and comprehensive but also accessible to end users (Zenetos et al. 2022a, b).

Today, 1006 NIS have been listed from Mediterranean marine and brackish waters (Galanidi et al. 2023), with a considerable invasion debt accumulating, especially in the eastern and central sectors of the basin. In the Mediterranean and European seas, information on the occurrence and distribution of NIS is currently handled by many online databases such as: the EU-funded project DAISIE (Roy et al. 2020); AquaNIS (2015, www.corpi.ku.lt/databases/aquanis); EASIN (https://easin.jrc.ec.europa.eu/); ESENIAS (http://www.esenias.org/); ELNAIS (https://www.eea.europa.eu/data-and-maps/data/external/elnais-invasive-alien-species-data); NOBANIS (https://www.nobanis.org/); MAMIAS

(https://www.eea.europa.eu/data-and-maps/data/external/mamias-marine-mediterranean-invasive-alien-species) and MedMIS (http://www.iucn-medmis.org). These databases, often developed with the participation of experts from different fields and organizations, contain a large body of information that covers a broad taxonomic spectrum of organisms and constitute invaluable repositories of knowledge. However, some of them are no longer maintained or updated and the interactive interplay is generally limited, with georeferenced records seldom being easily accessible or prominently displayed.

In addressing these limitations, we introduce the ORMEF web platform, which offers a novel user-friendly access system for exploring occurrences of exotic fishes in the Mediterranean Sea and adjoining waters. ORMEF innovates in several ways the above-mentioned online databases on the occurrence and distribution of NIS in the Mediterranean Sea. Firstly, it specializes in geospatial information, offering a user-friendly system for exploring occurrences of exotic fishes with accurate georeferenced data, easily filtered and queried. Secondly, it introduces a temporal dimension to fish invasions, providing animated reconstructions and customized time interval filters. Thirdly, it exclusively draws from scientifically validated data sources, utilizing a comprehensive historical database derived from the scientific literature. This database, presented for the first time in September 2022 (UNEP/MAP – SPA/RAC 2022) underwent rigorous and repeated checks for validation, ensuring its reliability, and is made publicly available through recognized scientific channels (Azzurro et al. 2021, 2022b).

Materials and methods

Overall architecture of the ORMEF web platform

The ORMEF web platform is based on a three-level architecture (Figure 1) consisting of:

1. *User interface:* developed and deployed using standard web development tools, it primarily features a geographic portal supporting information via a GIS-based graphical user interface. This interface includes a suite of user functional tools enabling the specific execution of a task or a group of tasks to view, add and modify data in ORMEF.
2. *Application layer:* comprises various web services that process data. Web services publish geographic content and functionality. Typical geographic web service functionality published on the ORMEF web platform includes map rendering, feature streaming, data projection, geographic and attribute-based queries, metadata query and management, and data extraction.
3. *Data layer:* where the application data is stored and managed. The database management system provides a managed relational environment for geographic content.

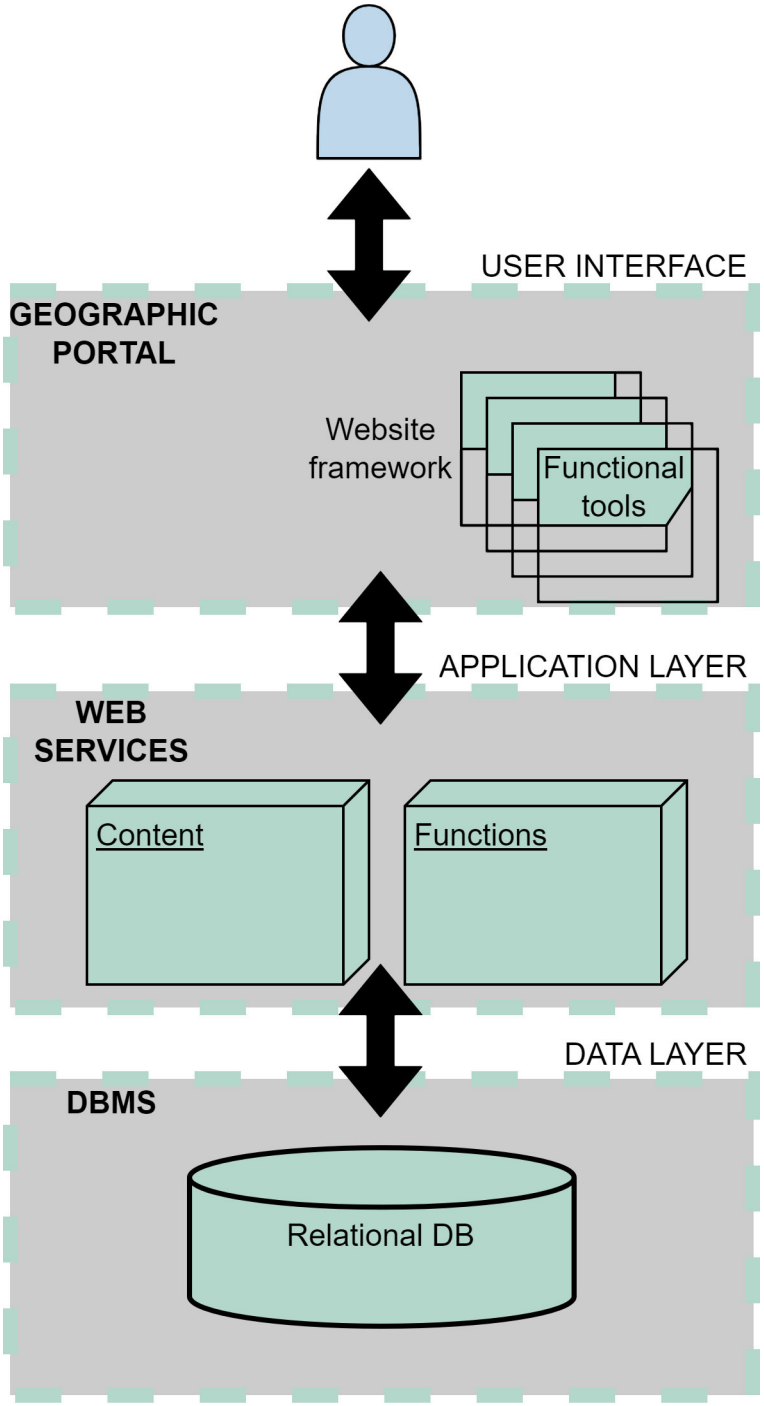

Figure 1. Overview of the ORMEF architecture: The three main components and their functional elements are illustrated.

Functional areas and modules

The ORMEF Web platform consists of two main sections (Figure 2): a public and a private functional area (https://www.ormef.eu/ormef-admin). Through the public functional area, the ORMEF Web platform provides a set of applications with capabilities for visualizing, searching, publishing, and administrating information using a geographic interface and then geographic data. The private section is accessible only to authorized staff and provides a set of functionalities to maintain the ORMEF database.

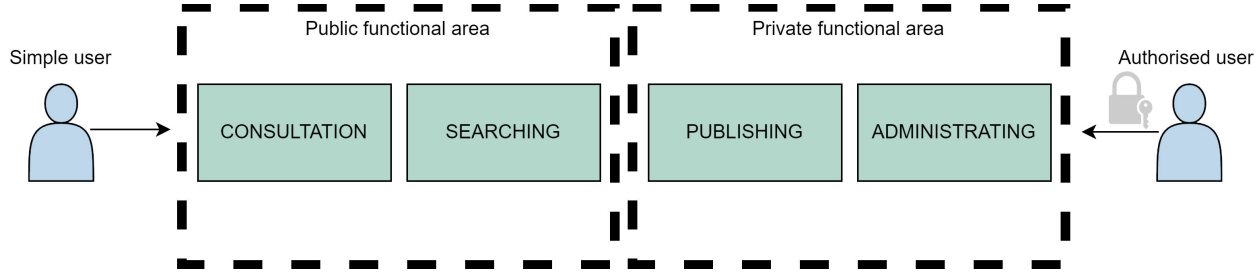

Figure 2. Functional areas and modules in the ORMEF Web Platform.

Consultation – The ORMEF web platform allows users to consult and visualize online geo-referenced data through maps and related non-spatial information on static pages. The consultation services allow the execution of the following operations: display, navigate, view scaling (zoom in, zoom out), and viewing information contained in the legends and any relevant metadata. ORMEF also enables the users to access an animation showing the detection of NIS over historical time.

Searching – Searching using geographical information in this web platform implementation is based on querying by title, abstract, and keyword metadata sections in combination with spatial and temporal filters. The geographic-based search uses geographic content and content metadata. Search functions are aggregations of multiple methods that can be executed jointly or in several ways, combining various filters that allow the selection of the species of interest based on the values associated with different metadata such as first record, most probable path, category of path, year of the record, record width, species names, family, and author.

Publishing/Updating data – The publishing process is a private function that entails adding metadata content. Publishing is manual and involves downloading a standard csv/xlsx/xls file, compiling it for updating data, and then uploading it. As a private function, 'Publishing/Updating data' is currently not open to common users, but only to registered administrators, who regularly update the database with new records from scientific literature. Nevertheless, potential data providers can contact the administrators to suggest new data uploads.

Administrating – Administration functions, also private, consist of generating backups and managing dropdown tables. The backup can be made up of exact copies of database directories, files and georeferenced records. The dropdown tables management allows the addition, modification, and deletion of items within the records and species dropdown tables.

API and functional tools development – ORMEF can exchange data with external applications via API. The database records are already made available —via API upon request—and it is possible for third-party developers to use them for their own applications. Furthermore, the platform is designed to be incremental to allow the development of new features by both the ORMEF team and third-party developers.

Results and tools

The georeferenced database and terminology used

The ORMEF web platform is built upon the extensive ORMEF database, a comprehensive compilation of exotic fish records derived from an exhaustive literature search, already published and freely available in its 2021 version (Azzurro et al. 2021, 2022a). Each record in the ORMEF database has undergone a meticulous validation process, cross-checked against original sources, and subjected to multiple peer reviews according to the publication procedures of the aforementioned papers. This database is playing a pivotal role in supporting various basin-scale scientific research projects and investigations (Parravicini et al. 2015; D'Amen and Azzurro 2020a, b; Azzurro and D'Amen 2022; D'Amen et al. 2024).

The ORMEF web platform at the date of January 2024, allows visualizing 12553 georeferenced occurrences on 221 accepted species of fish, and 88 families, plus the taxon of uncertain identification *Abudefduf* cf. *saxatilis/vaigiensis/troschelii* (Dragičević et al. 2021). The entire dataset spans from the earliest documented observation of *Pampus argenteus* in 1896 (Dulčić et al. 2004) to the last observations reported by Ragkousis et al. (2023), with ongoing updates for the years 2023 and 2024.

Data were extracted from 805 scientific papers published since 1902, providing a comprehensive, accurate and as complete as possible archive of historical occurrences available from the scientific literature. The taxa included in the ORMEF database, originally derived from the authoritative CIESM Atlas of exotic species (Golani et al. 2021), have undergone a recent update with the inclusion of 23 new species. Compared to Golani et al. (2021) and with the 2021 database (Azzurro et al. 2022a), the ORMEF 2023 version underwent a significant progress, with the inclusion of 8199 new validated georeferenced records sourced from the latest scientific literature. Among all examined papers, the work of Ragkousis et al. (2023) contributed the most with georeferenced data points. Initially, 7018 records were extracted from this study and a final list of 6940 records and 69251 documented individuals was curated after filtering out recent records of cryptogenic and freshwater species (e.g., *Dipturus nidarosiensis* and *Gambusia holbrooki*, respectively). Similarly, other cryptogenic and freshwater species recently reported in the Mediterranean literature were not considered in the current update (e.g., Carbonara et al. 2019; Elbaraasi et al. 2022). All scientific names of species were verified and aligned with current nomenclature standards using Fricke et al. (2023) and WoRMS Editorial Board (2023) as main references and taking into account recent taxonomic changes and documented misidentifications.

ORMEF datasets follow the FAIR principle of Findability, Accessibility, Interoperability, and Reusability of data (Wilkinson et al. 2016), and its vocabulary follows the Darwin Core Standard (DwC, https://dwctdwgorg/).

Each record extracted from the scientific literature was associated with a progressive code univocally identifying each record, the name of the species, the Aphia ID (unique identifier of the species provided by the World Register of Marine Species WoRMS; www.marinespecies.org), presumed introduction pathway, ecological and biological information, and the complete bibliographic reference and DOI plus a series of fields related to that specific observation such as: year of detection, month, location, geographical coordinates expressed in decimal degrees, precision of coordinates, country, and depth. The first records (first observation or collection) in the Mediterranean and/or Marmara and Black Seas were marked as such. In agreement with the approach used by the CIESM atlas, we considered three different groups of species according to their presumed introduction path EXOTIC CORR = fishes introduced through the Suez Canal; EXOTIC HM = fishes introduced by other human vectors, such as shipping, mariculture, or aquarium release; NRE (Natural Range Expansion) = fishes of Atlantic origin, which are supposed to have entered into the Mediterranean through Gibraltar, without direct assistance of human agency. Taking into account the mostly adopted definition of the terms exotic, alien, or NIS (e.g., Olenin et al. 2010), this latter group of *neonative* species (sensu Essl et al. 2019) cannot be considered "true" aliens or NIS. Nevertheless, its inclusion in the ORMEF web platform is motivated by two important considerations: first, scientific evidence about the introduction means is typically lacking or weak in the Mediterranean literature, and for many of these species we cannot completely discard the hypothesis of a possible introduction by human activities; second, Atlantic fishes entering the Mediterranean through the straits of Gibraltar are worth being closely traced to monitor the ongoing biodiversity change in the area (Golani et al. 2021; Azzurro et al. 2022b).

In agreement with Golani et al. (2021), we excluded cryptogenic, brackish, and vagrant species from our list of taxa, as well as doubtful records or observations of uncertain taxonomic identification. Species names were checked with Eschmeyer's catalog of fishes (Fricke et al. 2023) taking into account recent taxonomic changes and documented misidentifications. A first version of the database can be entirely downloaded from the SEANOE repository (Azzurro et al. 2021, 2022a). The ORMEF database is regularly updated by a team of collaborating experts, listed on the page "Team". A second, most updated version of the database, is being currently uploaded as csv files available for sharing, long-term access and reuse through the Life Watch Italy Data Portal https://dataportal.lifewatchitaly.eu/data and the Metadata Catalogs of LifeWatch Italy and LifeWatch ERIC https://metadatacatalogue.lifewatchitaly.eu.

Web platform resources and user interfaces

The ORMEF homepage (Figure 3) offers a range of visualization tools and interactive functions, including the visualization of occurrence maps, while

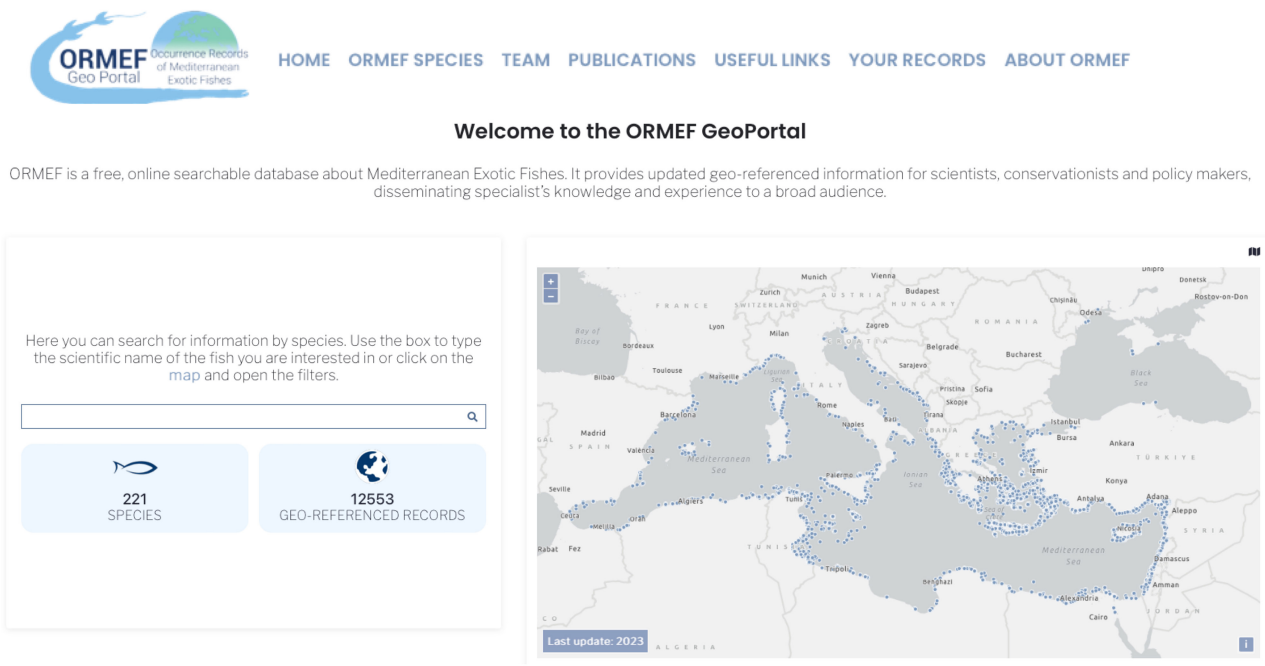

Figure 3. The homepage of the ORMEF web platform is freely consultable at the address https://www.ormef.eu (accessed 30 January 2024).

a top bar menu allows reaching the main sections. On the homepage, users have two options for species search: by selecting specific areas on the map, or by keywords. Map-based searches allow users to visualize species records on the map, and filter the data based on several fields including: First records, Most probable pathway, Category of pathway (Natural Range Expanding Species, Suez Canal, Human Mediated transport), Author, and Family. Additionally, filters include a temporal bar that enables users to select a specific time frame for filtering the records. Each point record on the map provides detailed information on the data source, bibliographic reference, and the details of each capture or observation. An expanded version of this information can be visualized on the species pages that can be reached by keyword searches. The species pages offer comprehensive details on the invasion history, such as the year of the first record in the Mediterranean, Black Sea, and Marmara Sea, the description of species distribution, and the location of records. The web platform system also allows for the production of animations of point records according to the selected filters and along the chosen temporal frame.

Information related to each species is accessible through a dedicated page (Figure 4), containing pictures and interactive links to the entire list of ORMEF species. Clicking on each of these species, users can access the related species summary (Figure 5), which contains basic information about the first record in the Mediterranean and/or Marmara and/or Black Sea, most probable path, native distribution, time series of occurrences, and a map showing the interactive point records.

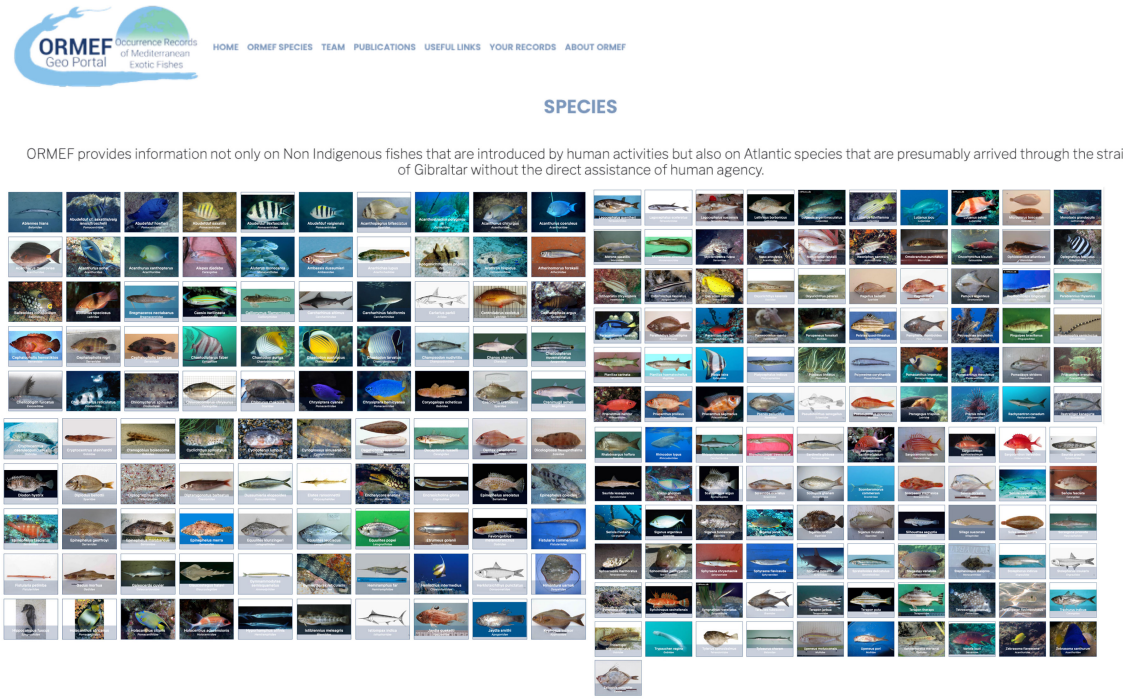

Figure 4. Screenshot of the ORMEF web platform "species" page, displaying interactive pictures of 221 fish species.

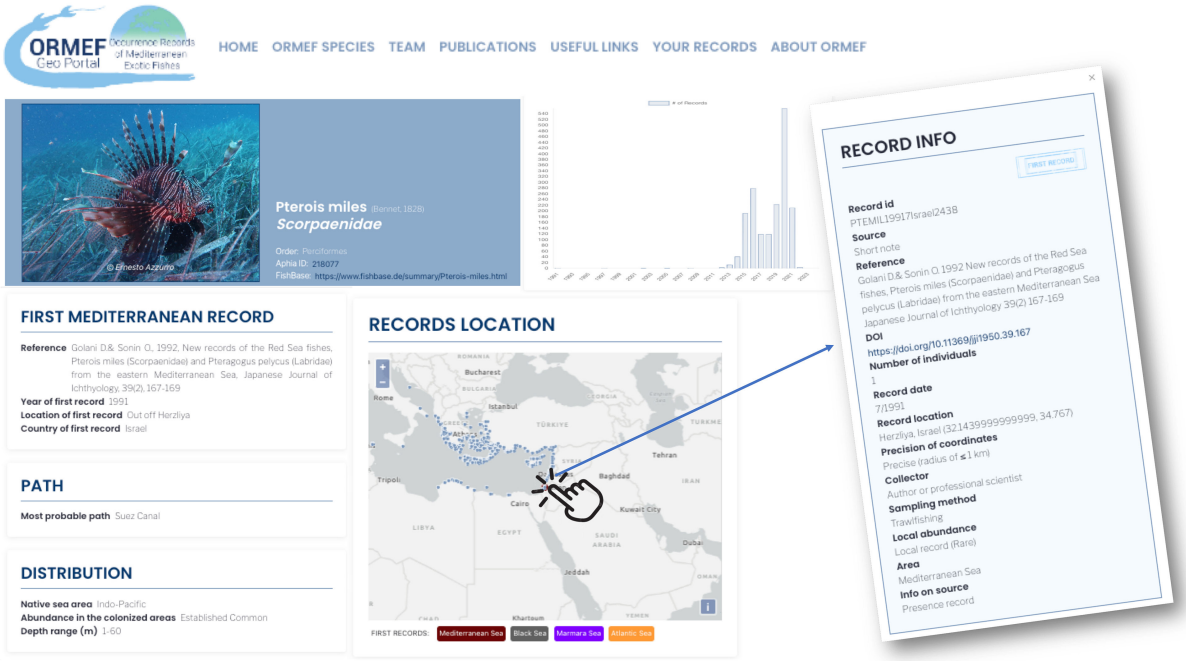

Figure 5. The species summary page, showing *Pterois miles* as an example. Each of these pages provides details on 221 species and their introduction pathways; a histogram displaying the number of records per year and an interactive occurrence map, where information associated with each point record (Record ID, Source, Reference, DOI, Record date, Record location and geographical coordinates, Precision of coordinates, Collector, Area, Info on source and Remarks) can be visualized. In total, there are 1764 interactive point records available for *P. miles*.

Users can employ a combination of filters to generate customized occurrence maps. These maps can therefore be tailored according to specific queries on introduction path, species, families, time span, and, of course, by selecting a specific geographical area (Figure 6). All these filters are available from the map interface. Different options are available to change the background layer.

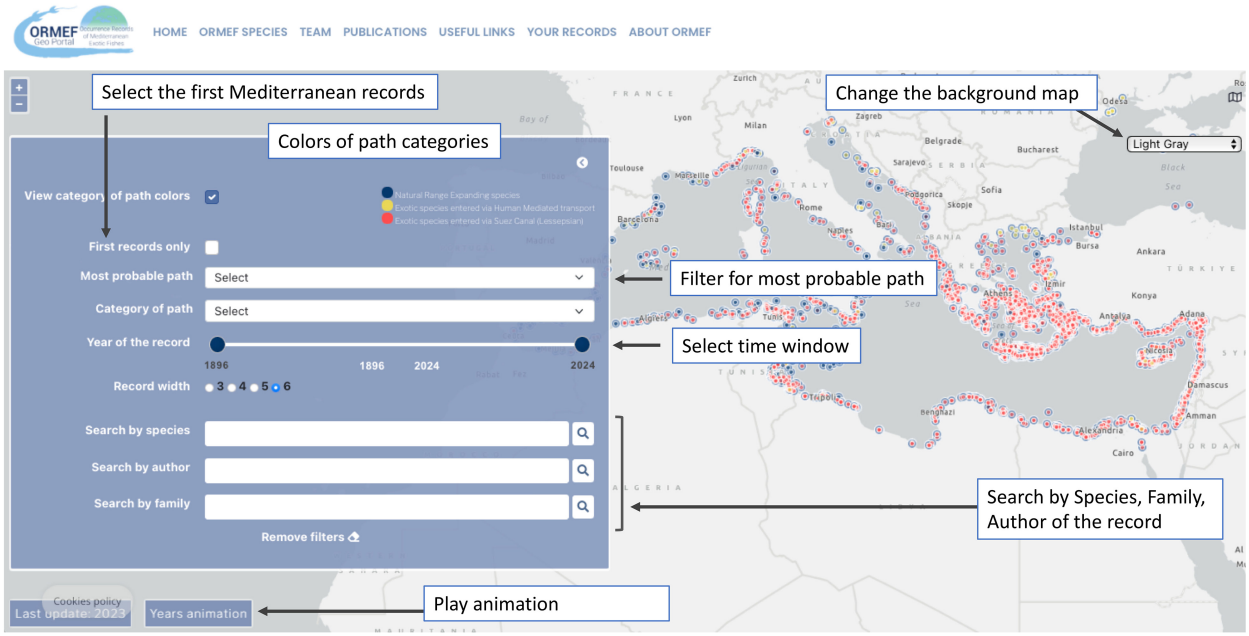

Figure 6. Presentation of the primary filters accessible from the map interface. Users can employ a combination of filters to visualize a customized map based on the introduction path, species, family, time span, and, of course, by selecting a specific geographical area. In this instance, the entire Mediterranean Sea is displayed and the different colors represent the main categories of the path: Corridor (red dots), Human-made introductions (yellow), and Natural Range Expansion through the Straits of Gibraltar (blue dots). Maps can also be customized by filtering occurrence records according to the authors of sightings. Moreover, through animation, a video can reconstruct the temporal sequence of records. This tool is particularly valuable in illustrating the temporal dynamics of specific invasions or entire groups of species.

Discussion

Relevance of the ORMEF web platform for European and Mediterranean Policy

The ORMEF web platform, accessible in the public functional area to any user at the link https://www.ormef.eu/, is an interactive resource designed and implemented to explore and visualize historical occurrences of exotic fishes (*sensu* Golani et al. 2021) in the Mediterranean and neighboring seas. It consolidates, updates, and presents information relevant to the European and Mediterranean policies, catering to the needs of researchers, scholars, and Marine Protected Areas managers, while also remaining easily accessible to the general public. It stands out as the preeminent and highly interactive source of information on the distribution of non-indigenous and native fishes in the Mediterranean Sea and serves as an authoritative benchmark, offering the most comprehensive georeferenced data on the occurrences of these species, providing real-time updates on the progression of each invasion. The platform caters to diverse needs in bioinvasion research and contributes to meeting international and regional legislation, aligning with Action 16 of Goal 5 of the EU 2020 Biodiversity Strategy and Aichi Target 9 of the Strategic Plan for Biodiversity 2011–2020 under the Convention on Biological Diversity, in line with the EU Biodiversity Strategy

for 2030, which emphasizes minimizing the introduction and establishment of NIS in the EU environment (EC, 2020). This is notably evident in the implementation of key directives, such as the Marine Strategy Framework Directive within the European Union and the Integrated Monitoring and Assessment Program of the Mediterranean Sea, even if not yet considered. Therefore, there is a recommendation to cross-check for such information when compiling or updating inventories at the country or Mediterranean subregional level (Galanidi et al. 2023). Although the contribution to Regulation 1143/2014/EC may be relatively minor, considering the very limited number of marine species falling under Union concern and the limited effectiveness of this directive in managing marine bioinvasions (Kleitou et al. 2021).

Limitations and future perspectives towards collaborations

The number of NIS is expected to increase in the future among all geographical regions, including the Mediterranean and Black Sea (Seebens et al. 2017), and climate change is enhancing the environmental suitability of many of these NIS, improving the ability of these species to further expand their invaded domains, a phenomenon that is particularly clear for Mediterranean fish invasions (D'Amen and Azzurro 2020a; 2020b; Azzurro and D'Amen 2022). The ORMEF web platform is committed to following the development of this phenomenon by regularly updating its database with the most recent information on new arrivals, range expansions, changes in abundance, and changes in identification/nomenclature/taxonomy. To this regard, it is crucial to remark that a significant subset of NIS included in ORMEF represents notable invaders undergoing a rapid geographical expansion. In particular, certain species have already made their way to the Black Sea via the Sea of Marmara, such as *Lagocephalus sceleratus*, whose first record in the Marmara Sea dates back to 2008 (Irmak and Altinağaç, 2015); then, it was recorded another time in the Marmara Sea in 2014 (Artüz and Kubanç 2015) and in the Black Sea in 2014 (Boltachev et al. 2014) and in 2017 (Bilecenoğlu and Öztürk 2018).

In the ongoing development of the ORMEF web platform, we are committed to enhancing its functionality by integrating both additional information fields and visualization tools, such as enhanced distribution maps. This expansion aims to provide a more comprehensive resource for informed decision-making in the management of NIS in the Mediterranean and neighboring seas. We recognize the significance of making existing information readily accessible and user-friendly, emphasizing the need to capture both the negative and positive consequences within the socioeconomic realm (Tsirintanis et al. 2022).

ORMEF actively fosters synergy with existing databases on invasive species, recognizing the collective strength that collaboration brings to the field. It also

promotes collaboration with individual data providers and organizations, such as the Mediterranean Science Commission, which is currently under consideration.

Finally, ensuring the accuracy of regional databases is an ongoing challenge that demands continuous scientific vigilance to minimize potential errors. This challenge is especially prominent for ORMEF databases, given the continuous scrutiny for new records and species owing to the dynamic nature of biological invasions. Occurrence data, carefully validated by ORMEF, and already available in public repositories, can be easily leveraged to update European platforms such as EASIN. This information can also contribute to major initiatives sharing georeferenced occurrences, primarily GBIF, as well as other public platforms such as WoRMS and WRiMS. Future developments of ORMEF will aim to enrich the availability of scientific knowledge, supporting NIS management and policy in the Mediterranean Sea and adjoining waters.

Conclusions

The ORMEF web platform serves as a dynamic and interactive resource for exploring historical occurrences of exotic fishes in the Mediterranean and neighboring seas. One of its key strengths lies in its extensive georeferenced data on non-indigenous fishes and other 'neonative' species, facilitating bioinvasion research and aligning with policy goals. The platform offers user-friendly visualization tools, catering to researchers, scholars, and Marine Protected Areas managers, as well as the general public. Future plans include expanding information fields, promoting collaboration, and furthering support for effective NIS management in the Mediterranean and adjacent waters.

Authors' contribution

Research conceptualization EA, NB, MD; sample design and methodology; EA, NB, MD, FF, PG, EN; investigation and data collection; EA, MC, SS, PS, GL; data analysis and interpretation; NB, SS; funding provision; EA, GL; roles/writing – original draft; writing – review and editing EA and all authors.

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the European Union – NextGenerationEU; Award Number: Project code CN_00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, CUP D33C22000960007, Project title "National Biodiversity Future Center - NBFC"; The ORMEF database was updated thanks to the financial support of the @CNR USEIt project - funded by the Italian National Research Council. Both grants were received by EA: The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Software availability

Name of software and products: ORMEF Occurrence Records of Mediterranean Exotic Fish.
Designers: National Research Council of Italy, Institute of CNR-IRBIM (Ancona) and developers: CNR IRPPS (Rome).
Maintenance: CNR-IRBIM (Ancona) and *Software development and maintenance:* CNR IRPPS (Rome).
Year first available: 2021.
Hardware required (webserver): 16 GB or more; 22 GHz processor with 4 cores (additional processing power may be required for multiple concurrent styling renderings); a baseline of 50 GB–100 GB for production deployment.
Software required (client/users): All modern Internet browsers (eg, Google Chrome, Mozilla Firefox, Microsoft Edge, Apple Safari), including mobile versions.
Software availability: 90% of annual time available (except updating and maintenance periods).
Data availability: https://www.seanoe.org/data/00730/84182/ up to 2021. For the latest updates, contact the corresponding author.
Software licence: Source code Property of CNR and not available. The application is available at: https://ormefeu/ and its use is free.

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