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Citizens' Eyes on *Mnemiopsis*: How to Multiply Sightings with a Click!

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Abstract: Monitoring the spreading of marine invasive species represents one of the most relevant challenges for marine scientists in order to understand their impact on the environment. In recent years, citizen science is becoming more and more involved in research programs, especially taking advantage of new digital technologies. Here, we present the results obtained in the first 20 months (from 12 July 2019 to 8 March 2021) since launching avvistAPP. This new app was conceived to track the spreading of the invasive ctenophore *Mnemiopsis leidyi* in the Adriatic Sea; it was also designed to collect sightings of 18 additional marine taxa (ctenophores, jellyfish, sea turtles, dolphins, salps and noble pen shell). A total of 1224 sightings were recorded, of which 530 referred to *Mnemiopsis*, followed by the scyphozoan jellyfish *Rhizostoma pulmo* (22%), *Cotylorhiza tuberculata* (11%) and *Aurelia* spp. (8%). avvistAPP produced data confirming the presence of *Mnemiopsis* (often in abundances > 20 individuals m^{-2}) along almost the entire Italian coast in the summer of 2019 and 2020.

Keywords: *Mnemiopsis leidyi*; gelatinous zooplankton; non-indigenous species; citizen science

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1. Introduction

Mnemiopsis leidyi A. Agassiz, 1865 is a ctenophore listed by the International Union for Conservation of Nature (IUCN) as being among the 100 World's Worst Invasive Alien Species, due to its serious impact on biological diversity and human activities [1]. This planktonic gelatinous species is characterized by high reproductive rates [2–4] and high predation rates on zooplankton communities [5–7], giving *Mnemiopsis* the ability to severely impact the invaded ecosystems at ecological and economical levels [8–10].

Native to the Atlantic coast of the Americas, *M. leidyi* invaded the Black Sea in the early 1980s and, since then arrived in the Azov, Caspian, Marmara and Mediterranean Seas. Later, in 2005–2006, *Mnemiopsis* also invaded the North Sea and the Baltic Sea. As of now, it inhabits almost all European marine water bodies [11]. It was first reported in the northern Adriatic Sea (NAD), in October 2005 [12], although it disappeared from the water column soon after, only reappearing in the summer of 2016 [4]. Since then, *M. leidyi* has formed blooms in the NAD every year (2016, 2017, 2018, 2019 and 2020) ([4], unpublished data) and caused increasing problems for fisheries, especially in the lagoon areas.

Monitoring invasive species is essential to understand their impact on new environments, but it often represents a challenge for researchers, especially in marine ecosystems. This is particularly true for planktonic species that are transported by currents and are often difficult to observe in coastal areas. In recent years, the help given by ordinary people to researchers (the so-called marine citizen science, MCS) has played a fundamental role in supporting scientists, that could not collect the amount of data necessary to advance knowledge in a reasonable range of time due to scale, accessibility and variety of seas and oceans alone [13].

As digital capabilities and available technologies such as smartphones and internet connection are continuously improving, the opportunities to design projects where citizen scientists can participate are rapidly evolving. Therefore, it is not surprising that mobile phone applications have been reported as one of the emerging digital technologies recognized by UNEP [14,15]. Such applications are fundamental for the involvement in MCS when monitoring natural resources and anthropogenic impacts. As exampled in the Mediterranean Sea, the app Meteomedusa has allowed the reporting of jellyfish presence along the coasts of Italy in the period of 2009–2015 [16–18], while the Spanish app Infomedusa was adopted in 2015 as a tool for citizens to provide information on incidences of jellyfish swarms on beaches in Malaga (south-western Spain) [19]. Other examples of sightings reported by citizens to help in the observation and geographical distribution of jellyfish and algal blooms are listed by the European Marine Board [20]. These include the EU funded strategic project Med-Jellyrisk, for the introduction of measures to reduce the impact of jellyfish proliferation in the Mediterranean Sea, and Spot the Jellyfish, the Maltese project designed for younger citizens to record and locate jellyfish species in Malta.

Accurate species identification is one of the biggest limitations in projects involving non-expert volunteers' data collection. It is recommended that citizen scientists are trained where possible, or that clear instructions on physical characteristics of target taxa are provided [21]. This will ensure improved data quality. With this in mind, the distribution of a macroplanktonic species such as *M. leidyi* (also known as a sea walnut) perfectly fits within the context of a citizen science project: the species is easily recognizable, big enough to be seen by the naked eye, it floats near the surface, and is therefore visible from a boat or from the coastline, and it has the potential to be widespread both in- and off-shore. Thus, the success of previous citizen science projects for jellyfish monitoring encouraged us to test this approach by following the spreading of *M. leidyi* in the northern Adriatic using avvistAPP.

We developed avvistAPP in 2019 as part of the activities under the one-year project "Noce di Mare" (Sea Walnut) funded by the Regione Autonoma Friuli Venezia Giulia (Italy). The citizens' participation in avvistAPP encouraged us to maintain this app into 2020–2021, without any funds. Here, we present the data obtained by avvistAPP in its first 20 months of operation, from 12 July 2019 to 8 March 2021.

2. Materials and Methods

avvistAPP is a citizen science mobile app, which is freely downloadable for iOS and Android operating systems. The app is supported by a management system that receives the reports sent by the app and allows their organization, validation and representation into maps. Moreover, researchers can autonomously add and modify the species to be reported.

Conceived in 2019 to monitor the spreading of *Mnemiopsis leidyi* in the Gulf of Trieste (Italy), avvistAPP was also designed to collect sightings of jellyfish, sea turtles, dolphins and salps; since September 2020, this also included the noble pen shell *Pinna nobilis* Linnaeus, 1758 (Table 1). In addition, the category "Not identified" was created to signalize organisms not included in the app or not immediately identified. It can register sightings from everywhere and, thanks to the geolocation system of smartphones, the geographical coordinates of the sighting are collected automatically. This allows easy positioning on a map. The functioning of avvistAPP is not based on trained volunteers, but it provides information (simple text and pictures) which are useful for the identification of the targeted marine organisms and to avoid misidentifying (e.g., *M. leidyi* vs. *Bolinopsis vitrea* (L. Agassiz, 1860)). Citizens are asked to register by giving an e-mail address; they can then send their sightings simply by taking a photo with their mobile phone and sending it through the app, accompanied by information about the observed quantity of animals (presented as a range of abundances, see Table 1). They may also add an optional short text. A researcher validates each sighting and, once this step is completed, an email is sent to the user providing feedback about the correctness of the recorded sighting, stimulating the user to continue using the app. Occasionally, users have been also individually contacted by email

in the case of particularly interesting observations or if there was the need for additional information for validation.

Table 1. List of the taxa that can be reported with avvistAPP and their selectable abundance range.

Taxon	Abundance Range		
Mnemiopsis leidyi A. Agassiz, 1865 *Leucothea multicornis* (Quoy and Gaimard, 1824) *Beroe* spp. Muller, 1776 *Aequorea forskalea* Péron and Lesueur, 1810 *Aurelia* spp. Lamarck, 1816 *Cotylorhiza tuberculata* (Macri, 1778) *Rhizostoma pulmo* (Macri, 1778) *Carybdea marsupialis* (Linnaeus, 1758) *Chrysaora hysoscella* (Linnaeus, 1767) *Pelagia noctiluca* (Forsskål, 1775) Salps *Mawia benovici* (Piraino, Aglieri, Scorrano and Boero, 2014)	1 ind. m^{-2}	1–10 ind. m^{-2}	>20 ind. m^{-2}
Pinna nobilis Linnaeus, 1758	1–3 ind. m^{-2}	4–10 ind. m^{-2}	>10 ind. m^{-2}
Caretta caretta (Linnaeus, 1758) *Chelonia mydas* (Linnaeus, 1758) *Dermochelys coriacea* (Vandelli, 1761)	1–3 ind.	4–10 ind.	>10 ind.
Tursiops truncatus (Montagu, 1821) *Stenella coeruleoalba* (Meyen, 1833) *Delphinus delphis* Linnaeus, 1758	1–5 ind.	6–20 ind.	>20 ind.
Not identified	1–3 ind.	4–10 ind.	>10 ind.

avvistAPP was launched on 12 July 2019 and it was immediately promoted through scientific networks in Italy, interviews in newspapers and radio, public events and dissemination of postcards and posters (Figure 1). On 9 November 2019, a popular Italian television broadcaster ("Linea Blu") presented the situation of the *M. leidyi* invasion in the Grado and Marano Lagoon (Italy) and launched avvistAPP as a new tool for marine organisms monitoring by crowdsourcing. Moreover, in 2020, a marathon of sightings by avvistAPP was carried out from February to August 2020, within the framework of the ECSA2020 (European Citizen Science Association) conference. These events and the additional increase of media attention for avvistAPP strongly contributed to efficiently disseminate avvistAPP on a national level. Since the summer of 2020, an English version of the app was also made available, thus further broadening the breadth and impact of avvistAPP within the international community.

Figure 1. Example of a poster used to promote avvistAPP, showing its working. Step 1: download the app; step 2: register and log in; step 3: identify the organism; step 4: take a picture of the animal and send it through avvistAPP (if you are unable to take a photo of the animal seen, send us your report anyway by sending a photo of the place of the sighting); step 5: you will receive an email when researchers have validated your sighting.

3. Results and Discussion

3.1. avvistAPP: Citizens Partecipation

From 12 July 2019 to 8 March 2021, avvistAPP has been downloaded 2343 times (1108 and 1235 downloads through Apple Store and Google Play, respectively) (Figure 2). As expected, citizens downloaded avvistAPP mainly in the summer, when many people spend holidays at coastal marine locations in Italy. Promotion events for avvistAPP gave the possibility to engage more citizens in this initiative. For example, on 9 November 2019, the app was downloaded 684 times in a single day following a dedicated video aired during a television broadcast (Linea Blu, RAI1 Italy) (Figure 2).

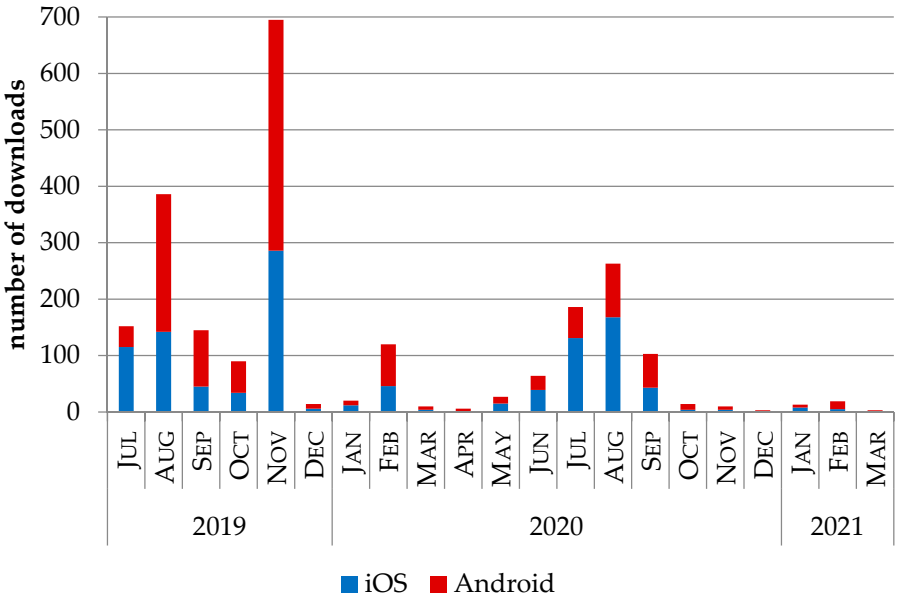

Figure 2. Number of downloads of avvistAPP per month.

Of the 971 registered users, 40% (385 users) sent at least one sighting, resulting in a total of 1224 sightings. The highest number of sightings were related to observations made along the Italian Adriatic coast (with a particular focus in the Gulf of Trieste) but several sightings also arrived from Croatia and Slovenia, as well as from the Tyrrhenian coast of Italy (Figure 3).

On average, avvistAPP received two sightings per day, but as expected, citizens concentrated their observations during the summer months. Each year, the highest number of sightings were sent during August, which is the time of year in Italy when most of the people are on holiday, usually by the coast, whilst the lowest number were registered in the coldest months (November, December and January) (Figure 4). Unexpectedly, sightings also arrived in spring 2020, when the COVID-19 pandemic strongly limited movement within Italy. This could partially find an explanation in the spur of the avvistAPP marathon (www.avvistapp.it; accessed on 30 April 2021).

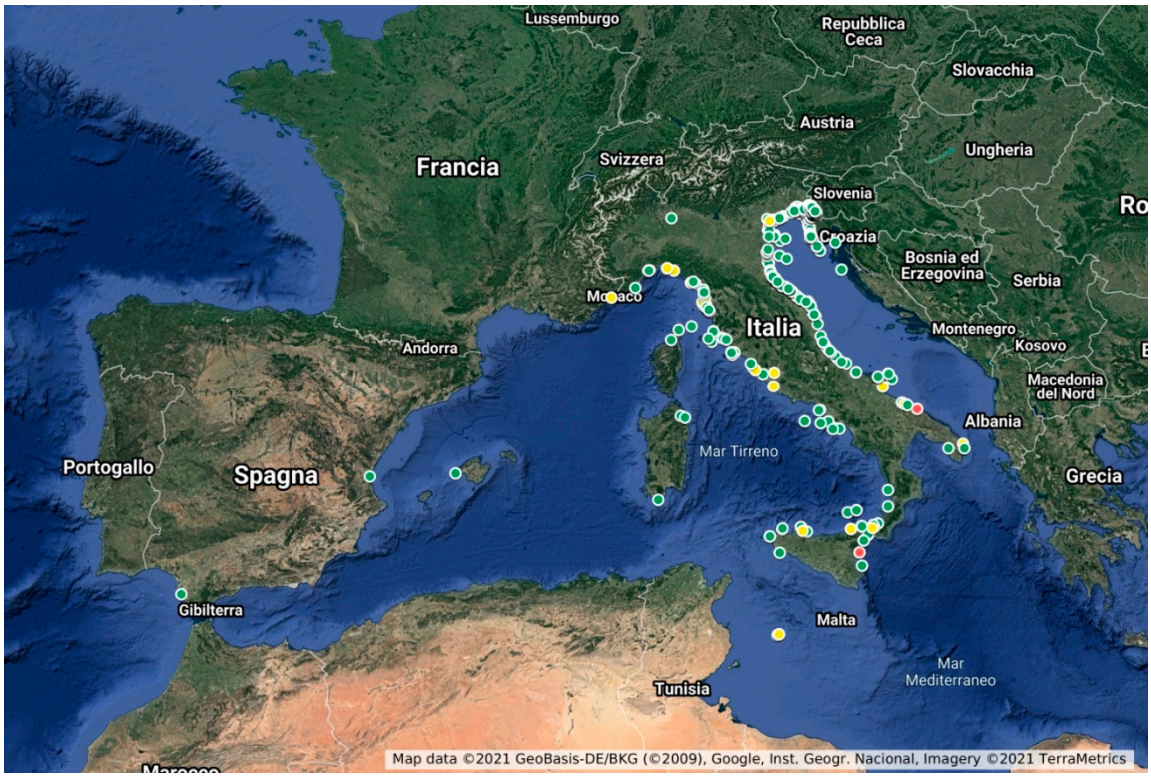

Figure 3. Map of the Mediterranean coast showing the locations of the sightings (green dot: correct sighting; yellow dot: incomplete sighting; red dot: wrong sighting).

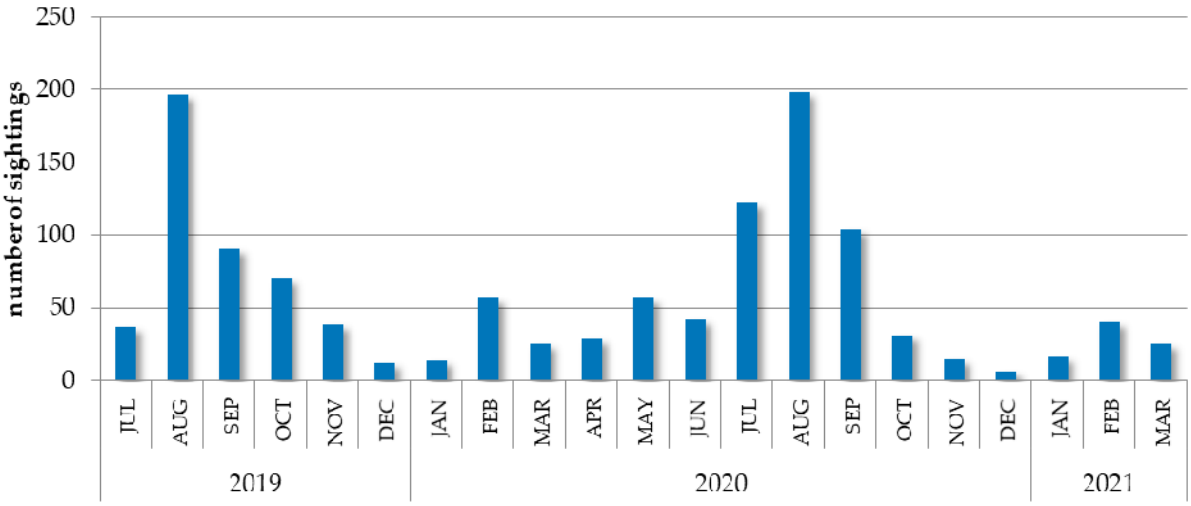

Figure 4. Monthly sightings from 12 July 2019 to 8 March 2021.

Overall, 97% of the received sightings (1188) were correct records, while only 0.7% were incorrect (eight sightings), or incomplete (e.g., species correctly identified, but incomplete information about area or time of the observation; 28 sightings). In total, 13 taxa were reported. The ctenophore *Mnemiopsis leidyi* was by far the most correctly observed species (45% of total correct sightings) followed by the scyphomedusae *Rhizostoma pulmo* (Macri, 1778) (22%), *Cotylorhiza tuberculata* (Macri, 1778) (11%) and *Aurelia* spp. Lamarck, 1816 (8%) (Figure 5).

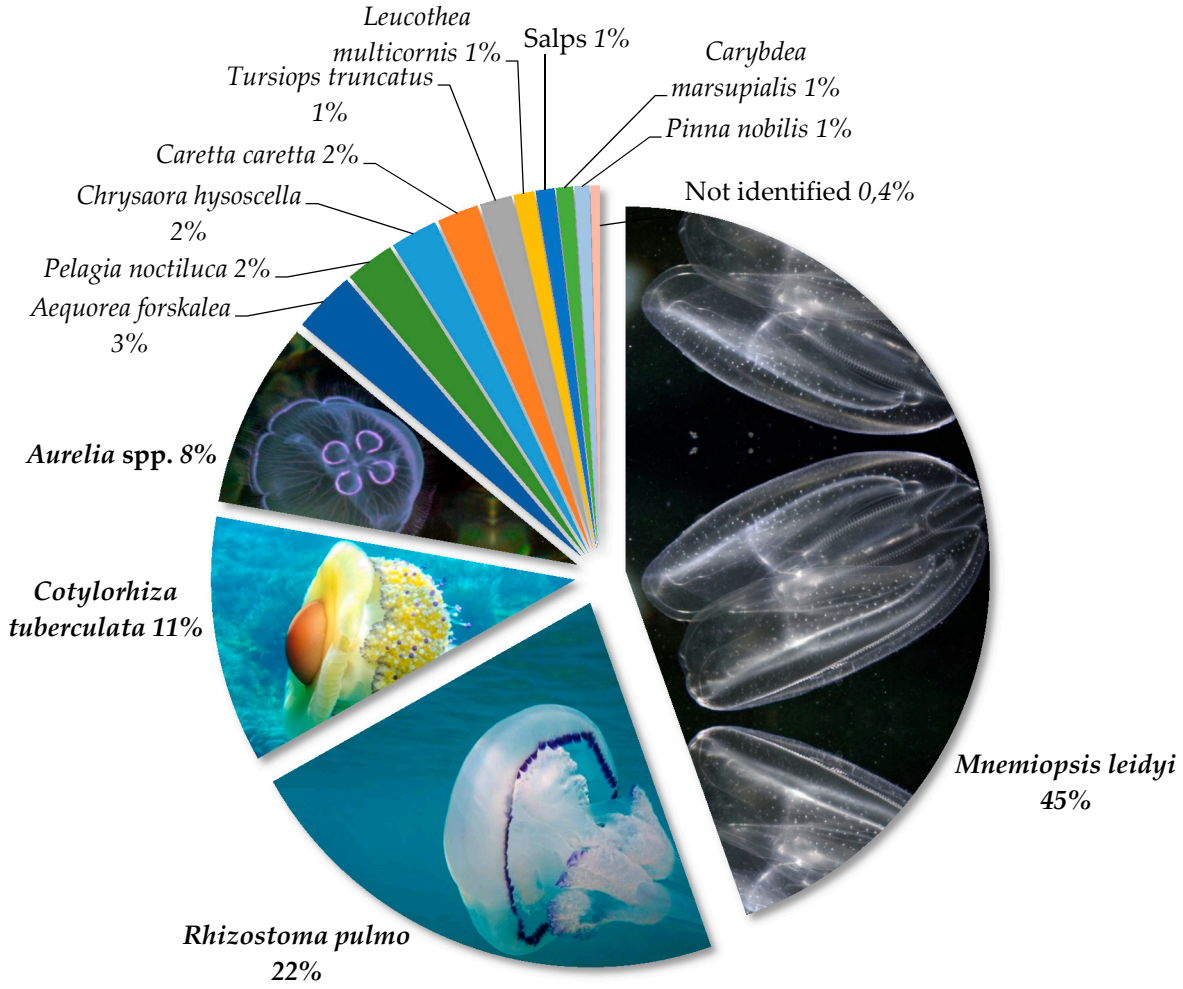

Figure 5. Reported taxa with avvistAPP from 12 July 2019 to 8 March 2021. Total sightings: 1188.

3.2. *Mnemiopsis leidyi*

Mnemiopsis leidyi was recorded for the first time along the Italian coast thanks to the citizen science initiative of the Jellywatch Programme. From May to September 2009, *M. leidyi* was spotted in the Ligurian Sea (where it also formed large aggregations) and in both the Tyrrhenian and Ionian Sea [22]. In the following six years (2010–2015), "Occhio alla medusa" campaigns collected sightings of *M. leidyi* from the western coast of Italy, where it was mainly observed in the summer time [17]. Despite the large participation in this citizen science initiative, no observation of *M. leidyi* were recorded in the Adriatic Sea, supporting the absence of this species in this area. Shiganova and Malej [12] had previously observed *M. leidyi* in 2005, in the Gulf of Trieste (northern Adriatic), although this ctenophore was not reported again in the Adriatic Sea before the summer of 2016 [4]. Hereafter, blooms of *Mnemiopsis* have been consistently observed along the eastern and western coasts of the Northern Adriatic in the summer months [4,23,24].

Overall, 530 sightings of the invasive ctenophore *M. leidyi* were sent through avvistAPP (Figure 6). The majority of sightings arrived from coastal locations (n = 505) but off-shore observations were also recorded (n = 25).

Figure 6. Map of sighting locations of *M. leidyi* and reported abundance range (yellow dot: 1 ind. m^{-2}; orange dot: 1–10 ind. m^{-2}; red dot: >20 ind. m^{-2}).

Mnemiopsis was mainly observed in warmer seasons (summer and early autumn) with a peak of observations in August (Figure 7). In these periods, *Mnemiopsis* was spotted mainly in large aggregations (1–10 ind. m^{-2}, or >20 ind. m^{-2}). The records of *M. leidyi* submitted during colder seasons (winter and spring) were more frequently related to sightings of single individuals (Figure 7, Table 2). avvistAPP received 43 sightings of this species in the period December–March, 91% of which arrived from the Gulf of Trieste. Winter sightings of *Mnemiopsis* were not recorded from the western coast of Italy, which is a similar trend to previous citizen science initiatives [17]. The presence of *Mnemiopsis* in the Adriatic is in agreement with results reported by Pierson et al. [25].

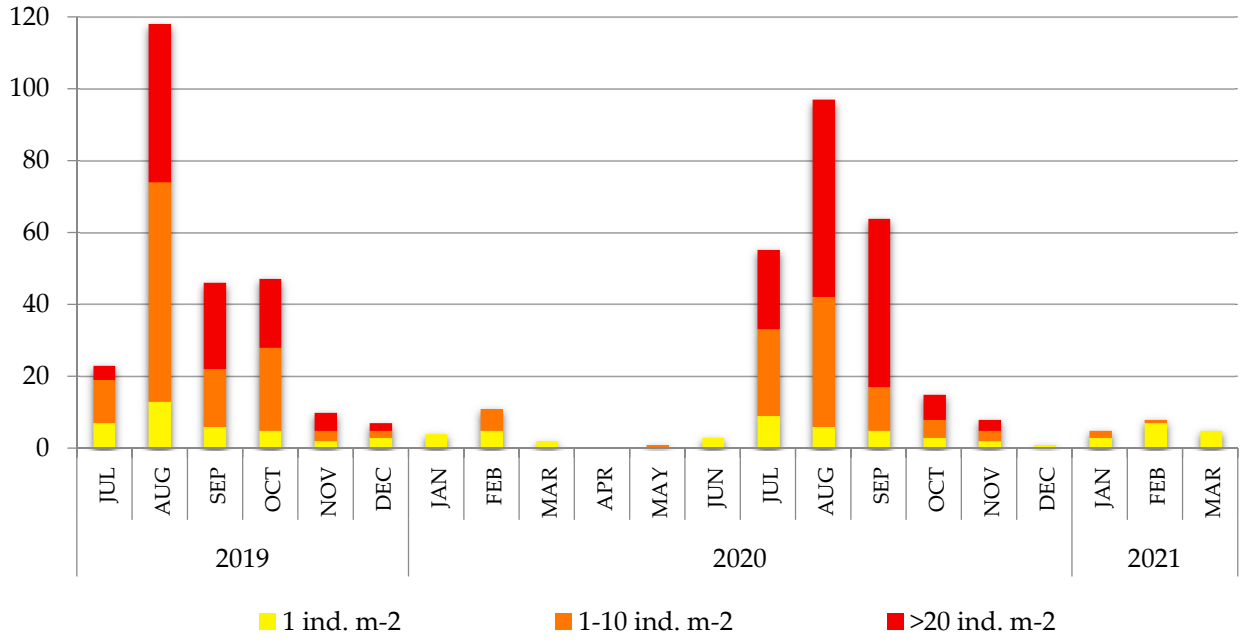

Figure 7. Number of sightings per month of *M. leidyi* and reported abundance range (yellow: 1 ind. m^{-2}; orange: 1–10 ind. m^{-2}; red: >20 ind. m^{-2}).

Table 2. Number of sightings collected for each signaled taxon. Sightings are separated per year and per reported abundance range.

Jellyfish	**2019**			**2020**			**2021**		
	1 ind. m^{-2}	**1–10 ind. m^{-2}**	**>20 ind. m^{-2}**	**1 ind.m^{-2}**	**1–10 ind.m^{-2}**	**>20 ind.m^{-2}**	**1 ind.m^{-2}**	**1–10 ind. m^{-2}**	**>20 ind. m^{-2}**
Mnemiopsis leidyi	36	117	98	40	8	134	15	3	
Leucothea multicornis		3		5	3				
Aequorea forskalea				10	4		12	7	
Aurelia spp.	1	1		52	35	6	1	1	1
Cotylorhiza tuberculata	52	8		40	26	4			
Rhizostoma pulmo	49	11		119	37	11	29	5	3
Carybdea marsupialis	4	1		4					
Chrysaora hysoscella	3			22					
Pelagia noctiluca	8	6	2	4	5	1			
Salps	4	1		3	2				
Molluscs	**1–3 ind. m^{-2}**	**4–10 ind.m^{-2}**	**>10 ind.m^{-2}**	**1–3 ind.m^{-2}**	**4–10 ind.m^{-2}**	**>10 ind.m^{-2}**	**1–3 ind.m^{-2}**	**4–10 ind.m^{-2}**	**>10 ind.m^{-2}**
Pinna nobilis				5		2		1	
Turtles	**1–3 ind.**	**4–10 ind.**	**>10 ind.**	**1–3 ind.**	**4–10 ind.**	**>10 ind.**	**1–3 ind.**	**4–10 ind.**	**>10 ind.**
Caretta caretta	13			8				1	
Dolphins	**1–5 ind.**	**6–20 ind.**	**>20 ind.**	**1–5 ind.**	**6–20 ind.**	**>20 ind.**	**1–5 ind.**	**6–20 ind.**	**>20 ind.**
Tursiops truncatus	6	2		8			1		

avvistAPP was designed for monitoring the spreading of this invasive ctenophore in the Gulf of Trieste, although sightings of *Mnemiopsis* arrived from almost the entire Italian coast (Figures 6 and 8b–d), with the exception of the coasts of Sardegna, Calabria and the southern part of Apulia. *Mnemiopsis* was reported along the western Adriatic coast, from Trieste (NAD) to south of Bari on the Apulian coast (Figure 8b), where it had never been observed before [26]; these sightings represent the southernmost observations of *M. leidyi* in the Adriatic Sea. Concerning the eastern Adriatic coast, sightings were sent mostly from the northernmost part of the basin, from the Slovenian and northern Croatian seashores. Numerous sightings of *M. leidyi* were sent from the Ligurian to the middle Tyrrhenian coasts. Several observations of *M. leidyi* were even sent from the Adriatic (Grado and Marano Lagoon and Venice Lagoon) and Tyrrhenian (Orbetello Lagoon) lagoons and the lake of Varano (southern Adriatic), confirming the importance of these brackish environments for this species [27].

Since its first observation in 2009 [22] (Figure 8a), *M. leidyi* has strongly enlarged its presence along the Italian coast (Figure 8b,c). In general, both in 2019 (July–December 2019) and 2020 (January–December 2020), the *M. leidyi* sighting locations corresponded, while in the winter of 2021 (January–8 March 2021), sightings were only obtained from the Gulf of Trieste (Figure 8d). Nonetheless, the interpretation of the latter results cannot disregard the fact that the COVID-19 pandemic restrictions have made it very difficult for both the promotion of avvistAPP and the mobility of citizens; therefore, we can not exclude the presence of *Mnemiopsis* in other areas.

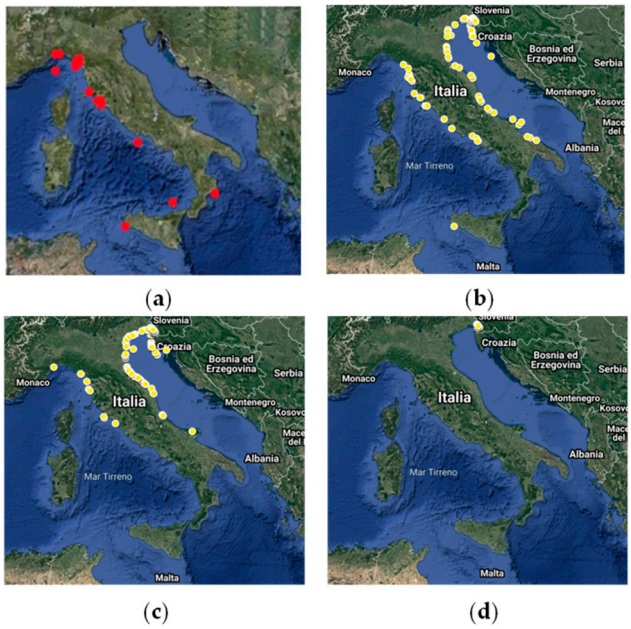

Figure 8. Maps of sighting locations of *M. leidyi*: (**a**) map with *M. leidyi* sightings modified after Boero et al. [20] received in summer 2009; (**b**) sightings sent through avvistAPP in 2019 (July–December 2019); (**c**) sightings sent through avvistAPP in 2020 (January–December 2020); (**d**) sightings sent through avvistAPP in 2021 (January–March 2021).

3.3. Other Gelatinous Taxa

The scyphozoan *Rhizostoma pulmo* was the second most reported taxon, with 264 sightings collected. Sightings of this species were sent throughout the entire examined period, from 12 July 2019 to 8 March 2021. The jellyfish was more frequently observed in February, May, July and August, whereas lower numbers of sightings were reported in November and December (Figure 9). *Cotylorhiza tuberculata* was spotted 130 times and solely from summer to the beginning of autumn (from July to October 2019 and 2020).

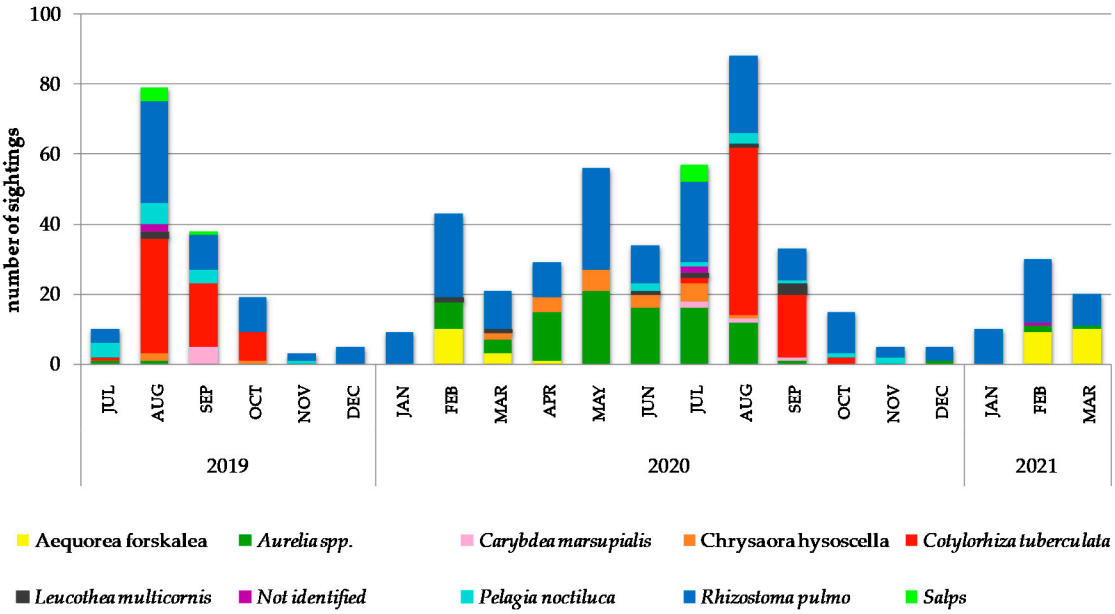

Figure 9. Sightings per month for reported gelatinous taxa other than *Mnemiopsis*.

Both *R. pulmo* and *C. tuberculata* were observed more frequently in the Adriatic Sea (Figure 10a,b) within the abundance range of 1 ind. m^{-2}, but *R. pulmo* was also observed in higher quantities (Table 2). *Aurelia* spp. was signalled mainly from February to September (2019 and 2020), with higher numbers of observations received for this scyphozoan from spring to midsummer (Figure 9). This taxon was mostly reported in the northern Adriatic (Figure 10c), both as isolated individuals and in the abundance range 1–10 ind. m^{-2}. *Aequorea forskalea* Péron and Lesueur, 1810 was only observed in February and March (Figure 9), both as single individuals and with abundances of 1–10 ind. m^{-2} (Figure 10d, Table 2).

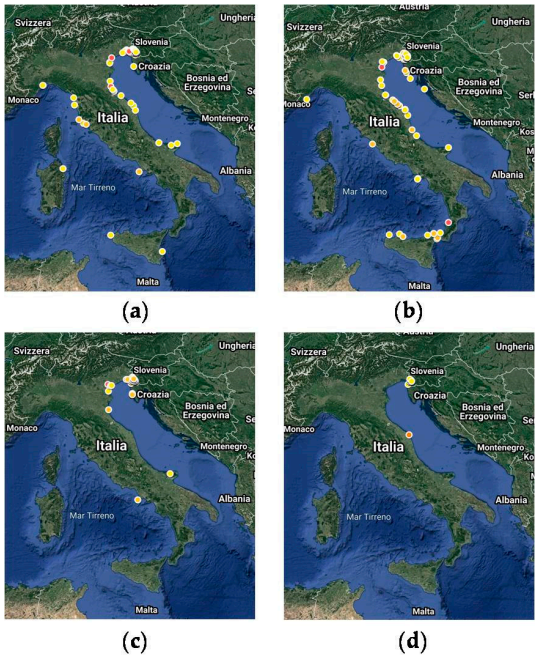

Figure 10. Maps of sighting locations with reported abundance range (yellow dot: 1 ind. m^{-2}; orange dot: 1–10 ind. m^{-2}; red dot: >20 ind. m^{-2}) for: (**a**) *R. pulmo*; (**b**) *C. tuberculata*; (**c**) *Aurelia* spp.; (**d**) *A. forskalea*.

Data from avvistAPP confirmed the seasonality previously reported for these gelatinous in the Adriatic Sea [25]. Other gelatinous organisms (scyphozoans *Carybdea marsupialis* (Linnaeus, 1758), *Chrysaora hysoscella* (Linnaeus, 1767), *Pelagia noctiluca* (Forsskål, 1775), the ctenophore *Leucothea multicornis* (Quoy and Gaimard, 1824) and salps were spotted less frequently, mainly from spring to the beginning of autumn, and generally as isolated individuals (Figure 9, Table 2).

3.4. Dolphins and Turtles

Out of the 1224 total sightings, 39 had marine turtles (22) and dolphins (17) as subjects of observations. *Caretta caretta* (Linnaeus, 1758) was the only species of turtle reported, usually as solitary specimens (range of abundance 1–3 for all the sightings reported). Both in 2019 and 2020, three dead floating animals were reported. *C. caretta* is the most common species of marine turtle in the Gulf of Trieste, which is considered to be an important feeding area [28] mostly frequented during the summer season. It is not surprising that the observations were also concentrated during this period (August–October in 2019 and June–October in 2020) (Figure 11). Sightings were distributed along the coastal area of the Gulf of Trieste with only two of them located off the area of the Po river mouth.

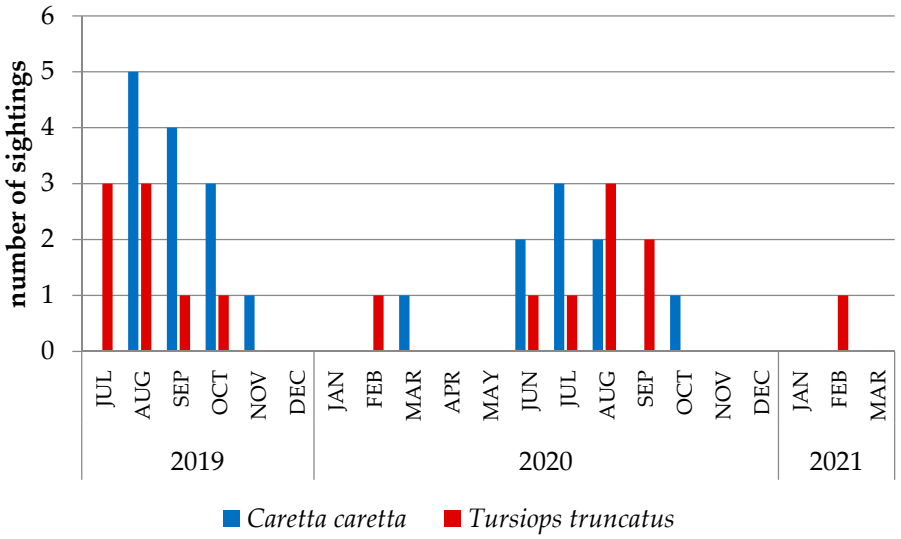

Figure 11. Number of sightings per month of marine turtles *C. caretta* and bottlenose dolphins *T. truncatus*.

As far as dolphins are concerned, we decided to insert in avvistAPP the three species (*Tursiops truncatus* (Montagu, 1821), *Stenella coeruleoalba* (Meyen, 1833) and *Delphinus delphis* Linnaeus, 1758) that frequented the area of the Gulf of Trieste in recent years. A population of bottlenose dolphins (*T. truncatus*) in the neighbouring Slovenian part of the Gulf has been subject to monitoring since 2002 [29], highlighting the fidelity to this area used for feeding and reproductive purposes all year long [30]. Genetics showed that this population is separated from the other groups living in the Adriatic [31] and, for this reason, knowing the range of movement of these animals is of utmost importance. The 17 sightings obtained with the app were of *T. truncatus*, always as solitary individuals or small groups (range of abundance 1–5) in 2019, 2020 and 2021, with two reports of groups of 6–20 individuals in 2019. Observations were concentrated during the summer months in 2019 and 2020, with one individual reported in February 2020 and one in February 2021. As for geographical distribution, the majority of reports were concentrated in the waters of the Gulf of Trieste and then 2 sightings in the Central Adriatic Sea and 2 sightings in the Tyrrhenian Sea around the islands of the Tuscan Archipelago were also reported.

3.5. Noble Pen Shell Pinna nobilis

The *Pinna nobilis* population in the Mediterranean is currently undergoing a severe mass mortality [32] and was listed as Critically Endangered in the IUCN Red List of Threatened Species [33]. Colleagues from the Marine Protected Area of Miramare (Italy) requested to include this species in the avvistAPP in order to evaluate its possible applicability in gaining insight from citizens about the presence of vital or dead individuals in the area of the Gulf of Trieste and, therefore, investigate the mass mortality phenomenon. Few sightings arrived in avvistAPP for this species until now, probably due to the recent introduction of this species in avvistAPP (September 2020) and the impossibility to promote it due to COVID-19 pandemic restrictions.

4. Conclusions

Citizen science programs can be effective ways in which to involve the public in management activities and strengthen positive attitudes towards the environment [34]. For this reason, many MCS projects have been supported to integrate research and monitoring programs in recent years [35].

Professional scientists need to explore their surroundings to gather information to advance knowledge, but time, budget and space [36] are becoming increasingly limited. People are not expected to become scientists, but have some interest in a specific issue and

want to help even only because it can be fun. avvistAPP takes advantage of this human curiosity towards the marine world and the interest in using smartphones and internet devices (Figure 12).

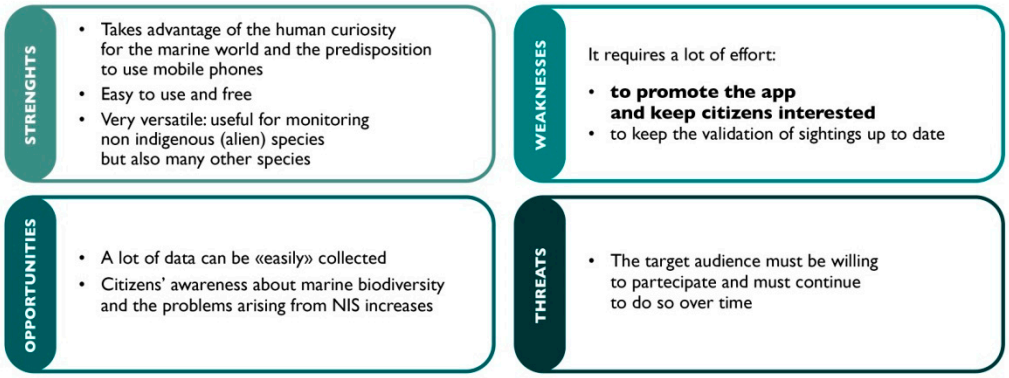

Figure 12. SWOT analysis of avvistAPP initiative.

The app is freely downloadable and easy to use and the uploaded pictures with short descriptions of the species to be sighted give citizens the opportunity to quickly learn information and details on them. This helps in raising citizens' awareness on marine biodiversity and, for *Mnemiopsis* in particular, to shed light on the problems arising from the presence of NIS (non-indigenous species). Another positive aspect of avvistAPP is the possibility to insert different species; the app was designed for monitoring the presence and distribution of gelatinous taxa (*Mnemiopsis*, above all), but it was also able to facilitate the generation of data related to mobile species (such as marine turtles and dolphins), as well as sessile species (such as the noble pen shell), which are listed as endangered and worthy of protection under international commitments.

The opportunity to obtain a large amount of data from the citizens via avvistAPP is not free of drawbacks. A considerable amount of work and time is required to (a) validate the sightings obtained from citizen scientists and keep them up to date and (b) maintain the interest of people to utilize the app over time. In only 20 months, avvistAPP provided important information, but a relaunch on a larger spatial scale is certainly needed. To this end, further efforts of collaboration among scientific institutions are advisable.

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