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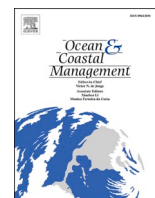
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## Review

## A review of biodiversity research in ports: Let's not overlook everyday nature!

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## ABSTRACT

Ports are urban and often quite-confined habitats within the aquatic (marine or freshwater) ecosystems, hosting biodiversity as any natural ecosystem under anthropogenic pressures as in many urban ecosystems. This scoping review seeks to give an overview of the state of knowledge on port biodiversity and port concerns about biodiversity based on scientific literature. Our aim was to highlight gaps and strengths in biodiversity knowledge and research in the port ecosystem, the outcomes of which are supposed to inform port authorities, guide port management and assist in planning research and management actions towards the implementation of relevant measures for port environmental sustainability. Results using Web of Science showed a recent trend in port biodiversity research (no references before 1999, most published after 2016) with a shift of research objective from empirical knowledge early-on towards non-indigenous species (NIS) concern recently. European, commercial ports and the NIS concern dominated the landscape. Fish, invertebrates such as crustaceans, major international and inland (freshwater) ports were under-represented. This review highlighted the need for a shift in port environmental awareness for biodiversity to expect resilience of the whole social-ecological system and for baseline knowledge and exhaustive inventories to assess how anthropogenic activities impact biodiversity and change ecosystem properties and functions.

### 1. Introduction

The rapid modification of coastal landscapes is on course to reach a critical point in terms of alteration and degradation threatening coastal ecosystem functioning and port areas represent the outmost of such landscape alteration (Sahavacharin et al., 2022). Ports generate structural transformation of the natural coastal habitats they modify to concentrate human activities and contribute to one of the most important threats for coastal and estuarine areas: habitat loss (e.g. a threat affecting the greatest number of marine taxonomic groups in the Mediterranean Sea (Coll et al., 2010)). In the context of national self-sufficiency and sovereignty, ports have seen their jurisdiction areas expand to play a strategic role in the development of marine renewable

energy which further alters the coastal ecosystem (Duin et al., 2014; Akbari et al., 2017).

So, in our interconnected economy, ports are central, with 80% of goods transported by merchant ships (Kalouptsidi, 2021). The growing trend in recreational boats (30 millions of small boats <50 feet) whose market is expected to expand continuously in the coming years (by 6.4% over the coming five years) also leads to coastal alteration with the development of an increasing number of marinas (BIMCO, 2021). Therefore, by the concentration of anthropogenic activities and the alteration of the aquatic ecosystems, ports are considered urban ecosystems where the aquatic ecosystems have been man-transformed, artificialized, modified and/or altered compared to the initial aquatic ecosystem, and are often quite-confined ecosystems. In such ecosystem,

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biodiversity faces many anthropogenic pressures: water pollution, constant disturbance of sediment, noise, invasive species introduction, loss of habitats (OECD, 2011). In this context, the maritime industry and port areas have been under scrutiny regarding their environmental impacts (e.g. driver of invasive species, fine particle emissions, noise, storm water runoff, spill and dredging material disposal), not only from environmental organisations, local governments, and media, but also from the industry customers (OECD, 2011; Puig et al., 2014). The creation of environmental labels is nonetheless, stepping the first stone to support port authority and stakeholder engagement towards environmental consideration as a part of the port environmental system. Port areas and their management are thus changing, demographically, technologically. But ports are also complex socio-ecological systems, in which biodiversity can be simultaneously a concept, a tool and a target for port management. And, if ports seem to be embracing a more sustainable path, the main focus on the environment in port pertains to the land and air components linked to nearby urbanised areas: in Europe, until 2018, only 2 out of the 10 environmental priorities in port were related to the marine component (i.e. water quality and dredging) (Puig et al., 2019). Nevertheless, in the context of the current environmental and biodiversity loss crisis, port environmental regulations have recently started to become stricter to mitigate the negative environmental impacts of ports (Woo et al., 2018). A baseline understanding of port biodiversity is thus, required to analyse and estimate the effects and benefits of environmental regulation, policy or incentive aiming at protecting and managing port biodiversity. Recent studies have started to highlight that the surrogate artificial habitats in ports provide key heterogeneous microhabitats and structural refugia for many species (Watchorn, 2022). Ports could even paradoxically host a biodiversity richer than previously thought by allowing the establishment and coexistence of more resistant species (Boulanger et al., 2021). This scoping review seeks to give an overview of the state of knowledge on port biodiversity and port concerns about biodiversity based on scientific literature. Our aim is to highlight gaps and strengths in biodiversity knowledge and research in the port ecosystem, the outcomes of which are supposed to inform port authorities, guide port management and assist in planning research and management actions towards the implementation of relevant measures for port environmental sustainability.

## 2. Material and methods

Our scoping review followed a classical strategy in terms of literature review with two phases, both divided in 3 major steps similar to Dupont et al. (2020) and Cabioch and Robert (2022): 1) identification and extraction of relevant references through a first listing using the relevant keywords and expressions to investigate the Web of Science database, 2) cleaning and exclusion of bycatch to progressively reduce the results to the most convincing data set and 3) screening, classification and analysis to characterise biodiversity research from the selected papers.

### 2.1. Scrutinising the scientific literature for papers on biodiversity research in ports

Phase 1 focused on gathering papers dealing with biodiversity studies in port settings. The Web of Science (WoS) database was explored in November–December 2022 and finalised on the 8th of December 2023, using queries designed to gather the largest number of papers dealing with biodiversity in ports. Therefore, queries included all port synonyms given that “port” referred to “a man-made marine and riverine shelter location for vessels”. The following terms were used as port synonyms: “harbour”, “harbor”, “marina”, “port” and “seaport” to cover all categories of freshwater and seaports (e.g. commercial, fishing, touristic, recreational, military). The term “biodiversity” is a contraction of “biological diversity”. The definition of “Biodiversity” in this review included the marine components of biodiversity and aspects of species

diversity, genetic diversity and functional diversity, as defined by the International Union for the Conservation of Nature (IUCN) (Farnham, 2007). We made various queries to find the query leading to the largest number of papers on biodiversity in port. The most convincing data set came from the query with “biodiversity”, “biological diversity” and all above port synonyms. As a result, our WoS query was made of 12 expressions:

[“biodiversity” AND “port”] OR [“biodiversity” AND “harbour”] OR [“biodiversity” AND “harbor”] OR [“biodiversity” AND “marina”] OR [“biodiversity” AND “seaport”] OR [“biological diversity” AND “port”] OR [“biological diversity” AND “harbour”] OR [“biological diversity” AND “harbor”] OR [“biological diversity” AND “marina”] OR [“biological diversity” AND “seaport”]

We queried the “topic” of the articles so that the research was performed taking in account the title, abstract and keywords. This initial dataset (Set 1) was composed of 6226 papers.

### 2.2. Removal of irrelevant subject areas & inclusion and exclusion criteria

The second phase consisted in removing irrelevant articles from Set 1. 1.71% of Set 1 were considered irrelevant and removed through an iterative checking process in 3 steps:

- 1 Exclusion of irrelevant topic fields (e.g. forestry, medical science): only articles from the following field were retained (2,527): Marine Biology (1,679), Zoology & Animal Ecology (298), Bioengineering (238), Biomonitoring & Bioindicators (51), Ocean Dynamics (34); Oceanography, Meteorology & Atmospheric Sciences (22); Sustainability Science (14); Climate Change (11); Environmental Sciences (6);
- 2 Exclusion of irrelevant keywords: within these 2527 articles, search for all articles using “harbour/harbor” (as a verb (i.e. to harbour/to harbor), an adjective or a city name) and “marina” in particular with “*Zostera marina*”;
- 3 Visual exploration of the 1811 remaining articles was necessary to remove irrelevant articles due to the ambiguous use of “harbour”/“harbor” despite step 2. Indeed, 90% of the 1811 articles still used “harbour”/“harbor” outside the definition of port targeted here and only abstract exploration led to the identification of the final set of relevant papers. Papers from 2022 were also removed as the year was incomplete when we gather the papers for this review. The final set comprised 169 papers.

A PRISMA flow diagram summarizing the selection of papers is available in Supplementary Material 1.

### 2.3. Screening and classification of references

Phase 3 finally focused on title and abstract exploration to classify the remaining 169 papers. Full text exploration was not considered necessary except for a few cases (e.g. if the port was not specified in the title or abstract but in the keywords). Four aspects were analysed for each of the collected papers: i) the main objective of the paper, ii) the studied taxa, iii) the economic area of the port, iv) the port type. For each of these aspects, defined *a priori*, a set of subcategories was defined. For the main objective of the study, subcategories referred to the three major groups of biodiversity concerns related to urban ecosystems (Savard et al., 2000): 1) concerns related to port anthropogenic impacts on biodiversity (hereafter ‘anthropogenic impact’), (e.g. in a port, these impacts could include water pollution, dredging, habitat modification through port development ...); 2) concerns related to the empirical knowledge (e.g. on species richness, genetic diversity, functional diversity, community characterization ...) and how to maximise biodiversity (e.g. studies of artificial habitats) (hereafter ‘empirical knowledge’); 3) concerns related to non-indigenous species (NIS) which are defined by the Convention on Biological Diversity as species whose

introduction or spread threaten biodiversity. For the studied taxa, we identified categories from the most global to the most specific biodiversity level: “wider biodiversity” (comprising studies focusing on the broadest level), “Community/Assemblage level” (“benthic community”, “epibiotic assemblage”, “fouling assemblage”, “plankton community”) and “broad category level” (“microorganisms”, “fish”, “macrophytes”, “other invertebrates” which comprised studies on invertebrates with one or two papers). The economic area of the port referred to continents: Africa, Asia, Europe, North America, Oceania and South America. Finally, for the port type, we distinguished commercial ports (including freshwater and maritime ports, e.g. for cargos and container ships, fishing ports, touristic ports) (hereafter ‘port’) from traditionally-smaller recreational ports, i.e. marinas (hereafter ‘marina’). ‘Port’ also included the terms harbour/harbour as the use of ‘port’ vs ‘harbour/harbor’ appeared highly cultural rather than typological.

### 2.3.1. Keyword analysis

We used the software VOSviewer (version 1.6.15) to construct a distance-based map of author keywords (i.e. keywords provided by the authors) based on co-occurrence data and using the association strength as similarity measure (van Eck and Waltman, 2010; David et al., 2015). In the network visualisation map, the size of a keyword reflected the number of publications in which it occurred, the proximity of two keywords, and how strongly related the keywords were. The colour of a keyword indicated the average publication year of the articles in which it occurred. The VOSviewer used a novel modularity-based clustering technique to identify clusters (also known as community detection) developed by Waltman et al. (2010) which is a variant of Clauset, Newman, and Moore’s (2004) community detection on weighted networks. VOSviewer clustering technique identified networks (or clusters) of similar and dissimilar keywords through the association strength and strength of the repulsive force between two keywords. Under this approach, keywords with a high association strength were pulled towards each other forming a cluster, while keywords with low associated strength were pushed away from each other. Please refer to Waltman et al. (2010) for details on the VOS clustering technique.

## 3. Results

### 3.1. Time, space and journals distribution of the papers

Most of the identified articles were published after 2016 ( $n = 101$ ,

60% of the articles in this review), hence it appeared a rather new concern in the literature with no references before 1999 from WoS. The first two publications listed in WoS that pertained to port biodiversity appeared in 1999: one in Sydney Harbour on epibiotic assemblage, the other in North America on NIS. Until 2006, there were less than 2 papers published yearly on the topic (none in 2002 and 2005). The numbers of papers and citations has then been on the rise from 2014 to 2015 to reach 20 published papers in 2021 (Fig. 1).

In terms of geographical distribution, this analysis highlighted great disparities with under-representation of the Asian and North American ports (respectively  $n = 18$  and  $n = 22$ ) (Fig. 2). European ports concentrated the greatest number of publications ( $n = 62$ ) with the Mediterranean basin representing 84% of European published papers on port biodiversity in this review. In Oceania, Sydney Harbour dominated the publication landscape (74%). Ports and marinas present in this review are listed in Supplementary Material 2.

The 169 papers of this review were published in 88 scientific journals emphasising a great distribution between various supports but also the scarcity of publications on port biodiversity with most journals publishing less than 5 papers on the subject. Only four journals contained more than 5 publications: Marine Pollution Bulletin ( $n = 19$ ), Mediterranean Marine Science ( $n = 11$ ), Marine Ecology Progress Series ( $n = 9$ ) and Marine Environmental Research ( $n = 6$ ).

### 3.2. Evolution of biodiversity research

Fig. 3 presented a network visualisation of the author keywords that had a minimum of 5 occurrences within the 169 papers: 75 terms occurred at least 5 times in the 169 papers and were grouped in 5 clusters (Table 1). The strength of associations between 2 keywords was related to their co-occurrence: the closer the words were in distance, the more they were used alongside in papers. Closely-associated keywords were grouped in clusters.

Interestingly enough, “harbours” and “ports” were only used as keywords by authors in respectively 7 and 8 papers and appeared relatively recently (respectively on average in 2017 and 2020). Cluster 1 gathered keywords used early on and linked to the topic of urban ecology and to New South Wales and Sydney Harbour (Australia); Cluster 2 appeared to be related to biodiversity dynamics in the context of climate change; clusters 3, 4 and 5 gathered more recent keywords and focused on NIS with an emphasis on Mediterranean ports (cluster 3), ballast water and eDNA (cluster 4) and management and biological invasions (cluster 5).

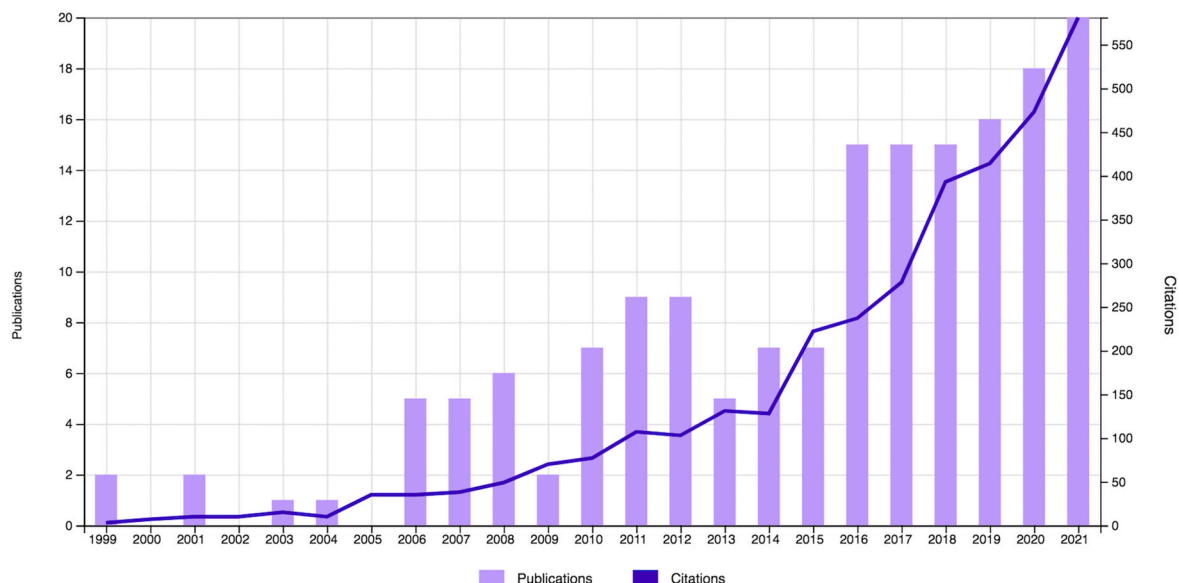


Fig. 1. Growth of published papers and citations on port biodiversity.

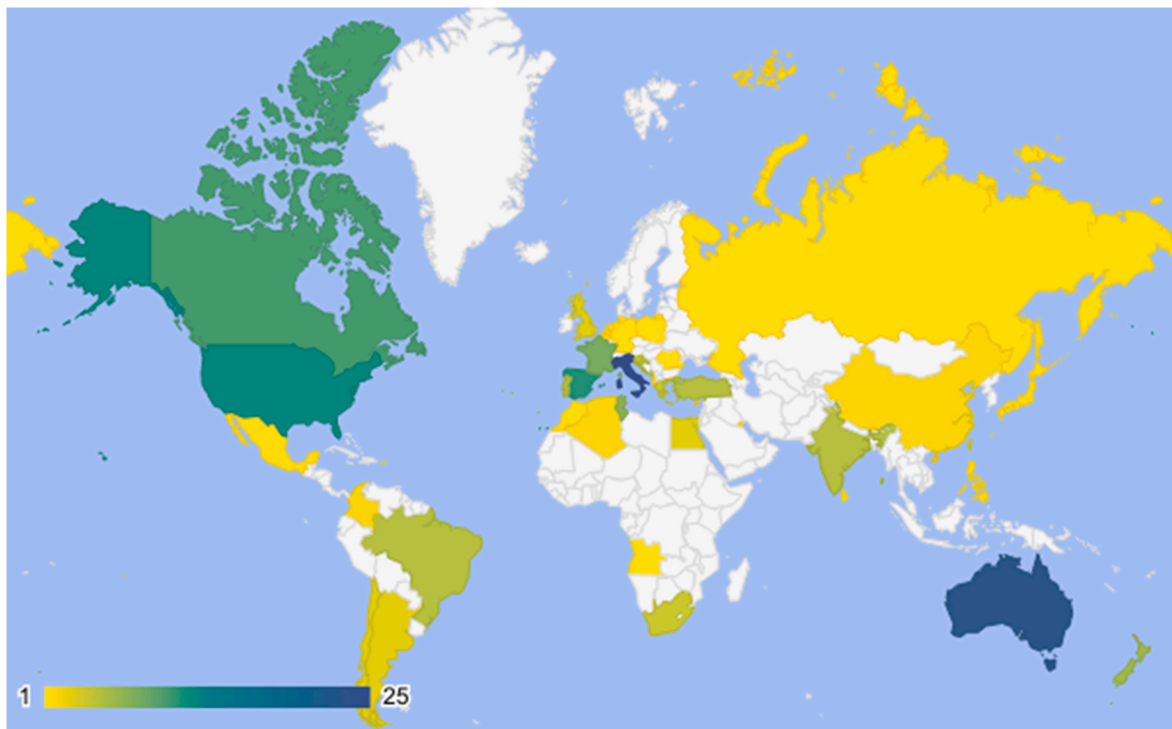


Fig. 2. Geographical distribution by country of the 169 papers.

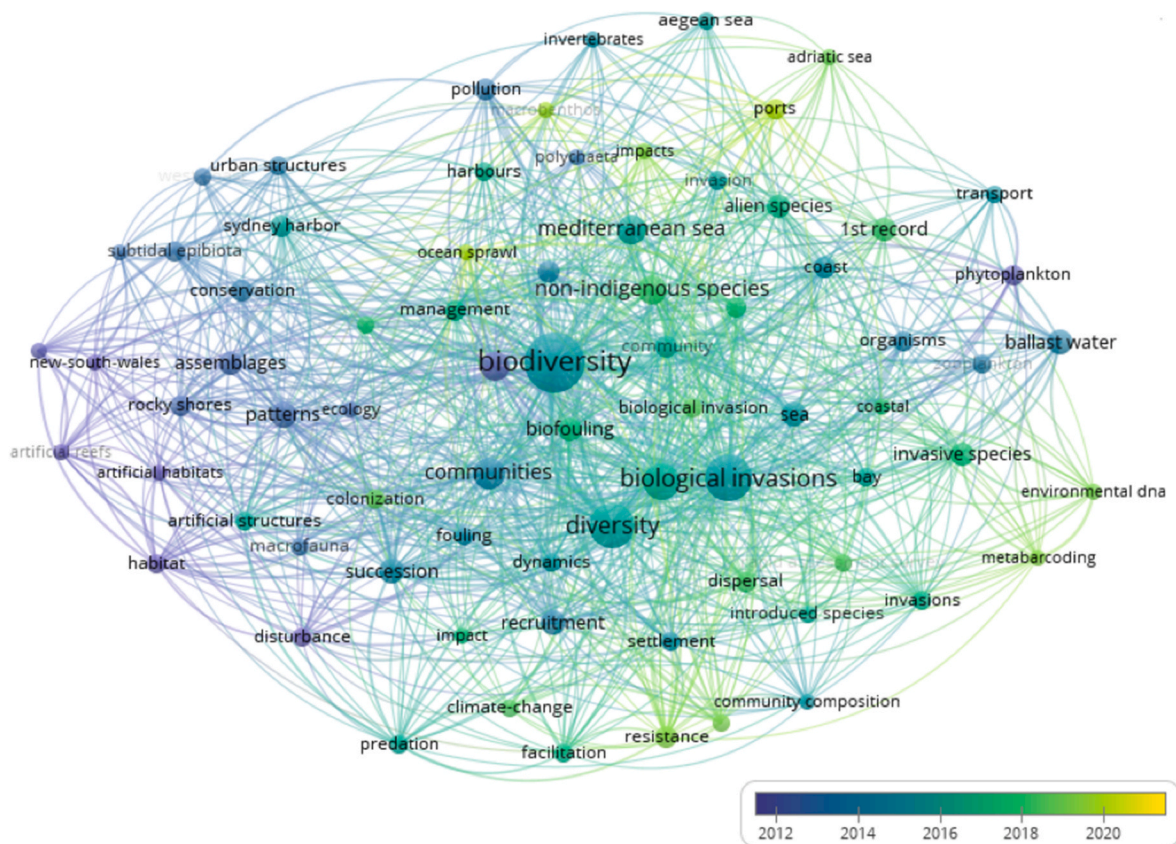


Fig. 3. Co-occurrence network of author keywords showing the temporal evolution and association of main keywords from the 169 papers. The bigger the keyword, the greater its occurrence. Keywords on the left of the figure, e.g. ‘assemblages’, ‘artificial habitats’ tended to be associated with earlier studies while keywords on the right, e.g. ‘metabarcoding’, ‘invasive species’, reflected recent trends in port biodiversity research. However, earlier keywords could also be located to the right of the network if they were associated with a cluster of more recent keywords, e.g. ‘phytoplankton’ from cluster 4 (Table 1).

**Table 1**  
Clusters, frequency and mean year of occurrence of the keywords.

Cluster 1			Cluster 4		
Keyword	n	Mean year	Keyword	n	Mean year
abundance	9	2014	ballast water	11	2014
artificial habitats	5	2007	bay	7	2016
artificial reefs	5	2007	coastal	5	2018
assemblages	10	2013	dispersal	8	2018
benthic communities	6	2018	environmental dna	5	2019
colonization	7	2019	invasion	7	2016
conservation	9	2014	invasions	7	2017
habitat	7	2009	invasive species	10	2017
intertidal assemblages	5	2013	metabarcoding	5	2019
new-south-wales	5	2010	organisms	8	2014
patterns	13	2013	phytoplankton	8	2012
rocky shores	8	2013	sea	12	2015
subtidal epibiota	8	2014	transport	6	2015
sydney harbor	9	2016	zooplankton	7	2014
urban structures	7	2014			
urbanization	5	2012			
west-coast	6	2014			
<b>Cluster 2</b>			<b>Cluster 5</b>		
Keyword	n	Mean year	Keyword	n	Mean year
climate-change	6	2018	artificial structures	7	2016
community composition	5	2015	biofouling	10	2017
disturbance	7	2011	biological invasion	7	2018
diversity	36	2016	biological invasions	39	2015
dynamics	7	2015	communities	19	2014
facilitation	7	2017	ecology	5	2013
fouling communities	6	2019	fouling	6	2015
impact	5	2017	impacts	5	2019
introduced species	6	2017	macrofauna	6	2014
marine	25	2016	management	8	2017
predation	7	2016	non-indigenous species	15	2018
rapid assessment survey	6	2018	ocean sprawl	5	2020
recruitment	12	2014			
resistance	9	2019			
settlement	7	2015			
succession	12	2015			
<b>Cluster 3</b>					
Keyword	n	Mean year			
1st record	10	2018			
adriatic sea	5	2019			
aegean sea	6	2016			
alien species	10	2017			
biodiversity	63	2015			
coast	9	2015			
community	9	2016			
community structure	15	2012			
harbours	7	2017			
invertebrates	5	2015			
macrobenthos	5	2019			
mediterranean sea	15	2016			
pollution	9	2014			
polychaeta	5	2014			
ports	8	2020			

The evolution of cluster focus from cluster 1 to cluster 5 indicated a shift of research objective from empirical knowledge early-on towards NIS concern recently.

### 3.3. NIS concern prevailed in studies on port biodiversity

While not an early subject of papers, with 3 clusters including

various synonyms of NIS, one of the first major findings of this review was the over-representation of the subject of NIS in biodiversity research in port: 82 out of 169 papers (and one of the 2 worldwide studies) focused on port biodiversity through the angle of the NIS concern (Fig. 4). There were also clear discrepancies between economic areas on the importance of NIS in port biodiversity research: In Europe and North and South America, the focus on NIS in port dominated the landscape of publications on port biodiversity (in Europe with 37 out of 62 papers and in North and South America with 27 out of 39 papers) for all port types. In Oceania, NIS did not appear as the main concern (5 out of 31) and cluster 1 closely related to Sydney Harbour, reflected an early focus of port biodiversity research dedicated to empirical knowledge (Fig. 4). Port biodiversity research in Oceania and Asia were focused on biodiversity knowledge (driven by studies on empirical biodiversity knowledge in Sydney Harbour for Oceania). Finally, there were no studies in Asia and Africa in both marinas and ports (“mixed”).

The focus on NIS also prevailed for wider biodiversity and fouling assemblage. The ‘fish’ category was the only category with no study on NIS (Table 2 and Supplementary Material 3).

### 3.4. An unequal interest for the biodiversity components

Biodiversity research in European ports produced the highest number of papers for most taxa except for fish and plankton community. Very few studies spanned over ports located in different economic areas (between Europe and Africa  $n = 3$  and between North America and Oceania  $n = 1$ ) and the only two papers on port biodiversity, on a global scale, focused on wider biodiversity and microorganisms (Table 2 and Supplementary Material 3). Some invertebrate groups, e.g., crustacea, sponges and tardigrades, were understudied with less than 2 studies and were pulled in one category “other invertebrates” (Table 2). Fish were also under-represented as a category with a maximum of  $n = 4$  studies in Oceania and a single study in all other areas. However, fish were also studied in papers on broader categories such as “benthic community” and “wider biodiversity” (Fig. 5). This review also highlighted a bias towards fauna: studies on phytoplankton were included in the “plankton community” but macrophytes were the subject of only one study in South America and 3 in Europe. Finally, the more specific the studied groups, the smaller the number of publications and the category. The largest number of studies was for “wider biodiversity”.

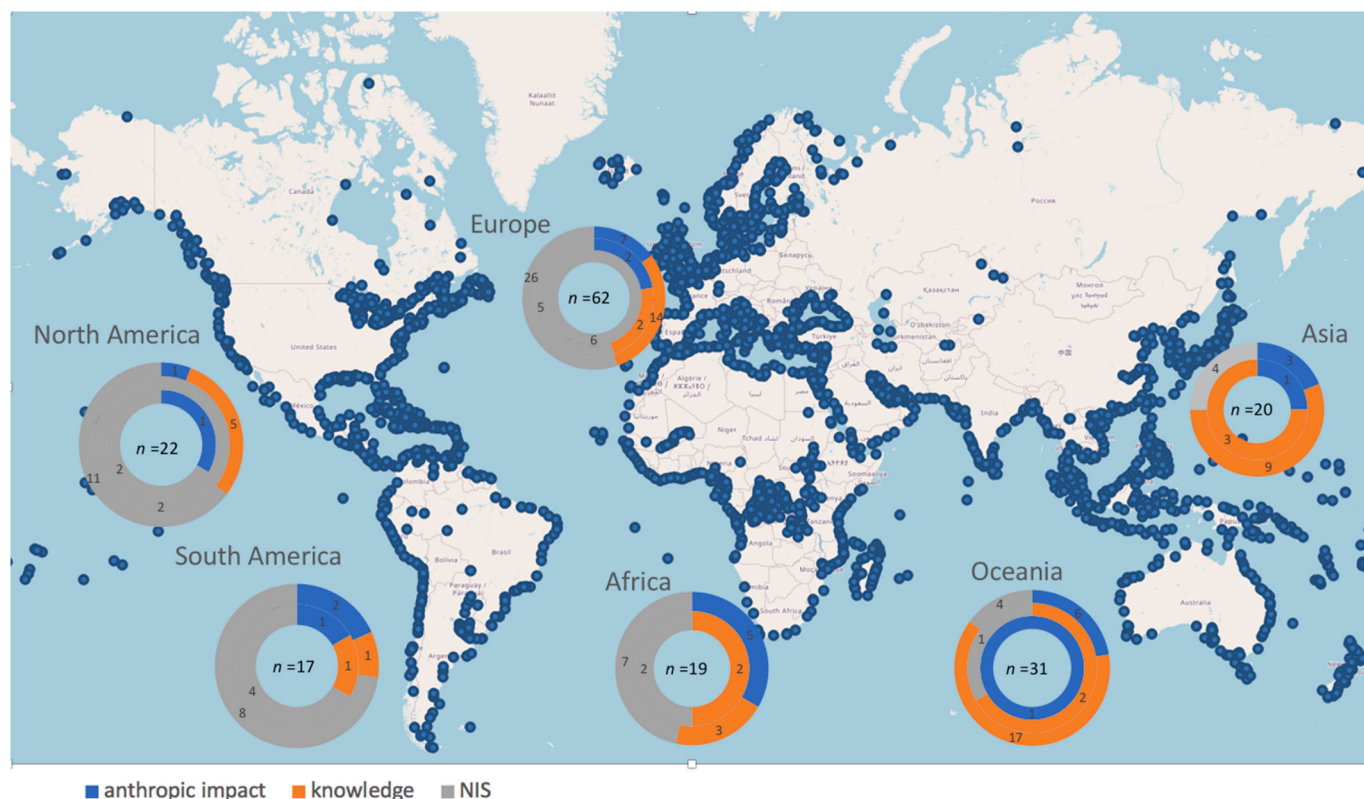
### 3.5. Biodiversity interest by port type

Marinas were largely underrepresented in all economic areas but again, given the focus of port biodiversity research on NIS, this was to be expected (Fig. 6). Mixed studies (i.e. including both marinas and commercial ports) occurred only in Europe ( $n = 6$ ), North Americas ( $n = 3$ ) and Oceania ( $n = 1$ ) and were completely absent from South America, Asia and Africa. The few mixed studies in marinas and ports were mainly focusing on ascidians. Proportionally, marinas tended to foster more research on invertebrates and ports more research on global biodiversity. Marinas also hosted research in less biodiversity components while ports covered all components. Finally, it is also worth noting that this review highlighted the absence of biodiversity studies in inland (fresh-water) ports except in the North America Great Lake ports ( $n = 7$ ).

## 4. Discussion, knowledge gaps and perspectives

### 4.1. Biases in the review

Our review is based on the WoS research database which is a powerful tool in indexation of scientific publications but has been shown to be more limited in coverage for some document types (e.g. book chapters, conference papers, thesis and dissertations) compared to the inclusive and unsupervised approach used by Google Scholar (GS) in some research areas (Martín-Martín et al., 2018). In the Life Sciences,



**Fig. 4.** Number of publications and biodiversity concerns in worldwide ports by economic area. Blue dots represent Worldwide Port locations (Ref: World Food Program, <https://gis.wfp.org/arcgis/rest/services/GLOBAL/GlobalPorts/MapServer>, wld\_trs\_ports\_wfp layer: Ports), circles represent port type (outer to inner circle: Port (Commercial Port) - > Marina - > Mixed (Marina + Port, category absent in Asia and Africa)).

**Table 2**

Number of papers per biodiversity components and research objective of the collected papers (Details of the collected papers per biodiversity component and research objective can be found in Supplementary Material 3).

Biodiversity Component	Research Objective		
	Anthropogenic Impact	Empirical Knowledge	NIS
Global level			
Wider biodiversity	3	14	17
Community/assemblage level			
Benthic communities	7	6	6
Epibiotic assemblage	1	3	3
Fouling assemblage	3	6	22
Plankton community	5	8	3
Broad category level			
Ascidians	0	2	12
Fish	1	8	0
Macrophytes	0	0	4
Microorganisms	4	1	2
Molluscs	2	6	5
Polychaetes	2	1	5
Other invertebrates	0	4	3

WoS and Scopus have a similar coverage and WoS appeared to offer a better trade-off than GS with a less error-prone and better-organised curated collection of documents, especially for scientific papers (91% indexation coverage with GS) which is the main type of documents produced in this area to convey research findings (Martín-Martín et al., 2018). WoS also conferred a higher reliability to the indexed papers compared to GS with regards to predatory journals since WoS relies on a set of source selection criteria for the choice of journals to be indexed.

With regards to the bias due to the indexation coverage, we could expect the exclusion of some papers, especially those dedicated to certain taxa in ports not mentioning “biodiversity” or “biological diversity”, e.g. Lambert and Lambert (1998). On one hand, the terms “biodiversity” or “biological diversity” have been in a rapid rise and a buzz word since the beginning of the 21st century (Farnham, 2007). So, it is likely that the term was picked up widely from the 2000s and that papers not properly referencing their study, are few and concerned mainly the 90s and before. On the other hand, using a wider array of search terms would have led to over-representation of the selected terms as it is impossible to build an exhaustive list of terms covering all facets of biodiversity as pointed out by Stork and Astrin (2014), and brought another bias to the dataset.

Environmental concern classification may appear arbitrary at times, especially between ‘anthropogenic impact’ and ‘empirical knowledge’. The choice was made upon the perception of the authors of this review on the perceived role of the port in these biodiversity studies: rather a negative perception of ports in the category ‘anthropogenic impact’ and a neutral to positive perception of ports in the category ‘empirical knowledge’, especially when artificial habitats were presented as a tool to improve port conditions for biodiversity.

The keyword analysis was based on keywords provided by authors. Journal guidelines often encourage to use different keywords in the title and in the keyword list. Therefore, some keywords, also present in the article titles, might be missing or underrepresented. Despite this bias, the keyword analysis conveyed information on the trends of scientific research and highlighted in particular, a shift of research objective from empirical knowledge early-on towards NIS concern recently. The analysis also revealed an emphasis on research on the impact of climate change on biodiversity between 2015 and 2019, although there may be a considerable time lag between the start of research and the publication of any research results. This keyword analysis had broader relevance

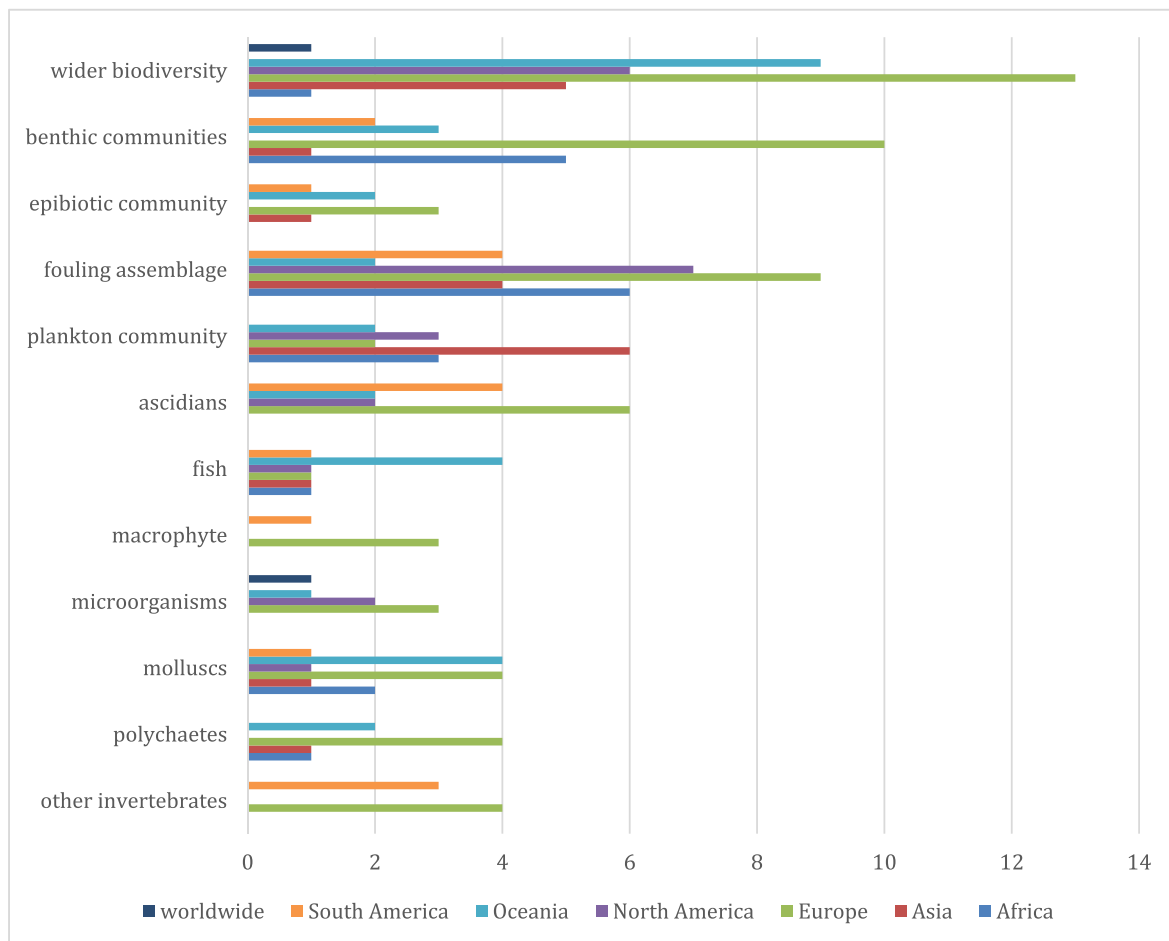


Fig. 5. Studied port biodiversity components per economic area.

than showing research trends alone and likely depicted regional and international funding programs and policy orientations. These often-competitive project funding schemes complement institutional funding and partially drive research trends and publication outputs. Publication outputs and therefore this review, may also be biased towards scientific journal policies and some scientific disciplines. However, the incentive, the need to publish and the productivity might vary between disciplines with different scientific culture, nature of research, journal impact factor and even number of scientists. Therefore, the observed research trends on port biodiversity through this review may be biased towards specific policies, funding program orientations, economic areas and disciplines without necessarily reflecting the true level of local and societal concern. Finally, this review based on scientific literature ignored knowledge on biodiversity conveyed by other supports such as grey literature, orally-transmitted, local (e.g. fishermen) and indigenous knowledge. But with more than 17,000 ports and 7000 marinas worldwide with multiple languages, this would be a very challenging endeavour.

## 4.2. Current knowledge of port biodiversity

### 4.2.1. Gap in knowledge on biodiversity change and drivers in ports

During the past decades, there was a growing recognition of urban areas as hosts of relatively high levels of biodiversity not because of, but rather in spite of urbanisation. Urban areas, such as ports, are disproportionately located in areas of high ecosystem productivity and at junctions of ecosystems (e.g. coastal ecosystem, estuary ...), thus naturally supporting high levels of biodiversity. Some studies in urban ecology showed that overall species richness might be higher with

urbanisation (Bang et al., 2012). These changes in biodiversity might result from both responses to local abiotic factors and species interaction and from dispersal capacity. Species richness is thought to peak at intermediate disturbance levels because moderate levels of disturbance promotes coexistence by preventing competitive dominant species from excluding less competitive species. Depending on the level of disturbance, ports could therefore host a biodiversity richer than previously thought by allowing the establishment and coexistence of more resistant species (Boulanger et al., 2021). Studies showing a higher biodiversity with urbanisation also highlighted the radical change in species composition associated with urbanisation, urban communities being 'reshuffled' with non-native or synanthropic or stress-tolerant species. However, mechanisms underlying patterns of urban biodiversity are complex and not well-understood (Faeth et al., 2012). Further research is needed in ports to understand biodiversity changes, loss or gain and their drivers to support spatial planning and conservation actions as emerging in other urban ecosystems (e.g. urban parks (Nielsen et al., 2014)).

### 4.2.2. An unbalanced interest in the different forms of biodiversity

Ports represent a very symbolic territory of congruence between extremely-concentrated human activities and a poorly-known biological richness. In these dynamic places, biodiversity and impacts of human activities have received little but increasing attention. Ports are a challenging and difficult environment for monitoring marine biodiversity. From a field and technological perspective, this review highlighted the discrepancy between biodiversity groups with sessile organisms (e.g. ascidians, fouling assemblage) being more studied than highly-mobile organisms such as fish. This unbalanced interest in the different form



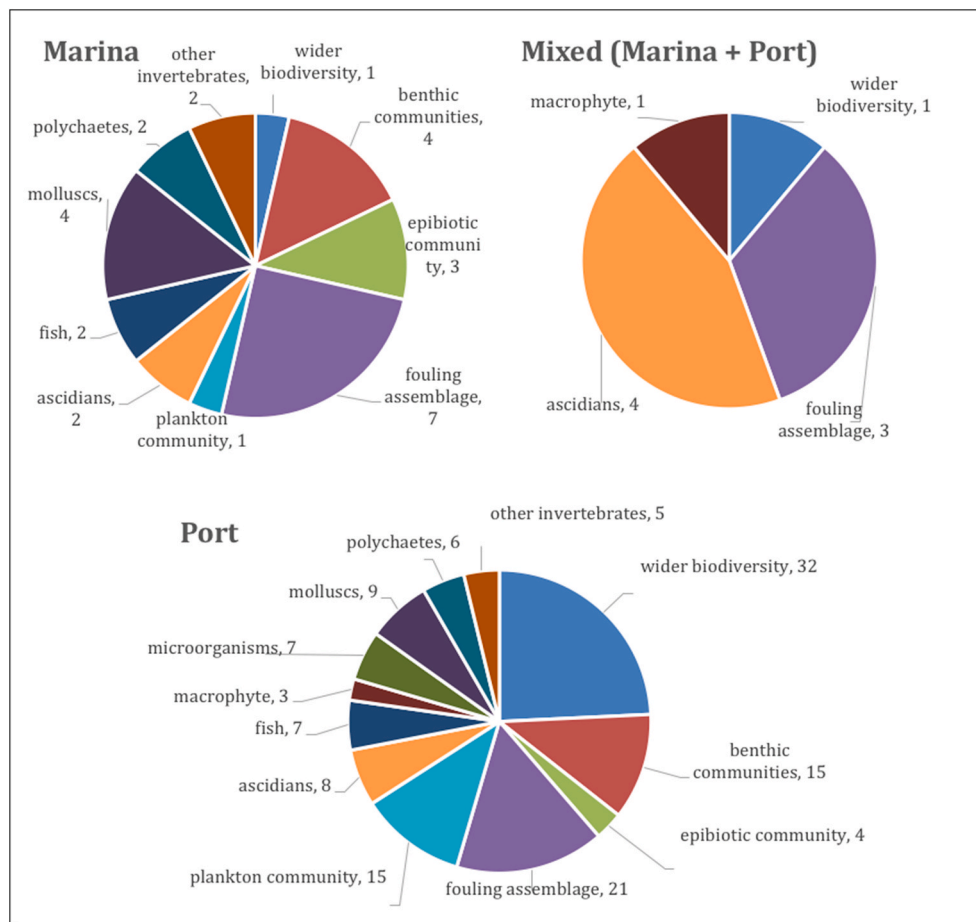


Fig. 6. Biodiversity component relative representation in the different port types (as relative number of papers on each biodiversity component per port type).

of biodiversity in port is partially due to the lack of effective methodologies for monitoring biodiversity in ports, the underwater field conditions (e.g. turbid waters, busy and risky areas) rendering any relevant direct marine species surveys challenging and biased. However, the rise of new technologies such as metabarcoding techniques through eDNA sampling could overcome the shortcomings of classic surveys (i.e. most rare, mobile and elusive species are missed through visual-based and capture surveys) to characterise marine assemblage and help filling the gap in knowledge on port biodiversity (Thomsen and Willerslev, 2015; Pearman et al., 2016; Brandl et al., 2018).

Some invertebrate groups such as crustaceans, sponges and tardi-grades were pulled into a larger group (i.e. “other invertebrate”) as they were the focus of single studies in ports (Accogli et al., 2011; Evcen and Cinar, 2020). These understudied groups also illustrated the need for expertise when studying biodiversity, in particular for taxonomists (e.g. Hochkirch et al., 2022). The lack of papers on these groups did not necessarily illustrate a poor interest for these groups but instead, the absence of experts to study them.

#### 4.2.3. Gaps in knowledge on port habitat, the effect of port size and ecological spillover dynamics

Habitat loss was recognised by the IUCN as the first cause of biodiversity loss. However, this review highlighted that habitats were never considered in these biodiversity studies, apart from the studies on artificial structures in Sydney Harbour to restore marine habitats, encourage the growth of native species population or maintain species assemblages and interactions. One of the most fundamental ecological relationship in ecology is the relationship between an increase in available areas for habitat and increase in species richness (Arrhenius, 1921). We found no studies focused on the species-area relationship (i.e.

effect of port size on biodiversity: do larger ports host greater biodiversity?) (Nielsen et al., 2014). Recent studies have started to highlight that the surrogate artificial habitats in ports can provide key heterogeneous microhabitats and structural refugia for many species (Watchorn, 2022). We found no study assessing the effect of port populations to adjacent (outer port) populations, habitats and food web. It is very unlikely that port populations have no influence on the survival or fitness of outer populations. As mentioned earlier, ports may allow the establishment and coexistence of more resistant species but we found no study on source-sink dynamics, on ports as potential ecological traps, disease pathway or prey-predator dynamics (Boulanger et al., 2021; Spear et al., 2018). The latter would also be key in understanding potential chain of contamination, e.g. heavy metals, from ports to the outer coastal ecosystems. Ports cannot be considered as isolated and on the contrary, better knowledge on these dynamics through the integration of ports in the ecological dynamics of coastal ecosystems is a necessary step towards the development of relevant measures for coastal biodiversity protection.

#### 4.2.4. Concern on NIS dominate biodiversity research in ports

For the other part, ports are considered as high-risk territories for the introduction of NIS where incoming biodiversity is perceived as an economical threat before being considered as a risk for the local communities. However, little attention has been given to local port biodiversity in these highly artificialized areas and the focus on the use of these artificial habitats by biodiversity in ports only appeared recently in scientific research and were driven by Oceania and Sydney Harbour. The fact that the research focus on biodiversity in port was largely dominated by NIS in most economic areas highlighted that ports were driven by economic constraints. A surprising finding was the fact that in

Oceania that otherwise tends to fiercely protect its endemic terrestrial biodiversity (Kingsford et al., 2009), NIS was not dominating the landscape of port biodiversity research. Sydney Harbour was considered in our review as a port while “Sydney Harbour” really referred to an estuary, considered as the most urbanised estuary in the world. As such, it concentrated many marinas and commercial port activities and appeared in this review as a hotspot of biodiversity research in this often highly-urbanised and modified coastal ecosystem. It is worth highlighting that another Australian port (Darwin harbour) was the only port presenting research on inner-port noise impact on biodiversity (Parsons et al., 2016).

#### 4.2.5. Biodiversity in port: a complex concept that needs to be integrated in the management of the port socio-ecological services

From a societal point of view, ports are characterised by a great socio-ecological complexity (Dimitrakiev and Gilev, 2021). This leads to difficulties in engaging port authorities in environmental research and in convincing several economic sectors towards more sustainable practices for biodiversity preservation and relevant socio-ecological services. Ports support a wide variety of socio-ecological services such as space required for the creation and survival of living beings, i.e. habitat or food and nutrient provision for humans by providing biomass for nutrition and food provision, including wild plants, algae and their outputs; wild animals and their outputs (e. g. fish, shellfish, hunt products, salicornia) (García-Onetti et al., 2021). However, port socio-ecological services are poorly-considered and less managed than those of high-value ecosystems, e.g. coralligenous habitats, while it is also likely that port biodiversity functions very differently in terms of ecosystem processes and services (Thierry de Ville d'Avray et al., 2019). In port social-ecological system, ‘biodiversity’ is a more complex concept than the scientific definition alone as it embraces the people alongside nature. It demands expertise in social systems, as well as natural systems. It is therefore fundamental for port authorities, managers and other relevant port stakeholders to be involved: very few papers proposed or mentioned management models that integrated interactions between different local authorities and/or public participation. Most of the papers simply did not address the issue of interactions with local authorities responsible for environmental management in ports. We also found no papers involving citizen or participatory science in the collected papers. In such an urban ecosystem, engaging citizens would be an opportunity to increase user awareness on biodiversity and to acknowledge people-wildlife interactions that also need to be considered in port biodiversity management (some species yielding positive interactions might be appreciated while others are perceived as nuisance by port users).

#### 4.2.6. Perspectives

When confronted with the increasing anthropogenic pressures on coastal ecosystems worldwide, the rhetoric of sustainability binds society, economy and ecology together in ports. This review highlighted that only roughly 0.01% of the world commercial ports (approximately 150 ports appearing in this review for 17,970 ports listed worldwide) and 0.03% of the world marinas (approximately 200 marinas appeared in the review for 6,977 marinas listed worldwide) host and contributed to biodiversity research in ports (de Loisy, 2019). The total absence of inland (freshwater) ports, except for North American Great Lake ports, was also noticeable and demonstrated the need for a further shift in port environmental consciousness towards biodiversity to expect resilience of the whole social-ecological system. The realisation that urban areas such as ports can actually be host of a high biodiversity facing great pressures led to various conventions (e.g. the Global Partnership on Cities and Biodiversity by the United Nations Environment Program or more recently the BiodiverCities by 2030 initiative by the World Economic Forum) to promote urban biodiversity and ways to conserve it. An improved and systematic-baselined knowledge and inventories on port biodiversity including a focus on habitats are thus required to be able to

assess how the cumulative anthropogenic activities impact local biodiversity and change ecosystem properties and functions to set up appropriate mitigation measures to protect biodiversity and the humans benefiting from it.

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#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

No data was used for the research described in the article.

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