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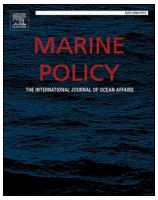

Invasive blue crabs and small-scale fisheries in the Mediterranean sea: Local ecological knowledge, impacts and future management

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ABSTRACT

The recent expansion of the two invasive Portunidae blue crabs *Callinectes sapidus* and *Portunus segnis* has generated great concern in the western Mediterranean basin. Here, we collected perception from artisanal small-scale fishermen on the socio-economic issues associated with this invasion. Professional fishers from France, Italy, and Tunisia were interviewed to survey their perception on: (i) the potential drivers of spatial expansion of blue crabs, (ii) the impact on the small-scale fisheries, and (iii) the management measures expected. The main reported impacts were the damage of fishing nets (median = 4.3), followed by a consequent associated increase in work intensity (median = 3.6) and by physical injuries to fishers (median = 3.1). Fishermen reported to have caught less fish (median = 3.4) in presence of blue crabs, as well fish damaged by blue crabs' bite (median = 3.8) inducing a decrease in the quality and value of catches (median = 3.5). The negative effects induced a decrease on global revenues (median = 3.6) as well despite the negative impacts of blue crabs on the fishery, the presence of these new species has been generally perceived as positive, being considered as a new revenue resource for some fishermen (median = 2.8). The majority of them (72 %) proposed fishing and marketing as main management measures. Despite the interested expressed for exploitation of this new resource, many questions emerged to promote and develop management strategies.

1. Introduction

Non-indigenous species (NIS) are one of the greatest biological issues of the 21st century [2,35,68], with their spread being facilitated by global climate change and anthropogenic pressures [59,76,79,80]. Invasive species often cause strong ecological and economic impacts through habitat modification and biodiversity loss, with subsequent impacts on ecosystem functioning (e.g., trophic interactions; [30]). NIS often modify the provision of ecosystem services with consequential socio-economic losses for human activities (e.g., fisheries, industry, and tourism; [30,86]).

The Mediterranean Sea has experienced a dramatic increase in non-native flora and fauna over the last few decades [90,91]. The Mediterranean Sea is continually exposed to biological invasions and the current situation is exacerbated by several environmental factors (e.g. global change; [61]) and increasing human pressures (e.g. commercial shipping, aquaculture trade and the creation of corridors such as the Suez Canal; [65,80]). The Mediterranean Sea is currently one of the most invaded marine areas in the world [21]. Current European Union (EU) policy for NIS management (Strategic Plan for Biodiversity

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(2011–2020), Target 9 of the Aichi Biodiversity Targets) states that, by 2020, (i) NIS should be identified and prioritized, and (ii) measures should be implemented to manage pathways of introduction and establishment in order to improve detection and early management in recipient regions [33]. But these objectives do not take into account the increasing number of introductions, their rapid geographic expansion, their ecological aspects as well as the difficulties in monitoring mass invasions [11,64], which limits the implementation of effective adaptation and mitigation policies [28]. This is notably the case of two invasive Portunidae blue crabs, *Callinectes sapidus* (Rathbun, 1896) and *Portunus segnis* (Forskål, 1775). Respectively native to the Western American coast and Indo-Pacific Ocean, these blue crabs have both recently showed large expansion in the Mediterranean Sea [53,82]. Both blue crabs are species of the same family (Portunidae), as well we know that they show the same ecology and behavior (aggressive and opportunistic behavior) [16,39,40,51,55,57,58,82]. In the literature, the same trends are observed in both species on the impacts on biodiversity and artisanal fisheries [15,16,32,44,46,56,82]. The biological traits of these both Portunidae, such as early maturity, rapid growth rates, opportunist diet, high reproductive rates, generalist habitat use, long-range larval dispersal, and effective physical and aggressive behavior [84] facilitate their invasive character and enhance the successful spread across regions [53,82]. Despite local observations of competitive interactions with native species [32,54] and impacts on the artisanal small-scale fisheries [44], the ecological and economic consequences of the invasion of these two blue crabs in the Mediterranean Sea are currently still only assumed [56,85]. Moreover, there is currently a lack of harmonized, salient, and credible measures to control these species at both the European and global level.

Scientifically collected data showing the presence of NIS in the environment is crucial [69] but often rare, temporarily, and spatially limited. However, the inclusion of public and/or stakeholder perceptions of NIS is becoming increasingly common in scientific studies through well-tested approaches such as the Local Ecological Knowledge (LEK) [5,23,38,60,63,79,88]. Public opinion can be influenced by the perceived ecological benefits, financial costs, and ethical issues associated with proposed management actions and can strongly influence the outcomes and potential success of non-native species management attempts [13,78,81,87]. As it is the case for blue crabs, public opinion is a very important component in making policy decisions about NIS to support management strategies for non-native species that can be ethically challenging, especially when it comes to removing species of commercial interest [10,38].

Complete elimination of blue crabs is currently unrealistic and efforts are being directed toward understanding and controlling [56]. But, both blue crabs are considered a valuable seafood and supports an important fishery along the coasts of the Northern America for *C. sapidus* [83] and in many Asian countries for *P. segnis* [49]. Further, in the last decade, several studies have highlighted the high nutritional qualities of Mediterranean blue crab meat [48,92] and artisanal small-scale fisheries of *C. sapidus* have developed in Turkey [4], in northern Greece [45], and in Tunisia [22].

One measure to control blue crab would be to commercially harvest them. Two options are possible: (1) commercial exploitation of blue crabs to reduce the numbers of these NIS, thus an exit option after and (2) considering the exotic species as a new resource to be integrated into the fishery activity. On the other hand, many undesirable effects can be observed: wild introduction in areas where the species was not present, the implementation of poorly selective fishing techniques that lead to significant by-catches, as well as cases where paradoxically the selective exploitation of the largest individuals has favored the dynamics of the species by decreasing intra-specific competition [71]. However, such management action involves a number of challenges, which may include a lack of management resources, diverse points of view of stakeholders on the value of invasive species and the opposition to removal techniques as observed for lionfish [52]. As a main consequence, due to the highly level of risk due to the social components affecting ecological dynamics in managing NIS-related aspects of management at sea, gaining socio-ecological and economic understanding of how make effective management strategies is recognized as crucial in modern conservation science. In doing it, to accommodate the social (human related) component, the use of questionnaires distributed to well suited target groups (e.g. artisanal small-scale fishermen) may assist the research and management programs.

Here, we collate and synthesize information collected by Local Ecological Knowledge (LEK) approach targeting artisanal small-scale fishermen from France, Italy and Tunisia. Questions were asked to survey their perception on: (i) the causes and occurrences of blue crab proliferations in their countries chosen as blue crabs are there by now commonly harvested, (ii) the impact on the fishing activity, and (iii) on possible management measures that could be put in place. This study is the first study quantifying the socio-ecological and economic impact of the blue crab invasion on small-scale fisheries in the Mediterranean Sea.

2. Materials and methods

This work is part of a cross-border multidisciplinary project (BLEU-ADAPT, Interreg Italy-Tunisia, 2020–2022) conceived to increase our understanding on the Portunidae blue crabs species (*C. sapidus* and *P. segnis*) invasion in the Mediterranean Sea, especially among Italy and Tunisia.

A questionnaires-based online survey (Google form format) was performed to identify the socio-economics impacts of blue crabs on the artisanal small-scale fisheries. The anonymous questionnaire was translated in four different languages, translated by native speakers (French, Italian, Arabic and English) and were distributed on well-known Facebook groups oriented towards artisanal small-scale fishery in the respective countries (see Supplementary material 1). The co-authors circulated the web link to the Google form also across their projects' mailing list and stakeholders' databases. The study was performed between May and October 2021. To minimize response bias respondents were asked to answer anonymously and on a voluntary basis.

Due to the inclusion of both blue crab species (*C. sapidus* and *P. segnis*) in the same family (e.g. Portunidae), their very similar ecology/behavior reported in the scientific literature (refer to the references cited in the introduction), and due to the difficulty of species identification by fishermen, we decided to refer generically to the term "blue crabs". Since the target group of our survey was fishermen, we decided to focus more on the effects of the blue crab invasion without creating barriers between their local ecological knowledge and our expert knowledge.

The first part of the survey dealt with the identification of both blue crab species and the perception of temporal changes facilitating the spreading (e.g., evolution of the density, seasonality, and the potential causes of proliferation), the second part dealt with the perception of the positive and/or negative effects of the presence of blue crab species on the associated marine systems and aimed to get the opinion of the artisanal small-scale fishermen on possible management solutions. Finally, a more detailed part focused in surveying the perception of artisanal small-scale fishing activities and on the positive and/or negative impacts of the invasive blue crabs. Responses were translated in English for the analysis.

Questions with importance indexes (e.g. importance of impact, etc., from 0 to 5) were plotted by violin plots (R package 'ggplot2', [42]), similar to boxplots but also showing the probability density of the data for the different values (e.g. kernel density estimator). These violin plots are useful to identify the density of responses. The maps were created using QGIS 3.16.13 'Hannover' and, the other plots using the software Sigmaplot 12.5.

A qualitative analysis was also conducted for the open-ended questions where stakeholders were given the opportunity to report their

knowledge of blue crab diet and their expectations and ideas for blue crabs' management. Responses were extracted and analyzed using the software IRaMuTeq textual analysis software [77]. On the diet, the number of words on the type of prey were counted and the frequencies calculated.

To contextualize the obtained records from interviews and the invasion history of the both blue crabs species in the three countries studied, the cumulative number of records was calculated by using data extracted from the literature ([53] for *C. sapidus*; [82] for *P. segnis*).

3. Results

The invasion patchwork of the two species of blue crabs (*C. sapidus* and *P. segnis*) in the Mediterranean Sea is different among the 3 surveyed countries (Fig. 1 A) as reported by plotting occurrence data from literature. Indeed, Italy was the first country to report the presence of these new species, respectively in 1949 for *C. sapidus* and in 1966 for *P. segnis*. Tunisia was the second country where both crabs rapidly spread, respectively since 2014 for *P. segnis* and since 2017 for *C. sapidus;* in France only *C. sapidus* has been observed since 2016 and there are no records on the other species. To date, Italy has the higher number of occurrence points (113 points in total, all species combined) followed by Tunisia (31 occurrence points) and France (24 occurrence points).

A total of 102 questionnaires (France: 14; Italy: 67; Tunisia: 21) were compiled between May 2021 and October 2021 (Fig. 1B). The sample was composed almost entirely by male respondents (95 %). Respondents were between 18 and 80 years old (7 % 18–29 y/o, 26 % 30–39 y/o, 30 % 40–49 y/o, 29 % 50–59 y/o, 5 % over 60 y/o; 3 % unreported). In the three studied countries, most of the interviewed artisanal small-scale fishermen reported to practice their small scale artisanal and coastal fishing activities all year round (France: 82 %; Italy: 66 %; Tunisia: 40 %) (Supplementary material 2). The blue crab invasion phenomenon recorded by knowledge shows differences between species and among countries. In Italy the majority of artisanal small-scale fishermen observed *C. sapidus* in the last decade, between 2010 and 2020 (with highest densities between 2016 and 2020), 61 years after its first record in 1949. In France, the years of first sightings (2016–2020) of *C. sapidus* coincide with the first reported record in the scientific literature in 2016. In Tunisia sightings by artisanal small-scale fishermen were reported between 2015 and 2016 and between 2018 and 2020 with the first published record in 2017 (Supplementary material 3). Regarding *P. segnis*, in Italy the first sightings was observed in 2019 and 2020 followed by the first scientific record in 2012, while in Tunisia, fishermen observed the crab from 2011, 3 years before its first scientific record (Supplementary material 3).

When stakeholders were asked about the causes of blue crab proliferation, global change and the presence of introduction vectors were widely reported 31 % and 28 % respectively (Fig. 2 A), with a 52 % of respondents reporting ballast water as main vector of spreading. Interestingly the 72 % of stakeholders have noticed an increase in temperature over the last 3 years (Fig. 2B).

The observed and reported temporal population dynamics of blue crabs in the three countries showed some differences (Fig. 2 C). In France, crabs are frequently observed in March and the frequency of observations increases from July to September (Fig. 2 C), whereas in Italy, the frequency of observation of crabs increases from April to July and decreases until December. A similar trend is observed in Tunisia where blue crabs are more frequently observed from July to October before decreasing.

The estimate of the increase in blue crab density is difficult to quantify for the artisanal small-scale fishermen (23 % of the respondents do not know), but on average the density of crabs is perceived to have increased by 3.0 ± 2.9 in France, 12.6 ± 4.0 in Italy and 3.7 ± 1.5 in Tunisia in the past 10 years (Fig. 2D). The present study revealed that, according to the view of many artisanal small-scale fishermen, the perceived trends of blue crabs spreading seem to indicate that

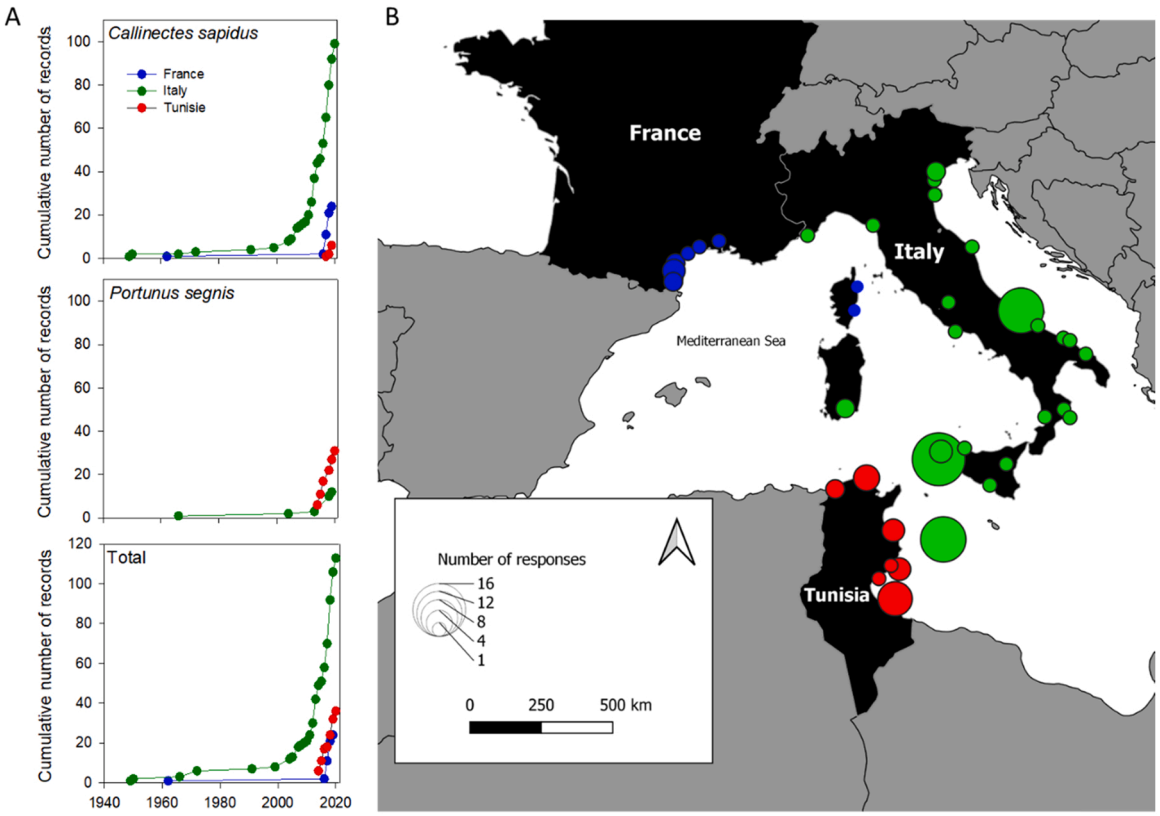

Fig. 1. (A) Invasion dynamics of *C. sapidus* (France, Italy, Tunisia) and *P. segnis* (Italy and Tunisia), and (B) distribution and number of questionnaires performed in France, Italy and Tunisia in 2021.

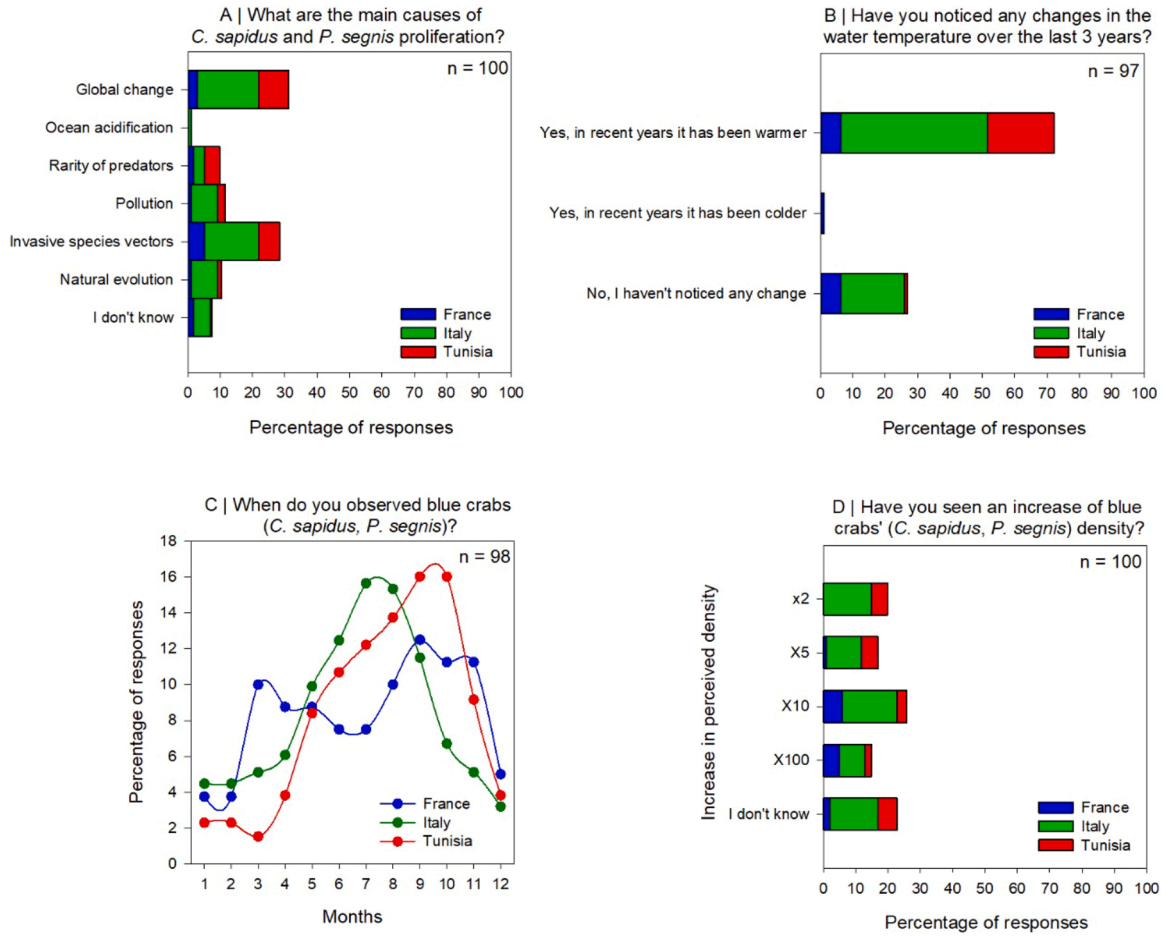

Fig. 2. (A) Causes of blue crab invasion, (B) perceived temperature increase, (C) frequency of observations of blue crabs, and (D) perceived density increase in France, Italy and Tunisia.

populations are still in the early stages of invasion in France (perceived increase of x10 or even x100), and an apparent stability was felt in Italy (perceived increase between x2 and x10), and in Tunisia (perceived increase of x2 to x5) (Fig. 2D).

The relevance of the perceived socio-economic and ecological issues associated with the blue crab invasion appears to be very salient among the interviewed fishermen from the investigated western Mediterranean countries (Table 1 A). Specifically, the blue crab invasion particularly affects fishing and aquaculture (64 %), but also coastal residents (14 %) and to a lesser extent the tourism industry (9 %) and recreational tourism activities (10 %) (Table 1B).

Small-scale fishing was specifically surveyed by the third part of our questionnaire as representing one of the main human activity most impacted by the blue crab invasion. Evidence collated from the interviews allowed to underline three aspects most affected by the presence of blue crabs, specifically: the fishing activity, the number of catches in the nets and the associated economic revenues (Fig. 3A). The main impact caused by the presence of blue crabs is the damage to fishing nets (median = 4.3), but also an increase in work intensity associated to net maintenance (median = 3.6) and physical injuries, to fishermen (median = 3.1) (Fig. 3A).

Preys into the nets (fixed nets) were also damaged by the presence of blue crabs being very voracious and active scavenger species preying over other died species in this case species entangled into the nets (Fig. 3B). Small-scale fishermen specifically reported to have caught less fish (median = 3.4) and they also reported that blue crabs create significant damage to fish (median = 3.8) leading to significant fish mortality in the fyke nets (median = 3.4) the common type of net used in

Table 1
(A) What are the main issues of blue crab invasion, and (B) what human activities are affected?.

A | When you examine the issue of blue crabs (*C. sapidus* and *P. segnis*), what do you think? (n = 100)			
Index of importance	**It's not your business *vs.* It's your business**	**It is a local problem *vs.* It is a global problem**	**It is a minor problem *vs.* It is a very important one**
0 = no	2 %	4 %	2 %
1	9 %	9 %	8 %
2	11 %	9 %	8 %
3	12 %	13 %	12 %
4	15 %	15 %	12 %
5 = extremely	49 %	48 %	58 %

B | What human activities are affected by the increase in blue crabs (*C. sapidus* and *P. segnis*)? (n = 100)	**France**	**Italy**	**Tunisia**	**Total**
The tourism industry	1 %	6 %	1 %	9 %
Coastal residents	4 %	9 %	1 %	14 %
Local governments	0 %	4 %	0 %	4 %
Fishing and aquaculture in general	9 %	40 %	14 %	64 %
Tourism and water-based recreation	2 %	7 %	1 %	10 %

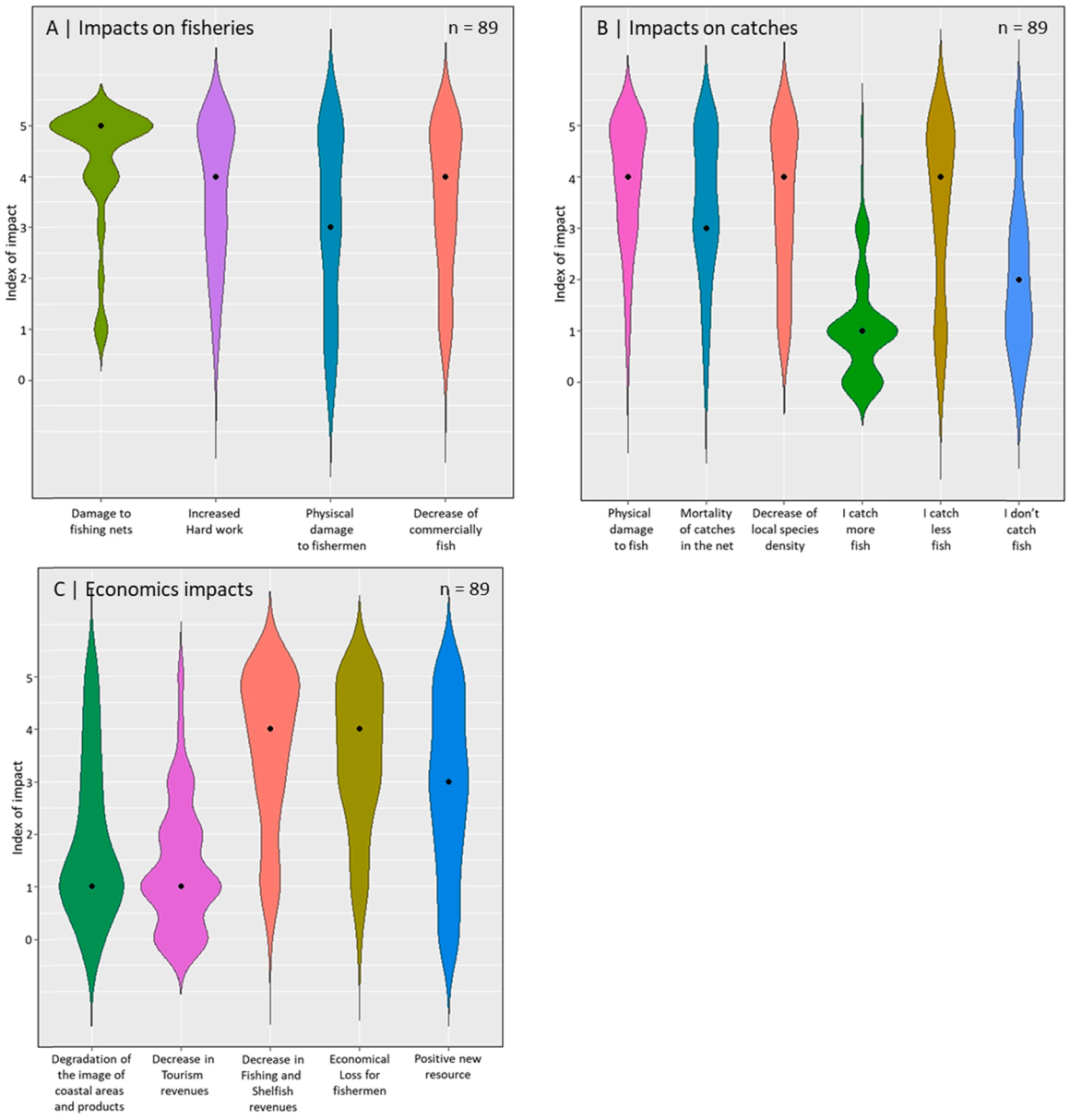

Fig. 3. Distribution of perceived impacts of blue crabs (*C. sapidus* and *P. segnis*) on (A) artisanal fisheries activities, (B) on catches, and (C) economics impacts. Black dots represent the median.

coastal and lagoon systems (Fig. 3B). This induces a decrease in the quantity of catches (median = 3.5) and more generally a decrease in the density of local species (median = 3.4) according to the artisanal small-scale fishermen interviewed. The 83 % of them shared their knowledge on observed blue crab diet (Fig. 4). Looking at their replies, the words "fish" and "omnivore" appear 44 and 29 times respectively. Shellfish are also mentioned 21 times and seem to be a consistent part of the blue crab diet, while seaweed (5 times) and worms (2 times) were only rarely mentioned.

The combination of these impacts on fishing gear and catches generated economic loss for small-scale fishermen (Fig. 3C) a main source of disruption into the short artisanal small-scale fishery's supply chain. Blue crabs' proliferation affects induce a decrease in fishing and aquaculture revenues (median = 3.6) and important economic losses for artisanal small-scale fishermen (median = 3.4). On the other hand, to the negative impacts of blue crabs perceived by most of the interviewed, the presence of this new species was also reported as a positive "revenue resource" for some fishermen (median = 2.8).

When asked about the consumption of blue crabs on their diet, the 58 % of fishermen reported of having consumed them (Table 2) and also appreciate them (median = 2.8 in France, 3.1 in Italy and 2.4 in Tunisia; Supplementary material 4), compared to 42 % who reported to do not have consume them. Local initiatives to sell blue crabs were reported mainly in Italy (27 %) and Tunisia (18 %) with only a 2 % in France (Table 2).

The collated perceptions shown differences among countries, since in France the distribution of responses clearly shows that the presence of blue crabs creates a significant negative impact (median = 3) and no positive impact (median = 0) (Fig. 5 A), while in contrast, in Italy and Tunisia, despite a majority of responses in favor of the negative impact (median = 3 in Italy; median = 2 in Tunisia), the responses shown a large distribution regarding the positive impact of blue crabs (median = 0 in Italy; median = 1 in Tunisia). Comparing the percentages of positive vs. negative impact responses for each response shows that for 16 % of stakeholders, the impact is both positive and negative (Fig. 5B) and for 22 % the impact is only negative (index between 3 and 4).

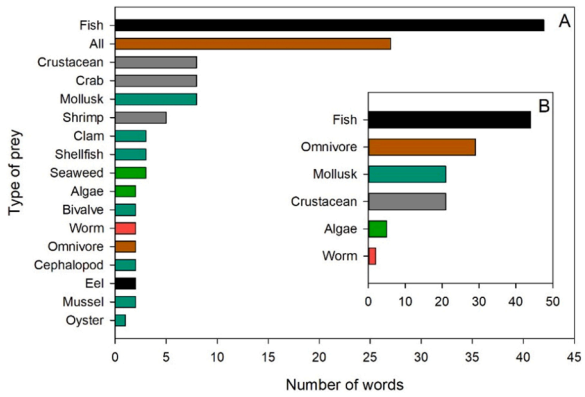

Fig. 4. Number of words according to (A) the prey types mentioned by the stakeholders on the diet of blue crabs (*C. sapidus* and *P. segnis*), and (B) prey categories regrouped by taxon groups. In the graph B, the mention "omnivore" indicates that blue crabs eat everything.

Table 2
Percentage of responses of stakeholders (A) on their personal consumption and (B) on the shell of blue crabs in France, Italy and Tunisia.

A | Do you eat blue crabs (*C. sapidus* and *P. segnis*)?				
(n = 89)	**France**	**Italy**	**Tunisia**	**Total**
Yes	12 %	33 %	13 %	58 %
No	1 %	30 %	10 %	42 %

B | Do you shell blue crabs (*C. sapidus* and *P. segnis*)?				
(n = 88)	**France**	**Italy**	**Tunisia**	**Total**
Yes	2 %	27 %	18 %	48 %
No	11 %	34 %	7 %	52 %

The valued meat and commercial potential of blue crabs has been perceived as a new source of income for artisanal small-scale fishermen, 72 % of them propose fishing and marketing as potential solutions to cope with the invasiveness (Table 3A), they also proposed that these management measures should be financed by local governments (44 %) and/or by Europe (28 %) (Table 3B) as confirmed also by the replies of the interviews to the open question.

As for example an Italian fisherman reported as necessary to "*begin to offer it for consumption as food could help reduce the pressure of this voracious predator on endemic species. However, people should start to learn about this resource as an alternative. Consumption, awareness campaigns on the problem and management implications of the proliferation of this species*". In France, the same expectations can be observed among the artisanal small-scale fishermen who indicate that it is necessary to implement "*an unlimited fishery in order not to reproduce the crayfish and catfish pattern in fresh water*". In Tunisia, the marketing of blue crabs has already been in place for several years [7,24], and in fact, the expectations of the artisanal small-scale fishermen's concern rather the bio-ecological aspects of blue crabs influencing their maintenance and the important presence of poaching of blue crabs, which are now highly coveted in Tunisia: "*control of the increase of the species. It is necessary to favor the predators and to follow the parameters / factors of increase. With the presence of blue crabs, illegal fishing has also increased. It is imperative to stop their invasion*" (Tunisia). Globally, the main solutions purposed by the artisanal small-scale fishermen is to implement the valuation and the commercialization of blue crabs to transform the pest in opportunity.

4. Discussion

The impact of blue crabs was quantified in the eastern part of the Mediterranean Sea in 2020 only on the recreative fisheries [15]. The present study provided a recent additional data collection that allowed

Table 3
Solutions purposed by the stakeholders to tackle the blue crab proliferation in France, Italy and Tunisia.

A | What solutions to tackle the blue crab (*C. sapidus* and *P. segnis*) problem?				
Solution purposed (n = 99)	**France**	**Italy**	**Tunisia**	**Total**
The blue crab fishery and its marketing	11 %	45 %	16 %	72 %
Addressing predator depletion of the blue crab	1 %	9 %	10 %	17 %
Increase wastewater treatment	16 %	7 %	1 %	11 %

B | Who should fund the implementation of blue crabs (*C. sapidus* and *P. segnis*) management measures?				
Solution purposed (n = 100)	**France**	**Italy**	**Tunisia**	**Total**
The government	3 %	27 %	13 %	44 %
Fishing and aquaculture in general	2 %	11 %	1 %	14 %
The tourism industry	1 %	2 %	0 %	3 %
Society as a whole through taxes	3 %	1 %	0 %	4 %
Environmental associations or groups	1 %	6 %	1 %	7 %
Europe	6 %	21 %	1 %	28 %

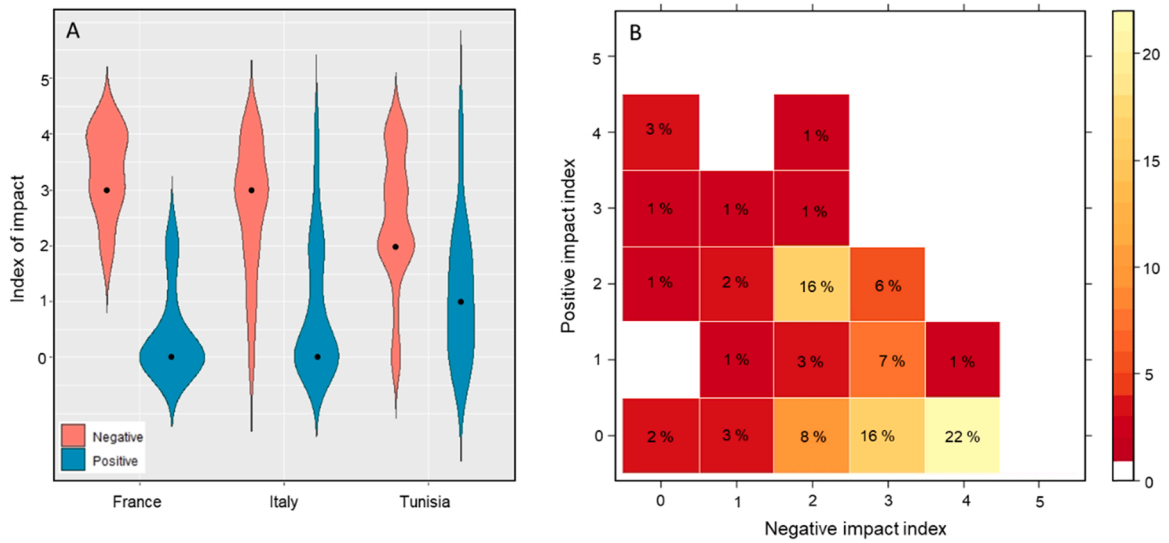

Fig. 5. (A) Positive and/or negative impacts of blue crabs (*C. sapidus* and *P. segnis*) perceived by the stakeholders and (B) comparison of percentages of responses in each category of impact index (positive vs. negative). Black dots on the plot A represent the median.

the analysis of the potential impacts exerted by the blue crabs on artisanal small-scale fishery in the Western Mediterranean Sea. LEK confirmed the value as a tool enabling the collection of crucial knowledge required to evaluate the distribution and socio-ecological impacts of invasive species in large geographical areas [18,36,62]. Specifically, artisanal small-scale fishermen have been recognized as the key target group to understand the effect of invasive species considering their background and daily life experience of the problem [43,63,89]. Something confirmed also by the collated responses regarding the main recognized causes of invasion perfectly aligned with the literature on the subject [56,66]. As felt by the majority of artisanal small-scale fishermen, the current trends of occurrence showed a global warming of the temperature in the Mediterranean Sea [72,79]. The present study revealed that, according to the view of many artisanal small-scale fishermen, the perceived trends of blue crabs spreading seem to indicate that populations are still in the early stages of invasion in France and an apparent stability was felt in Italy and in Tunisia. These trends were representative of the data available in the literature, and the invasion dynamics data presented in this study, where in France in particular the expansion and increase in blue crab (*C. sapidus*) density has been measured only since 2017 [50]. In Italy, data collected from recreational fishers showed that many of them rated the blue crab population trend as "stable or fluctuating" (43.5 %) or "increasing" (40.3 %; [15]). In Tunisia, no data were available in the literature on the trends perceived by the artisanal small-scale fishermen but, a LEK study on the impacts of the blue crab *P. segnis* showed that more than 60 % of artisanal small-scale fishermen systematically capture this species in their gill nets [46] and, since 2014, the *P. segnis* population has shown a continuous and increasing proliferation pattern [82]. As observed in many studies [8,26], artisanal small-scale fishermen demonstrated strong knowledge of the diet of blue crabs. In fact, artisanal small-scale fishermen indicated in our study, that blue crabs were omnivorous, eating mollusks and crustaceans and fish species in the nets. Whereas the algae and worms represented a little proportion of blue crabs' diet. Based on the data available in the literature, the knowledge of artisanal small-scale fishermen was strongly correlated to the diet studied scientifically: blue crabs are known to be mainly omnivorous, scavengers and generalist predators in competition with the native species [3,31,73,74]. In their native range, the diet composition of blue crabs generally consists of mollusks (from 30 % to 40 %; mussels, clams, oysters), from 15 % to 20 % of crustaceans (decapods, amphipods), 15–20 % of fishes, $<$ 5 % of polychaetes, and a highly variable percentage of algae, sediment, and detritus [9]. In the Mediterranean Sea, *C. sapidus* was identified as a fully carnivorous predator and share the same set of trophic resources with these benthivorous fish species in Croatia [58]. Recent isotopes analysis in Crete confirmed the predatory nature of *Portunus segnis* opportunistically feeding on a wide set of invertebrates (e.g., bivalves, gastropods, crustaceans, polychaetes) and fish species [57]. Due to the aggressiveness and omnivorous diet [84], the impact of both blue crabs species (*C. sapidus* and *P. segnis*) is important especially on the commercial species witch are decreasing [70] as perceived by the artisanal small-scale fishermen in this present study.

Some invasive species have strong negative ecological and economic effects and cause damage to fishing gear [27]. On the blue crabs, harmonized, credible, effective and cross border monitoring and data collection initiatives are still missing and, the impact of blue crabs on the artisanal small-scale fishermen remain unclear in the literature. As suggested in the literature and based on the results presented in this study, artisanal small-scale fishermen were the social component and economic sector to be most affected by the presence of blue crabs and considerable negative effects on fishing activities are recognized by local populations [56]. In this study, the main impacts of blues crabs on the fisheries were the degradation of the nets (physical damage) and the decrease quality and density of caught commercial fish. The clogging nets can be huge and can represent 150 kg per day in Tunisia [46] increasing the frequency of net hauling to avoid clogging [17,46]. In addition, blue crabs are capable of shredding nets [70] and in Tunisia, *P. segnis* damages the catches in the nets reducing fish catches resulting in a 37 % loss of catch [46]. The combination of the time and financial costs of mending and changing nets [46,70] imply a significant economic loss for the fishing sector as observed in our study. In Tunisia the average annual income *per* fisherman decreased from 73,000 € to 20,500 € after the invasion of *P. segnis* [46]. In Croatia, the cost of damages on the nets caused by *C. sapidus* represented $20 per week per artisanal small-scale fishermen [37]. In general, to address the economic loss associated with the invasive species, the artisanal small-scale fishermen deployed different strategies showing a true professional culture of adaptation [19,63]. Indeed, this profession had always been exposed to environmental hazards, leading to develop a culture that "manage" the problems that may arise with a strong capacity to adapt [1,6,12,19,63]. But, in the case of the blue crabs, these temporary adaptations (e.g. reduced net setting time, change of nets or fishing technique) tend to be costly and restrictive. The main solution for the management of blue crabs' populations in the Mediterranean Sea would be represented by exploitation as also reported by 72 % of the artisanal small-scale fishermen interviewed in our study.

As observed in the present study it can be difficult to assess the economic impacts of blue crabs because they may represent both negative (i.e. changes in habitats structure and associated biodiversity) and positive (i.e. shellfish resource) effects on ecosystem services [29]. The exploitation and consumption of edible non-indigenous species (NIS) is increasingly being promoted as a measure to increase pressure on NIS and turn these species into a food source and economic benefit for local communities [34,47]. After all the blue crab represent a well-recognized marine resource of high recognized economic interest in their native areas in the USA - for *C. sapidus* [83] - and Asia for *P. segnis* [75]. In the Mediterranean Sea, some local initiatives of commercial fisheries were observed in Turkey [4,41], Greece [45], Egypt [14] and in the Adriatic Sea where a blue crab market was developed by the restaurants in major tourist locations for live, cooked and extracted meat [37]. Also, since 2016 in Spain, the Ministry of Fishery has included the blue crab in the list of commercial fish species (VV.AA. 2016; BOE-A-2016-3357). Tunisia is the first country to have industrialized the blue crab fishery according to FAO [7,24] with an increase of blue crab exports in America and Europe in May 2021 to reach 2090.9 tons, worth some $7.2 million - compared to 796.1 tons worth $3.1 million in 2020. Within this framework, FAO has trained 90 artisanal small-scale fishermen in Djerba, Gabès and Kerkennah on the benefits of blue crab and distributed 1500 specifics traps to enable them to catch the blue crabs. Fishermen interviewed in our study reported the implementation of common and specific fishing tools for the blue crab fishery at a global scale as main management measure solution. The study of Glamuzina et al. [37] in the Adriatic Sea showed that the gross income for a traditional fisher for blue crab with a fyke net was $1117, and $4393 for the wire traps. The authors developed metal traps with a high potential to support the establishment and development of a blue crab fishery in the Neretva estuary area and in the Mediterranean Sea, showing remarkable selectivity and catch efficiency.

Despite this enthusiasm for blue crab exploitation, managers are still reluctant to promote and develop strategies for the exploitation of NIS in the Mediterranean Sea [56]. Recently, the General Fisheries Commission for the Mediterranean (GFCM) created adaptation strategies to address the potential impacts of invasive species on fisheries over the medium term (2017–2020) [25]. Following calls from Algeria, Tunisia, and the European Union, Recommendation GFCM/42/2018/7 establishes a regional research program to fill the scientific and research lack of knowledge concerning the crabs *C. sapidus* and *P. segnis* with the objective of maintaining Mediterranean blue crab stocks at Maximum Sustainable Yield (MSY) levels, as well as the socio-economic viability of blue crab fisheries [47]. However, there is a high risk associated with this strategy, which is the economic dependence of local fishing communities on a NIS or fishing technique that is detrimental to ecosystems

functionning and ecosystem services in a broad sense and which spatial and temporal provisioning is still unpredictable [47,67]. Incorporating an invasive species as a sustainable food resource can be a positive management plan for humans and the environment but presents important socio-ecological management challenges [67]. Before taking these control measures, it is therefore necessary to accurately consider the advantages and disadvantages on the ecosystem services associated with these measures to avoid the Tunisian situation. In fact, in Tunisia, the blue crab has become a new economic resource very much regulated by law. For example, it is currently forbidden to catch ovigerous blue crab females that are released under penalty of prosecution. In France, even if *P. segnis* is not present, it is classified as a level 2 by French law (Article L411–6 of the Environmental Code), which means that it is forbidden to introduce it into the natural environment, to hold live specimens, to transport it and to market it (and other forms of propagation, whether alive or dead). It is also prohibited to import and sell *P. segnis* caught in Tunisia. *Callinectes sapidus* is currently considered as a level 1 (e.g. prohibition of introduction into the natural environment, Article L411–6 of the Environment Code) but current discussions tend to classify this species as level 2 [20]. In fact, it is very likely that its fishing and marketing will not be possible in France as a population control measure.

The example of the blue crab thus provides a good starting point for the management of valuables NIS and the controversies related to its management in the Mediterranean. More generally, a structured, adaptive, and iterative management strategy that focuses on more of the NIS should be facilitated [67].

CRediT authorship contribution statement

Guillaume Marchessaux: Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Writing – original draft, Writing – review & editing. **Maria Cristina Mangano:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing. **Sergio Bizzarri:** Writing – review & editing. **Charaf M'Rabet:** Writing – review & editing. **Elena Principato:** Writing – review & editing. **Nicola Lago:** Writing – review & editing. **Dimitri Veyssiere:** Writing – review & editing. **Marie Garrido:** Writing – review & editing. **Steven B. Scyphers:** Conceptualization. **Gianluca Sarà:** Conceptualization, Funding acquisition, Project administration, Supervision , Writing – review & editing.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2022.105461.

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