frontiers in Environmental Science

ORIGINAL RESEARCH
published: 01 November 2021
doi: 10.3389/fenvs.2021.752705

Low-Cost Citizen Science Effectively Monitors the Rapid Expansion of a Marine Invasive Species

João Encarnação, Vânia Baptista, Maria Alexandra Teodósio and Pedro Morais*

Centre of Marine Sciences (CCMAR), Universidade do Algarve, Faro, Portugal

Citizen science and informed citizens have become fundamental in providing the first records and accounts about the expansion of numerous non-indigenous species. However, implementing a successful citizen science campaign can be expensive and particularly difficult for aquatic species. Here, we demonstrate how a low-cost citizen science campaign and its outreach plan in social and traditional media enabled to track the expansion of the Atlantic blue crab *Callinectes sapidus* Rathbun, 1896 along the coast of Algarve (southern Portugal, Europe). We describe the outreach strategy and a cost-benefit analysis of the first year of the citizen science campaign. Social media platforms allowed us to reach a significant number of citizens (over 31,500 clicks in Facebook publications), while traditional media gave national visibility to the citizen science campaign and biological invasions. In only 1 year, we documented the spread of the invasive Atlantic blue crab across the entire 140 km of the Algarve coast with 166 valid observations referring to 1747 specimens, submitted by 62 citizen scientists. We spent 0 € on the citizen science campaign, but considering the time invested in the campaign the cost would have summed up to 3,751 €, while the total minimum cost for one scientist to go to the field and retrieve the equivalent information would have exceeded 11,000 €. We used free online tools of communication to obtain the records about the Atlantic blue crab, instead of a dedicated web platform or mobile app, and handled social media accounts ourselves, which saved us at least 18,815 €. The citizen science campaign revealed that the Atlantic blue crab is unequivocally established in southern Portugal and that females appear to exhibit summer migrations to coastal areas to spawn as in the native area. Overall, our low-cost citizen science campaign effectively documented the rapid spread of a marine invasive species while providing some insights into its ecology. Our strategy can be easily replicated and implemented elsewhere in the world to tackle the ever-growing problem of biological invasions while increasing the scientific literacy of local populations.

Keywords: biological invasions, non-indigenous species, range expansion, blue crab, *Callinectes sapidus*, social media, facebook, Portugal

OPEN ACCESS

Edited by:
Reuven Yosef,
Ben-Gurion University of the Negev, Israel

Reviewed by:
Pedro A. Quijón,
University of Prince Edward Island, Canada
Jakub Kosicki,
Adam Mickiewicz University, Poland

****Correspondence:***
João Encarnação
jpencarnacao@ualg.pt

Specialty section:
This article was submitted to Conservation and Restoration Ecology, a section of the journal Frontiers in Environmental Science

Received: *03 August 2021*
Accepted: *08 October 2021*
Published: *01 November 2021*

Citation:
Encarnação J, Baptista V, Teodósio MA and Morais P (2021) Low-Cost Citizen Science Effectively Monitors the Rapid Expansion of a Marine Invasive Species. Front. Environ. Sci. 9:752705. doi: 10.3389/fenvs.2021.752705

1 INTRODUCTION

Environmental agencies and scientists struggle to implement efficient monitoring and management programs focused on biological invasions given its pervasive nature (Pyšek and Richardson, 2010; Courchamp et al., 2017), despite the increased global awareness about biological invasions and their impacts on the environment, biodiversity, and economy (Simberloff and Rejmánek, 2011; Dehnen-

Schmutz et al., 2018). Aquatic invasive species are particularly challenging to monitor and study due to the difficulty in accessing their habitats which increases costs while delaying the detection of new non-indigenous species (NIS) (Streftaris et al., 2005; Havel et al., 2015). The ability to detect a potentially invasive species during the initial phase of colonization is of the utmost importance, especially if control and mitigation measures are to be applied (Mehta et al., 2007; Simpson et al., 2009). With funding increasingly scarce towards long-term scientific projects and monitoring campaigns, scientists must consider every available tool to increase early detection rates, including citizen science (Gallo and Waitt, 2011; Azzurro et al., 2013; Morais et al., 2019; Encarnação et al., 2021; Pernat et al., 2021). Citizen science is defined as "any environmental and/or biological data collection and analysis, including data quality control, undertaken by members of the general public, as individuals or as organized groups of citizens, with the guidance and/or assistance of scientists towards solving environmental and/or community questions" (Encarnação et al., 2021). Additionally, reports from Local Ecological Knowledge experts—e.g., professional fishers, farmers, land managers, forest rangers—provide critical and timely insights into species distribution and behavior. For example, citizen scientists reported the first records of several marine NIS in the Mediterranean Sea (Azzurro et al., 2013, 2019; Zenetos et al., 2013), while fishers reported two new marine NIS in southern Portugal (Morais and Teodósio, 2016; Morais et al., 2019).

One of the fastest spreading marine invasive species across Europe is the Atlantic blue crab *Callinectes sapidus* Rathbun, 1896, which has been listed as one of the 100 worst marine invasive species in the Mediterranean Sea (Streftaris and Zenetos, 2006; Nehring, 2011; Mancinelli et al., 2017). The species is native to the western Atlantic Ocean and found from the coast of Massachusetts in the United States to central Argentina (Alencar et al., 2013; Johnson 2015). It was recorded for the first time on the Atlantic coasts of Europe in 1900 and the Mediterranean Sea in 1935 (Bouvier, 1901; Nehring, 2011). Nowadays, several established populations exist in the North Sea (Belgium and Netherlands), Atlantic coasts of the Iberian Peninsula (Nehring, 2011; Morais et al., 2019; Vasconcelos et al., 2019), and across the Mediterranean Sea (Mancinelli et al., 2017; Taybi and Mabrouki, 2020). The contribution of citizen scientists in tracking the expansion of this species has been critical in the Mediterranean Sea. Fishers helped tracking the species' range expansion in Morocco (Taybi and Mabrouki, 2020), Algeria (Benabdi et al., 2019), Greece (Perdikaris et al., 2016), Albania (Beqiraj and Kashta, 2010), Italy (Suaria et al., 2017; Cerri et al., 2020), and Spain (Castejón and Guerao, 2013; González-Wangüemert and Pujol, 2016).

In Portugal, the first record of the Atlantic blue crab dates back to 1978 in the Tagus estuary (western coast) (Gaudêncio and Guerra, 1979), and the second record was made in 2009 in the Sado estuary just 30 km south of the Tagus estuary (Ribeiro and Veríssimo, 2014). This extended time lag indicates that the species failed to establish a population on the west coast of Portugal. However, on the southern coast of Portugal, the Algarve region, the establishment process was quite distinct. The first Atlantic blue crabs were collected in the Ria Formosa coastal lagoon in 2016, while reports from 2017 indicate that the species already occupied a 25 km stretch of the Guadiana estuary in the border between Portugal and Spain (Morais et al., 2019). Subsequent collections made between November 2018 and January 2019 in Ria Formosa and adjacent coastal areas have confirmed the presence and establishment of the species in the Eastern Algarve (Vasconcelos et al., 2019). Its presence in southern Portugal was hypothesized to be due to the expansion of neighbor populations from south Spain or even owing to a new introduction event (Morais et al., 2019; Vasconcelos et al., 2019).

The apparent fragmented distribution of the Atlantic blue crab in two ecosystems in southern Portugal (Morais et al., 2019), led us to hypothesize that this species has gone unnoticed by the scientific community, as it happens so often with other NIS (i.e., Azzurro et al., 2013; Morais and Teodósio 2016; Grason et al., 2018). This article focuses on the Atlantic blue crab as it became the most prominent marine invasive species in the Algarve, and aims to demonstrate the usefulness of citizen science to track the expansion of aquatic invasive species by 1) describing how we designed and implemented a citizen science campaign called NEMA (*Novas Espécies Marinhas do Algarve*—New Marine Species of the Algarve), and how it may serve as a model to other citizen science campaigns, 2) illustrating how effective a citizen science campaign can be in tracking the expansion of NIS using the Atlantic blue crab in Algarve as a model species, 3) elaborating a cost-benefit analysis to provide evidence on why we label NEMA as a low-cost citizen science campaign. This cost-benefit analysis includes an estimate of the range of savings that we achieved by using free online tools, such as social media, e-mail and biodiversity platforms, instead of custom-designed options, by handling social media ourselves, and lastly an estimate of the minimum costs for a scientist to retrieve the same information gathered by citizen scientists.

2 MATERIALS AND METHODS

2.1 Study Area

Southern Portugal (south-western Europe), which coincides with the Algarve region, is a Mediterranean climate region and the only arid or semiarid region in Portugal since annual rainfall is lower than 400 mm (Santos et al., 2010). Mean air temperatures range between 11°C in January and 27°C in August (World Weather Online 2021). The Algarve has four estuarine ecosystems, the Guadiana estuary and Ria Formosa lagoon in the eastern Algarve and the Arade estuary and Ria de Alvor lagoon in the western Algarve (**Figure 1**). The eastern zone of the south coast is mostly sandy, only interrupted by the Ria Formosa lagoon and its barrier islands, while the central and western zones of the south coast are characterized by limestone and sandstone rocky shores along with pocket sandy beaches, and cliffs towards the west coast (Moura et al., 2006). The continental platform also follows this typology, displaying a wider shelf (>40 km) and gentle slope to the east of Cape Santa Maria, while from here and towards Cape Saint Vincent (Sagres) the shelf is narrower (<15 km), the slope is steeper, and depths of 100 m can be reached within 10 km from the coast (Relvas and Barton, 2002; Garel

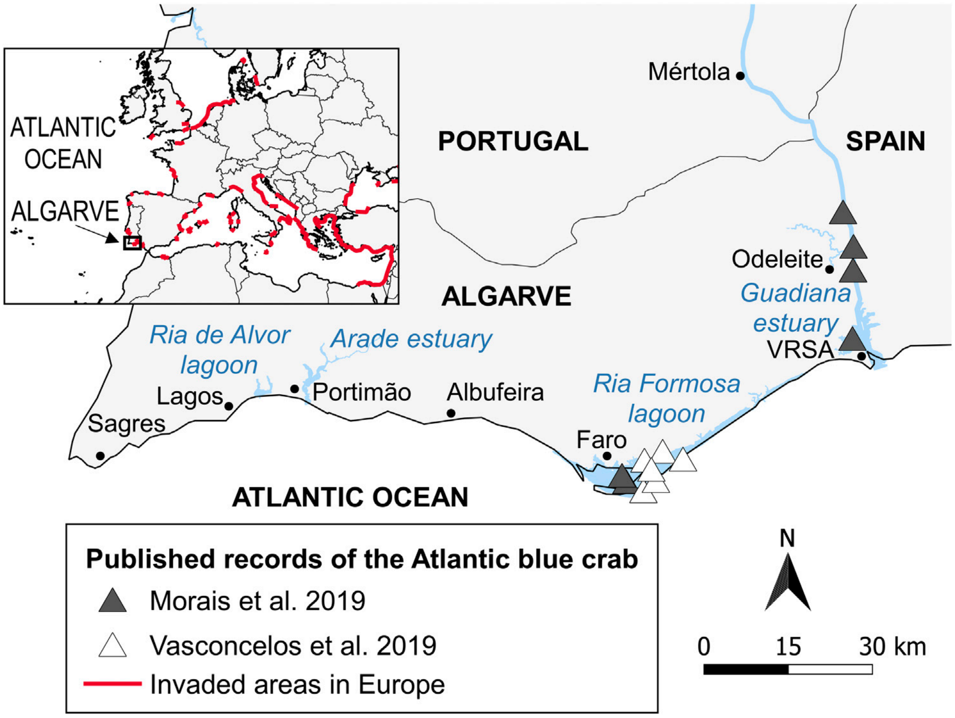

FIGURE 1 | Location of the Algarve region (southern Portugal, south-western Europe), and the areas with published records of the Atlantic blue crab across Europe and the Algarve, based on the available literature. Maps generated with QGIS 3.12 Bucuresti (QGIS.org, 2021).

et al., 2016). Mean sea surface temperature in the southern coast of the Algarve range between 15°C in January and February and above 20°C during summer, and it is increasing at a rate of +0.2°C decade^{-1} (Baptista et al., 2018).

2.2 Setting up a Low-Cost Citizen Science Campaign

NEMA is a citizen science campaign launched in April 2019 that focuses on the new aquatic species found along the Algarve coast, including estuaries and lagoons. We created a logo design that matches with the institutional image of the research centre (CCMAR—Centre of Marine Sciences) to increase credibility, facilitate outreach, and ultimately the number of submitted records (**Figure 2A**). The logo was designed for free by Dr. Sarita Camacho, as part of her graduation internship in Communication Design at the University of Algarve. The taxa chosen for the logo include some of the most emblematic new species in the Algarve and encompassing different taxonomic groups, as the invasive Atlantic blue crab *Callinectes sapidus* and bloom-forming jellyfish *Catostylus tagi*, or subtropical species like the ornate wrasse *Thalassoma pavo,* or the bearded fireworm *Hermodice carunculate* which may pose public health risks (Verdes et al., 2017; Encarnação et al., 2019). The website of NEMA (www.NEMAlgarve.com) was launched in May 2020, so it did not influence the outreach and outcomes of the first year of NEMA.

During NEMA's first year, we only used free web tools to promote the campaign and increase communication with citizen scientists. So, we created accounts on the main social media platforms—Facebook (link), Instagram (link), Twitter (link)—to promote NEMA and reach a high number of citizens in the shortest period possible. Additional communication channels were created, as a dedicated email account (nemalgarve@gmail.com) and a project page on BioDiversity4All (link)—a free biodiversity citizen science platform which is the Portuguese version of iNaturalist. NEMA's account on BioDiversity4All gathers the validated records received across all communication channels and are publicly available for consultation.

2.3 Promoting a Low-Cost Citizen Science Campaign

We actively promoted NEMA on social media platforms with information about its objectives, species of interest, and how citizens could participate in the campaign. We also made regular publications with the observations submitted by citizen scientists to acknowledge their contribution. To increase outreach, publications were often shared by our research centre (CCMAR) on their social media accounts. A poster with the species of interest (**Figure 2B**) was created and shared regularly on NEMA's social media accounts. Every month, from June to October 2019 and also January 2020, this poster was used as an outreach tool to engage with the public on several Facebook groups related to fishing and general ocean activities. On average, we reached out to 23 ± 6.3

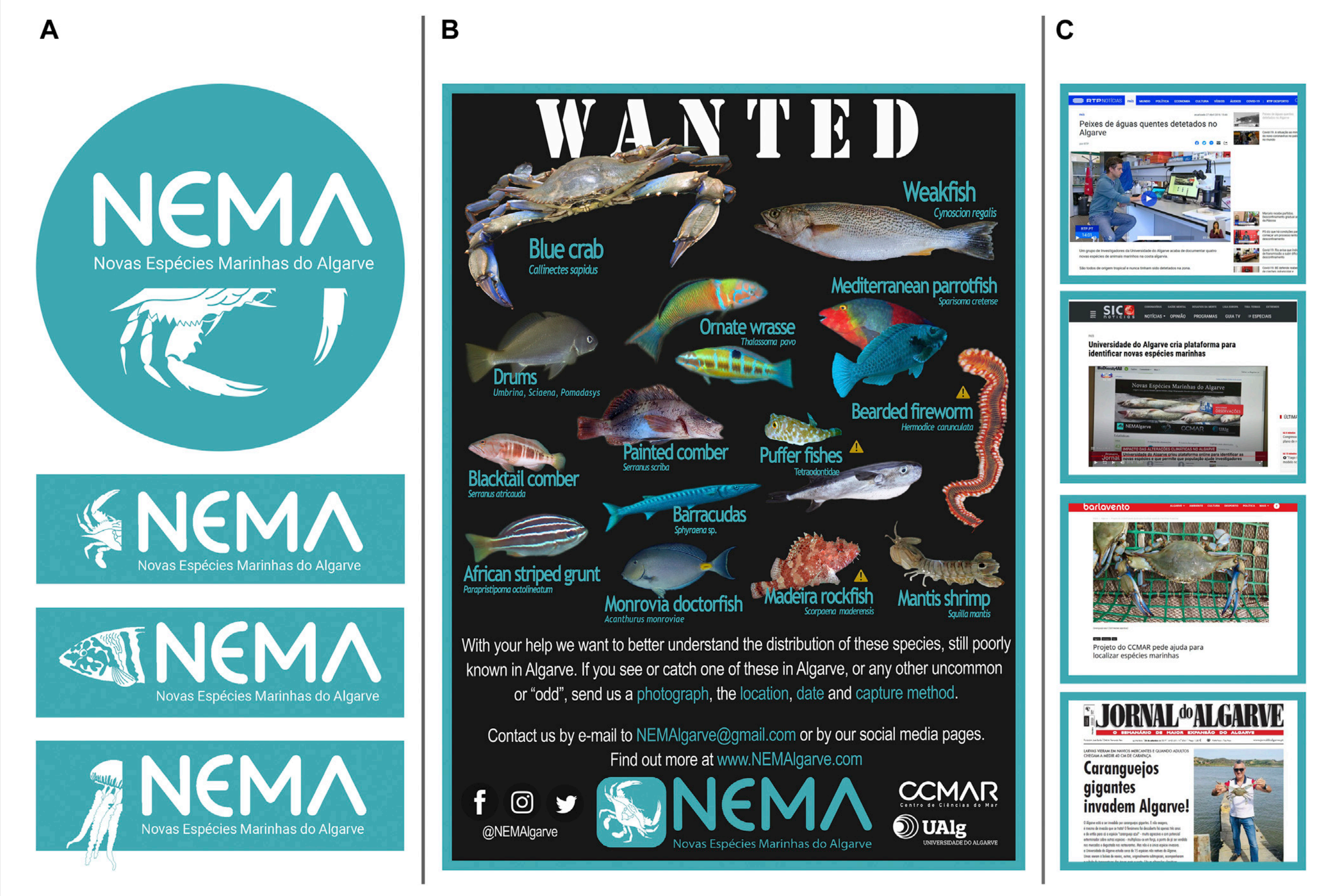

FIGURE 2 | Outreach materials and actions used to promote the NEMA citizen science campaign. **(A)** The NEMA institutional image includes a main logo, incorporating the Atlantic blue crab *Callinectes sapidus*, and complementary logos. **(B)** The NEMA "WANTED" poster used to promote the campaign on social media and call citizens for participation. **(C)** NEMA outreach actions resulted in tremendous media coverage, including interviews given to national television, and printed and online newspaper articles. For a complete list of media coverage, see **Supplementary Table S1** of the online Supplementary Material.

Facebook groups per month in this period. In most instances, we used the Portuguese version of the poster.

In May 2019, we issued a press release to local and national media about NEMA and its objectives. The visibility of NEMA on social media, in tandem with the press release, led to a growing interest from traditional media on the NEMA campaign, biological invasions, and species reaching southern Portugal owing to climate change (**Figure 2C**).

2.4 Data About Species Records

We asked citizen scientists to provide information about the species of interest and for five details about their observations: 1) a photograph of the specimen(s), 2) date, 3) location, 4) method of capture or observation, and, whenever possible, 5) the inclusion of an object to serve as a scale in the photograph. Only observations that included, at least, one photograph to allow the species identification, date of observation and a detailed location were considered valid and included in NEMA's database. The direct communication channels provided the opportunity to obtain all the details to validate observations and permission to add the observation to the database. Observations classified as "personal communications" refer to direct messages sent by friends or colleagues about an observation, or with a link or contact to the citizen scientist that made the observation.

Several observations pre-dating NEMA—before April 2019 and hereafter named pre-NEMA—were included in the present database. These were mostly made by two informed citizens, Mr. Gonçalves and Mr. Fernandes, that continued to provide records after the ones published by Morais et al. (2019). With the launch of NEMA, we were also able to reach several citizen scientists that already had older observations stored in digital devices and such records are also labelled as pre-NEMA.

Facebook was our most popular social media account, so we retrieved several metrics to assess the impact of social media outreach on the number of records. These metrics include the number of daily new Facebook followers, daily total impressions, and daily total consumers. Facebook defines daily total impressions as the number of times any content from the page or about the page entered a person's screen (e.g., posts, stories, check-ins, ads, and social information from people who interact with the page), while daily total consumers are the number of people who clicked on any of the account's content. We used linear regressions to assess the relationship between these metrics and the number of submitted observations.

2.5 Data Analyses

2.5.1 Documenting the Rapid Expansion of the Atlantic Blue Crab

First, we compared the number of validated Atlantic blue crab observations and specimens reported before and after the launch of NEMA to assess its impact. Second, we analyzed the number of validated observations and specimens according to distance to the eastern point of the Algarve (the mouth of the Guadiana estuary) to track the species' expansion along the coast. A third analysis considers the sex of the specimens which was only made when citizen scientists provided photographs that allowed such assessment or accurate descriptions of morphology. All other specimens were classified as unsexed. The classification of reproductive months for the present analysis—August, September, October—was based on the observations of ovigerous females (two in August 2019 and three in September 2019) and capture of females swimming at the surface at night (one in August 2019 and one in October 2019), which is associated with spawning events (Tankersley et al., 1998; Forward et al., 2005). Differences in the proportions of sexes (excluding unsexed) between reproductive periods (non-reproductive vs. reproductive) and ecosystems (coastal vs. estuarine) were evaluated with chi-square tests, using 2 × 2 contingency tables for each of the comparisons (de Sá 2007). Estuarine ecosystems, as opposed to coastal areas, refer to any body of water towards the inside of a river mouth, barrier island, or inlet. The non-parametric chi-square test was chosen because the assumptions of data normality (Shapiro-Wilk's test for normality) and homogeneity of variance (Levene's test) failed ($p < 0.01$), therefore disabling the use of a parametric analysis of variance test (de Sá 2007). Statistical analyses were done using R Studio version 1.4.1106 (RStudio Team, 2021).

We must highlight the significant contributions made by one informed citizen, Mr. Gonçalves, because he reported the first Atlantic blue crab captured in the Guadiana estuary in 2017 (Morais et al., 2019) and we kept a close collaboration since then. All the observations made by this fisherman from the Guadiana estuary since July 2018 were included in this database. These observations were analyzed separately because of their singularity—close collaboration, the high number of records, and small geographical range. Mr. Gonçalves uses mostly gillnets and traps on few occasions. Three independent gillnets, with an average size of 41 m length by 1.80 m heigh, were usually deployed during the afternoon and retrieved the following morning.

2.5.2 Cost-Benefit of a Low-Cost Citizen Science Campaign

We conducted a cost-benefit analysis of NEMA based on the costs of producing and running all the outreach platforms, and on retrieving the same Atlantic blue crab observations submitted by citizen scientists and informed citizens. To estimate the hypothetical costs we would have by running NEMA, we indexed the amount of time invested in each task to the daily stipend of a Ph.D. fellowship financed by the Foundation for Science and Technology (FCT, Portugal)—i.e., 51.20 € per workday, and compared it with service quotes from three companies.

This analysis was based on three components. The first component consisted in giving a cost to creating NEMA's communication channels, i.e., the campaign's accounts on BioDiversity4All, social media (Facebook, Instagram, and Twitter), and email. We spent seven work-days to create these platforms and then compared its cost, indexed to the FCT fellowship, with the cost of outsourcing the production of a website, mobile app, and create NEMA's social media accounts to obtain the records made by citizen scientists and informed citizens.

The second component consisted in giving a cost to handling NEMA's social media accounts, i.e., to create, publish, and follow-up each publication. We spent, on average, 1.5 h with each publication: 30 min for designing the publication, 20 min for publishing it, and 40 min for following up the publication, retrieving relevant information, or communicating with people that actively engaged with it. We compared the cost of the total number of publications, indexed to the FCT fellowship, with the cost of hiring a social media manager.

The third component consisted in calculating the expenses we would have in going to the field and collect the same information provided by citizen scientists or informed citizens. In a real situation, we would have needed to go to the field multiple times to increase the chances of making an observation, but due to the unforeseen nature of fieldwork, we can only calculate the minimum cost to retrieve the same record (one specimen or group of specimens) as the one made by a citizen scientist or informed citizen. The cost was calculated as the money spent by one scientist to travel to the observation site from the university campus, considering a car that spends 6 € 100 km^{-1} of gas, toll costs for a class 1 car (ViaLivre 2021), plus the daily stipend of the FCT fellowship. Distances were estimated with Google Maps, between the University campus in Faro (37.0428, −7.9735) and the closest road to the observation site (GPS positions available in **Supplementary Table S2**). For observations in the vicinities of Faro (between Albufeira and Tavira), no toll costs were included (n = 22). No costs related to boat renting and fuel, nor equipment depreciation were included in this analysis. The cost per trip was then divided by the number of specimens in each observation to obtain the cost per individual. Data is described by its range (minimum-maximum), the mean, and standard deviation was used as a measure of data dispersion. Lastly, this value was compared with the cost of retrieving the total number of observations through NEMA's communication channels, indexed to the FCT fellowship. We invested 10 min per observation, on average, to retrieve all the necessary parameters.

3 RESULTS

3.1 Media Coverage

During NEMA's first year, we focused mainly on social media outreach which resulted in traditional media becoming interested in the subject (**Figure 2C**). Between April 2019 and March 2020, two interviews were broadcasted on national television, fifteen online articles were published, two articles published on printed newspapers with one making cover page, and two interviews given to radio stations. The content of these news pieces included the discovery of NIS in Algarve and NEMA's citizen science campaign. The full list of articles and details about each one is available in **Supplementary Table S1**.

3.2 Impact of Social Media on Reports

Facebook was the social media platform most used by citizen scientists to contact NEMA—68% of all 84 validated observations of the Atlantic blue crab. NEMA's Facebook account received 57% of these observations (n = 48) and the other 11% (n = 9) were made through Facebook groups, or as a direct response to our explanatory publications in these groups (**Figure 3A**). No observations were reported through Instagram or Twitter. Observations uploaded on BioDiversity4All accounted for 12% of the records (n = 10), despite that most first contacts were also made through social media, followed by the upload of the observations on this platform by citizen scientists. NEMA's email received 7% of the observations (n = 6) and the remaining observations (13%, n = 11) were personal communications sent to us (**Figure 3A**).

The significant interest in NEMA's Facebook publications is shown by six sudden increases in the number of impressions (**Figure 3B**). The peak occurred on October 14, 2019, when these publications reached 40,905 people (daily total impressions) and generated 825 interactions (daily total consumers) (**Figure 3B**). The maximum number of interactions with NEMA's Facebook account was registered on December 21, 2019—2,839 interactions and 17,414 people reached (**Figure 3B**). During NEMA's first year, publications in Facebook reached a total of 669,417 people (impressions) and 31,565 interactions (consumers). We registered a positive relationship between the number of observations received with the daily total impressions (R^2 = 0.976), daily total consumers (R^2 = 0.973), and also with the number of Facebook followers (R^2 = 0.968). The number of observations reported on Facebook followed the increase in Facebook followers—2,163 by the end of March 2020 (**Figure 3C**). The main sources of new Facebook followers occurred after the publication of monthly explanatory posts on Facebook groups (**Figure 3D**), the coverage made by traditional media (dark arrows on **Figure 3B**), and publication of regular posts in NEMA's Facebook account.

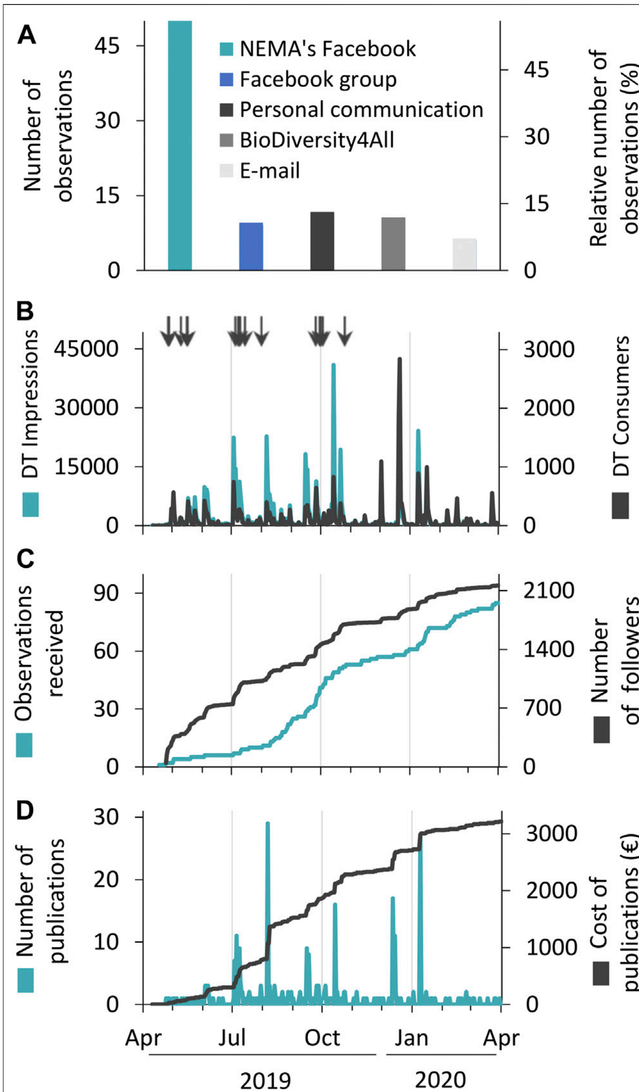

FIGURE 3 | (A) Contribution of each communication platform used by citizens to submit observations of the Atlantic blue crab to NEMA. **(B)** Facebook metrics between April 2019 and the end of March 2020, namely daily total (DT) impressions and daily total (DT) consumers. **(C)** The number of observations received in relation to the number of Facebook followers. **(D)** The total number of publications (including publications in NEMA's Facebook page and the monthly explanatory publications on Facebook groups related to fishing and ocean activities) and the estimated cost associated with such media handling. These estimates represent a minimum cost, as they were estimated based on the daily value of a Ph.D. fellowship of one scientist, and not a professional in social media management. Dark arrows indicate the date when newspaper and online articles and interviews were published or broadcasted by traditional media (full list in **Supplementary Table S1** of the online Supplementary Material). The observations made by Mr. Gonçalves (informed citizen) in the Guadiana estuary are not included in these figures.

3.3 Data on the Atlantic Blue Crab

Most Atlantic blue crab records were collected with a fishing gear (48.0%, n = 59), mostly with fishing nets (32.5%, n = 40), but also by hand (14.6%, n = 18) or found dead (18.7%, n = 23) (**Figure 4**). By the end of March 2020, NEMA's database, and therefore our sample size, included 166 valid observations from 1747 Atlantic blue crabs, submitted by 60 citizen scientists and two informed citizens (**Figure 5A**). Citizen scientists recruited by NEMA submitted 84 valid observations of 117 Atlantic blue crabs, while informed citizens contributed with 82

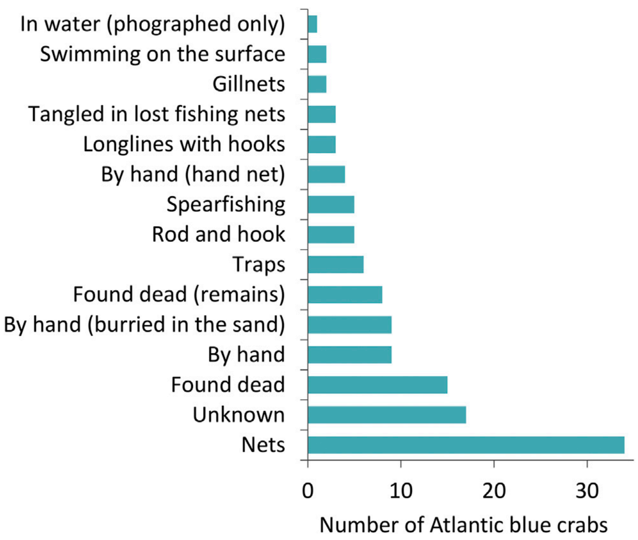

FIGURE 4 | Type of observation or method of capture reported by citizen scientists to NEMA about the Atlantic blue crab between April 2019 and the end of March 2020.

observations of 1,630 specimens. Observations registered before the launch of NEMA in April 2019, included observations mostly provided by the two informed citizens already mentioned (n = 23), while six citizen scientists provided seven observations (blue symbols in **Figure 5A**). These pre-NEMA observations were made in locations where the species had not been recorded before: one female in Ria de Alvor (May 15, 2018, record #20); one male in the eastern sector of the Ria Formosa near Tavira (March 4, 2019; record #12); one male in the coastal area off "Barrinha", an inlet of the Ria Formosa (March 27, 2019, record #4). The complete list of observations and NEMA's references are available in **Supplementary Table S2**.

The Guadiana estuary and the contributions made by Mr. Gonçalves represent a particular sub-set of records. This informed citizen alone reported 1,624 Atlantic blue crab specimens, all captured along a 12 km stretch of the middle Guadiana estuary, close to the village of Odeleite (**Figures 1, 5A**). Most specimens were males (58.8%, n = 955) and females only accounted for 6.0% (n = 97), while the remaining specimens were not sexed (35.2%, n = 572). Two months stood out—September 2019 (125 males, 6 females, 508 unsexed specimens) and March 2020 (456 males, 0 females). In 2019, the maximum daily catch was 105 specimens (September 17), and it reached 110 and 130 specimens in 2020 during two consecutive days, March 4 and March 5, respectively. No similar amount of daily catches were ever reported anywhere in Portugal. An additional 16 observations were made in this estuary by 11 citizen scientists about 21 specimens (**Supplementary Table S2**). Observations were mostly done in the middle and lower Guadiana estuary, but one dead specimen was found in Mértola at 70 km from the river mouth on October 6, 2019 (**Figure 5A**).

3.4 The Expansion of the Atlantic Blue Crab in the Algarve

Citizen scientists alone contributed with 77 valid observations about 109 Atlantic blue crabs, observed between April 2019 and March 2020—44.0% males (n = 48), 43.1% females (n = 47), 12.8% unsexed (n = 14) (**Figure 5A**). Observations made in estuarine ecosystems (Ria de Alvor, Arade estuary, Ria Formosa, and Guadiana estuary) accounted for 50.6% (n = 39) of the observations—61.7% males (n = 29), 34.0% females (n = 16), 4.3% unsexed (n = 2) (**Figures 5A, 6**). Observations made in coastal areas represented 49.4% (n = 38) of all records—30.6% males (n = 19), 50.0% females (n = 31), 19.4% unsexed (n = 12) (**Figures 5A, 6**). There were differences in the proportion of sexes between coastal and estuarine areas during the non-reproductive (p = 0.044) and reproductive periods (p = 0.065) (**Table 1**). In both cases, females were more frequent in coastal areas (31 specimens) than in estuarine ecosystems (16 specimens) (**Figure 6**).

In the first 3 months of NEMA (April-June 2019), only one Atlantic blue crab specimen was reported. Nonetheless, five specimens captured during July 2019 extended the known distribution westwards by over 50 km, from Faro to the Arade estuary in Portimão (**Figure 5A**). Two specimens captured in Ria de Alvor (one male, one female) further extended the distribution westwards by 8 km in August 2019. On September 19, 2019, one male specimen captured near the beach of Zavial further extended the western distribution limit by 23 km (**Figure 5A**).

Between August and November 2019, 16 observations (20 specimens: 7 males, 7 females, and 6 unsexed) confirmed the establishment of the Atlantic blue crab in the area between Albufeira and Alvor (green and orange symbols in **Figure 5A**). In the same period, between Faro and Vila Real de Santo António, 19 observations were made (21 specimens: 3 males, 13 females 4 unsexed) of which nine females have washed ashore in the beaches close to the mouth of the Guadiana estuary (**Figure 5A**). In August and September 2019, ovigerous females were reported (**Figure 5B**), one found dead in a beach close to the mouth of the Guadiana estuary (observation #34), two inside the Ria Formosa lagoon (observations #26 and #41), one in the Arade estuary (observation #17), and another one in the coastal zone of Portimão (observation #31). It is worth mentioning that two non-ovigerous females were captured at night while swimming at the surface on August 27, 2019, and October 2, 2019 (observations #22 and #42). In December 2019, a single observation (observation #66) reported one male and six females in the lower Guadiana estuary near Vila Real de Santo António, and one additional female was captured in the Sagres' harbor (observation #63). This last record extended the western distribution limit by another 4.5 km (**Figure 5**).

In January 2020, one fisherman made three observations on subtidal areas off Alvor and Lagos and mentioned that the Atlantic blue crab was a "frequent" bycatch. Two of these observations narrowed the gap of records made between Alvor and Sagres (**Figure 5A**). One of such observations reported 8 males and 3 females, all captured at night with a fishing net set near the Porto de Mós beach (Lagos, January 17, 2020) (**Figure 5C**). During the first 3 months of 2020, 10 observations confirmed the presence of the species in vicinities of Ria de Alvor and the Arade estuary (red

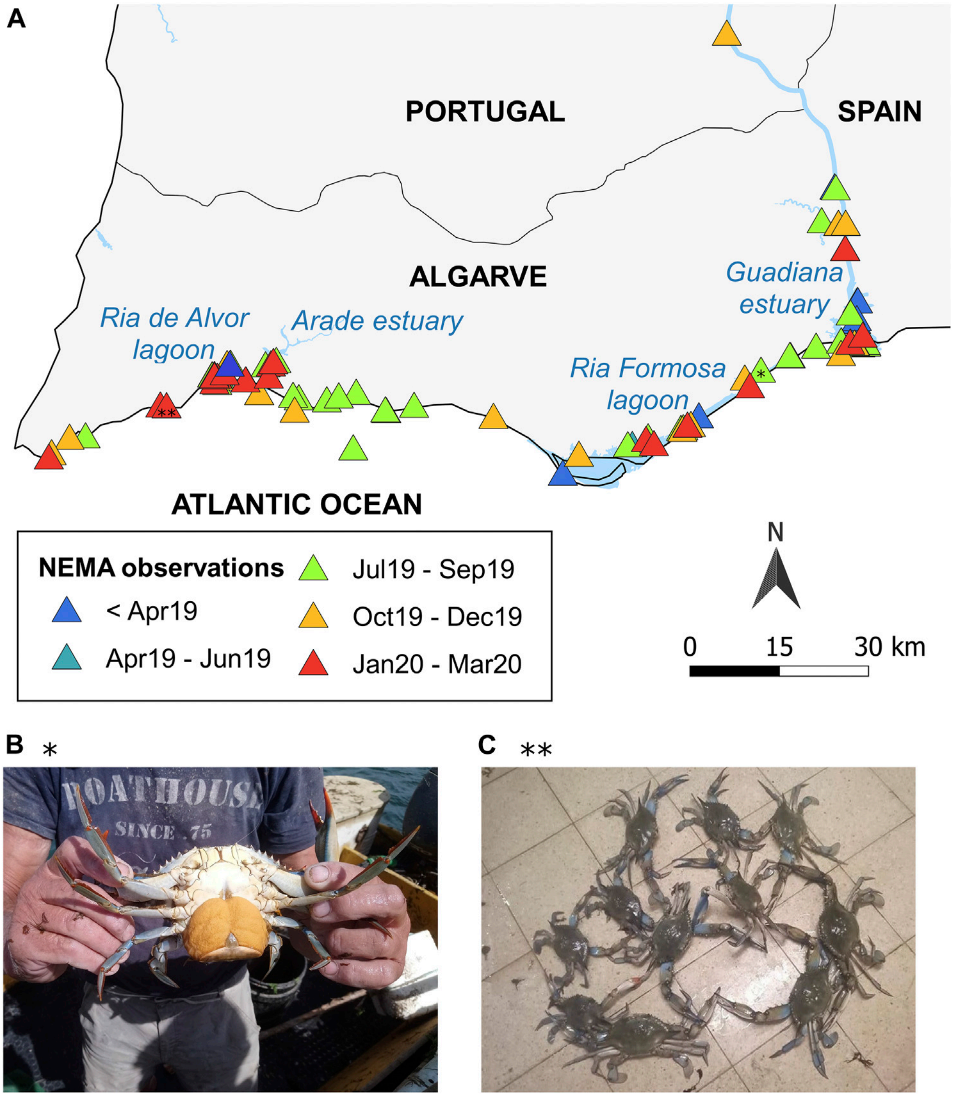

FIGURE 5 | (A) Observations documenting the expansion of the Atlantic blue crab from East to Western Algarve until the end of March 2020. Information submitted by informed citizens and citizen scientists to the NEMA citizen science campaign. Each icon represents an observation that may include more than one specimen. **(B)** An ovigerous Atlantic blue crab specimen collected in the Ria Formosa lagoon on September 20, 2019 (observation #41 submitted by D. Barragão). **(C)** Atlantic blue crabs collected off Lagos on January 17, 2019 (observation #70 submitted by V. Gomes). For a detailed list and description of each observation, please see **Supplementary Table S2** of the online Supplementary Material. Map generated with QGIS 3.12 Bucuresti (QGIS.org, 2021).

symbols in **Figure 5A**). The entire south coast of the Algarve was formally colonized by the Atlantic blue crab when a female specimen was recorded in the Mareta beach (Sagres) on March 3, 2020 (observation #86, westernmost red symbol in **Figure 5A**).

3.5 Cost-Benefit of a Low-Cost Citizen Science Campaign

Based on the number of hours we invested in launching and handling NEMA, the corresponding cost during its first year would have summed up to 3,751.47 € (**Figure 7**). Hiring the services of professionals to develop and handle all the digital platforms plus gathering the same number of records of the Atlantic blue crab in the field, would have cost between 29,815.58 € and 153,485.58 € (**Figure 7**).

The service quotes from three software developers to build a website and a smartphone app with basic features (i.e., submission of a photograph, location, date, and contact of the citizen scientist) were quite distinct—12,115 €, 55,350 €, and 81,180 €. The cost associated with the time invested in creating NEMA's social media accounts, e-mail, and project page on Biodiversity4All was only 358.40 € (**Figure 7**).

Between April 2019 and the end of March 2020, we made a total of 335 publications on Facebook—198 publications on

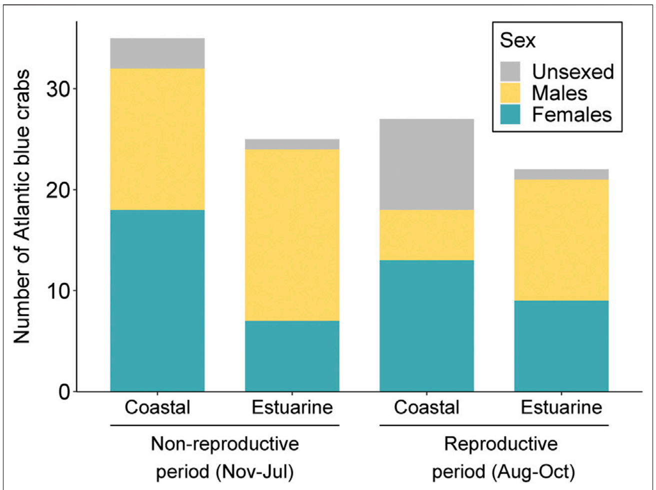

FIGURE 6 | Records of Atlantic blue crabs made in coastal or estuarine ecosystems of Algarve, according to the reproductive or non-reproductive period and their sex, submitted to NEMA by citizen scientists between April 2019 and the end of March 2020.

NEMA's Facebook account and 137 explanatory publications on Facebook groups (**Figure 3C**). Considering a value of 9.60 € per publication, the cost of media handling associated with these publications would correspond to a total of 3,216 € for this first year of NEMA (**Figures 3C**, **7**). For the same 355 publications, service quotes provided by professional social media managers were at 20 €, 50 €, and 183 € per publication, which would result in a total of 6,700 €, 16,750 €, and 61,305 € respectively (**Figure 7**).

The total cost for a NEMA scientist to go to the field and make the same 166 observations (1747 Atlantic blue crabs) would have reached 11,000.58€. The observations made before NEMA would sum up to a minimum of 2,015.61 €, while during the first year of NEMA, the total minimum cost would have been 8,984.96€—4,965.06 € for records made by citizen scientists and 4,019.90 € for records made by informed citizens. This represents an average minimum savings of 748.75 ± 505.77 € month^{-1} during NEMA's first year. The maximum cost per individual was 75.73 € for the westernmost observation (record #86, Mareta beach, Sagres) and averaged 36.59 ± 28.05 € individual^{-1} (**Figure 8**). The cost per individual was on average higher for observations provided by citizen scientists (6.59–75.73 € individual^{-1}, 58.99 ± 16.20 € individual^{-1}) than informed citizens (0.52–68.06 € individual^{-1}, 13.64 ± 16.73 € individual^{-1}) because observations made by informed citizens were mostly made in the Guadiana estuary and many individuals were reported in most observations (**Figure 8**). The minimum average cost per trip for a NEMA scientist to obtain the same record (one individual or several) as those made by citizen scientists was 64.35 ± 6.42 € trip^{-1}. This value was similar to the cost to obtain the same record as of informed citizens (68.23 ± 0.56 € trip^{-1}) since all these observations were done in the middle and lower Guadiana estuary (**Figure 8**). By investing our time in handling the digital communication channels to retrieve the 166 observations submitted by citizens scientists and informed citizens, we saved 177.07 € (**Figure 7**).

4 DISCUSSION

NEMA's citizen science campaign has demonstrated the value of citizen science in tracking biological invasions (Encarnação et al., 2021), while also showing the value of a set of low-cost tools that can be used to replicate this approach in other regions of the world. The high engagement of citizen scientists allowed to monitor the expansion of the invasive Atlantic blue crab along the Algarve coast, while providing relevant clues for future research hypotheses. These two aspects are detailed in the following sections.

4.1 Low-Cost Citizen Science With High Engagement

Detecting the presence of aquatic non-indigenous species after their introduction is extremely challenging and, in most cases, they only become noticed when an invasive status is reached (Mehta et al., 2007; Pyšek and Richardson, 2010). This has been tackled across the globe with rapid assessment surveys in artificial structures (Collin et al., 2015) or systematic surveys with fishing gears (Yamada et al., 2015; Poirier et al., 2017), but also using new technologies (e.g., eDNA analyses) that enhance the success of detecting NIS with low abundances (Rees et al., 2014). However, implementing eDNA monitoring programs is unfeasible in most regions due to the financial costs associated with this technology. In some cases, citizen sciences campaigns may mitigate the lack of intensive monitoring programs. For example, several successful citizen science campaigns have focused on crustaceans (e.g., Asian shore crab *Hemigrapsus sanguineus* and the European green crab *Carcinus maenas* (Delaney et al., 2008; Grason et al., 2018)), algae (e.g., *Caulerpa taxifolia* (Ellul et al., 2019)), or fish (e.g., lionfish *Pterois miles* (Azzurro et al., 2017; Giovos et al., 2018)). However, the running costs of citizen science

TABLE 1 | Chi-square test results, applied to 2 × 2 contingency tables, to assess differences in proportions of sexes between reproductive periods and ecosystems where Atlantic blue crabs were observed by citizen scientists.

	Value	df	*p* value
Coastal ecosystems (Non-reproductive vs. Reproductive)	1.247	1	0.264
Estuarine ecosystems (Non-reproductive vs. Reproductive)	0.916	1	0.339
Non-reproductive period (Coastal vs. Estuarine)	4.071	1	0.044
Reproductive period (Coastal vs. Estuarine)	3.399	1	0.065

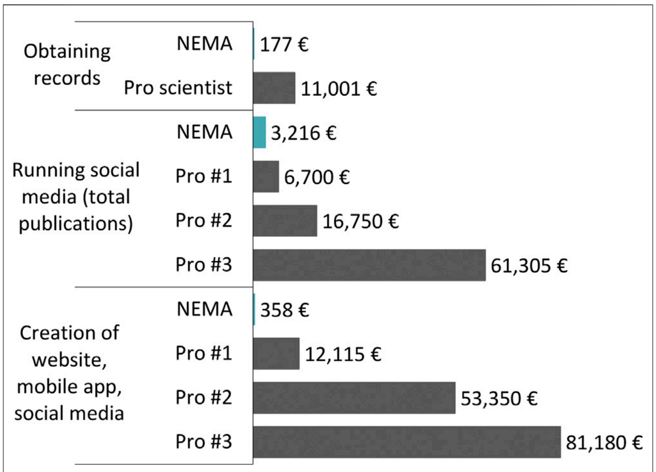

FIGURE 7 | Cost comparison between investing our time in running the citizen science campaign ourselves (NEMA); the minimum cost for a professional scientist to retrieve the same 166 observations submitted by citizen scientists; and three quotations provided for a social media manager to handle the same 335 publications made by NEMA's Facebook account, and for a professional to create all of NEMA's communication channels.

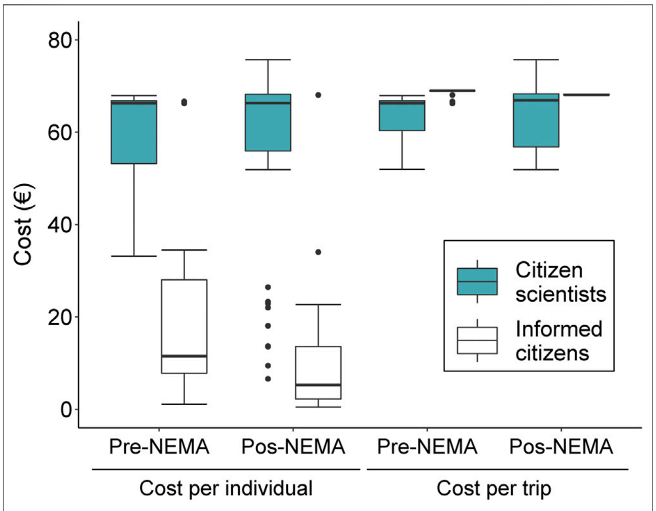

FIGURE 8 | Minimum cost for a scientist to obtain the same 166 observations (1747 Atlantic blue crabs) submitted by informed citizens and citizen scientists before (April 2018-March 2019) and during the NEMA campaign (April 2019-March 2020). These are minimum costs, as they only include transportation costs and the daily value of a Ph.D. fellowship of one scientist.

campaigns are unavailable to analyze and validate the cost-benefit of this approach.

During NEMA's first year, the campaign relied mostly on social media to communicate with potential citizen scientists. Social media provides a dual-communication channel with citizen scientists, i.e., allows promoting the project while providing updates on recent discoveries, increasing scientific literacy, and interact directly with citizen scientists. Direct communication with citizen scientists on Facebook provided valuable records about the Atlantic blue crab in the Algarve. However, asking citizen scientists to independently register their observations on BioDiversity4All citizen science platform was unsuccessful—only 11% of observations were registered on this platform by citizen scientists. Relying on free digital platforms (social media, e-mail, and citizen science platforms) meant running NEMA with no associated costs during its first year and save over 11,000€ for the total of 166 observations received (8,900€ for observations made only in the first year period). This is the minimum amount of money that we would need to obtain the exact same information on the field and with just one scientist. In comparison to the methods applied with NEMA's digital channels of communication, the corresponding cost in gathering these records would still be much lower (358 €).

Other successful citizen science projects relied on dedicated websites and/or smartphone apps (Gallo and Waitt, 2011; Azzurro et al., 2013, 2019; Zenetos et al., 2013; Marchante et al., 2017; Eritja et al., 2019). Such technologies are extremely costly to produce and maintain. Additionally, NEMA is being implemented as a long-term detection campaign, and such web platforms also require recurring annual fees. NEMA's approach to engage with citizen scientists mostly through online outreach is still a time-consuming methodology, that requires constant communication with participants and all the tasks associated with social media handling. If the time invested would result in a direct cost to create all the platforms and handling the social media pages ourselves, the correspondent cost during this first year of NEMA would have summed up to 3,574 €, which is still much lower than hiring professionals (18,815 €—142,485 €).

In Portugal, obtaining funding to establish long-term monitoring programs on aquatic invasive species is extremely unlikely. To overcome the idiosyncratic nature of Portuguese science funding, we opted for this low-cost approach which turned out to be extremely successful, while increasing the regional and national scientific and environmental literacy of the population. We will continue promoting NEMA for the foreseen future and we endorse the implementation of similar approaches in other regions of the world where scientific funding is scarce. Finally, biological invasion scientists should establish at least an "open communication channel" with citizens, even if not running a citizen science project, so that they can receive spontaneous contacts about new records while scouting social media and online forums (e.g., naturalists, fishers, hikers) for records of new NIS.

4.2 Tracking the Expansion of Invasive Aquatic Species

The best strategy to maximize participation and increase the number of records reported by citizen scientists is to establish multiple communication channels with scientists and research institutions (Encarnação et al., 2021). Despite following this recommendation, we acknowledge that our data may be biased since it likely engaged citizen scientists already concerned with environmental issues or with a strong interest in fishing (i.e., fishers and anglers). One informed citizen recorded 93.0% of the total 1747 Atlantic blue crabs reported to NEMA. Yet, the other 117 Atlantic blue crabs allowed to track the fast westward expansion of the species for over 90 km along the coast of the Algarve (**Figure 5A**). Furthermore, the number of reported individuals represents a 46-fold increase in comparison to data obtained during the 3 years prior to NEMA (Morais et al., 2019; Vasconcelos et al., 2019). NEMA also brought to light a record made in May 2018 at Alvor (**Figure 5A**, observation #20) which would have extended the known distribution in 65 km by the time the two scientific publications were made in 2019 (Morais et al., 2019; Vasconcelos et al., 2019).

Our study made clear that citizen scientists have different engagement levels, yet equally valuable to monitor biological invasions. Without a wide network of citizen scientists, we could not track the westward expansion of the Atlantic blue crab. Without an informed citizen from the Guadiana estuary (Mr. Gonçalves), we could not obtain precious information about the presence of the species in this estuary for an extended period of time. Therefore, all connections should be nourished. Developing short-training actions with citizen scientists will provide valuable long-term data while giving more autonomy for citizen scientists to gather data with different methodologies.

NEMA also obtained interesting details about the ecology of the Atlantic blue crab. Two females were reported to be swimming at the surface during the night close the coast, which is a typical behavior of ovigerous females that perform vertical migrations at night during the spawning periods (Tankersley et al., 1998; Aguilar et al., 2005; Forward et al., 2005). NEMA's data also showed that female Atlantic blue crabs were more common in coastal areas throughout the year, and not only during the reproductive period (August–October). Ovigerous females in coastal areas were only recorded once off Portimão, but the other three ovigerous individuals were found in the lower Arade estuary and Ria Formosa. The high mobility of Atlantic blue crabs and its fast adaptation to environmental conditions, namely salinity, are key factors for the selection of spawning areas (Forward et al., 2003; Aguilar et al., 2005), therefore spawning areas in Algarve seem to include both the lower section of estuaries and coastal areas.

5 CONCLUSION

Overall, we demonstrated that a low-cost citizen science campaign was able to track the rapid expansion of a marine invasive species. The model we implemented with NEMA can be easily replicated elsewhere in the world, while being adapted to the social context of each region or country and target species. NEMA tracked the establishment and expansion of the invasive Atlantic blue crab along the entire southern coast of Portugal, including multiple estuaries and lagoons. We also obtained interesting ecological information about the reproductive strategies of females which can be tested in future works. Finally, our work demonstrates that biological invasion scientists should include citizen science in their toolkit while nourishing the collaborations with informed citizens to detect, track, and study non-indigenous species.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

JE had the idea to develop and implement NEMA; JE collected data during the NEMA campaign and VB collected data before NEMA; Data analyses were made by JE, PM, and MAT; JE and PM led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

FUNDING

This study received partial financial support from the Foundation for Science and Technology (FCT, Portugal) with Portuguese national funds through the project UIDB/04326/2020, and from the Atlazul project (Poctep/Interreg 0755_ATLAZUL_6_E—Impulso da Aliança Litoral Atlântica para o Crescimento Azul). JE has a Ph.D. scholarship (SFRH/BD/140556/2018) funded by the Foundation for Science and Technology (FCT, Portugal).

ACKNOWLEDGMENTS

The authors greatly appreciate each contribution and information provided by all citizen scientists and informed citizens, particularly Mr. Gonçalves. NEMA's institutional image was designed by Dr. Sarita Camacho. We would also like to acknowledge the valuable comments of the two reviewers whose suggestions greatly increased the scope of the article.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.752705/full#supplementary-material

REFERENCES

Aguilar, R., Hines, A. H., Wolcott, T. G., Wolcott, D. L., Kramer, M. A., and Lipcius, R. N. (2005). The Timing and Route of Movement and Migration of post-copulatory Female Blue Crabs, *Callinectes sapidus* Rathbun, from the Upper Chesapeake Bay. *J. Exp. Mar. Biol. Ecol.* 319 (1-2), 117–128. doi:10.1016/j.jembe.2004.08.030

Alencar, C. E. R. D., Morae, S. A. S. N. d., Araújo, P. V. D. N., Brito, V. L. G., and Freire, F. A. d. M. (2013). New Record of Blue Swimming Crab *Callinectes sapidus* Rathbun, 1896 (Crustacea: Portunidae) for the State of Rio Grande Do Norte, Northeastern Brazil. *CL* 9 (6), 1567–1570. doi:10.15560/9.6.1567

Azzurro, E., Bolognini, L., Dragičević, B., Drakulović, D., Dulčić, J., Fanelli, E., et al. (2019). Detecting the Occurrence of Indigenous and Non-indigenous Megafauna through Fishermen Knowledge: A Complementary Tool to Coastal and Port Surveys. *Mar. Pollut. Bull.* 147, 229–236. doi:10.1016/j.marpolbul.2018.01.016

Azzurro, E., Broglio, E., Maynou, F., and Bariche, M. (2013). Citizen Science Detects the Undetected: the Case of *Abudefduf saxatilis* from the Mediterranean Sea. *Manag. Biol. Invasions* 4 (2), 167–170. doi:10.3391/mbi.2013.4.2.10

Azzurro, E., Stancanelli, B., Di Martino, V., and Bariche, M. (2017). Range Expansion of the Common Lionfish *Pterois miles* (Bennett, 1828) in the Mediterranean Sea: an Unwanted New Guest for Italian Waters. *Bioinvasions Rec.* 6 (2), 95–98. doi:10.3391/bir.2017.6.2.01

Baptista, V., Silva, P. L., Relvas, P., Teodósio, M. A., and Leitão, F. (2018). Sea Surface Temperature Variability along the Portuguese Coast since 1950. *Int. J. Climatol* 38 (3), 1145–1160. doi:10.1002/joc.5231

Behrens Yamada, S., Peterson, W., and Kosro, P. (2015). Biological and Physical Ocean Indicators Predict the success of an Invasive Crab, *Carcinus maenas*, in the Northern California Current. *Mar. Ecol. Prog. Ser.* 537, 175–189. doi:10.3354/meps11431

Benabdi, M., Belmahi, A. E., and Grimes, S. (2019). First Record of the Atlantic Blue Crab *Callinectes sapidus* Rathbun, 1896 (Decapoda: Brachyura: Portunidae) in Algerian Coastal Waters (Southwestern Mediterranean). *Bioinvasions Rec.* 8 (1), 119–122. doi:10.3391/bir.2019.8.1.13

Beqiraj, S., and Kashta, L. (2010). The Establishment of Blue Crab *Callinectes sapidus* Rathbun, 1896 in the Lagoon of Patok, Albania (South-east Adriatic Sea). *AI* 5 (2), 219–221. doi:10.3391/ai.2010.5.2.16

Bouvier, E. (1901). Sur un *Callinectes sapidus* M. Rathbun trouvé à Rochefort. *Bull. du Muséum Natl. d'Histoire Naturelle* 7, 16–17. doi:10.5962/bhl.part.1625

Castejón, D., and Guerao, G. (2013). A New Record of the American Blue Crab, *Callinectes sapidus* Rathbun, 1896 (Decapoda: Brachyura: Portunidae), from the Mediterranean Coast of the Iberian Peninsula. *Bioinvasions Rec.* 2 (2), 141–143. doi:10.3391/bir.2013.2.2.08

Cerri, J., Chiesa, S., Bolognini, L., Mancinelli, G., Grati, F., Dragičević, B., et al. (2020). Using Online Questionnaires to Assess marine Bio-Invasions: A Demonstration with Recreational fishers and the Atlantic Blue Crab *Callinectes sapidus* (Rathbun, 1986) along Three Mediterranean Countries. *Mar. Pollut. Bull.* 156, 111209. doi:10.1016/j.marpolbul.2020.111209

Collin, S., Tweddle, J., and Shucksmith, R. (2015). Rapid Assessment of marine Non-native Species in the Shetland Islands, Scotland. *Bioinvasions Rec.* 4 (3), 147–155. doi:10.3391/bir.2015.4.3.01

Courchamp, F., Fournier, A., Bellard, C., Bertelsmeier, C., Bonnaud, E., Jeschke, J. M., et al. (2017). Invasion Biology: Specific Problems and Possible Solutions. *Trends Ecol. Evol.* 32 (1), 13–22. doi:10.1016/j.tree.2016.11.001

de Sá, J. P. M. (2007). *Applied Statistics Using SPSS, Statistica, MatLab and R. Germany*. Berlin: Springer Science & Business Media.

Dehnen-Schmutz, K., Boivin, T., Essl, F., Groom, Q. J., Harrison, L., Touza, J. M., et al. (2018). Alien Futures: What Is on the Horizon for Biological Invasions? *Divers. Distrib.* 24 (8), 1149–1157. doi:10.1111/ddi.12755

Delaney, D. G., Sperling, C. D., Adams, C. S., and Leung, B. (2008). Marine Invasive Species: Validation of Citizen Science and Implications for National Monitoring Networks. *Biol. Invasions* 10 (1), 117–128. doi:10.1007/s10530-007-9114-0

Ellul, T., Evans, J., and Schembri, P. J. (2019). Invasion Alert: Rapid Range Expansion of *Caulerpa Taxifolia* Var. *Distichophylla* in Maltese Waters (central Mediterranean). *Bioinvasions Rec.* 8 (2), 208–217. doi:10.3391/bir.2019.8.2.02

Encarnação, J., Morais, P., Baptista, V., Cruz, J., and Teodósio, M. (2019). New Evidence of marine Fauna Tropicalization off the Southwestern Iberian Peninsula (Southwest Europe). *Diversity* 11 (4), 48. doi:10.3390/d11040048

Encarnação, J., Teodósio, M. A., and Morais, P. (2021). Citizen Science and Biological Invasions: A Review. *Front. Environ. Sci.* 8, 303. doi:10.3389/fenvs.2020.602980

Eritja, R., Ruiz-Arrondo, I., Delacour-Estrella, S., Schaffner, F., Álvarez-Chachero, J., Bengoa, M., et al. (2019). First Detection of *Aedes Japonicus* in Spain: an Unexpected Finding Triggered by Citizen Science. *Parasites Vectors* 12 (1), 1–9. doi:10.1186/s13071-019-3317-y

Forward, R., Cohen, J. H., Darnell, M. Z., and Saal, A. (2005). The Circatidal Rhythm in Vertical Swimming of Female Blue Crabs, *Callinectes sapidus*, during Their Spawning Migration: A Reconsideration. *J. Shellfish Res.* 24, 587–590. doi:10.2983/0730-8000(2005)24[587:tcrivs]2.0.co;2

Forward, R., Tankersley, R., and Pochelon, P. (2003). Circatidal Activity Rhythms in Ovigerous Blue Crabs, *Callinectes sapidus*: Implications for Ebb-Tide Transport during the Spawning Migration. *Mar. Biol.* 142 (1), 67–76. doi:10.1007/s00227-002-0923-5

Gallo, T., and Waitt, D. (2011). Creating a Successful Citizen Science Model to Detect and Report Invasive Species. *BioScience* 61 (6), 459–465. doi:10.1525/bio.2011.61.6.8

Garel, E., Laiz, I., Drago, T., and Relvas, P. (2016). Characterisation of Coastal Counter-currents on the Inner Shelf of the Gulf of Cadiz. *J. Mar. Syst.* 155, 19–34. doi:10.1016/j.jmarsys.2015.11.001

Gaudêncio, M., and Guerra, M. (1979). Note sur la presence de *Callinectes sapidus* Rathbun 1896 (Crustacea Decapoda Brachyura) dans l'estuaire du Taje. *Boletim do Instituto Nacional de Investigação das Pescas* 2, 67–73.

Giovos, I., Kleitou, P., Paravas, V., Marmara, D., Romanidis-Kyriakidis, G., and Poursanidis, D. (2018). Citizen Scientists Monitoring the Establishment and Expansion of *Pterois miles* (Bennett, 1828) in the Aegean Sea, Greece. *Cahiers de Biologie Mar.* 59, 359–365. doi:10.21411/CBM.A.8DFA67CE

González-wangüemert, M., and Pujol, J. A. (2016). First Record of the Atlantic Blue Crab *Callinectes sapidus* (Crustacea: Brachyura: Portunidae) in the Segura River Mouth (Spain, Southwestern Mediterranean Sea). *Turk J. Zool* 40 (4), 615–619. doi:10.3906/zoo-1511-23

Grason, E., McDonald, S., Adams, J., Litle, K., Apple, J., and Pleus, A. (2018). Citizen Science Program Detects Range Expansion of the Globally Invasive European green Crab in Washington State (USA). *Manag. Biol. Invasions* 9 (1), 39–47. doi:10.3391/mbi.2018.9.1.04

Havel, J. E., Kovalenko, K. E., Thomaz, S. M., Amalfitano, S., and Kats, L. B. (2015). Aquatic Invasive Species: Challenges for the Future. *Hydrobiologia* 750 (1), 147–170. doi:10.1007/s10750-014-2166-0

Johnson, D. S. (2015). The Savory Swimmer Swims north: a Northern Range Extension of the Blue Crab *Callinectes sapidus*? *J. Crustacean Biol.* 35 (1), 105–110. doi:10.1163/1937240X-00002293

Mancinelli, G., Chainho, P., Cilenti, L., Falco, S., Kapiris, K., Katselis, G., et al. (2017). The Atlantic Blue Crab *Callinectes sapidus* in Southern European Coastal Waters: Distribution, Impact and Prospective Invasion Management Strategies. *Mar. Pollut. Bull.* 119 (1), 5–11. doi:10.1016/j.marpolbul.2017.02.050

Marchante, H., Morais, M. C., Gamela, A., and Marchante, E. (2017). Using a WebMapping Platform to Engage Volunteers to Collect Data on Invasive Plants Distribution. *Trans. GIS* 21 (2), 238–252. doi:10.1111/tgis.12198

Mehta, S. V., Haight, R. G., Homans, F. R., Polasky, S., and Venette, R. C. (2007). Optimal Detection and Control Strategies for Invasive Species Management. *Ecol. Econ.* 61 (2-3), 237–245. doi:10.1016/j.ecolecon.2006.10.024

Morais, P., Gaspar, M., Garel, E., Baptista, V., Cruz, J., Cerveira, I., et al. (2019). The Atlantic Blue Crab *Callinectes sapidus* Rathbun, 1896 Expands its Non-native Distribution into the Ria Formosa Lagoon and the Guadiana Estuary (SW-Iberian Peninsula, Europe). *Bioinvasions Rec.* 8 (1), 123–133. doi:10.3391/bir.2019.8.1.14

Morais, P., and Teodósio, M. (2016). The Transatlantic Introduction of Weakfish Cynoscion Regalis (Bloch & Schneider, 1801) (Sciaenidae, Pisces) into Europe. *Bioinvasions Rec.* 5 (4), 259–265. doi:10.3391/bir.2016.5.4.11

Moura, D., Albardeiro, L., Veiga-Pires, C., Boski, T., and Tigano, E. (2006). Morphological Features and Processes in the central Algarve Rocky Coast (South Portugal). *Geomorphology* 81 (3-4), 345–360. doi:10.1016/j.geomorph.2006.04.014

Nehring, S. (2011). "Invasion History and success of the American Blue Crab *Callinectes sapidus* in European and Adjacent Waters," in *In the Wrong Place - Alien Marine Crustaceans: Distribution, Biology and Impacts, 6*. Editors B. Galil, P. Clark, and J. Carlton (Dordrecht: Springer), 607–624. doi:10.1007/978-94-007-0591-3_21

Perdikaris, C., Konstantinidis, E., Gouva, E., Ergolavou, A., Klaoudatos, D., Nathanailides, C., et al. (2016). Occurrence of the Invasive Crab Species *Callinectes sapidus* Rathbun, 1896, in NW Greece. *Walailak J. Sci. Techn.* 13 (7), 503–510.

Pernat, N., Kampen, H., Jeschke, J. M., and Werner, D. (2021). Citizen Science versus Professional Data Collection: Comparison of Approaches to Mosquito Monitoring in Germany. *J. Appl. Ecol.* 58 (2), 214–223. doi:10.1111/1365-2664.13767

Poirier, L. A., Ramsay, A. P., St-Hilaire, S., and Quijón, P. A. (2017). Revisiting Recent History: Records of Occurrence and Expansion of the European green Crab across Prince Edward Island, Atlantic Canada. *Mar. Biodivers Rec.* 10 (1), 1–11. doi:10.1186/s41200-017-0132-z

Pyšek, P., and Richardson, D. M. (2010). Invasive Species, Environmental Change and Management, and Health. *Annu. Rev. Environ. Resour.* 35, 25–55. doi:10.1146/annurev-environ-033009-095548

QGIS.org (2021). QGIS Geographic Information System. QGIS Association. Available at: http://www.qgis.org. (Accessed September 01, 2021).

Rees, H. C., Maddison, B. C., Middleditch, D. J., Patmore, J. R. M., and Gough, K. C. (2014). REVIEW: The Detection of Aquatic Animal Species Using Environmental DNA - a Review of eDNA as a Survey Tool in Ecology. *J. Appl. Ecol.* 51 (5), 1450–1459. doi:10.1111/1365-2664.12306

Relvas, P., and Barton, E. D. (2002). Mesoscale Patterns in the Cape São Vicente (Iberian Peninsula) Upwelling Region. *J. Geophys. Res.* 107 (C10), 28-21–28-23. doi:10.1029/2000JC000456

Ribeiro, F., and Veríssimo, A. (2014). A New Record of *Callinectes sapidus* in a Western European Estuary (Portuguese Coast). *Mar. Biodivers. Rec.* 7, e36. doi:10.1017/S1755267214000384

RStudio Team (2021). *RStudio*. Boston, MA: Integrated Development for R. RStudio, PBC. Available at: http://www.rstudio.com/. (Accessed September 01, 2021).

Santos, J. F., Pulido-Calvo, I., and Portela, M. M. (2010). Spatial and Temporal Variability of Droughts in Portugal. *Water Resour. Res.* 46 (3). doi:10.1029/2009WR008071

Simberloff, D., and Rejmánek, M. (2011). *Encyclopedia of Biological Invasions*. Oakland, USA: University of California Press, 792.

Simpson, A., Jarnevich, C., Madsen, J., Westbrooks, R., Fournier, C., Mehrhoff, L., et al. (2009). Invasive Species Information Networks: Collaboration at Multiple Scales for Prevention, Early Detection, and Rapid Response to Invasive Alien Species. *Biodiversity* 10 (2-3), 5–13. doi:10.1080/14888386.2009.9712839

Streftaris, N., and Zenetos, A. (2006). Alien Marine Species in the Mediterranean - the 100 'Worst Invasives' and Their Impact. *Medit. Mar. Sci.* 7 (1), 87–118. doi:10.12681/mms.180

Streftaris, N., Zenetos, A., and Papathanassiou, E. (2005). "Globalisation in marine Ecosystems: The story of Non-indigenous marine Species across European Seas," in *Oceanography and Marine Biology: An Annual Review*. Editors R. N. Gibson, R. J. A. Atkinson, and J. D. M. Gordon (Boca Raton: Taylor & Francis), 43, 419–453.

Suaria, G., Pierucci, A., Zanello, P., Fanelli, E., Chiesa, S., and Azzurro, E. (2017). *Percnon Gibbesi* (H. Milne Edwards, 1853) and *Callinectes sapidus* (Rathbun, 1896) in the Ligurian Sea: Two Additional Invasive Species Detections Made in Collaboration with Local Fishermen. *Bioinvasions Rec.* 6 (2), 147–151. doi:10.3391/bir.2017.6.2.10

Tankersley, R. A., Wieber, M. G., Sigala, M. A., and Kachurak, K. A. (1998). Migratory Behavior of Ovigerous Blue Crabs *Callinectes sapidus*: Evidence for Selective Tidal-Stream Transport. *Biol. Bull.* 195 (2), 168–173. doi:10.2307/1542824

Taybi, A. F., and Mabrouki, Y. (2020). The American Blue Crab *Callinectes sapidus* Rathbun, 1896 (Crustacea: Decapoda: Portunidae) Is Rapidly Expanding through the Mediterranean Coast of Morocco. *Thalassas* 36, 267–271. doi:10.1007/s41208-020-00204-0

Vasconcelos, P., Carvalho, A. N., Piló, D., Pereira, F., Encarnação, J., Gaspar, M. B., et al. (2019). Recent and Consecutive Records of the Atlantic Blue Crab (*Callinectes sapidus* Rathbun, 1896): Rapid Westward Expansion and Confirmed Establishment along the Southern Coast of Portugal. *Thalassas* 35 (2), 485–494. doi:10.1007/s41208-019-00163-1

Verdes, A., Simpson, D., and Holford, M. (2017). Are Fireworms Venomous? Evidence for the Convergent Evolution of Toxin Homologs in Three Species of Fireworms (Annelida, Amphinomidae). *Genome Biol. Evol.* 10 (1), 249–268. doi:10.1093/gbe/evx279

ViaLivre (2021). ViaLivre. Available at: https://www.vialivre.pt/pt-pt/portagens/portagens-a22/(Accessed September 01, 2021).

World Weather Online (2021). World Weather Online. Available at: https://www.worldweatheronline.com/(Accessed September 01, 2021).

Zenetos, A., Koutsogiannopoulos, D., Ovalis, P., and Poursanidis, D. (2013). The Role Played by Citizen Scientists in Monitoring marine Alien Species in Greece. *Cahiers de Biologie Mar.* 54, 419–426. doi:10.21411/CBM.A.F59BBF3E

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.