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ORIGINAL PAPER

Synergistic use of facebook, online questionnaires and local ecological knowledge to detect and reconstruct the bioinvasion of the Iberian Peninsula by *Callinectes sapidus* Rathbun, 1896

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Abstract The widespread use of social network sites and smart phones has enhanced the potential of Citizen Science (CS), i.e. to enlist the general public in gathering scientific information across large spatial–temporal scales. This research describes a CS application to reconstruct the bioinvasion of the Iberian Peninsula by the Atlantic blue crab (*Callinectes sapidus* Rathbun, 1896) and obtain reliable information about the potential socio-ecological and economic implications. *C. sapidus* is one of the 100 worst invasive alien species in the Mediterranean Sea. It was first reported in Venice in 1949 and then colonized the Northern Levantine basin of the Mediterranean Sea. Over half a century later, the species is spreading rapidly in the Western basin. Overall, this research detected *C. sapidus* in more than 300 locations, including several Natura2000 areas and 18 rivers. The blue crab in the Mediterranean Andalusia was not registered most likely due to the lack of freshwater and sedimentary habitats together with the biogeographic border of the Almerian front. Thus, the blue crab in the Balearic Sea and the Gulf of Cadiz might respond to different colonization events and should be managed independently. From a socio-ecological perspective, professional fisheries seem to benefit from the exploitation of *C. sapidus*, while recreational fishers perceive the presence of the crab as detrimental for the ecosystem. Managers, decision makers and scientists might use this research *i)* to better understand the implications of *C. sapidus* in non-native areas, *ii)* to early detect, mitigate and optimize management resources in future bioinvasions events of alien species.

Keywords *Callinectes sapidus* · Recreational fisheries · Citizen science · Coastal monitoring · Alien invasive species · Local ecological knowledge

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Introduction

The development of Social Network Sites (SNSs), broadly used by all age classes of the population worldwide, has enhanced the potential of Citizen Science (CS). One of the multiple applications of CS is to enlist the public in gathering scientific information allowing scientists to sample across large spatio-temporal scales, in a cost and time-effective way (Bhattacharjee 2005). CS can provide vast sources of comprehensive data for other researchers, resource managers, policy makers, educators and, even the general public all over the world. A few decades ago, already, the British Trust for Ornithology Project *Garden Bird Watch in the UK* showed how CS can provide large data sets (six million birds sampled) and involve large numbers of people (circa 400,000) spread over a wide array of locations (i.e., 228,000; Devictor et al. 2010 and references therein). Despite marine studies based on CS being initially scarce compared to terrestrial studies, more and more studies are now benefiting from CS's potential (Sandahl and Tøttrup 2020). Apace with the globalization process, the spread of non-native species has led to a plethora of bioinvasions, which can be monitored by means of CS (Johnson et al. 2020). Recently, Giovos et al. (2019), monitored the spatial distribution of several invasive alien species (IAS) in the Eastern Mediterranean through public engagement, in one of the most comprehensive and systematic CS efforts carried out in the Mediterranean Sea so far.

Focusing on the Mediterranean Sea, *Callinectes sapidus* Rathbun (1896), is one of the 100 worst IAS (Streftaris and Zenetos 2006). The natural distribution of this species spans the length of the Atlantic coast of the Americas, from Nova Scotia to Northern Argentina (Williams 1974). However, *C. sapidus* is also rapidly spreading along the North Atlantic East Coast and in the Mediterranean Sea (Mancinelli et al. 2021) with significant environmental, economic and social consequences (Vilà and Hulme 2017). According to Galil et al. (2002 and references therein), *C. sapidus* was first reported within the boundaries of the Mediterranean Sea in Venice (northern Adriatic Sea) in 1949. The spread of *C. sapidus* in the Western Mediterranean basin has not been as fast as in the Eastern basin, where the species has colonized a number of areas (Beqiraj and Kashta 2010; Dulčić et al. 2011; Mancinelli et al. 2013). Once *C. sapidus* colonizes a new area, it might become a fishing resource for local fisheries, which could help mitigating the expansion of this invasive crab (Glamuzina et al. 2021). Nutritional aspects of *C. sapidus* versus its potential harmfulness due to bioaccumulation of hazardous substances (e.g. heavy metals) must be studied (Gökoðlu and Yerlikaya 2003; Türkmen et al. 2006; Ayas and Ozugul 2011; Zotti et al. 2016) to guarantee public health and food safety (Atar and Seçer 2003; Sumer et al. 2013; Daban et al. 2016). Besides, the eradication of the species seems impossible (Mancinelli et al. 2017b) and social concern might arise due to negative interactions with traditional users of the coastal zone, such as professional fisheries (Fuentes et al. 2019; Kampouris-Thodoros et al. 2019).

The development of management policies to prevent and mitigate the negative socio-ecological and economic effects of *C. sapidus* should be based on science. However, information is not always easy to obtain, especially in the early stages of bioinvasions when time is crucial (Ojaveer et al. 2018). Despite new records of *C. sapidus* being recently published for the Iberian Peninsula (Castejón and Guerao 2013; Izquierdo–Gómez and Izquierdo–Muñoz 2016; González–Wangüemert and Pujol 2016; Garcia et al. 2018; Fuentes et al. 2019; Morais et al. 2019; Vasconcelos et al. 2019), they merely describe the presence of *C. sapidus* at a local level. Consequently, there is still a lack of a more holistic approach (e.g., ecological, social, environmental) to increase our understanding of the spatio-temporal bioinvasion of C. *sapidus* in the Iberian Peninsula (i.e., Spain and Portugal). It is worth noting that *C. sapidus* preys upon the blue mussels (*Mytilus galloprovincialis;* Prado et al. 2020) jeopardizing the shellfish industry in the River Ebro delta. Additionally, *C. sapidus* preys on *Melicertus kerathurus* (Guijarro-García et al. 2019), one of the key economic resources for local fishing fleets in the Balearic Sea and the Southeast of the Iberian Peninsula. Thus, information about the dynamics of the *C. sapidus* bioinvasion is needed to better manage the potential negative effects in recently invaded areas. Therefore, this research describes four years exploring the *C. sapidus* bioinvasion of the Iberian Peninsula by a methodology based on Local Ecological Knowledge (LEK), online questionnaires and SNSs (i.e., Facebook). Firstly, this study aims *i)* to shed light on the very first establishment areas of *C. sapidus* and *ii)* detect the existence of self-sustained populations. Secondly, more detailed goals are envisaged such as: *i)* to unravel the spatio-temporal dispersion of *C. sapidus* in the context of the Iberian Peninsula and *ii)* to explore the social concern arising from the presence of *C. sapidus* in the ecosystem.

Materials and methods

Context of the study

The data collection in this research evolved apace with the *C. sapidus* bioinvasion. Despite several reports of *C. sapidus* having been published in scientific journals, at the time this study started to be conceived (spring 2015), none of them seemed to report the presence of a stable population on the Iberian Peninsula, neither were there consistent contacts on a yearly basis or social concern due to fishery interactions. Thus, for this study, the reports of *C. sapidus* mentioned in *i)* WWF Adena (2002) (page 9; document available in the Online resource 1 of the Supplementary materials) in the River Guadalquivir in 2001 (Huelva), *ii)* Cabal et al. (2006) in 2004 in Gijon (Cantabrian Sea), *iii)* Abelló (2010) in the Mar Menor in 2010 (Murcia) and Ribeiro and Veríssimo (2014) are considered colonization attempts not leading to the current bioinvasion process. In the context of this study, Castejón and Guerao (2013) was the first geographical area where the current *C. sapidus* bioinvasion in the Iberian Peninsula started.

Dissemination of the study and data collection

C. sapidus was detected in the catches of artisanal trammel netters in Alicante and Valencia in summer 2015 (SE of Spain; Izquierdo-Gomez and Izquierdo-Muñoz 2016). The presence of the crab persisted in spring 2016 (*pers. obs.* in the River Guardamar). González-Wanguemert and Pujol (2016) had already reported the species a few months before in the River Segura in Alicante (38.112°N, −0.639°W; December 2014). Thus, from June 2016, recreational fishers aware of the presence of *C. sapidus* were sought in the most relevant groups with recreational fishing interest of the SNS Facebook (www.facebook.com). A photo of *C. sapidus* was posted once per week/two weeks in different Facebook fishing groups in order to elicit interaction with recreational fishers (i.e., “likes” and/or comments). The posted pictures of *C. sapidus* included the sentence “have you seen this crab?” (in Spanish: ¿Has visto este cangrejo?) in order to encourage fishers to send orthogonal pictures of the dorsal part of captured crabs, with a single crab per picture (Fig. 1). Subsequently, all fishers interacting with the posts were further contacted via public

Fig. 1 Example of an orthogonal photo of *C. sapidus* with a reference object (i.e., euro coin) sent by respondents

comments (to promote *engagement*), and/or via private messages. The goals for each conversation with a given fisher were *i)* to identify the species as *C. sapidus* to validate the report, *ii)* to determine the sex and size of each individual and *iii)* to geolocate the capture of the crab. In parallel, an active search of posts about *C. sapidus* in the timeline of Facebook groups with fishing interest was also carried out; this represented an alternative source of potential collaborators already familiar with *C. sapidus*. The same methodology was applied in 2017 and in 2018 (i.e., June 2017-October 2017 and June 2018-October 2018).

From 2019, the strategy changed, and an online questionnaire was launched in January to seek more detailed information on *i)* the temporal aspect of the *C. sapidus* bioinvasion and *ii)* the main social concerns. The questionnaire was created with the Facebook Survey tool (https://survey.app.do; Code Rubik inc.) and contained two sections. The first section had a header with the photo of *C. sapidus* and sought to obtain personal information of the respondents: Question (Q) 1) Facebook name, Q2) hometown, Q3) gender, Q4) age, Q5) educational background and Q6) the preferred fishing type. In the second section, specific details about *C. sapidus* were asked: Q7) the exact location(s) where *C. sapidus* was caught in the *year of first detection* (YOFD), Q8) the specific YOFD of *C. sapidus*, Q9) the source of awareness about the presence of *C. sapidus* and Q10) the temporal distribution of ovigerous females of *C. sapidus*. Finally, the respondents were given the option to express their opinion about the presence of *C. sapidus* in the coastal ecosystem (Q11), and to give their opinion about the potential effect of *C. sapidus* on the ecosystem (opinion index; Q12). The respondents could choose among nine categorical options (*i.e., extremely positive = 4, highly positive = 3, medium positive = 2, small positive = 1, neutral = 0, small negative = −1, medium negative = −2, highly negative = −3 and extremely negative = −4*). For instance, the choice of "extremely negative influence of *C. sapidus* on the ecosystem" was transformed into a score of −4, whereas the choice "medium negative effect on the ecosystem" was given a score of −2. At the end of the questionnaire, between the last question and the "*send answers*" button, the respondents were asked to upload a picture of the crab (if they had one). Differences in the mean opinion index between provinces, as well as the differences in the opinion index between provinces recently colonized and those having been colonized earlier in time were assessed by a Kruskal–Wallis test. All formulated questions were open type, meaning that answers like "other" or "*blank*" were available within the choices for the respondents. None of the questions was mandatory. The online questionnaire was disseminated by posting the link in groups on Facebook with recreational fishing interest once per week/two weeks. The questionnaire was available from the 1st of January 2019 to the 31st of December 2019, and the time needed to complete it was estimated between 10 and 15 min. Detailed information about the questions of the questionnaire can be found in the tabs "*question names" and "question details" of the "File 1 Callinectes sapidus database 2019 Izquierdo Gomez David.xlsx"*, uploaded to the following *Open Science Framework* repository (OSF): https://osf.io/nk3ph/).

Data cleansing

The first step to remove unsuitable responses, which could potentially mislead the results of this study, consisted of the removal of completely blank answers (respondents not filling a single question of the questionnaire but clicking the "send answers" button). In a second step, the remaining questions with blanks in personal data (i.e., Facebook name, province of origin or age) were removed. Additionally, answers stating the capture or a visual contact of *C. sapidus* but lacking a specific capture/sighting location were discarded. Additionally, answers not stating a preferred type of fishing were also removed. Finally, the answers of Facebook users filling in the questionnaire more than once were identified, and the less complete attempt of each Facebook user was removed.

Image analysis

The carapace width (CW) of each crab was measured using a reference object placed by fishers next to each specimen (e.g., ruler, coin). Any pictures without a reference object or taken from a non-orthogonal perspective were discarded. Specialized software (ImageJ; Abràmoff et al. 2004) was used to measure the CW of each crab (maximum distance between the posterior anterolateral spines). Following the size classes established by Harding (2003), the crabs were classified as small (CW < 80 mm), medium (80 < CW < 120 mm) and large (CW > 120 mm). The size frequency of crabs was determined based on sex and catch location. Only the pictures sent in the first study period were analyzed in this fashion. The pictures obtained from the online questionnaire launched in January 2019 were used to validate the reports of *C. sapidus*.

Newspapers, scientific journals and CS as a validation proxy of LEK

The frequency of articles per province published in online newspapers was used as a proxy to cross-validate the spatio-temporal bioinvasion of *C. sapidus* in the Iberian Peninsula, based on Q7) the exact location(s) where *C. sapidus* was caught in the *year of first detection* (YOFD), Q8) the specific YOFD of *C. sapidus.* Moreover, systematic online searches including the combinations "cangrejo azul" or "*Callinectes sapidus"* + the boolean operator "AND" + a given province name (e.g., "cangrejo azul" AND Alicante or "Callinectes sapidus" AND Alicante) were carried out with Google Chrome browser (https://www.google.com/chrome/) in the search engine (http://www.google.com). The advance search settings were configured to perform the searches *i)* in Spanish and *ii)* within the Spanish territory for each year of the study period (2010–2019). The same methodology was carried out for Portuguese online newspapers using the words "caranguejo azul" instead of "cangrejo azul". Furthermore, a thorough bibliographic search was conducted on Google Scholar (https://scholar.google.com/) in order to detect the first citation of *C. sapidus* in scientific literature at a regional level both in Spain and Portugal.

Once the list of newspapers and scientific journals was obtained, the YOFD both from scientific papers (*science* YOFD) and from newspapers (*newspapers* YOFD) was extracted from the text, as the publishing date and the reporting date might differ. The difference between the scientific publication date and first report of *C. sapidus* was calculated (*delay*). Additionally, the dates of first detection of *C. sapidus* were determined by means of LEK for each province. Thus, a comparative table including the dates of first detection based on *i)* scientific literature, *ii)* online newspapers and *iii)* LEK was obtained for each province. It is important to note that all subjective data obtained via CS must be handled with caution (Budde et al. 2017). Therefore, three potential YOFD were determined for each province and based on the LEK obtained through the online questionnaire: *i)* an *absolute* YOFD = the first YOFD declared by at least one respondent, *ii)* a *consecutive* YOFD = the first year of a sequence of, at least, two consecutive years declared as YOFD by respondents), iii) a *precautionary* YOFD = the previous YOFD to the largest increase in number of respondents reporting a given year as the YOFD, in a sequence of *consecutive* YOFD by respondents. Furthermore, significant differences between YOFD based on science, newspapers and LEK (all three: *absolute* YOFD, *consecutive* YOFD and *precautionary* YOFD) were inspected to assess the fastest method to detect the IAS presence. Specifically, the difference between pairs of vectors (e.g., *science* YOFD and *newspapers* YOFD) were explored by means of a single t-test ($\mu = 0$), at a province level. If both YOFD of a given province were not represented in the compared vectors (no record of the species), the province was removed from the analysis (e.g., single t-test ($\mu = 0$) of *science* YOFD—*newspapers* YOFD). In order to detect differences in the chronology of the geographical dispersion of *C. sapidus*, correlations of the LEK data (*precautionary* YOFD) and both *science* YOFD and *newspapers* YOFD, were conducted. At a spatial level, Pearson's correlations between all sources of knowledge were performed in order determine the consistency of the spatial chronology of the *C. sapidus* bioinvasion obtained from all three sources of knowledge (i.e., LEK, science and newspapers). In order to ease the readability, the *absolute*, *consecutive* and *precautionary* YOFD are referred to as *absolute*, *consecutive* and *precautionary* LEK throughout the discussion section.

The leading marine CS organization in Spain is *Observadores del mar* ("Sea watchers" in English language;https://www.observadoresdelmar.es; Abelló 2012). Thus, the frequency of the reports of *C. sapidus* per province in the database of *Observadores del Mar* was inspected to compare and contextualize the performance of the methodology presented in this study with the performance of a dedicated CS organization.

Results

First study period: *C. sapidus* establishment (Jun 2016–Dec 2018)

The collaboration of 16 different fishers allowed the identification and measurement of 159 individuals of *C. sapidus* (e.g., Fig. 1). The report of *C. sapidus* catches were mostly from Tarragona (River Ebro delta, n = 42), Alicante (Guardamar, n = 36) and Valencia (Gola del Perellonet, n = 34; Estany de Cullera, n = 34). To a lesser extent, catches from Castellón (Gola de Nules; n = 10), Murcia (Mar Menor, n = 2) and Gandia (Marenys beach; n = 1), were also reported (Fig. 2). Crabs from Alicante were mostly caught in open saltwater near the coast and not deeper than five meters, whereas the crabs reported from Valencia, Castellón and Cullera were caught in brackish/freshwater (mostly in channels and brackish waters of the Albufera de Valencia, Gola de Nules and Estany de Cullera, respectively). In Tarragona (River Ebro delta), crabs caught in saltwater were reported by recreational and professional fishers, whereas the crabs caught in fresh/brackish waters were reported exclusively by recreational fishers.

The minimum and maximum CW were 9.73 cm (female, Guardamar) and 22.82 cm (male, Cullera). The maximum differences between CW were calculated for each province (CW dispersion). The largest difference was detected in male crabs of the Estany de Cullera (CW_{max}–CW_{min} = 9.89 cm), while the minimum was registered in male crabs of Gola del Nules (CW_{max}–CW_{min} = 4.91 cm) (Table 1SM in supplementary materials), respectively. The vast majority of crabs reported from Guardamar (Alicante) were

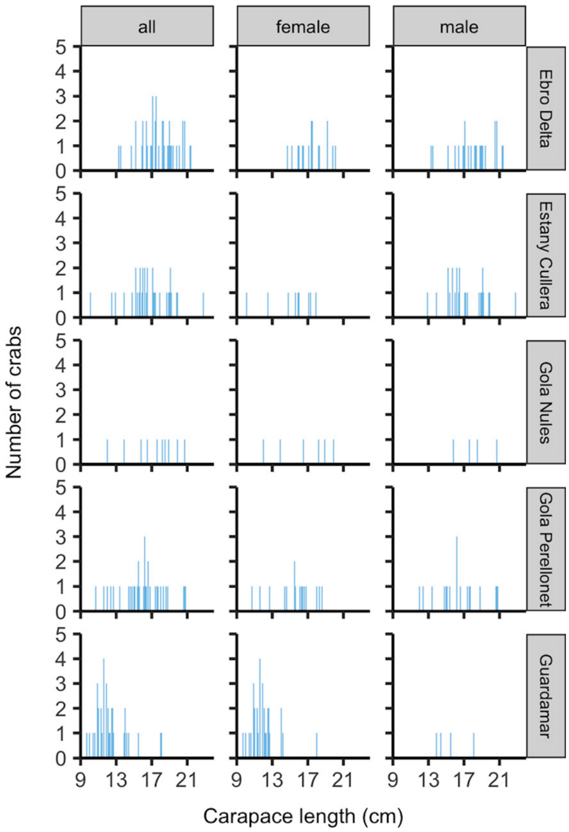

Fig. 2 Bar plot depicting the carapace width (CW) distribution of individuals of *C. sapidus* estimated from the orthogonal photos sent by respondents

caught by professional fishers in seawater (92%), and 95% of them were females (♀/♂ = 32/4). On the other hand, the lowest number of females was caught in brackish waters of Cullera (i.e., Estany de Cullera; ♀ = 26%) by anglers. A total of 80.7% of the crabs showed large CW, 19.3% medium and no small individuals were reported (for detailed information see Table 1S in the Online resource 2 of the Supplementary materials). Non-orthogonal pictures and/or pictures containing multiple crabs in a bucket were discarded. Despite no pictures being sent by collaborators either in 2017 or in 2018 by recreational fishers, there was an exchange of LEK via conversations. Although no quantitative analyses were carried out, some issues such as *i)* an increasing presence of *C. sapidus*, *ii)* controls of the catches and fines issued by authorities, *iii)* trophic interactions with target species and *iv)* negative interactions with the fishing gear were identified in these conversations.

Second study period: Online questionnaire (Jan–Dec 2019)

The online questionnaire was launched due to the increase in social concern detected via personal conversations with fishers from Catalonia and the Valencian regions as well as via the increase in the number of reports in online newspapers in late summer/autumn 2018 (for more information see "Newspapers, scientific publications and CS as a validation proxy of LEK" Section.)

Participation and origin of respondents

The Facebook posts including the questionnaire link were seen by a total of 2893 Facebook users, and 1068 opened the link (click conversion = 36.9%). A total of 450 answers were completely blank, and 18 were duplicates. The answers lacking specific information such as personal information or the catch location were 48. Therefore, a final subset of 552 answers were used for further analyses. Although, the results are mostly expressed at a provincial level, they are also referred to at a regional level in some parts of the text. For clarification, a region is a larger administrative organization than a province or city, but smaller than country (i.e., *Country* > *Region* > *Province* > *City*).

Within the 552 respondents, those from the Valencian region contributed the most to the study (33.87%), both at provincial and regional levels (Alicante = 10.14%, Castellón = 11.41% and Valencia = 12.32%; Fig. 3). The second-highest rate of participation came from Andalucía (Almería, Cadiz, Huelva, Granada, Málaga and Sevilla; total = 22.65%), followed by Catalonia (Barcelona, Girona and Tarragona; total = 21.19%), the Balearic Islands (9.42%) and Murcia (4.89%). The regions of Murcia and Balearic Islands are formed by a single province named as the region, i.e., Murcia and Balearic Islands (also Baleares), respectively. The region showing the lowest participation were those in the Cantabrian Sea, i.e., Galicia (Pontevedra, A Coruña, Lugo and Ourense; total = 3.08%), Asturias (1.09%; single province/region), the Basque Country (Vizcaya and Gipuzkoa; total = 0.36%). Within the scope of the study, respondents from overseas regions like the Canary Islands (Santa Cruz de Tenerife and Las Palmas; total = 0.9%) and Melilla (0.18%; single province) participated in the study, as well as, non-

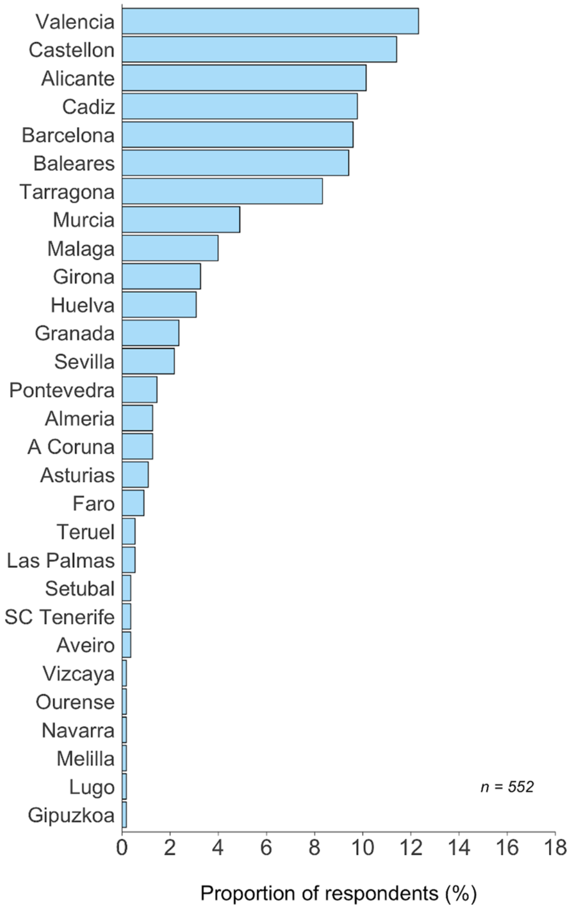

Fig. 3 Bar plot depicting the frequency of respondents by province

coastal provinces like Teruel (0.54%; single province/region) and Navarra (0.18%; single province/region). Respondents from Portuguese provinces, namely Faro (0.91%), Setúbal (0.36%) and Aveiro (0.36%) accounted for 1.66% of the total respondents. Portuguese fishers used Facebook groups of neighboring provinces in Spain such as Huelva. This is the reason why they took part in the study. Although the questionnaire was written in Spanish, the similarity of the Spanish and Portuguese languages allowed the participation of Portuguese fishers in the study. Potential respondents from other neighboring countries as France, Andorra or Great Britain (Gibraltar) did not collaborate with the study. A total of 28 respondents were women (n = 23; 4.16%), while the rest of respondents were men (n = 529; 95.84%). The mean age of the respondents per province ranged between 41.46 ± 14.25 years and 32.29 ± 6.55 years, with no significant differences between provinces (H = 52.79, p-value = 0.67; see Fig. 1S in the Online resource 2 of the Supplementary materials).

Fishing profiles of respondents and awareness of the C. sapidus bioinvasion

Overall, angling was the most preferred type of fishing (83.33%) compared to spearfishing (9.6%) and professional (4.71%; Fig. 4). A total of 2.36% stated that they did not practice fishing at all. At a provincial level, angling was still the most common fishing type for all provinces except for Granada (range: 100–50%) where 60% of the respondents were spear fishers and 15.38% anglers. The only province with no spear fishers within the respondents was Sevilla. Professional fishers from Baleares, Murcia, Castellón and Girona did not contribute to this study.

Approximately half of the respondents stated having caught *C. sapidus* (40.76%). The next reason why respondents were aware of the presence of *C. sapidus* in their fishing areas was by visual contact (17.02%), whereas, via diving (3.2%), reading newspapers (5.07%) or due to "other reasons" (8.33%) was an order of magnitude less frequent. Only 0.54% of the respondents stated having been attacked by *C. sapidus* while swimming in the sea. At a provincial level, the remarkable proportion of 41.30% of the respondents from Tarragona (n = 46) (Fig. 5) were aware of the presence of *C. sapidus* crabs because they had seen them (not caught). The provinces showing the highest absence of *C. sapidus* were those from the Atlantic Andalusia (between 71.43% and 81.82% in Almería and Málaga, respectively) and the Cantabrian Sea (100%).

Spatio-temporal distribution of C. sapidus in the Iberian Peninsula

Overall, 660 locations where *C. sapidus* was detected were registered via the LEK of respondents (Q7). A total of 307 unique locations where *C. sapidus* was present were geolocated on a map (Fig. 6). Most of the locations were in the Valencian region, specifically in Valencia (18.48%), Castellón (15.67) and Alicante (13.45%), followed by the Catalonian provinces of Tarragona (10.36%), Barcelona (9.24%), and Baleares (9.52%). Other provinces such as Cadiz, Murcia,

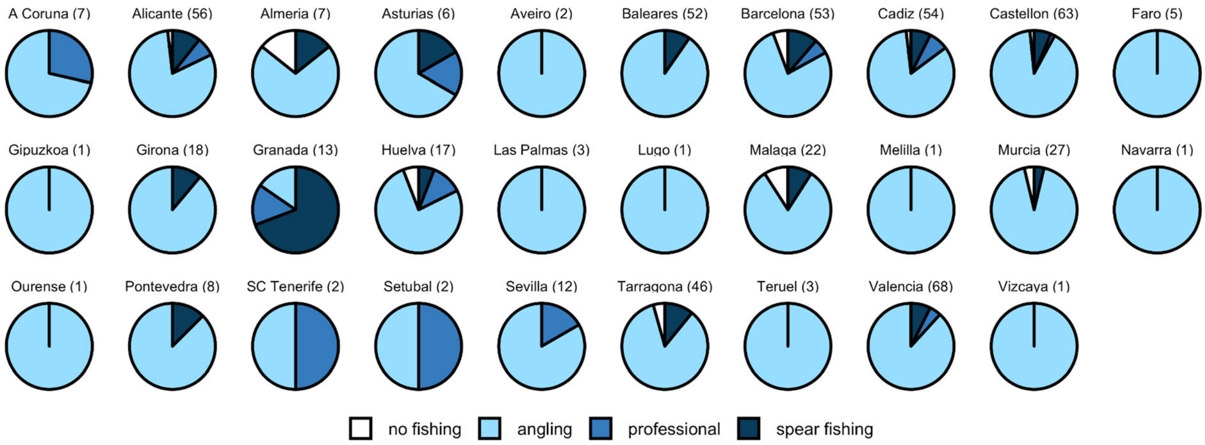

Fig. 4 Pie charts showing the preferred fishing modality of respondents. Headers = Province (number of respondents)

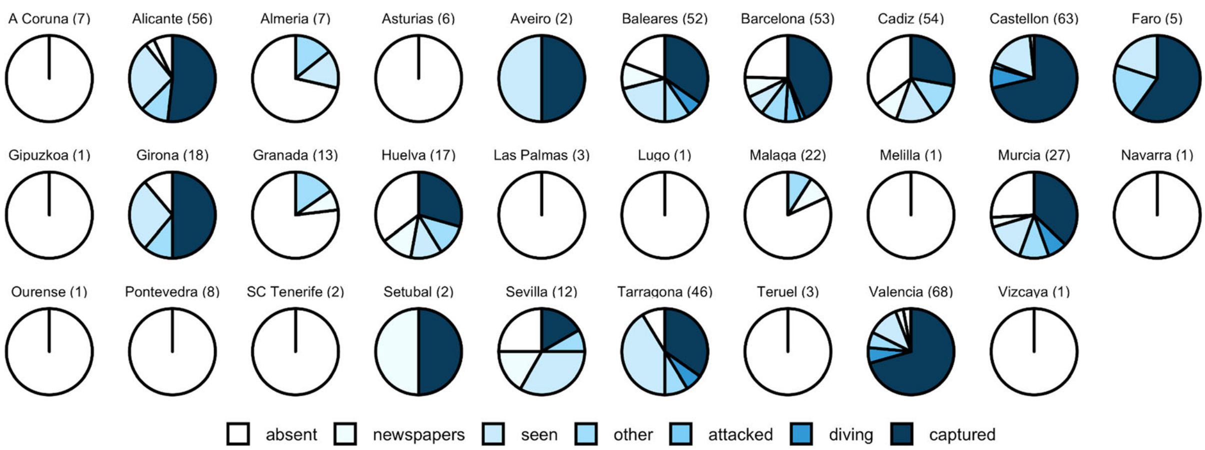

Fig. 5 Pie charts showing the modality through which respondents became aware of the presence of *C. sapidus* in their fishing areas. Headers = Province (number of respondents)

Girona, Huelva and Sevilla (in this order) showed intermediate values of catch locations (range: 8.68–2.24%). The lowest proportion of registered locations (all < 1.5%) belonged to Faro, Almería, Aveiro, Málaga and Setúbal in this order (Fig. 6). Visually, there was a high spatial overlap between the locations reported by respondents and the sedimentary fraction of the Iberian Peninsula coast, described by Templado et al. (2009) as part of the Spanish inventory of Natura2000 habitats (see Fig. 2S in Online resource 2 of the Supplementary materials). A complete list of the georeferenced locations of *C. sapidus* catches is available in the tab "*answers database" of the "File 1 Callinectes sapidus database 2019 Izquierdo Gomez David.xlsx"*, uploaded to the following *Open Science Framework* repository (OSF): https://osf.io/nk3ph/).

From a temporal perspective and applying the precautionary principle to extract the YOFD using LEK (*precautionary* YOFD), Tarragona seems to have been the first province colonized by *C. sapidus* in 2011 (Fig. 7). For clarification reasons and as an example, the *precautionary* YOFD for the province of Alicante was 2014, as the largest difference between participants stating a given year as a YOFD was between 2014 (n = 1) and 2015 (n = 7). This said, from the initial point of the bioinvasion (i.e., Tarragona), *C. sapidus* appears to have spread south-east, along the coast of the Balearic Sea, starting in Valencia and Castellón (2013), followed by Alicante (2014). Throughout 2016, the invasive crab colonized Murcia, and the Balearic Islands. Moreover, in 2017, a northwards expansion from the origin of the

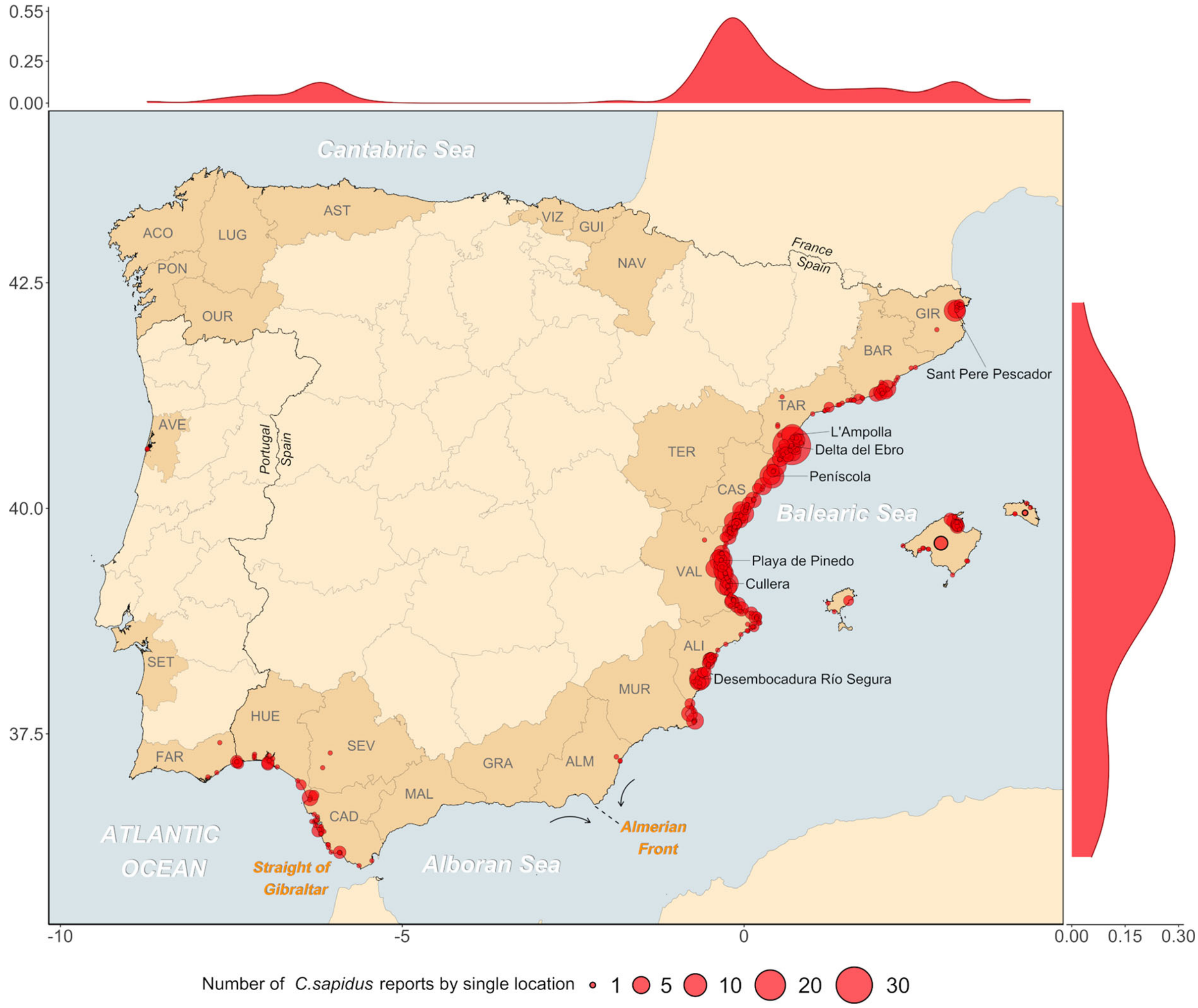

Fig. 6 Spatial distribution of *C. sapidus* based on the comments of respondents. Marginal density plots show the relative frequency of the origin of respondents. Circle size = number of times a specific location was mentioned by respondents. The specific locations labeled on the text are the most mentioned locations (n > 7). Inland circles correspond to catches in brackish/freshwater areas (e.g., rivers, marshes). Inland circles with a thicker black contour represent respondents reporting unspecifically the presence of *C. sapidus* in Mallorca (Lat: 39.61°N; Lon: 2.88°E) and Menorca (Lat:39.95°N; Lon: 4.11°E) respectively. ACO: A Coruña, ALC: Alicante, ALM: Almería, AST: Asturias, AVE: Aveiro, BAR: Barcelona, CAD: Cádiz, CAS: Castellón, FAR: Faro, GIR: Girona, GRA: Granada, GUI: Guipuzkoa, HUE: Huelva, LUG: Lugo, MAL: Málaga, MUR: Murcia, NAV: Navarra, OUR: Ourense, PON: Pontevedra, SET: Setúbal, SEV: Sevilla, TAR: Tarragona, TER: Teruel, VAL: Valencia, VIZ: Vizcaya

colonization (Tarragona) to the rest of Catalonia seems to have taken place, thus, Barcelona and Girona were invaded. In the same year (2017), the largest distance between a new colonized area and the origin of the *C. sapidus* bioinvasion was registered. The colonization of the SE of the Iberian Peninsula seemed to start in Huelva and Faro (the first Portuguese province to be colonized). The rest of Atlantic Andalusia (Sevilla and Cadiz) was colonized in 2018, though it was not until 2019 when *C. sapidus* was registered in an intermediate area (Almería), between the SE of Spain and the Balearic Sea. No records of *C. sapidus* were registered in the provinces of Málaga and Granada, which are located between the Alboran Sea and the Balearic Sea. Still in terms of LEK but based on the *consecutive* YOFD (instead of the *precautionary* form), the above colonization pattern would have arrived earlier in time, but the

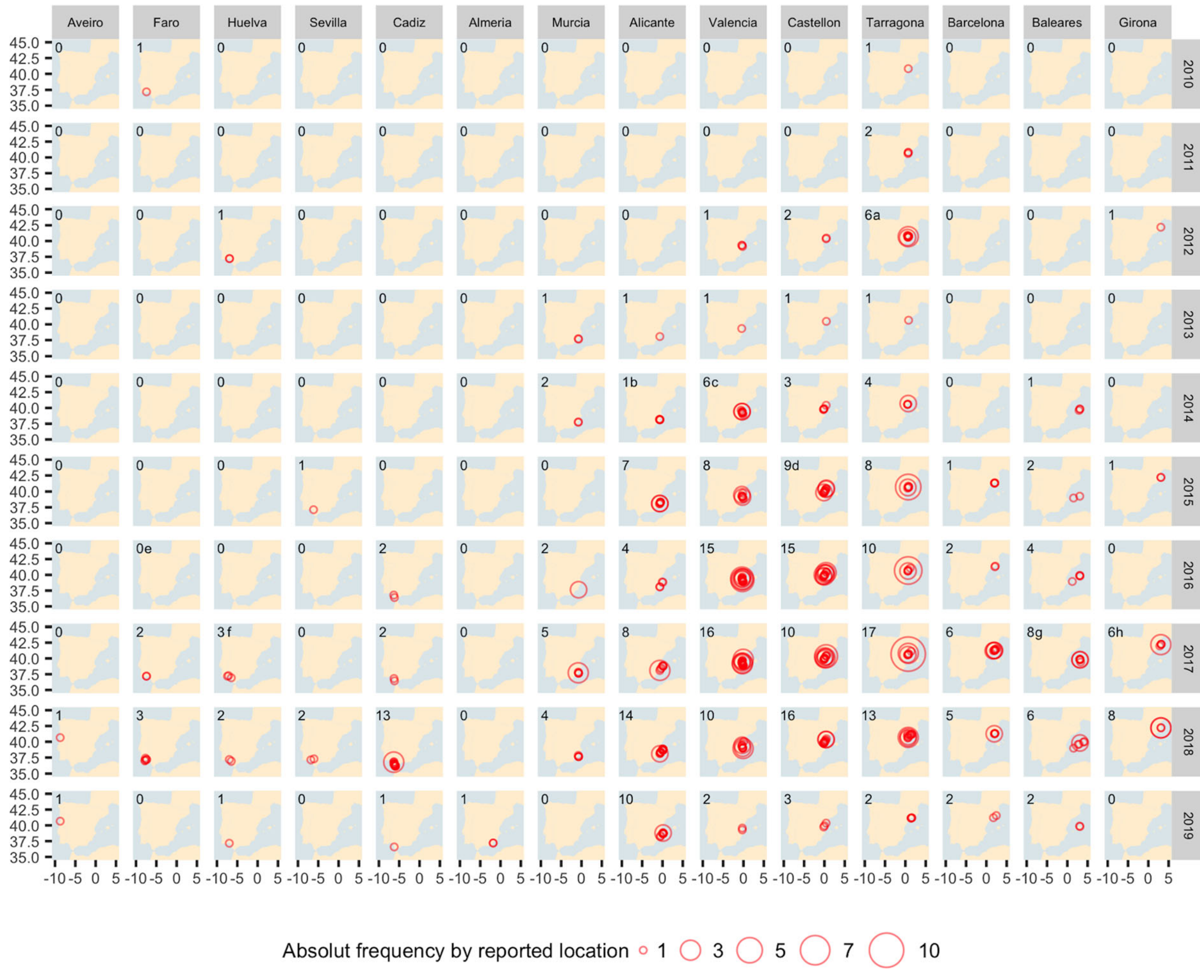

Fig. 7 Spatial–temporal distribution of *C. sapidus* in the Iberian Peninsula during the period 2010—2019. The vertical axis of the general plot corresponds to the temporal span of the study, from 2010 to 2019. The provinces (headers) are geographically ordered from South-West to North-East to facilitate the interpretation of the dispersion pattern of the blue crab. The top left number on maps represents the number of respondents contributing with information per year and province. The letters correspond to the publications reporting the crab in a given province, the absence of a letter in a given column indicates the lack of scientific reports of the species in that province. Subplots vertical axes = latitude; subplots horizontal axes = longitude. a) Castejón and Guerao 2013; b) Gonzalez-Wanguemert and Pujol 2016; c) and d) Servicio de vida silvestre Comunidad Valenciana (2016); e) and f) Morais et al. 2019; g) Garcia et al. 2018; h) Fuentes et al. 2019

chronology at provincial level would have remained very similar. On the other hand, the colonization pattern described by the *absolute* YOFD shows dissimilarities caused by the report of *C. sapidus* in Faro (2010), Huelva (2012), Girona (2012) or Sevilla (2015). Information on YOFD (*absolute*, *consecutive* and *precautionary*) are summarized in Table 1. Both the scientific YOFD and newspapers YOFD of *C. sapidus* are further detailed in the “Newspapers, scientific publications and CS as a validation proxy of LEK” Section .

The presence of *C. sapidus* in Girona, Barcelona, Tarragona, Castellón, Valencia, Alicante, Murcia, Cadiz, Huelva and Faro was successfully verified by means of pictures (n = 30) sent by respondents via the Facebook survey app (more details in “Newspapers, scientific publications and CS as a validation proxy of LEK” Section).

Table 1 Summary of the *year of first detection* (YOFD) in all its forms (i.e., *absolute*, *consecutive* and *precautionary*) for all provinces and all sources of knowledge (i.e., Local Ecological Knowledge (LEK), Newspapers and Scientific/Technical reports)

Province	LEK			Newspapers	Scientific/Technical literature			
	YOFD *absolute*	YOFD *consecutive*	YOFD *precautionary*	YOFD	YOFD	Date of first detection	Delay (years)	Reference
Tarragona	2010	2010	2011	2012	2012	03-11-2012	1	Castejón and Guerao (2013)
Valencia	2012	2012	2013	2014	2014	01-10-2014	2	Servicio de vida silvestre Comunidad Valenciana (2016)
Alicante	2013	2013	2014	2015	2014	06-12-2014	2	Gonzalez-Wanguemert and Pujol (2016)
Castellon	2012	2012	2013	2017	2015	01-06-2015	1	Servicio de vida silvestre Comunidad Valenciana (2016)
Baleares	2014	2014	2016	2017	2017	01-06-2017	1	Garcia et al. (2018)
Murcia	2013	2013	2016	2015	2015	23-06-2015	1	Servicio de vida silvestre Comunidad Valenciana (2016)
Faro	2010	2017	2017	2019	2016	01-07-2016	3	Morais et al. (2019)
Girona	2012	2017	2017	2018	2017	13-07-2017	2	Fuentes et al. (2019)
Huelva	2012	2017	2017	2017	2017	01-07-2017	2	Morais et al. (2019)
Barcelona	2015	2016	2017	2016	*NR*	*NR*	*NR*	*NR*
Sevilla	2015	2018	2018	2018	*NR*	*NR*	*NR*	*NR*
Cadiz	2016	2016	2018	2017	*NR*	*NR*	*NR*	*NR*
Almeria	2019	2019	2019	2019	*NR*	*NR*	*NR*	*NR*
Asturias	*Abs*	*Abs*	*Abs*	*NR*	2004	22–09-2004	2	Cabal et al. (2006)
Setubal	*Abs*	*Abs*	*Abs*	*NR*	2009	05–04-2009	5	Ribeiro and Veríssimo (2014)
Pontevedra	*Abs*	*Abs*	*Abs*	*NR*	2015	25–11-2015	0	Bañón et al. (2016)
Malaga	*Abs*	*Abs*	*Abs*	*NR*	*NR*	*NR*	*NR*	*NR*

The date of first detection corresponds to each of the scientific references (*Reference*). The column *delay* shows the difference between the year of publication and the year of first detection. *NR* = *C. sapidus* non-reported in scientific literature. *Abs* = absence of *C. sapidus* stated by respondents

Opinion index

Overall, the opinion index was negative for all provinces (Fig. 8). Within the provinces with the highest rate of participation, the most negative perception of the ecological influence of *C. sapidus* in the ecosystem was registered in Castellón (−3.16 ± 0.95; mean opinion index ± SD) and Barcelona (−3 ± 0.98), followed by Tarragona (-2.84 ± 1.24), Girona (−2.68 ± 1.35) and Murcia (−2.57 ± 1.34). The provinces of Valencia (−2.49 ± 1.41), Alicante (−2.22 ± 1.42) and Baleares (−2.17 ± 1.37) showed intermediate values. By contrast, Cadiz (−1.78 ± 1.86), Huelva (−1.43 ± 1.62), Sevilla (−1.33 ± 1.53), Faro (−0.83 ± 1.33) and Aveiro (0) showed the lowest negative opinion values. Overall, the bioinvasion of C. sapidus was perceived as being detrimental for the ecosystem in all provinces (Fig. 8). However, provinces colonized later (SE of the Iberian Peninsula: Almería, Cádiz, Huelva, Sevilla and Faro) showed lower values of negative perception than those

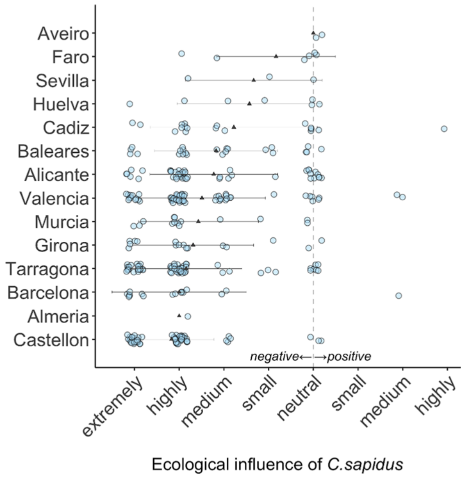

Fig. 8 Perceptions of fishers (opinion index) on the ecological consequences of the *C. sapidus* invasion. ▲ = mean value ± standard deviation. Left hand side of the dash line = negative scores; right hand side of the dash line = positive scores; Dash line = neutral score

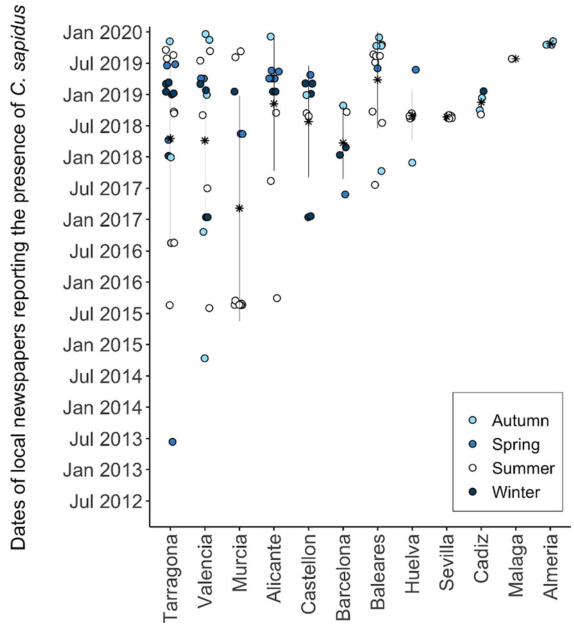

Fig. 9 Temporal distribution of *C. sapidus* articles published in local newspapers at a province level. Asterisks indicate the average year values and the bars the standard deviation

colonized earlier (Balearic Sea: Girona, Barcelona, Tarragona, Castellón, Valencia, Alicante and Murcia) (Kruskal–Wallis rank sum test = 16.685, p-value < 0.001). Only four respondents perceived the presence of *C. sapidus* as positive for the ecosystem.

Newspapers, scientific publications and CS as a validation proxy of LEK

A total of 124 publications about *C. sapidus* in online newspapers were detected (Fig. 9). Tarragona (n = 23) gathered the largest number of publications, followed by other provinces located near the Balearic Sea such as Valencia (n = 16), Baleares (n = 14) and Castellón (n = 9). Provinces like Alicante (n = 13) and Murcia (n = 11) located southwards from the Balearic Sea recorded intermediate numbers of online publications (for a summary table see Table 2S in the Online resource 2 of the Supplementary materials). The northern provinces of Catalonia (i.e., Girona and Barcelona) as well as those from the SE of the Iberian Peninsula (i.e., Faro, Sevilla, Cadiz and Málaga) had the fewest publications (between 8 and 1). Almería (n = 3) and Málaga (n = 1) were the only provinces with all its online publications in 2019, the last year analyzed in this study. It was in 2017 when a significant increase in online publications (n = 16) was registered, compared to the previous year (only four publications in 2016). This increase was also noticeable at the provincial level, as more than 50% of the provinces published C. *sapidus* information. The highest number of *C. sapidus* publications were registered in 2018 (40% of the total; n = 39) as well as being the year with the highest the proportion of provinces, which represented ca. 80% both in 2018 and 2019. A total of 75% of the publications were issued from 2018, and if 2017 is taken into account, the proportion increases to 80% of the total number of publications using 2013 as reference. A complete list of the georeferenced catch locations of *C. sapidus* is available in the tab "*newspapers database*" *of the "File 2 File 2 Callinectes sapidus newspapers 2019 Izquierdo Gomez David.xlsx"*, uploaded to the following *Open Science Framework* repository (OSF): https://osf.io/nk3ph/). Moreover, there were significantly more publications in summer compared to the other three seasons (H = 18.6, p-value < 0.001; see Fig. 3S in the Online resource 2 of the Supplementary materials). No differences were found between spring, autumn and winter.

In terms of scientific literature, reports of *C. sapidus* were found for all studied provinces except for Barcelona, Sevilla, Cadiz, Almería and Málaga. According to the publication date, the chronology of the bioinvasion started in Tarragona in 2013 (Table 1), followed by the peninsular coast of the Balearic Sea (i.e., Valencia and Castellón), and the adjacent provinces to the south, namely, Alicante and Murcia, all in 2016. Moreover, the Baleares was colonized in 2018 as well as the north of Catalonia (Girona). In the same year, 2018, the bioinvasion continued in the SE of the Iberian Peninsula (Huelva and Faro).

The geographical chronology of the bioinvasion based on the different sources of knowledge is consistent, and significant correlations were found both between *precautionary* LEK and newspapers ($R^2 = 0.8$, p-value < 0.001), as well as, between *precautionary* LEK and scientific publications ($R^2 = 0.79$, p-value < 0.003; Fig. 10; Table 2). Among the three sources of knowledge, LEK (*absolute* and *consecutive*) provided significantly faster first reports of *C. sapidus* than newspapers and scientific publications. The *precautionary* LEK, although faster, did not show significant differences compared to newspapers and scientific publications. In order to maximize the potential of scientific publications in the detection of *C. sapidus*, the date of the first report and not the date of scientific publications is used. However, the *precautionary* LEK significantly outperformed the scientific publications when the publication date was used.

The internet portal "*Observadores del Mar*" (https://www.observadoresdelmar.es) has been the leading organization in terms of marine citizen science in Spain since 2012 (Abelló, P. 2012). More than 2,400 volunteers, 240 entities (including schools) and 60 scientists from more than 40 research institutions and universities are part of the organization, which nowadays coordinates 13 projects raising social awareness on marine issues (Garrabou 2020). By October 2016, six collaborators of *Observadores del mar* had reported the presence of 15 crabs in 9 different locations in Murcia, Alicante, Valencia and Tarragona (https://www.observadoresdelmar.es/MAP). In the same period, a total of 15 collaborators had sent orthogonal pictures of *C. sapidus* from 13 different locations in Murcia, Alicante, Valencia, Castellón and Tarragona. Furthermore, by the end of the second study period (December 2019), a total of 209 reports (166 in Barcelona) were registered by collaborators of *Observadores del mar* in Girona (n = 3), Barcelona (n = 166; 162 in the mouth of the River Foix in Cubelles), Tarragona (n = 10; 3 in Delta del Ebro), Castellón (n = 2; Benicarló), Valencia (n = 5), Alicante (n = 8), Murcia (n = 5), Cadiz (n = 2). By means of SNSs (i.e., Facebook), a total of 552 (filtered out of 1068) respondents reported a total of 660 locations (307 unique) where *C. sapidus* were present in all provinces of the Mediterranean Iberian

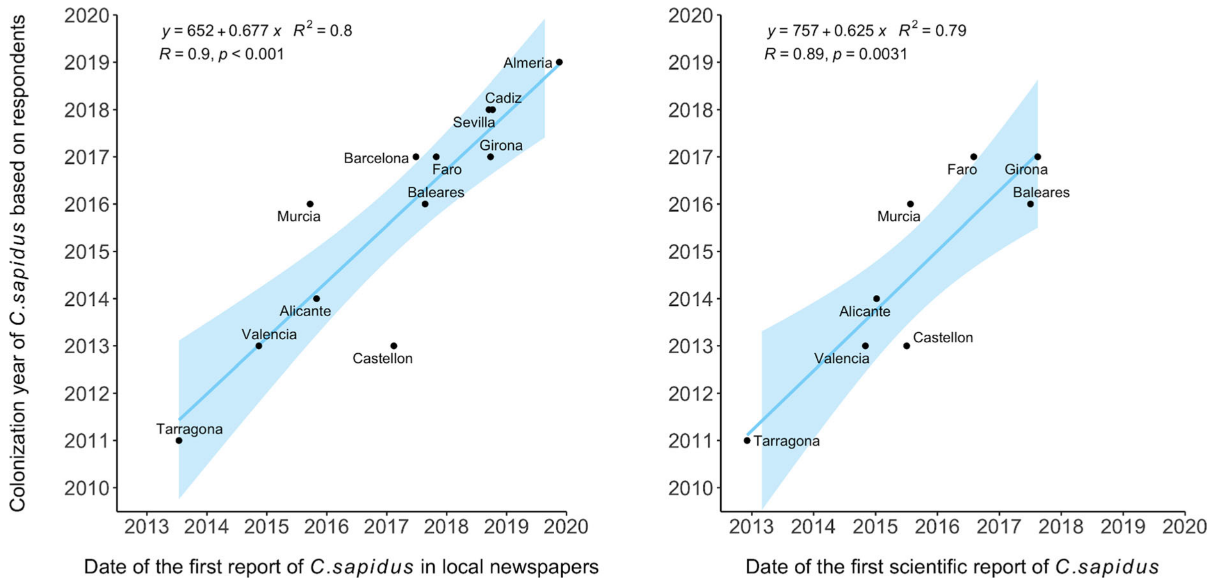

Fig. 10 Correlations between the *precautionary year of first detection* (*precautionary* YOFD) declared by respondents, and the first-year publication (y-axis) for the presence of *C. sapidus* in local newspapers (left plot) and in scientific publications (right plot)

Table 2 Detail of the single t-test outcomes of the comparisons between different sources of detection of *Callinectes sapidus*

Comparisons	Estimate	Statistic	*p*.value	Parameter	Σ vector (years)	Outcome
Newspapers VS LEK absolute	− 3.286	− 5.056	< 0.001	13	46	LEK faster*
Newspapers VS LEK consecutive	− 1.429	− 3.68	0.003	13	20	LEK faster*
Newspapers VS LEK precautionary	0.429	1.578	0.139	13	6	LEK faster
First scientific detection VS LEK absolute	3.4	6.278	< 0.001	9	29	LEK faster*
First scientific detection VS LEK consecutive	1.2	2.714	0.024	9	12	LEK faster*
First scientific detection VS LEK precautionary	0.1	0.429	0.678	9	16	LEK faster
First scientific detection VS newspapers	0.429	1.578	0.139	13	−7	science faster
First scientific publication date VS LEK precautionary	1.8	7.216	< 0.001	9	16	LEK faster*

LEK = Local Ecological Knowledge. Newspapers = online newspapers. The different types of LEK (i.e., *absolute*, *consecutive* and *precautionary*) are explained in the materials and methods section. YOFD = *year of first detection*. Σvector = number of years obtained when summing all the values of the vector obtained after subtracting the YOFD of one source of knowledge from the one being compared (*Comparisons*)

*Indicates significant differences in the statistical test

Peninsula (not Málaga and Granada) and the Portuguese provinces of Faro and Aveiro. A total of 30 reports were validated with pictures of the crab (see Fig. 4S in the Online resource 2 of the Supplementary materials). The pictures validated the reports from Girona (n = 2), Cadiz (n = 4), Baleares (n = 4), Murcia (n = 2), Barcelona (n = 2), Tarragona (n = 5), Valencia (n = 6), Castellón (n = 2), Faro (n = 1), Alicante (n = 1) and Huelva (n = 1).

Discussion

Overall, the present research describes how citizen science combined with Social Network Sites and online questionnaires is a sound approach to obtain valuable information of the *C. sapidus* bioinvasion of the Iberian Peninsula. Thus, decision makers, managers, local administrations or scientists studying invasive species could use the same methodology *i)* to obtain information on size structure in order to study the establishment of self-sustainable populations, *ii)* to describe the crab´s presence over a large spatial scale (hundreds of kilometers), *iii)* to reconstruct potential colonization patterns over time, and *iv)* to assess the perceptions of a specific guild (e.g., recreational fishers) about concerns for the ecosystem. Specifically, from the LEK of recreational fishers, it seems that *C. sapidus* colonized the River Ebro delta and then spread southwards along the mainland coast of the Balearic Sea until the Mar Menor (border between Alicante and Murcia region). Secondly, the species colonized North-Eastern areas of Catalonia (i.e., Barcelona and Girona) and the Balearic Islands. Finally, *C. sapidus* invaded the SE of the Iberian Peninsula, i.e., Cadiz, Huelva, and the Portuguese province of Faro. A potential new invasion in the north of Portugal (Aveiro) was also registered. A number of protected Natura2000 areas were also colonized, as well as some freshwater ecosystems (rivers, channels, marshes and lagoons), areas protected by the Ramsar Convention (Iran, 1971; Secretariat 2006). From a management perspective, the use of an IAS detection methodology based on LEK and SNSs can perform, at least, at the same level as scientific literature or newspapers. However, the interpretation of isolated reports based on LEK, if non-validated should be taken with caution. Nevertheless, this methodology can help optimize time and the economic resources needed to detect early stages of invasions and trigger the eradication/mitigation measures if required.

Invasion timeline of *C. sapidus*

It appears that the first location invaded by *C. sapidus*, within the Iberian Peninsula, was the River Ebro delta in early 2010s (Tarragona, Catalonia; Castejón and Guerao 2013). Thereafter, the evidence gathered in the first part of this study highlights *i)* the intermittent presence of *C. sapidus* along 430 km of the Levantine coast of the Balearic Sea (from River Ebro delta to Mar Menor), *ii)* the simultaneous presence of ovigerous females and large adult males separated by tens to hundreds of kilometers (e.g., Alicante, Cullera, Castellón), together with *iii)* a wide range of carapace lengths (on average 5.63 ± 3.58) encompassing subadult to adult sizes. These all point towards the establishment of *C. sapidus* population(s) along the Levantine coast of the Balearic Sea. However, whether there were multiple population sources, only the River Ebro delta, or both, driving the dispersal of the species is still to be confirmed. It is true that, pictures of juveniles of *C. sapidus* were not reported at a local level along the coast of the Balearic Sea. However, the reason for this might be the characteristics of the fishing gear used by collaborators (i.e., fishing rod), whose lure and hook sizes are unsuitable to catch small crabs. The generalized presence of large adult males, which colonize fresh/brackish waters in a larval stage to then develop and live within the influence of freshwater bodies, indicates that the colonized environment is suitable for the species for all age classes. Additionally, for the case of the River Segura in Guardamar (Alicante), the consistent reports of large male individuals and ovigerous females on a yearly basis since late 2014 (González–Wangüemert and Pujol 2016; Izquierdo–Gómez and Izquierdo–Muñoz 2016) reinforces the hypothesis of established populations in the other areas with a larger range of size classes and which were closer to the original bioinvasion origin (Delta del Ebro; Tarragona). Based on previous reports of the species in the same area, the colonization process could have started in mid-2014 or 2015 (Servicio de vida silvestre 2016). Interestingly, the highest proportion of reports based on recreational fishers' LEK (obtained in 2019) coincided with the spatial pattern of the reports based on orthogonal pictures obtained in 2016 (from River Ebro delta to Mar Menor in Murcia). The colonization pattern described either by scientific literature or local newspapers is also consistent (further discussed in the "Citizen science vs scientific literature and newspapers" Section of the discussion).

Focusing on LEK, the *precautionary* YOFD (the *absolute* and *consecutive* interpretations will be discussed in the "Current and future management scenarios" Section) point towards two colonization processes, which based on biogeography might be independent (further discussed in the next "Origins and factors influencing the distribution of *C. sapidus*" Section). First, the bioinvasion of the Balearic Sea and adjacent areas (i.e., Catalonia, Valencian Community, Balearic Islands and Murcia) took a maximum of six years, between 2011 (Tarragona) and 2017 when Girona was invaded. Within the Balearic Sea event, the coast southwards from Tarragona was first colonized, i.e., Valencia and Castellón, followed by the adjacent regions to the south of the Balearic Sea. Thus, the Balearic Islands were colonized at the same time as the north of Catalonia (i.e., Barcelona and Girona). Arguably, a second colonization event occurred in the SE of the Iberian Peninsula in the River Guadalquivir, the border between the Spanish province of Huelva and the Portuguese province of Faro. This second colonization event took only one year (2017 to 2018) and an intentional introduction cannot be discarded. Finally, the reports from Almería in 2019 and Aveiro (consistent from 2018) might respond to early colonization processes. However, whether a *C. sapidus* population has become established in the area or not, is still to be confirmed.

Origins and factors influencing the distribution of *C. sapidus*

Although the current *C. sapidus* bioinvasion of the Iberian Peninsula seems to have started in the River Ebro delta in the early 2010s, such colonization could have started, at least, a decade before in the early 2000s. Several authors had already reported the species previously, for example, WWF/ADENA (2002) in the River Guadalquivir in 2001 (Huelva), *ii)* Cabal et al. (2006) in 2004 in Gijon (Cantabrian Sea), Abello, P. (2010) in the Mar Menor in 2010 (Murcia), as well as, Ribeiro and Veríssimo (2014) in 2009 in the Sado Estuary (Setúbal, Portugal). However, none of these attempts was mirrored in reports of *C. sapidus* or gave rise to the socio-ecological concerns that have been raised these days.

This said, the *consecutive* and *precautionary* interpretations of LEK agree with a colonization process via egg/larval dispersion from the River Ebro delta towards the South of the Balearic Sea, driven by a mainly South-Westerly coastal current descending along the Levantine coast (Millot and Taupier-Letage 2005). This is consistent, as well, with the delayed colonization of northern provinces of Catalonia (i.e., Barcelona, Girona), which are closer to the River Ebro delta compared to southern locations of the Balearic Sea (i.e., Valencia and Alicante) but are in a counter-current direction. Colonization via egg/larval dispersion is also hypothesized for the Balearic Islands, located at 180–200 km off the Levantine coast of the Iberian Peninsula. This dispersion pattern driven by water currents, in which the south and central Balearic Sea (i.e., Castellón and Valencia, including Alicante), and the Balearic Islands would be more connected by coastal currents compared to the north of Catalonia (i.e., Barcelona and Girona). This agrees with the dispersion pattern of *Haplosporidium pinnae*, which recently caused the massive mortality event of *Pinna nobilis* in the same area (Vázquez-Luis et al. 2017; Cabanellas-Reboredo et al. 2019).

Despite egg/larval dispersion being the most plausible hypothesis for the spread of *C. sapidus* in the Balearic Sea, the counter-current colonization of the northern Catalonia is also a fact, and could also be due to local migrations of adult crabs on a scale of tens of kilometers, as described by Turner et al. (2003) in the native distribution range of *C. sapidus*. In addition to the egg/larval dispersal, *C. sapidus* can migrate hundreds of kilometers (McConaugha et al. 1983; Hines et al. 1987). Consequently, the active dispersion of adult individuals should not be discarded either. Indeed, the large-scale migratory behavior of *C. sapidus* has not been studied in the Mediterranean Sea, however, it could be the case in the River Ebro delta, where high biomasses of *C. sapidus* are consistently caught by trawlers all through the year off the coast. In the same way but to a lesser extent, sporadic catches of adult individuals have been reported by trawlers in Huelva, six nautical miles off the mouth of the River Guadalquivir at 50–60 m depth (Landing port of Muelle de Bonanza in Sanlucar de Barrameda, Cádiz, Spain; 36.80°N, −6.34°W; *pers.-com.* landing port of *Lonja de Sanlucar de Barrameda*).

Interestingly, the colonization of *C. sapidus* did not continue to adjacent areas Southwards in the Balearic Sea, and a gap of *circa* 500 km was observed until the next colonization areas, namely, the Atlantic Andalusia (SW of Spain) and Faro (South of Portugal) regions. This allows to hypothesize that the colonization of the SE of the Iberian Peninsula by *C. sapidus*, might be the consequence of a new colonization event. Although hard to demonstrate, the alternative hypothesis of a human-made introduction should not be discarded, due to the high commercial value of *C. sapidus*. Whatever the case may be, the colonization of the SE of the Iberian Peninsula (i.e., Cadiz, Huelva and Faro) occurred very quickly throughout 2017. The overall absence of *C. sapidus* in the south of the Iberian Peninsula (i.e., Málaga, Granada, Almería and the southwest of Murcia) could be due to the low abundance of estuarine habitats with the salinity gradients needed by *C. sapidus* to complete its life cycle: *i)* freshwater to overwinter (especially males and juveniles), *ii)* brackish waters to mate and *iii)* high salinity waters to spawn (Tankersley et al. 1998; Hines et al. 2008; Templado et al. 2009). The coasts of the above provinces belong to the Alboran Sea (from Gibraltar to Gata Cape in Almería), a different biogeographic region to the Balearic Sea, with clear abiotic differences in terms of salinity and temperature and coastal current dynamics. All along the Iberian coast of the Alboran Sea, sedimentary habitats linked to freshwater discharges are rare, and temperatures are much lower than in the Balearic Sea due to the influence of Atlantic waters (Templado et al. 2009). Nehring (2011) stated that low water temperatures are an important factor hindering the establishment of *C. sapidus* in northern Europe and in the Black Sea. This could be one of the reasons why *C. sapidus* is not as widely distributed in the S and SW of the Iberian Peninsula as it is in the Balearic Sea. Additionally, the boundary between the Alboran and the Balearic Sea (and adjacent waters) is the Almerian front. This marine front is formed when the current descending from the Balearic Sea encounters an ascending current driven by the entrance of Atlantic waters through the Strait of Gibraltar (Siokou-Frangou et al. 2010). Thus, *i)* the Almerian front, *ii)* the characteristic clockwise gyres in the Alboran Sea, together with *iii)* the rare presence of sedimentary habitats linked to freshwater bodies in the south of the Iberian Peninsula, could have hindered the coastal dispersal of eggs and/or larval development needed for the establishment of *C. sapidus*. Additionally, the larvae of *C. sapidus* develop in shelf waters to then reinvade estuarine habitats (Sulkin and Epifanio 1986; Little and Epifanio 1991). In this regard, the same situation would occur northwards from the Aveiro province, rendering the

Ria of Aveiro and its marshes as the most suitable area for the establishment of *C. sapidus* in the North of Portugal. Therefore, the lack of continental shelf and sedimentary habitats from Murcia to the SE of the Iberian Peninsula (Cadiz, Huelva and Faro), combined with the effect of the Almerian front as a natural barrier for the bioinvasion of *C. sapidus*, might point towards the colonization of the SE of the Iberian Peninsula and the Balearic Sea as independent colonization events.

Furthermore, provinces such as Almería, Huelva and Cadiz showed *i)* a lower number of respondents, *ii)* a lower number of published articles in newspapers reporting the presence of *C. sapidus* and *iii)* a higher proportion of respondents declaring the absence of *C. sapidus* in their fishing areas. Arguably, and considering the large number of users in Facebook groups of all provinces (i.e., several thousand), it could be stated that in areas where *C. sapidus* is less abundant or absent, Facebook posts would neither elicit the participation in the study nor the publication of information in newspapers, due to the lack of knowledge, awareness, and hence, social concern. The absence of *C. sapidus* is also confirmed by other CS organizations in Spain (*Observadores del mar*: https://www.observadoresdelmar.es/Map) and at a global level (Global Biodiversity Infrastructure Facility GBIF: https://registros.gbif.es). The same scenario of an incipient colonization of the area seems to have occurred in the Adriatic Sea in 2019, where only 10% of respondents affirmed the presence of *C. sapidus* (Cerri et al. 2020). Therefore, the colonization of Cadiz, Sevilla, Huelva, Faro and Aveiro could still be incipient at the time this study took place (2019). Due to the high colonization potential of *C. sapidus*, freshwater influenced areas between Málaga and the south of Murcia are expected to be colonized by the invasive crab, in fact, sightings have been already declared in the lagoons and freshwater environments of Almería province at the end of this study in 2019 (i.e., Vera). Despite the above dynamics of the *C. sapidus* bioinvasion, the hypothesis of a deliberate introduction and/or eggs/larval stages being transported in ballast waters should not be discarded.

Citizen science vs scientific literature and newspapers

CS can provide valuable resources and data for scientists, as well as strengthen monitoring programs, boost collaboration, and promote education (Bonney et al. 2009). In this regard, this research provided a geographical data set with locations spread all over the Iberian Peninsula for further research studies in a cost and time-effective way. Future dissemination events of the results gathered in this study will help empower the use of citizen science bringing science, nature and environmental issues closer to citizens. The results will be transferred to society faster than traditional science since respondents are prone to transfer the results of the study as they feel part of its achievements.

One of the main applications of this study is to explore the use of CS via SNSs and online questionnaires, as an early detection methodology for bioinvasions. All LEK interpretations outperformed newspapers and traditional science to detect early stages of a bioinvasion (only the *precautionary* LEK was non-significant when compared to science and newspapers). Despite the latter, the main pitfall for scientists using CS is to accept the subjective LEK data without any validation or objective evidence. This is why most of the spatio-temporal conclusions of this study derive from a *precautionary* interpretation of LEK. However, the *consecutive* and *absolute* interpretations of LEK can also be used by managers and decision makers, especially to help optimize economic resources and time when implementing mitigation measures. This is the case of Aveiro region where respondents have been reporting the presence of *C. sapidus* since 2018, meaning that a new colonization process might have started. Additionally, respondents from Galician provinces affirming the absence of *C. sapidus* in their fishing areas might indicate an unsuccessful colonization of individuals reported in Vigo (Pontevedra) in late 2015 (Bañón et al. 2016). Interestingly, for the case of Portugal, the provinces of Faro and Setúbal are the only where reports of *C. sapidus* exist: *i)* in both the Tagus and Sado Estuaries (in 1978 and 2009 respectivelly) and *ii)* the River Guadalquivir (2002) in Faro Province (see Ribeiro and Verissimo 2014 and references therein). Thus, the *absolute* interpretation of LEK might indicate that in 2010, there was a potential colonization attempt of the area by *C. sapidus*. However, this could be an error by respondents while answering the questionnaire or a subjective perception of respondents without a significant scientific value. In the same way, *C. sapidus* (Cabal et al. 2006) has not been reported in Asturias since 2010. Moreover, the report of *C. sapidus* in Sevilla in 2015 (*absolute* LEK; Fig. 7) could have been an early alert of the colonization event which started in 2018.

It is worth highlighting that most of the scientific reports of *C. sapidus* arise from collaborations with professional fishers, as they are constantly "*pseudosampling*" all along the coast including inland water bodies, at the same time as they conduct their professional activity. However, remote areas in freshwater bodies are hard to control and this is when CS can be very useful. Specifically, two respondents stated the presence of *C. sapidus* in the "*Assut of Xerta*" (dam of Xerta; lat: 40.924°N; lon: 0.492°E), which is located more than 50 km upstream from the River Ebro delta mouth. Moreover, one respondent declared the presence of blue crab in Flix (further upstream than Xerta; lat: 41.228°N; lon: 0.544°E). Given the low number of respondents from Xerta and Flix, the presence of the crab should be further confirmed by in situ studies. A similar scenario has occurred in the River Guadalquivir, where crabs have been observed in freshwater zones, several kilometers upstream. The organization *Obsrevadores del mar* reported a similar case in the same area in 2019 (https://www.observadoresdelmar.es/Observations/4/14770), adding value to the above report.

Based on the comparison between the results of this study and those obtained by a CS organization like *Observadores del Mar*, the use of SNSs and online questionnaires have been able to obtain similar results at a provincial level. Participation levels cannot be compared between the present study and *Observadores del mar*, because the reports shown in the map viewer (https://www.observadoresdelmar.es/Map) correspond only to validated reports. This said, the use of SNSs and online questionnaires showed similar results at a provincial scale as *Observadores del mar* (two more provinces using SNSs). At an international level, *Observadores del mar* has conducted collaborations in Corsica (France) but not in Portugal, where, in 2019, the *C. sapidus* invasion had already started. Therefore, it is in the SE of the Iberian Peninsula where the use of SNSs might have worked slightly better than *Observadores del mar*, since no validated reports exist either from the west of Huelva or from Faro provinces. Additionally, SNSs and online questionnaires might have detected (although not validated yet) an early colonization process in Aveiro. *Observadores del mar* has not reported any Portuguese report of *C. sapidus* so far. The significant differences between the number of *C. sapidus* reports recorded by *Observadores del mar* between 2016 and 2019 are not only due to the very recent dispersion of *C. sapidus* all over the Iberian Peninsula, but also to the increasing development of the organization on the internet in the last few years.

Current and future management scenarios

The bioinvasion of the Iberian Peninsula by *C. sapidus* can be considered as advanced in the Balearic Sea and as intermediate in the SE of the Iberian Peninsula (Faro and the Atlantic Andalusia). By contrast, in the Mediterranean Andalusia (i.e., Almería) and in the northern part of Portugal (i.e., Aveiro), the bioinvasion could be at an early stage. On the other hand, the invasion in the Cantabrian Sea seems not to have started yet. Interestingly, Cerri et al. (2020) successfully described the geographical distribution of *C. sapidus* in Italy and adjacent countries via online questionnaires, concluding an early state of the colonization process, and although the reports used in this study were not validated with pictures, they still provided very useful and interesting information. This type of information can play an important role to prioritize mitigation efforts on a large geographical scale. However, to improve mitigation and control measures, sound information on the migration behavior and potential connectivity between areas where *C. sapidus* is already present is needed. Thus, the main focus and economic efforts should be placed on the geographical sources of early life stages of *C. sapidus* dispersed by water currents. In the case of ballast waters, the control of freight boats filling ballast water tanks in areas with high presence of *C. sapidus* should be prioritized, especially in summer and autumn, when eggs and larval stages exist.

Furthermore, a knowledge gap also exists on whether the provenance of the ovigerous females found along the coast is local or regional. However, the presence of overwintering individuals in freshwater environments, together with ovigerous females simultaneously reported in geographically separated areas, might point towards a scenario where multiple population sources already exist, separated by several tens to hundreds of kilometers (e.g., from north to south: River Ebro delta, Estany de Nules, Estanys d'Almenara, Albufera de Valencia, the River Jucar, Marjal de Pego-Oliva, Estany de Cullera, the River Segura and Mar Menor). Freshwater bodies are present in all the mentioned locations, and saltwater catches were mostly females. Tankersley et al. (1998) described a seaward migration of *C. sapidus* females from low-salinity areas of estuaries to spawn near the entrance, and this seems to apply to western Mediterranean areas. Therefore, this affords the opportunity to implement control measures to eradicate the species when migrating towards higher salinity waters from freshwater bodies. Early detection of IAS has been recognized a long time ago by invasion biologists as the best way to increase the probability of a successful eradication (US Congress OTA 1993; Myers et al. 2000; Delaney et al. 2008 and references therein). Therefore, potential management plans both in the Balearic Sea and in the SE of the Iberian Peninsula, if enforced, should be applied consistently and uniformly by all the provinces involved. Moreover, both invasion events could and should be managed, at some point, independently. Despite Mancinelli et al. (2017b) affirming that the eradication of *C. sapidus* in southern European waters would not only be costly, but actually unfeasible, an early alert might have helped mitigate the negative effects of the bioinvasion in certain areas. The SE of the Iberian Peninsula has been declared as a hotspot for invasions of non-native decapod crustaceans (González-Ortegón et al. 2020). Thus, these areas should be prioritized to carry out monitoring and mitigation measures. As an example of successful implementation of mitigation measures, in the SE of the Iberian Peninsula, eradication measures were applied against the IAS Chinese mitten crab (*Eriocheir sinensis*; Garcia de Lomas et al. 2010) in the River Guadalquivir. Nowadays, the population seems to be under control (*pers. comm.* Rangers Division in Doñana National Park). The enforcement of this type of measures against the proliferation of *C. sapidus* with the help of LEK might help reduce costs and time in the context of an early stage of the colonization.

From a Spanish legal perspective, *C. sapidus* has not been declared yet as an invasive species (Royal Decree 630/2013 of August 2nd) because that would challenge the commercial exploitation of the invasive crab, as the exploitation of exotic/invasive species is not allowed. Fishing seems to be, so far, the only sound method to counteract the dispersion of *C. sapidus*. In 2016, the Spanish government allowed the commercial exploitation of *C. sapidus* under the FAO code CRB (BOE-A-2016-3357; Permalink ELI: https://www.boe.es/eli/es/res/2016/03/28/(1)). Nowadays, provinces such as Alicante, Valencia and Castellón allow the capture of this species either by professional or recreational fishers. However, in the case of recreational fishers, there is a clear difference between continental and marine waters. The capture of *C. sapidus* is allowed in continental waters with no restrictions in terms of size or quota, whereas in marine waters, a professional license is mandatory to catch *C. sapidus* (Resolution num. 8494 of October 30th 2020 in DOGV num. 8946 of November 6th 2020; document available in the Online Resource 3 of the Supplementary materials). In the Balearic Islands (enforced in Mallorca) the *Govern Balear* issues specific fishing licenses to catch *C. sapidus* under very specific conditions and in collaboration with researchers leading the European Life project INVASAQUA (LIFE17 GIE/ES/000515). In the case of Catalonia, the *SRM/1/2019,* enforced the 19th of May 2019 allow the capture of *C. sapidus* exclusively to professional fishers, in continental waters and/or in marine waters (Instruction SRM/1/2019, of 17th Mai 2019; document available in the Online resource 4 of the Supplementary materials). Before the enforcement of these regulations (2017–2018), catching *C. sapidus* by recreational fishers was completely banned, and a number of them were fined. This could be the reason why recreational fishers did not collaborate with the study in 2017 and 2018, since in 2016 the information of *C. sapidus* distribution was scarce and the authorities had not taken any decision yet. Eventually, regulations allowing recreational fishers to catch *C. sapidus* were enforced in 2019. Additionally, the lack of motivation on a topic which had already become common and taboo (due to the legal issues) could have discouraged recreational fishers to participate in the study. Delaney et al. (2008) already stated that an excess of information or tasks to be accomplished might result in limiting the interest of citizen scientists to provide data to the study on a steady basis.

From a socio-economic perspective, management plans might help *i)* to mitigate the spread of the species and *ii)* to increase economic profit of professional fishers, due to the commercial value of *C. sapidus*. However, social issues arise from marine recreational fishers that are frustrated as they are not allowed to help eradicate *C. sapidus* from a jeopardized ecosystem. Additionally, marine recreational fishers perceive as unfair the fact that professional fishers are profiting from *C. sapidus* (*pers. obs.*). Moreover, *C. sapidus* cuts the lines of fishing rods, detaching hooks and lures several times per day. This not only seems to represent a negative economic impact for recreational fishers but also could change their fishing habits and the fishing pressure in certain areas. However, such social issue will be analyzed in further stages of this project. Furthermore, not all fishers are aware of the legal fishing regulations enforced by the public authorities. Consequently, some recreational fishers have been fined by the authorities, giving rise to a certain distrust when it comes to catching *C. sapidus*. This aspect could be mitigated by campaigns disseminating the results of this CS study. Negative experiences of fishers when in contact with *C. sapidus* might partly explain the negative perceptions of recreational fishers toward the bioinvasion of *C. sapidus*. Indeed, the highly negative perception of recreational fishers arising from the presence of *C. sapidus* in the Iberian Peninsula was much more negative than in the Adriatic (Cerri et al. 2020). Since the degree of *C. sapidus* establishment is related to the negative perceptions of recreational fishers (also in Cerri et al. 2020), the situation of the Iberian Peninsula could be much more serious than the situation in the Adriatic.

Another social issue enhancing negative perceptions towards *C. sapidus* involves mariculture. Based on the losses caused by *C. sapidus* in the blue mussel (*Mytilus galloprovincialis*) industry in the River Ebro delta, the authorities should stay alert in order to mitigate potential negative effects of *C. sapidus* in the production of blue mussels (*Mytilus edulis*) in Galician waters, which produces half of all European production (261.513 t; APROMAR 2020). Regarding professional fisheries, the ecological and economic influence of *C. sapidus* on *Melicertus kerathurus* should also be assessed, as this species is one of the main economic drivers of fishing fleets where the penaeid species is present in the Iberian Peninsula (Balearic Sea and the SE of the Iberian Peninsula). Recreational fishers commented that eggs and juvenile stages of target species, crustaceans and bivalves are prey for *C. sapidus* (not analyzed in this study), both in freshwater and saltwater, and there were concerns about implications at an ecological level and in their fishing catches in the future to come. Such predation preferences have started to be described (Prado et al. 2020; Guijarro-García et al. 2019), including plants, macroalgae or primary consumers as well as the potential effects on the benthic food web (Mancinelli et al. 2013, 2017a). Therefore, the forecast to any potential interaction of *C. sapidus* with fisheries resources is crucial.

From an ecological perspective, several Natura2000 areas (i.e., individual areas of the network of protected areas covering Europe's most valuable and threatened species and habitats) were colonized by *C. sapidus*, with special ecological concern in the River Ebro delta, Albufera de Valencia, Doñana and the whole coastline of the Balearic Islands. Similarly, a total of 18 rivers have been invaded by *C. sapidus*, namely: the Rivers Antas, Barbate, Belcaire, Bullent, Ebro, Fluviá, Guadalete, Guadalquivir, Guadiana, Jara, Júcar, Llobregat, Piedras, San Pedro, Seco, Serpis, Tinto and Vaca. A total of 10 out of the 17 Sustainable Development Goals outlined by the 2030 European Agenda for Sustainable Development are jeopardized by IAS, and *C. sapidus* is within the worst 100 IAS in the Mediterranean Sea (Streftaris and Zenetos 2006). Therefore, given the European character of the Natura2000 areas jeopardized by *C. sapidus*, mitigation efforts to achieve the European goals will have to be implemented. In terms of the bioinvasion of the SE of the Iberian Peninsula, potential mitigation measures co-developed between Spain and Portugal are recommended.

The presence of *C. sapidus* in the menu of restaurants around the Ebro river delta indicates the stable establishment of the species in the area in less than a decade (Forner-Valls and Badenes i Franch. 2019). One of the positive effects deriving from the exploitation of *C. sapidus* is the inclusion of high valued species in the value chain, which can increase economic profit for fisheries, retailers, restaurants and markets. Moreover, fisheries might help controlling the abundances of the invasive species, which might mitigate the negative effects of the invasive crab in the ecosystem (Glamuzina et al. 2021). At the same time, the negative perceptions towards *C. sapidus* might diminish. However, the presence and exploitation of *C. sapidus* needs to be managed from a holistic perspective, therefore, a consortium including of all potential coastal users attained by the presence of *C. sapidus* in the coastal zone must be orchestrated (i.e., science, public administration, decision makers, managers, recreational and professional fisheries, tourism and aquaculture industry). It is worth highlighting that the prevention of deliberate introductions of *C. sapidus* should be relentlessly pursued and severely sanctioned.

Conclusion

This research represents a comprehensive description of the *C. sapidus* bioinvasion on a large spatial scale based on citizen science. The information obtained in this study highlights the potential of online questionnaires, local ecological knowledge and social network sites applied to recreational fishers as a suitable tool to study marine bioinvasions by managers, local administrations, decision makers and scientists. Local ecological knowledge from recreational fishers can be the base of a cost and time-effective alert system to control/monitor a bioinvasion. However, it is worth mentioning that despite the benefits of citizen science, data quality is paramount, and mistaken or biased results arising from citizen science might have negative environmental, social, and/or political implications (Budde et al. 2017). Therefore, standardizing monitoring protocols, field-tests with citizen scientists working under realistic conditions is the ideal scenario to maximize data quality and future citizen science projects in coastal areas. Moreover, complementary in situ studies are recommended, from an ecological, economic and social perspective in order to develop better integrated approaches to manage the *C. sapidus* invasion, as well as other potential bioinvasions in a future to come.

In the Iberian context, once the distribution of *C. sapidus* has been thoroughly described, further studies revealing the environmental effects of this invasive crab, especially in Natura2000 areas, should be carried out. Genetic studies and modeling the dispersion of *C. sapidus* along the coasts are strongly suggested. Further research to mitigate predation in shellfish cultures are also strongly recommended to guarantee the sustainability of this industry, especially in the River Ebro delta. The same scenario applies for Galician waters, where *C. sapidus* is not yet established, though it could have devastating effects on the shellfish aquaculture industry, as occurred in the River Ebro delta. Additionally, further research is needed to evaluate potential negative influences of *C. sapidus* on other commercially important species as the caramote prawn (*Melicertus kerathurus),* European eel (*Anguilla anguilla*) or the common octopus (*Octopus vulgaris)*. The information provided by this study is valuable for scientists, managers and stakeholders aiming to achieve the European Commission's goal *i)* to develop its own fisheries and aquaculture regulations, *ii)* ensure sustainable fishing practices (http://ec.europa.eu/fisheries/cfp/eff/national_plans/index_es.htm), and *iii)* to carry out a comprehensive analysis of introduction pathways of invasive species, as stated in the Article 11 of the new European Regulation on invasive species (EU n. 1143/2012).

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