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## ORIGINAL ARTICLE

# Jellyfish diversity, trends and patterns in Southwestern Mediterranean Sea: a citizen science and field monitoring alliance

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Jellyfish (Cnidaria and Ctenophora) are an essential component of marine ecosystems and represent a potential effect, positive or negative, for several economic activities. Jellyfish blooms and non-indigenous species (NIS) introduction can shift ecological community structure and energy transfer. Despite their importance in ecosystem function and services, knowledge of jellyfish fauna diversity and phenology are largely lacking for the southern Mediterranean Sea. Here, we present an overview of the current state of jellyfish biodiversity in Tunisia. Based on a comprehensive literature survey, historical records and unpublished data, 66 jellyfish species, including 11 non-indigenous species, have been recorded in Tunisia between 1994 and 2020. Additionally, based on field surveys and a citizen science sighting program between 2004 and 2020, we present data on the spatial distribution of 13 conspicuous jellyfish taxa and the phenology of the eight most frequently detected species (*Aurelia solida*, *Cotylorhiza tuberculata*, *Pelagia noctiluca*, *Phyllorhiza punctata*, *Rhizostoma pulmo*, *Rhopilema nomadica*, *Olindias muelleri* and *Velella velella*) in Tunisian two ecoregions, the Western Mediterranean and the Tunisian Plateau. The 17 year survey showed a shift in *R. pulmo*, *A. solida* and *P. noctiluca* phenology. Additionally,

citizen science revealed an increase in the spatial range of *P. punctata* (NIS) and the distinct phenologies of populations in the two ecoregions.

**KEYWORDS:** Hydrozoa; Scyphozoa; Cubozoa; Ctenophora; phenology; spatial distribution; ecoregions; Tunisia

## INTRODUCTION

The Mediterranean Sea is considered a biodiversity hotspot (Coll *et al.*, 2010), characterized by a large proportion of endemic species and the coexistence of temperate and subtropical biota. Such biodiversity is threatened by climate change, habitat modification, resource exploitation, pollution, eutrophication and alien species (Bianchi and Morri, 2000). Overall, Mediterranean Sea biodiversity exhibits a northwestern-to-southeastern decreasing gradient of species richness in most of the phyla (Coll *et al.*, 2010), including Hydrozoa (Bouillon *et al.*, 2004). On the other hand, the non-indigenous species (NIS) display an opposite trend, with an increase of the species from the western to the eastern Mediterranean Sea (Galil *et al.*, 2018). This gradient is globally allocated to critical environmental factors, such as temperature, salinity, productivity and distance to the Strait of Gibraltar and the Suez Canal (Fredj, 1974; Quignard and Tomasini, 2000). However, this pattern might also be influenced by the uneven distribution of the research studies, the Southern Mediterranean Sea being less investigated than the northern regions. Tunisian waters are divided into two ecoregions (Spalding *et al.*, 2007). The north coast, including the Tunis Gulf, belong to the Western Mediterranean (WM) ecoregion. The eastern coasts, including the Gulfs of Hammamet, Gabès and Boughrara, belong to the Tunisian Plateau (TP). This geographical position, straddling the western and the central/eastern Mediterranean Seas, makes Tunisia an ideal location to investigate marine biodiversity, and its relationship with the different environments while being a lookout point for recording the NIS expansion between the two basins (Daly-Yahia *et al.*, 2013; Gueroun *et al.*, 2015a; Ounifi-Ben Amor *et al.*, 2016). Tunisia has one of the shallowest exclusive economic zone (EEZ) in the Mediterranean Sea, as its continental shelf represents 64.5% of the EEZ (66 000 m<sup>2</sup>) (Halouani *et al.*, 2015). For comparison, the continental shelf does not represent more than 32% of the EEZ in several Mediterranean countries (Pauly *et al.*, 2014).

The main proportion of this shelf is situated on the eastern and south coasts, the northern showing a shorter continental shelf and a steeper continental slope, followed in the north of EEZ by important canyons between Tunisia and Sardinia (Wurtz, 2010).

Among the zooplankton taxonomic groups, jellyfish, here referred to as Hydrozoa (species with exclusive benthic stage excluded), Scyphozoa, Cubozoa and Ctenophora, have led during the last decade a rise of interest in the Mediterranean Sea due to the various impacts of their mass proliferation, such high bathers stung records (Bordehore *et al.*, 2011) (e.g. 45 000 people stung in summer 2004 in Monaco (Purcell *et al.*, 2007)), tourism economic (Ghermandi *et al.*, 2015) and fisheries losses (Bosch-Belmar *et al.*, 2021). However, this interest increase is not only driven by their potential negative impacts but also by their ecology. Jellyfish, as a component of the ecosystem, play an essential role in the trophic web: they are renowned for their predation potential on a wide range of food items, including copepods, fish eggs and larvae, small fishes, and other gelatinous planktonic taxa (Purcell, 1999). They are also prey for several fishes, sea birds, sea turtles and scavengers (crustaceans) (Purcell and Arai, 2001; Orsi Relini *et al.*, 2010; Milisenda *et al.*, 2014; Sweetman *et al.*, 2014; Marques *et al.*, 2016). Several jellyfish species (e.g. *Cyanea* spp., *Rhizostoma* spp., *Chrysaora melanaster*, *Stygiomedusa gigantea*, *Catostylus mosaicus*, *Aurelia labiata*, *P. noctiluca*, *Velella* sp., *Porpita* sp., *Physalia physalis* and *Aequorea forskalea*) are associated with various organisms such as juveniles' fishes, copepods, amphipods and other crustaceans (Arai, 1997; Browne and Kingsford, 2005; Purcell and Greer *et al.*, 2018). For instance, in the Mediterranean Sea, *Trachurus mediterraneus*, *Trachurus trachurus* and *Caranx rhonchus* fishes are usually associated with the scyphozoan *R. pulmo* and *C. tuberculata* (Tilves *et al.*, 2018). The jellyfish hosts provide shelter to developing larval and juvenile fishes and, at the same time, represent a primary food source for the associated fish species (D'Ambra *et al.*, 2014), therefore promoting larval fish survival and recruitment.

In Tunisia, jellyfish impact has been little studied (Gueroun *et al.*, 2020), despite outbreaks (Fig. 1). Some of these gelatinous outbreaks already caused economic losses in some aquaculture farms in the Hegla and Mahdia areas, where tons of farmed fishes (*Dicentrarchus labrax* and *Sparus aurata*) were killed in 2009 and 2013 (Daly Yahia, personal observation) due to gill disorders induced by *P. noctiluca* envenomation (Bosch-Belmar *et al.*, 2016).

We present the first comprehensive checklist of Hydrozoa, Scyphozoa, Cubozoa and Ctenophora species on Tunisian coasts, obtained by combining field surveys and



**Fig. 1.** Examples of jellyfish bloom events in Tunisia. (A) *Pelagia noctiluca*, Bizerte, February 2012; (B) *Aurelia solida*, Bizerte lagoon, April 2014; (C) *Rhizostoma pulmo*, Gabès, May 2008; and (D) *Velella velella*, Bizerte, March 2014 (Photo credit. A, D: Mehdi Aissi; B: Sonia KM Gueroun; C: Mohamed Néjib Daly-Yahia).

citizen science. Additionally, we documented the spatial distribution of 13 taxa and the seasonal and interannual abundances of the eight most frequent jellyfish species over 17 years between 2004 and 2020.

## METHOD

Three datasets were used in the present study. Diversity data were extracted from the scientific literature and unpublished data, while scientific field surveys (published and unpublished data) and citizen science datasets were used to analyze the spatial distribution and phenology of the most conspicuous microspecies. For meroplanktonic species, only the pelagic stage is considered in the present study.

### Diversity data collection

The diversity dataset and spatial distribution were based on the compilation of the scientific literature published until August 2021, masters and PhDs thesis, citizen science records (see the section below) and unpublished data. The search mainly involved exploring the Google Scholar database for the following relevant keywords: “Hydrozoa”, “Scyphozoa”, “Cubozoa”, “Medusa”, “Ctenophore”, “jellyfish” associated (AND) with “Tunisia” and “South Mediterranean Sea” in English and French languages. Species taxonomic validity status, synonyms and names were checked on the World Register of Marine Species database (WoRMS) (Horton *et al.*, 2020). The classification adopted was proposed by Daly *et al.* (Daly *et al.*, 2007) for the Cnidaria phylum and from the WoRMS (in 2021) for the Ctenophora phylum.

### Phenology

Data on macroscopic (i.e. conspicuous) jellyfish (some Hydrozoa, Scyphozoa and Cubozoa) presence/absence and abundance between 2004 and 2020 were collected

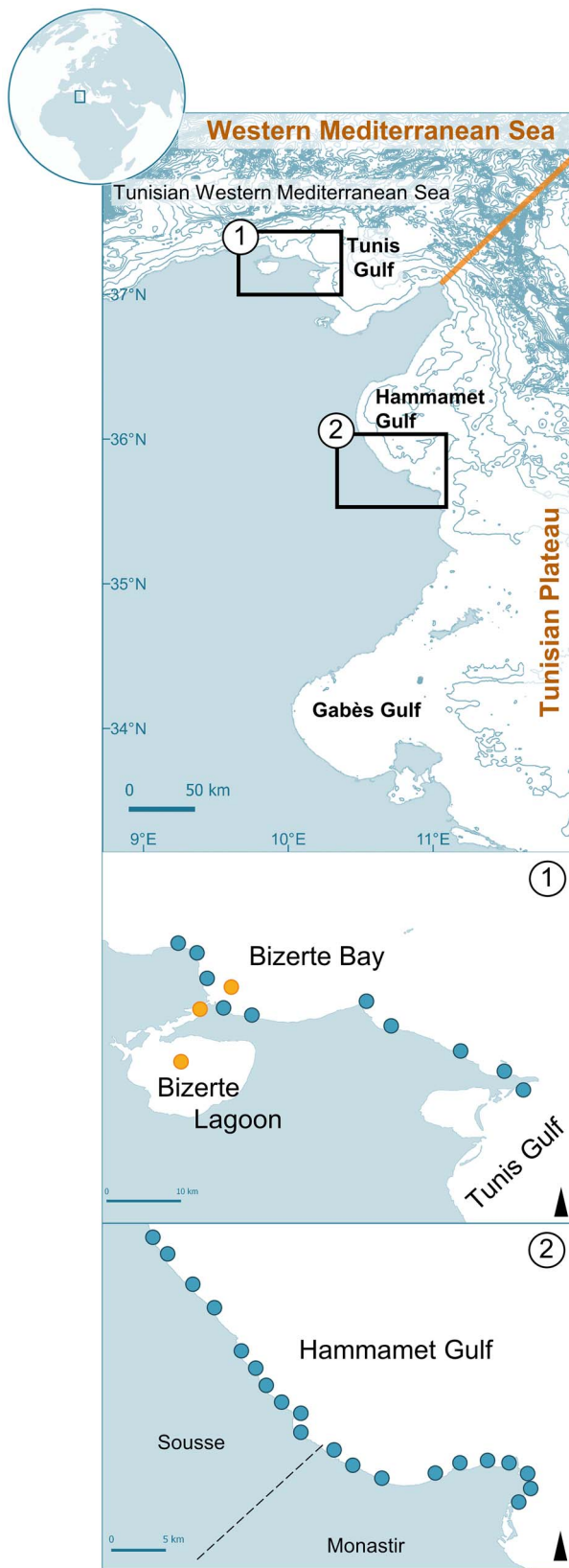
from scientific campaigns, citizen science reports and literature searches. The phenology of species only recorded once was not presented.

#### Scientific field campaigns

Scientific surveys were performed in three fixed stations (long-term survey), namely Bizerte Bay, Lagoon and Channel, during different periods: Bizerte Lagoon and Bay from 2004 to 2005 and from 2012 to mid-2016 and Bizerte Channel from 2004 to 2018. Moreover, thirty stations were added between 2013 to mid-2015, extending the survey on Bizerte, Sousse and Monastir coasts (Fig. 2). For offshore and seawater surveys (Bizerte Lagoon, Channel and Bay), abundances were assessed using a protocol developed by (Verity *et al.*, 2011) that consisted of visual counting from a boat running at a constant slow speed (1 kt) for a fixed distance (4.54 km). Over the transect, all medusae lying within 1 m on either side of the boat bow were counted. For simplicity, we considered that the observed medusae generally lie in the upper 1 m depth. For the other 30 stations, surveys were conducted along the coastlines, and specimens stranded or visible in the shallow water were identified and counted on 1 km of the shoreline in each station. The observation frequency varied weekly to monthly, depending on the stations and the season.

#### Citizen science

Citizen science has been promoted and introduced in our research strategy since 2013 in the framework of the ENPI-CBC-MED MEDJELLYRISK Project. To ensure a high degree of accuracy and quality of the collected data, mass-distributed species recognition tools such as identification guides and posters in Arabic and French languages (Supplementary 1), were distributed in early 2013 along with performing training sessions for stakeholders, lifeguards and various civilians’ associations (e.g. scouts, environmental associations). The posters



**Fig. 2.** Geographical areas where monthly to bi-monthly scientific jellyfish surveys were performed in Tunisia. Blue dots: beaches survey between 2013 and 2014; yellow dots: water survey between 2004 and 2016. Isobath: 50 m.

*Table I: Jellyfish abundance categories based on semi-quantitative and quantitative data*

Category	Citizen science report Semi-quantitative	Scientific field data Quantitative
0	No data	No data
1 (absence)	0 individual	0 ind.m <sup>-3</sup>
2 (rare, low)	1 individual	<0.1 ind.m <sup>-3</sup> <0.1 ind.m <sup>-2</sup>
3 (medium)	2–10 individuals	0.9–0.1 ind.m <sup>-3</sup> 0.9–0.1 ind.m <sup>-2</sup>
4 (high or bloom)	> 10 individuals	>1 ind.m <sup>-3</sup> >1 ind.m <sup>-2</sup>

presented the targeted species and the procedure for the report (date, location, number of specimens observed, joined the picture and video). Besides promotion in the field, a Facebook social network page, *Meduses. Tunisie* (<https://www.facebook.com/Meduses.Tunisie>) was created in May 2013. This public page presented all relevant information and guide for species identification, stinging potential, known season and spatial distribution along the Tunisian coast and treatment in case of stinging.

### Data treatment

For diversity analysis, genera with un-identified species (genus sp. or genus spp.) were removed from the analysis unless the genus was only recorded once.

For the phenology analysis, data compiled from scientific campaigns (published and unpublished data) and citizen science were standardized using Pestorić *et al.* (Pestorić *et al.*, 2021) semi-quantitative abundance index. Each month of the year is assigned a value between 0 and 4 according to the following criteria: 0—no data; 1—jellyfish are not seen at all; 2—low abundance; 3—medium abundance and 4—high abundance or outbreaks (Table I) (Leoni *et al.*, 2021; Pestorić *et al.*, 2021). Each value represents the highest semi-quantitative abundance index, regardless of the number of reports received (Pestorić *et al.*, 2021). The number of records per year, varying from 2 (2019) to 2573 (2013) on a total of 4532 observations and their origin (field survey or citizen science) are presented in Supplementary 2. Figures were generated with QGIS software (maps) (QGIS Development Team, 2021), R software (version 4.1.2) (R Core Team, 2021) and the associated package *ggplot2* (Wickham, 2016).

## RESULTS AND DISCUSSION

### Taxonomic composition

We compiled 66 recorded species belonging to the Hydrozoa, Scyphozoa, Cubozoa classes (phylum Cnidaria) and the phylum Ctenophora. Fifty-two species were recorded

Table II: Jellyfish checklist in Tunisia

Species	TWM	TP	Source
<b>CNIDARIA</b>			
<b>Hydrozoa</b>			
<b>Anthoathecata</b>			
<i>Bougainvillia muscus</i> Allman, 1863	●	○	1
<i>Cladonema radiatum</i> Dujardin, 1843	●	○	1
<i>Corymorpha nutans</i> M. Sars, 1835	●	○	3
<i>Paragotoea bathybia</i> Kramp, 1942	●	○	3
<i>Euphysa aurata</i> Forbes, 1848	●	●	2, 3
<i>Coryne eximia</i> Allman, 1859	●	●	3, 2, 8
<i>Stauridiosarsia ophiogaster</i> Haeckel, 1879	○	●	2
<i>Slabberia</i> sp. Forbes, 1846	○	●	2
<i>Stauridiosarsia gemmifera</i> Forbes, 1848	○	●	2
<i>Eucodonium browni</i> Hartlaub, 1907	●	○	1, 3
<i>Podocoryna carnea</i> M. Sars, 1846	●	○	1
<i>Fabienna oligonema</i> Kramp, 1955	●	○	1
<i>Odessia maeotica</i> Ostroumoff, 1896	○	●	2
<i>Niobia dendrotentaculata</i> Mayer, 1900	○	●	2
<i>Amphinema dinema</i> Péron and Lesueur, 1810	●	○	3
<i>Velella velella</i> Linnaeus, 1758	●	●	1, 2, 8
<i>Porpita porpita</i> Linnaeus, 1758	●	○	9
<i>Lizzia blondina</i> Forbes, 1848	●	○	1, 3, 8
<i>Podocorynoides minima</i> Trinci, 1903	●	●	2, 3
<i>Rathkea octopunctata</i> M. Sars, 1835	●	○	8
<i>Zanclaea costata</i> Gegenbaur, 1857	●	○	1
<b>Leptothecata</b>			
<i>Aequorea forskalea</i> Péron and Lesueur, 1810	●	○	3
<i>Clytia macrogonia</i> Bouillon, 1984	○	●	2
<i>Clytia hemisphaerica</i> Linnaeus, 1767	●	○	3
<i>Clytia mccradyi</i> Brooks, 1888	●	○	3
<i>Clytia</i> spp.	●	●	2, 3
<i>Obelia</i> spp.	●	●	2, 3
<i>Eutima gracilis</i> Forbes and Goodsir, 1853	●	○	3
<i>Eutima mira</i> McCrady, 1859	●	○	3
<i>Laodicea undulata</i> Forbes and Goodsir, 1853	○	●	2
<i>Eucheilota paradoxica</i> Mayer, 1900	●	○	3
<b>Siphonophorae</b>			
<i>Abylopsis tetragona</i> Otto, 1823	●	○	3, 8
<i>Bassia bassensis</i> Quoy and Gaimard, 1833	●	○	3
<i>Ceratocymba sagittata</i> Quoy and Gaimard, 1827	●	○	3
<i>Chelophyes appendiculata</i> Eschscholtz, 1829	●	●	2, 3
<i>Chelophyes</i> sp. Totton, 1932	○	●	2
<i>Diphyes chamissonis</i> Huxley, 1859	●	○	3
<i>Diphyes</i> sp. Cuvier, 1817	○	●	2
<i>Eudoxoides mitra</i> Huxley, 1859	●	○	3
<i>Eudoxoides spiralis</i> Bigelow, 1911	●	●	2, 3, 8
<i>Lensia conoidea</i> Keferstein and Ehlers, 1860	●	●	2, 3
<i>Lensia multicristata</i> Moser, 1925	○	●	2
<i>Lensia subtilis</i> Chun, 1886	●	○	8
<i>Muggiaea atlantica</i> Cunningham, 1892	●	●	2, 3
<i>Muggiaea kochii</i> Will, 1844	●	●	2, 3
<i>Physalia physalis</i> Linnaeus, 1758	●	○	9
<i>Sphaeronectes koellikeri</i> Huxley, 1859	●	●	2, 3
<b>Limnomedusae</b>			
<i>Liriope tetraphylla</i> Chamisso and Eysenhardt, 1821	●	○	3
<i>Geryonia proboscoidalis</i> , Forsskål, 1775	●	○	8
<i>Gossea</i> sp. L. Agassiz, 1862	○	●	2
<i>Olindias muelleri</i> Haeckel, 1879	●	●	2, 8, 9
<b>Narcomedusae</b>			
<i>Solmaris corona</i> Keferstein and Ehlers, 1861	●	○	8
<i>Solmundella bitentaculata</i> Quoy and Gaimard, 1833	●	○	3
<b>Trachymedusae</b>			
<i>Aglaura hemistoma</i> Péron and Lesueur, 1810	●	○	3
<i>Sminthea eurygaster</i> Gegenbaur, 1857	●	○	1
<i>Rhopalonema velatum</i> Gegenbaur, 1857	●	○	3

(Continued)

Table II: Continued

Species	TWM	TP	Source
<b>Scyphozoa</b>			
<b>Semaeostomeae</b>			
<i>Aurelia solida</i> Browne, 1905	●	○	3, 8
<i>Pelagia noctiluca</i> Forsskål, 1775	●	●	2, 3, 9
<b>Rhizostomeae</b>			
<i>Cotylorhiza tuberculata</i> Macri, 1778	●	●	3, 9
<i>Phyllorhiza punctata</i> von Lendenfeld, 1884	●	●	5, 7
<i>Rhizostoma pulmo</i> Macri, 1778	●	●	2, 3, 9
<i>Rhopilema nomadica</i> Galil, Spanier and Ferguson, 1990	●	●	4
<i>Stomolophus meleagris</i> Agassiz, 1860	●	○	4
<b>Cubozoa</b>			
<b>Carybdeida</b>			
<i>Carybdea marsupialis</i> Linnaeus, 1758	○	●	6, 9
<b>CTENOPHORA</b>			
<b>Nuda</b>			
<b>Beroida</b>			
<i>Beroe</i> sp. Milne Edwards, 1841	●	○	9
<b>Tentaculata</b>			
<b>Lobata</b>			
<i>Leucothea</i> sp. Mertens, 1833	○	●	9

Source: 1: (Daly-Yahia *et al.*, 2003); 2: (Touzri *et al.*, 2004); 3: (Touzri *et al.*, 2012); 4: (Daly-Yahia *et al.*, 2013); 5: (Gueroun *et al.*, 2015a); 6: (Gueroun *et al.*, 2015b); 7: (Rabaoui and El Zrelli, 2017); 8: (Gueroun, 2012); 9: present study. TWM: Tunisian Western Mediterranean Sea; TP: Tunisian Plateau. ●: recorded; ○: not recorded

in the Tunisian Western Mediterranean (TWM) ecoregion and 31 species in the Tunisian Plateau ecoregion (TP) (Tables II and III).

A total of 57 Hydrozoa species belonging to 45 genera, 27 families and six orders were recorded in Tunisia (Fig. 3). Anthoathecata was the most speciose order at the highest taxonomic level, with 21 species in 20 genera. The other speciose orders included Siphonophorae with 16 species in 10 genera and Leptothecata with 10 species in 6 genera. Seven species of Scyphozoa belonging to seven genera and six families were recorded in Tunisia: *A. solida*, *P. noctiluca*, *R. pulmo*, *Rhopilema nomadica*, *Stomolophus meleagris*, *C. tuberculata* and *P. punctata*. All species belonged to the sub-Class of Discomedusae, with Rhizostomeae the most speciose order with four species, *R. pulmo* and *R. nomadica* (Rhizostomidae family), *P. punctata* (Mastigiidae family) and *S. meleagris* (Stomolophidae family). Only one Cubozoa species, *Carybdea marsupialis*, was recorded. Ctenophora diversity was represented by two species, *Beroe* sp. and *Leucothea* sp.

Several families (66%) were represented by a single species: 20 (66.6%) in the TWM ecoregion and 17 (71%) in the TP ecoregion. The most speciose Hydrozoa family was the Diphyidae (Siphonophorae) with 11 species, eight species in each of the TWM and TP ecoregions. *Clytia* (Campanulariidae, Hydrozoa) was the most speciose genus with three species (Table III). Overall, jellyfish in Tunisia were dominated by meroplanktonic species (61%), a pattern observed in both TWM (59%) and TP (61%) ecoregions. In both Tunisian ecoregions (TWM

and TP), the Anthoathecata dominated the meroplankton community (35.1%), while Siphonophorae were the most speciose holoplankton order (28.1%).

Only 17 species (26%) were common between the two ecoregions mainly hydrozoan (12 species, 21.4% of the Hydrozoa). Among the six Scyphozoa observed in Tunisia, only *A. solida* was not recorded in the TP.

Tunisian jellyfish diversity included 11 Non-Indigenous Species (NIS). Seven were Hydrozoa (12.3%), namely *Coryne eximia*, *Fabienna oligonema*, *Clytia mccradyi*, *Eutima mira*, *Diphyes chamissonis*, *Eucoilota paradoxical* and *P. physalis*, and four were Scyphozoa (67%), namely *A. solida*, *P. punctata*, *R. nomadica* and *S. meleagris*.

Jellyfish diversity in the Mediterranean Sea has been estimated to be 510 species, including 457 hydrozoans (Bouillon *et al.*, 2004), 20 scyphozoans and one cubozoan (while old samples suggested more cubozoan species) (Acevedo *et al.*, 2019) and 32 ctenophores (Pestorić *et al.*, 2021). Based on the jellyfish diversity checklist collected in the present study, Tunisian jellyfish diversity only represents 12.7% of the total Mediterranean jellyfish diversity. More specifically, 12.5% of the hydrozoans, 30% of the scyphozoans and 6.3% of the ctenophores. Compared to other investigated areas in the Mediterranean Sea, Tunisian jellyfish exhibit a low diversity. Total non-siphonophore Hydrozoa, the most speciose taxa, did not exceed 40 species in Tunisia waters while 51 species were recorded only in the Salento Peninsula (Italy) (Gravili *et al.*, 2015) and 54 species on the Catalan coast (Guerrero *et al.*, 2018). This low species number is more likely to be

Table III: Jellyfish diversity (*Hydrozoa*, *Scyphozoa*, *Cubozoa* and *Ctenophora*) along Tunisian coasts

	Tunisia	TWM	TP
No. of species			
All	66	52	31
Hydrozoa	56	44	24
Scyphozoa	7	7	5
Cubozoa	1	0	1
Ctenophora	2	1	1
No. of genera			
All	54	52	12
Hydrozoa	45	45	8
Scyphozoa	7	7	2
Cubozoa	1	0	1
Ctenophora	2	1	1
Range of species per genus	1-3	1-2	1-2
Most speciose	<i>Clytia</i> , <i>Lensia</i>	<i>Clytia</i> , <i>Eutima</i> , <i>Eudoxoides</i> , <i>Lensia</i> , <i>Muggiaea</i>	<i>Lensia</i> , <i>Muggiaea</i>
No. of family			
All	36	30	17
Hydrozoa	27	23	11
Scyphozoa	7	7	5
Cubozoa	1	0	1
Ctenophora	2	1	1
Range of species per family	1-9	1-8	1-5
Most speciose	Diphyidae	Diphyidae	Diphyidae
Life strategy			
No. of meroplankton (%)	40 (61%)	30 (59%)	19 (61%)
No. of holoplankton (%)	26 (40%)	22 (43%)	12 (39%)

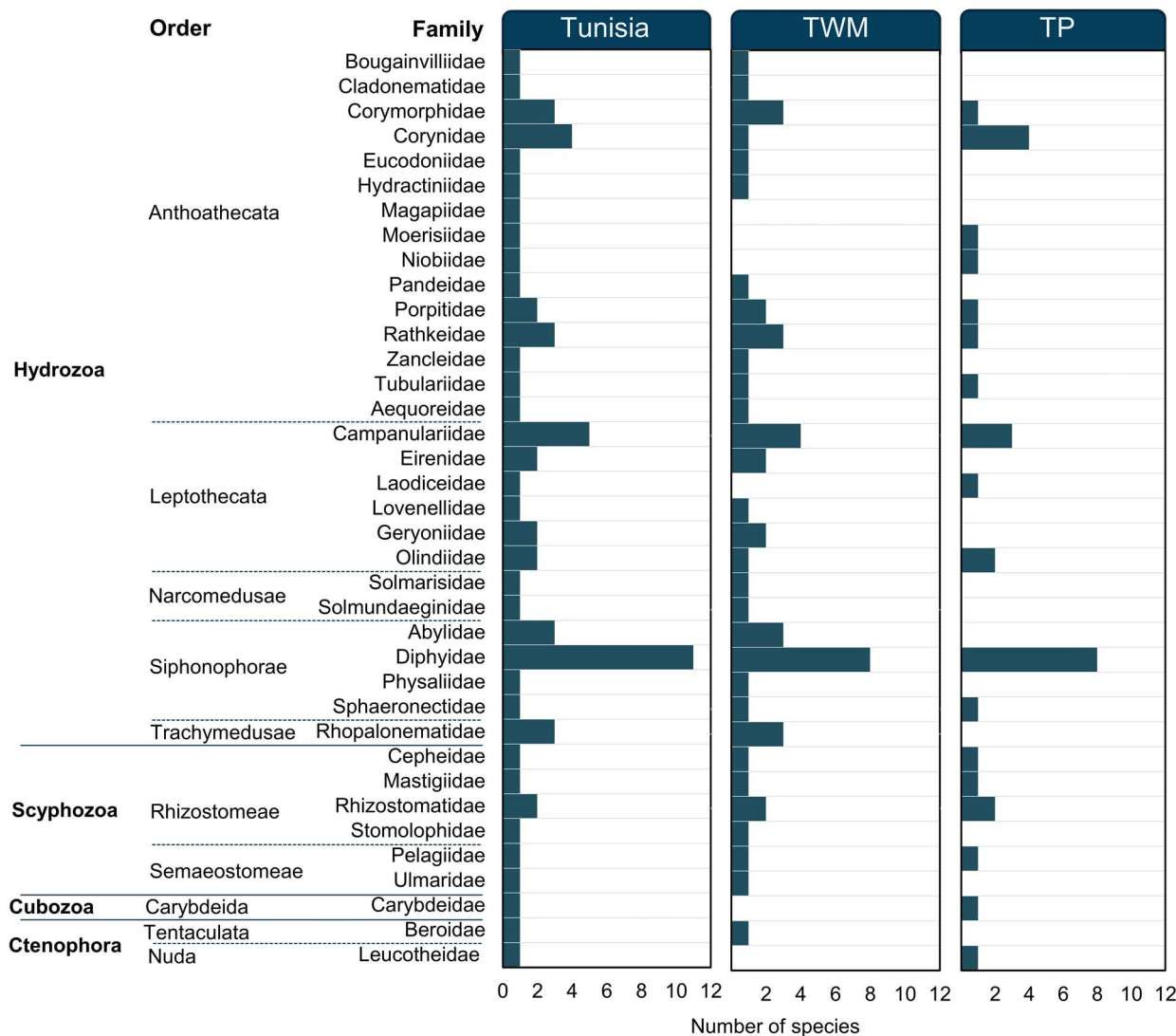
TWM: Tunisian Western Mediterranean Sea; TP: Tunisian Plateau

related to the few studies in the area than the northern Mediterranean shores than a true low richness. The unevenness in Hydrozoa biodiversity research within the Mediterranean Sea has already been highlighted (Bouillon *et al.*, 2004). The higher speciosity of Hydrozoa in the Western Mediterranean than in the Eastern basin seems to be related to a higher sampling effort (Bouillon *et al.*, 2004). In Tunisia, the same pattern in Hydrozoa richness is noticed between the northern and eastern shores. Most of the jellyfish taxa (78.5%) have been recorded in the north Tunisian shores (TWM) due to more extended history in biodiversity investigations than on the Eastern coasts, reflecting by publications number and sampling efforts. Hydrozoa diversity on the eastern shores was the result of 6 sampling campaigns performed from 2001 to 2002 (Tourzi *et al.*, 2004), while 53 campaigns were conducted on the north coasts between 1993 and 2012 (Daly-Yahia *et al.*, 2003; Gueroun, 2012; Touzri *et al.*, 2012), additionally to the monthly and bi-monthly survey dedicated for the Scyphozoa phenology.

Nonetheless, the taxonomic checklist is likely not complete in the TWM and certainly not in the TP. Due to the jellyfish life cycle and seasonality, a single sample in a given area cannot report a complete species list. Moreover, the pelagic stage of some hydrozoan species exhibits brief occurrence period and can be absent for several years (Bouillon *et al.*, 2004). Overall, diversity monitoring should be not limited in time. Climate change,

habitat alterations, NIS and invasive alien species introduction and species expansion unceasingly lead to biodiversity modification (Mannino *et al.*, 2017; Guerrero *et al.*, 2018). These changes drive modifications in the ecosystem's structure and functioning, potentially affecting the ecosystem service and social-economical ground (Gaines *et al.*, 2019; Bahri *et al.*, 2021). While Hydrozoa and Scyphozoa diversity is limited by the sampling frequency and the covered area, knowledge of ctenophore richness has been restricted by the sampling technics. Except for the specimens recorded from beach strandings or conspicuous swarms (Daly Yahia *et al.*, 2013), jellyfish studies performed in Tunisia used classical plankton nets (Daly-Yahia *et al.*, 2003; Touzri *et al.*, 2004, 2010; Gueroun, 2012; Gueroun *et al.*, 2015a, b), which do not suit the ctenophores' body fragility (Raskoff *et al.*, 2003). Indeed, the only ctenophores records in Tunisia have been done through snorkeling, diving and opportunistic surface sampling using jars (Gueroun, personal observation).

Most hydrozoan species recorded in Tunisia are meroplanktonic, reflecting the global and western Mediterranean Sea Hydrozoa diversity (Gili and Pagès, 1987; Bouillon *et al.*, 2004; Sabatés *et al.*, 2010). While the trend may be attributed to sampling campaigns that did not exceed 100 m depth (Tunis Bay), mero- or holoplanktonic hydrozoan predominance has been associated with geologic features (e.g. depth and extension of the continental shelf) (Sabatés *et al.*, 2010; Gueroun *et al.*, 2021). Another



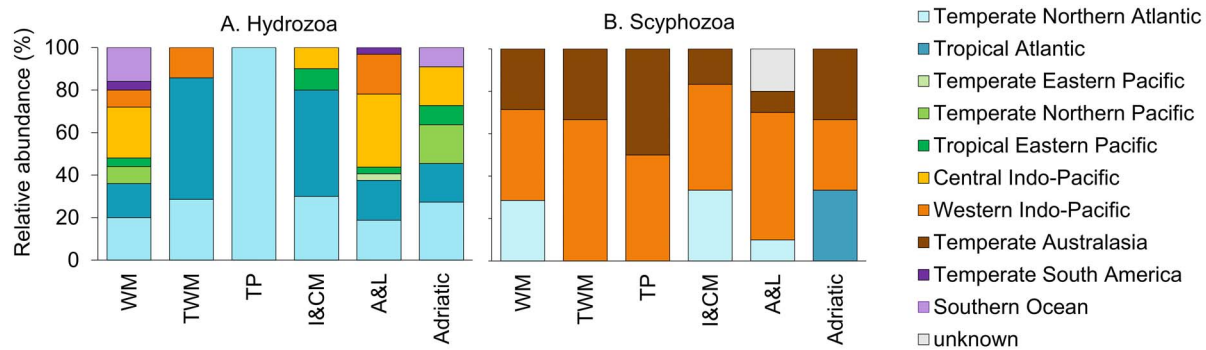
**Fig. 3.** Hydrozoans, scyphozoans, cubozoan and ctenophores diversity by families across Tunisia. TWM: Tunisian Western Mediterranean Sea, TP: Tunisia Plateau.

consequence of the shallow sampling is the absence of Coronatae (Coronamedusae) records. At least five mesobathypelagic scyphozoans occur in the Mediterranean Sea, namely *Nausithoe marginata*, *N. punctata*, *Paraphyllina ransoni*, *Paraphyllina rubra* and *Periphylla periphylla* (Isinibilir *et al.*, 2010; Pestorić *et al.*, 2021). While the continental shelf represents 64.5% of the Tunisian EEZ, the presence of canyons (Wurtz, 2010) in the northern area of the international zone between Tunisia and Sardinia could be the host of deep jellyfish species (Bouillon *et al.*, 2004).

Non-indigenous jellyfish (Hydrozoa and Scyphozoa) recorded in Tunis, represented 15% of total diversity. Their native distribution differs depending on the taxonomic classification: Indo-Pacific for Scyphozoa NIS and Atlantic origin for Hydrozoa NIS (except for *D.*

*chamissonis* with Indo-Pacific origin). The native distribution of Tunisian scyphozoans NIS follows the general trend observed in the Mediterranean Sea (Fig. 4) (except Adriatic) (Gravili and Rossi, 2021). On the other hand, the hydrozoans NIS patterns observed in TWM and TP ecoregion differ from the general trend in their respective biogeographic realm (Fig. 4). In fact, while hydrozoans NIS in the Western Mediterranean ecoregion are mainly native from the Central Indo-Pacific (24%) and Temperate Northern Atlantic (20%), Tunisia hydrozoans NIS are principally exhibiting a tropical Atlantic origin (*C. mccradyi*, *E. paradoxica*, *E. mira*, *Fabienna oligonema*) (Gravili and Rossi, 2021). The different patterns noticed between TWM and the Western Mediterranean Sea hydrozoan NIS might either be due to the investigation paucity in





**Fig. 4.** Proportion of the major native distribution ranges of (A) hydrozoans and (B) scyphozoans non-indigenous species in the Mediterranean ecoregions (following Spalding *et al.* (Spalding *et al.*, 2007) for biogeographic realms classifications). Data on native distribution were extracted from Gravili and Rossi (Gravili and Rossi, 2021). Species with only hydroid stage were excluded. WM: Western Mediterranean Sea; TWM: Tunisian Western Mediterranean Sea; TP: Tunisian Plateau; I&CM: Ionian and Central Mediterranean Sea; A&L: Aegean and Levantine Sea (note: *Stomolophus meleagris* is not considered as the species was never reported after its unique observation).

the studied area (Tunisia) or be an additional clue to the tropicalization of the Western Mediterranean Sea (Logan *et al.*, 2002; Bianchi and Morri, 2003). Although the sparse data do not allow the detection of a potential shift in the hydrozoan's phenology and spatial distribution in Tunisia, records collected through Citizen Sciences provided updates on the temporal and spatial distribution of macroscopic species.

## Geographical and temporal distribution of the macro-jellyfish

### Hydrozoa

*V. velella* and *O. muelleri* are the two most common conspicuous hydrozoans on Tunisian coasts, while *Porpita porpita* and *P. physalis* have rarely been observed only in TWM. *V. velella* and *O. muelleri* have been recorded in TWM and TP (Fig. 5). *O. muelleri* displayed a southernmost distribution while *V. velella* blooms were recorded in the TWM, mainly in the Bizerte region. The colonial *V. velella* occurred during spring, from March to June, while *O. muelleri* were always recorded in summer, from July to September (Fig. 6). Despite frequent mass strandings of *V. velella* (Sibley, 2007; Purcell *et al.*, 2015), little is known about their potential impact on the trophic web; the colonies mainly capture non-motile prey as fish eggs and euphausiid eggs, as well as fish and euphausiid larvae, copepods and cladocerans (Purcell *et al.*, 2015; Zeman *et al.*, 2018; Rodrigues *et al.*, 2020). Moreover, little is known about its ecology (colony and hydromedusa stages) and the ecological impact of their mass stranding.

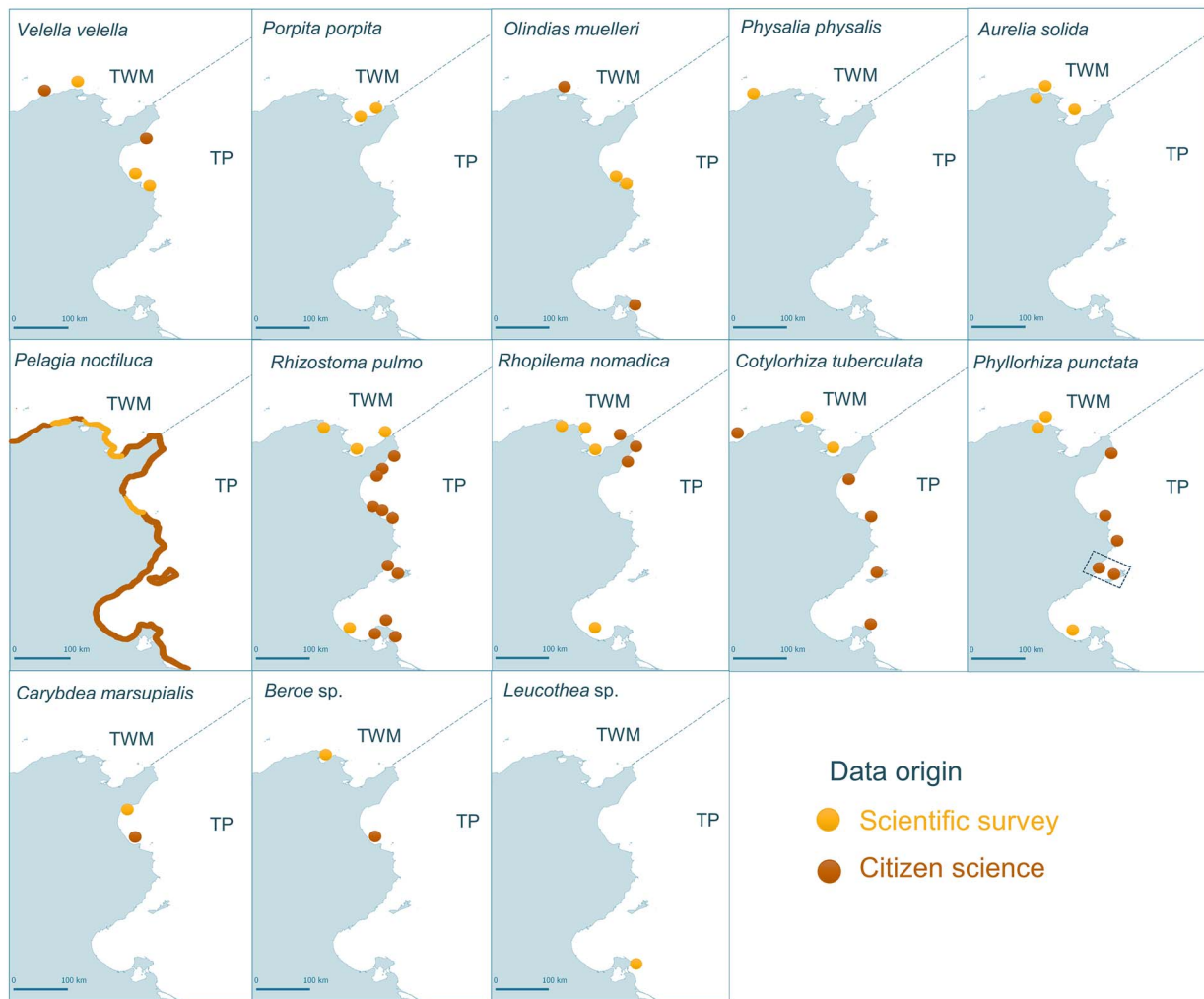
### Scyphozoa

*A. solida* (*Semaeostomeae*, *Ulmaridae*): *Aurelia* genus was first recorded in Tunisian waters in 1994, with specimens

observed in the Bizerte lagoon (Chakroun and Aloui-Bajaouin, 1995) and Tunis Gulf (Daly-Yahia *et al.*, 2003). After morphometric and molecular analyses, the species identified as *Aurelia aurita* was reassigned as the Red Sea *A. solida* (Scorrano *et al.*, 2017). The distribution of *A. solida* in Tunisia seems limited to TWM (Fig. 5), with an established population in the Bizerte Lagoon, a unique area where ephyrae have been found. *A. solida*'s absence in the TP is still unclear.

After the observations in the Tunis Gulf between 1994 and 1995, the species was never recorded again in this area. This absence is more likely due to a lack of specific surveys in the Tunis Gulf than a real absence. In the Bizerte area, the specimens were regularly observed in February since 1998 (Daly Yahia, personal observation). Then, the species disappeared between 2004 and 2005 (Touzri *et al.*, 2012). Since 2012, the species has frequently been re-observed in Bizerte Bay and Lagoon (Gueroun *et al.*, 2020) (Fig. 6). While *A. solida*'s first occurrences were limited to May and June (1994–1995), the species phenology changed drastically with a presence from December (ephyrae) to July with a relatively high abundance and frequent blooms usually observed between February and April (Gueroun *et al.*, 2020).

In the Mediterranean Sea, *A. solida* has been recorded in the North of the Adriatic (Malej *et al.*, 2012) with similar phenology to the Bizerte population. This occurrence in cooler ecosystems would suggest that the oligotrophic, warmer and saltier water in the south of Tunisia would be unfavorable (Drira *et al.*, 2010; Hamza *et al.*, 2021). However, *A. solida* is native to the Red Sea, one of the most saline water bodies in the world's ocean (Ngugi *et al.*, 2012) and where temperature varies from 15°C to 33°C during *A. solida* occurrence (El-Serehy and Al-Rasheid, 2011). Moreover, under laboratory conditions, *A. solida* polyps and ephyrae, originated from the Adriatic Sea,



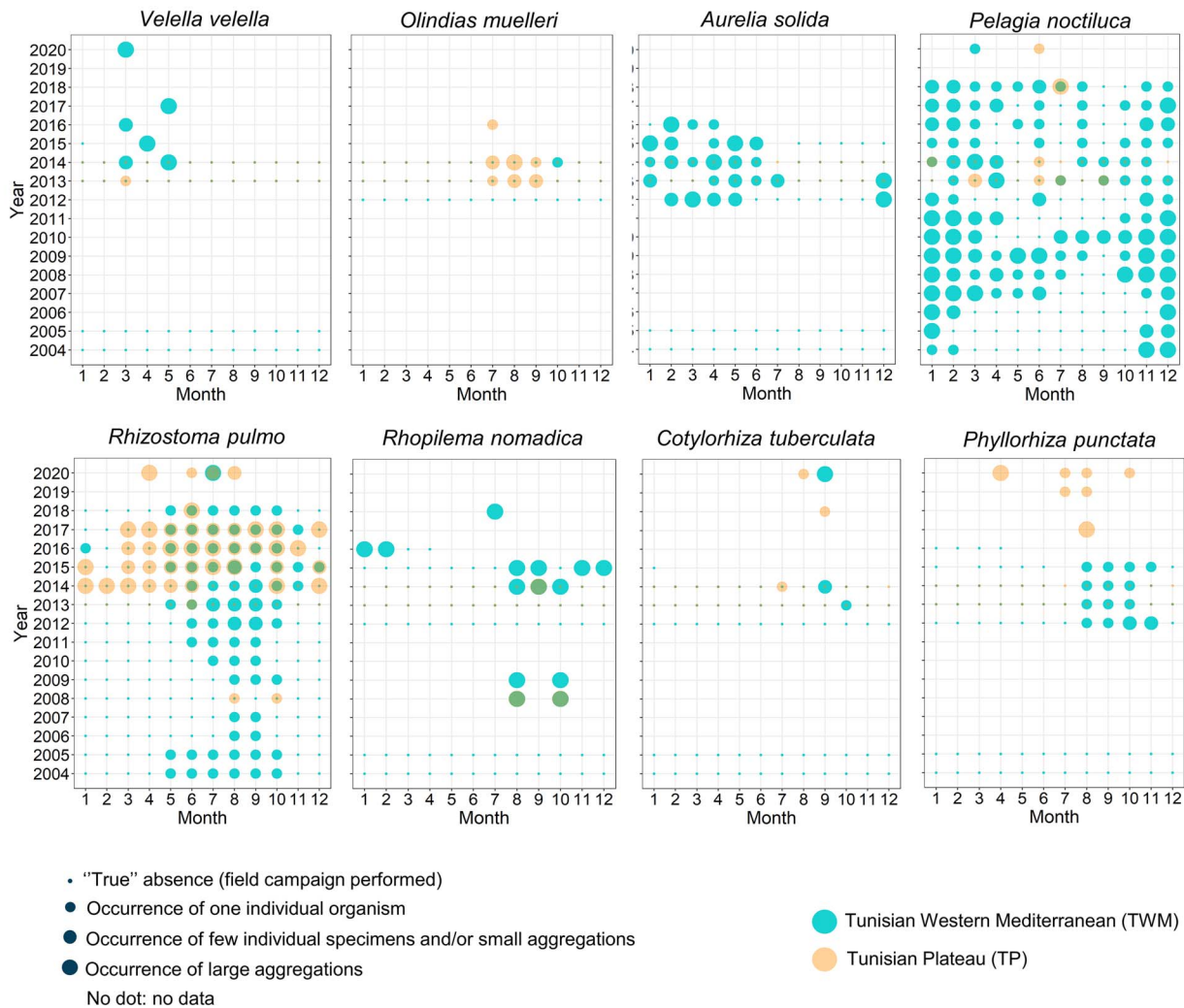
**Fig. 5.** Geographical distribution of jellyfish along Tunisian coast. TWM: Tunisian Western Mediterranean Sea; TP: Tunisian Plateau (note: the square in *Phyllorhiza punctata* indicates new established population).

displayed optimum conditions in survival, asexual reproduction and somatic growth in estuaries-like salinities (20–35) and for temperatures varying between 10°C and 20°C (Schäfer *et al.*, 2021). Therefore, the probable existence of metapopulations with different ecological characteristics might explain the virtual absence of *A. solida* in the TP ecoregion.

*P. noctiluca* (Semaestomeae, Pelagiidae): *P. noctiluca* is the most common Scyphozoa in Tunisia, with a wide distribution on all the coasts (Fig. 5). An analysis of the temporal dynamics of *P. noctiluca* in TWM showed two periods, pre- and post-2007 (Fig. 6). During the first period, *P. noctiluca* were only recorded between November and February and were visually absent during the remaining months. However, starting in 2007, its occurrence period extended, showing a virtually constant presence, with some exceptions (2011, 2012 and 2013). A shift in the

*P. noctiluca* dynamics model developed by Goy *et al.* (Goy *et al.*, 1989), suggesting a 2- to 3- years outbreaks cycle followed by a low abundance period (11–12 years), was reported in the studied area and other Mediterranean Sea locations (Adriatic Sea, Aegean Sea; Balearic Sea) early 2000 (Daly Yahia *et al.*, 2010). Those changes in the frequency and intensity of the outbreaks were driven by positive northern hemisphere temperature anomaly (Daly Yahia *et al.*, 2010), nutrient-rich environment (Legović, 1987), sea surface temperature increase and southern winds (Daly Yahia *et al.* in preparation).

*R. pulmo* (Rhizostomeae, Rhizostomatidae): This species is the second dominant species in the Tunisian jellyfish community, with a wide distribution (Fig. 5) but with a located area in each ecoregion: the Gulf of Gabès in the TP and the Tunis Gulf in the TWM. The *R. pulmo* population exhibited different season duration in both ecoregions.



**Fig. 6.** Temporal variability (month/year) of relative abundance of jellyfish in Tunisian coasts. No dots: no data; 1: jellyfish are not seen at all; 2: low abundance; 3: medium abundance; 4: high abundance or bloom.

In TWM, the *R. pulmo* season has been restricted to late spring (May)—to early mid-autumn (October), with a shorter period between 2006 and 2011 (Fig. 6). On the other hand, the species is reported almost all year round in the TP ecoregion. A second distinction lay in abundance: the southern populations (TP) were essentially reported as blooms, while the abundances in the northern area range between single registered individual to medium aggregations (a unique bloom reported in July 2020). The different seasonal and abundance patterns in *R. pulmo* dynamics in the two ecoregions can be interpreted as the results of different environmental conditions. Winter mean temperature, a key trigger for the asexual reproduction and strobilation onsets, is considerably higher in the Gulf of Gabès (16°C) (Drira *et al.*, 2014) than in the Tunis Gulf (13.2°C) (Daly-Yahia *et al.*, 2003). The relation

between warmer winter and early *R. pulmo* season was highlighted by Leoni *et al.* (Leoni *et al.*, 2021). Higher temperature not only induces earlier jellyfish outbreak but also boost *R. pulmo* population abundance. Under experimental conditions, *R. pulmo* buds produced per polyp increase with the temperature (0°C at 14°C,  $2.5 \pm 1$  at 21°C and  $8.8 \pm 5.6$  at 28°C) (Purcell *et al.*, 2012). Diet type might be a second reason for the bloom in the TP. Food supply (type and abundance) plays an essential role in the jellyfish blooms by increasing the asexual reproduction and the growth rate (Webster and Lucas, 2012; Wang *et al.*, 2015; Wang and Li, 2015). Gut contents analysis of *R. pulmo* showed a diet mainly constituted by large diatoms and tintinnids in Mar Menor (Pérez-Ruzafa *et al.*, 2002) and copepods and dinoflagellates in the Black Sea (Dönmez and Bat, 2019). The Gulf of Gabès, *R. pulmo* blooms

hotspot in Tunisia, is a paradox in the oligotroph Eastern Mediterranean Sea. The area has been recognized as a phytoplankton blooms ecoregion (Ayata *et al.*, 2018), leading to a small-copepod-dominated-zooplankton density higher than in the TWM (Annabi-Trabelsi *et al.*, 2005; Ben Ltaief *et al.*, 2015; Gueroun *et al.*, 2020). The area is also an essential nursery for several fish species (Koched *et al.*, 2015), contributing to  $\approx 40\%$  of the national fish production. *R. pulmo* outbreaks might therefore represent, in the first stage, a threat to zooplanktivorous fish larvae recruitment through competition and/or its top-down control of the plankton community, and in the second stage, affect higher trophic levels. Moreover, recent investigations on phytoplankton communities in relation to long-term hydroclimate variability of the Tunis Bay have shown a shift in the community structure characterized by an increase of small-sized species and diversity loss affecting the food web dynamics of this eutrophic bay (Ramirez-Romero *et al.*, 2020). Those changes may be considered a determinant for *R. pulmo* outbreaks observed in the TWM, specifically in the Tunis Gulf.

*Rhopilema nomadica* (Rhizostomeae, Rhizostomatidae): *Rhopilema nomadica* is the second NIS scyphozoan recorded in Tunisia. Its origin is still not clearly defined, Galil *et al.* (Galil *et al.*, 1990) located it in the Indian Ocean while Gravili and Rossi (Gravili and Rossi, 2021) situate *R. nomadica* origin from the Indo-Pacific. The scyphozoan was recorded and described for the first time in the Mediterranean Sea in 1977 on Israel's coast (Lotan *et al.*, 1994). Then, the species extended its spatial distribution in the Eastern Mediterranean Sea (Egypt, Lebanon, Syria, Turkey, Greece, Malta, Tunisia) (Galil *et al.*, 1990; Lotan *et al.*, 1994; Siokou-Frangou *et al.*, 2006; Brotz *et al.*, 2012; Daly-Yahia *et al.*, 2013; El-regal and Temraz, 2016) and reaching the western Mediterranean Sea in 2015 (Sardinia) (Balistreri *et al.*, 2017).

The first official record was back in 2008, with specimens observed in the Gulf of Gabès (TP) (Daly-Yahia *et al.*, 2013). The species was then recorded successively in the Tunis Gulf (2010–2013) and Bizerte (2011). *Rhopilema nomadica* spatial distribution extended to the southern Cap Bon (Kélibia and Al Ghezaz) (TP) (Fig. 5).

Some specimens were sporadically observed in August and October (Fig. 6) until a shift in the phenology in TWM. The continuous survey in the Bizerte area (lagoon, channel, bay) since 2012 showed the absence of *R. nomadica* until 2014 when few individuals (adults; 30–50 cm bell diameter) were observed between August and October. In 2015, the species displayed a more prolonged occurrence from August (2015) to February (2016), with the presence of small-medium individuals (10–30 cm bell diameter) in August–September (2015) and January–February

(2016), suggesting the establishment of a population in Bizerte Lagoon. This continuous occurrence coincided with peculiar warm winter; Bizerte Lagoon water temperature ranged from 13°C to 15°C (usually between 11°C and 14°C) and a higher salinity ( $38 \pm 0.2$  in 2016; usually between 32 and 37, with an average of  $35.8 \pm 2$  between 2012 and 2015) (Béjaoui *et al.*, 2008; Gueroun *et al.*, 2020; Gueroun, unpublished data).

The other established *R. nomadica* population in the Mediterranean Sea is in the Levantine coastal zone. There, the species was mainly observed from January to July (when most of the blooms occur) with small (0–10 cm) and medium (10–30 cm) individuals dominating the population between August ( $\approx 30^\circ\text{C}$ ) and December ( $\approx 20^\circ\text{C}$ ) (Edelist *et al.*, 2020).

A shift in the *R. nomadica* phenology was reported in the Levantine Sea, hypothetically due to climate change. While warm summers ( $30.5\text{--}31.5^\circ\text{C}$ ) in Levantine may accelerate the mortality of adults (Edelist *et al.*, 2020), those temperatures have not been recorded yet in Tunisia (max  $28^\circ\text{C}$ , in Bizerte Lagoon). However, warmer winter might promote polyps' strobilation, blooms and the extension of *R. nomadica* occurrence in the TWM (Lotan *et al.*, 1994). This last scenario could severely negatively impact ecological and socioeconomic fields (e.g. fisheries, recreational activities, public health) (Ghermandi *et al.*, 2015).

*C. tuberculata* (Rhizostomeae, Cepheidae): Despite being distributed on all Tunisian coasts (Fig. 5), knowledge of *C. tuberculata* phenology in the area is limited. Although the frequent field survey in TWM (Bizerte area), the species first sporadic records only started in 2013 (Fig. 6). Mass occurrences were never observed until the summer of 2021 in Djerba Island (TP) (Gueroun, personal observation). Overall, *C. tuberculata* phenology in Tunisia, from July to October, seems to follow the one observed in the Adriatic Sea, the Ionian Sea and Mar Menor lagoon (Kikinger, 1992; Pagès, 2001; Pestorić *et al.*, 2021), where the species occurs during the warm season. Few studies investigated the factors triggering *C. tuberculata* polyps' asexual reproduction and strobilation rate, and the species tolerance ranges. Salinity changes, light and nutrient availability do not affect the polyps, while temperature increase boosts the polyps' bud production and release of ephyrae (Prieto *et al.*, 2010; Purcell *et al.*, 2012).

*P. punctata* (Rhizostomeae, Mastigiidae): *P. punctata* is the most recent NIS scyphozoan recorded in Tunisia (Gueroun *et al.*, 2015b). The scyphozoan, native to the southwestern Pacific (Graham *et al.*, 2003), has been documented in the Mediterranean Sea since 1965 along the Israeli coast (Galil *et al.*, 1990). Then its spatial distribution extended to Egypt (1986), Greece (2005), Italy (2009), Turkey (2010),

Syria (2011) and Malta (2011), reaching the southwestern Atlantic coast of Spain in 2018 (Enrique-Navarro and Prieto, 2020; Madkour et al., 2021).

The species was recorded in Tunisia for the first time in the summer of 2012 in the Bizerte Lagoon (Gueroun et al., 2015b). The species is well established in this area, as proven by the presence of ephyrae and the frequent occurrence of the species since then. The spatial distribution of *P. punctata* was restricted to TWM until records of several specimens in Gabès Gulf (TP) in 2017, but with a potential anterior presence (since 2012) according to interviewed local fishermen (Rabaoui and El Zrelli, 2017). Juveniles ( $\approx 5$  cm) recorded in Kelibia and Ghadabna (TP) in 2019 confirmed the establishment of new populations on the TP coasts (Fig. 5).

Additionally, to the new spatial distribution, a shift was observed in *P. punctata* phenology (Fig. 6). In TWM, *P. punctata* occurred from August to November (2012–2015), and metaephyrae and juveniles were recorded in August (Gueroun et al., 2015b). However, in the TP, juveniles were observed earlier in April (2020). While *P. punctata* spatial distribution is well known, and some studies investigated the dynamics of the species (Rippingale and Kelly, 1995; Rato et al., 2021), very little is known about the effect of the environment factor on its asexual reproduction. For most of the scyphozoan, the temperature is one of the primary triggers for strobilation. *P. punctata* strobilation does not seem to occur at temperatures lower than 20°C (Wahab Jufri, 2001). In the Bizerte Lagoon, the metaephyrae and small juveniles (5 cm bell diameter) were found at 27.8°C (Gueroun et al., 2015b). Usually, 20°C is reached around April and May in Bizerte Lagoon, i.e. when it is assumed that *P. punctata* polyp strobilation starts. In that case, the absence of ephyrae in the sampling might be explained by their predation by *A. solida* present during this period (Purcell, 1991).

Even if *P. punctata* does not represent a threat to human health, its outbreak may be an issue for the ecosystem (Garcia and Durbin, 1993; West et al., 2009) and the local economy. *P. punctata* hosts symbiotic zooxanthellae providing a proposition of the jellyfish energy. In the absence of zooxanthellae (blue-colored *P. punctata*), the jellyfish depends solely on zooplankton and fish eggs predation for their nutrition leading to a depletion of this trophic key compartment and a threat to the fish stock (Graham et al., 2003). A direct negative impact of *P. punctata* is therefore observed on fisheries activities. A substantial decrease in shrimp and fish landings in Mississippi (26.7%, estimated commercial loss of USD 10 million) and Louisiana (37.3%) have been attributed to net clogging by the *P. punctata* outbreak (Graham et al., 2003). In the Bizerte area, several fishermen reported net clogging by *P. punctata* during the summer and early autumn of

2012 (Gueroun, personal observation). This scyphozoan is the third highest-scoring potential invasiveness of non-native jellyfish species in the Mediterranean Sea (Killi et al., 2020) and should therefore be closely monitored along the Tunisian coast and the possible socioeconomic loss assessed.

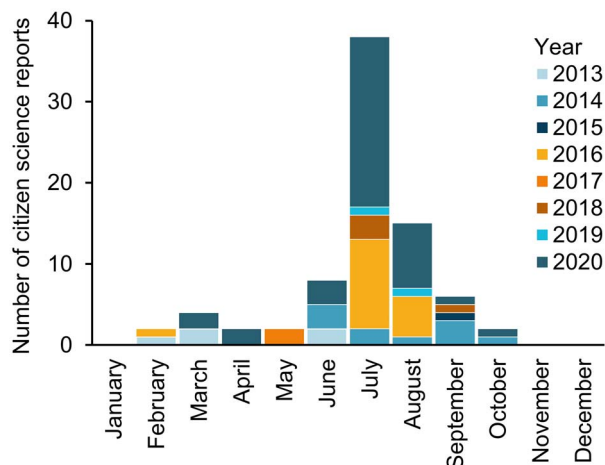
*S. meleagris* (unconfirmed; Rhizostomeae, Stomolophidae): The unique sighting of *S. meleagris* (a 1 cm diameter individual) was near an international harbor (La Goulette), suggesting an introduction through shipping. Unlike the three previous non-indigenous Scyphozoan, *S. meleagris* has never been observed since its unique records in May 1995 in Tunis Bay (Daly-Yahia et al., 2003). *S. meleagris* failure to establish a reproductive population might be explained by unfavorable environmental conditions. This scyphozoan is present in estuaries and coastal areas in the Gulf of Mexico and the USA eastern Atlantic, where it has been harvesting since the 1990s (Brotz et al., 2016). In those areas, specimens were associated with salinities lower (17.7–36.5, average 33.8 (Griffin et al., 2015)) than the one recorded in Tunis Bay during its observation (37–38.5) (Daly-Yahia et al., 2003). So unfavorable salinity might be the hurdle to the species' establishment in the area and the Mediterranean Sea.

#### Cubozoa

*C. marsupialis* is the only Cubozoan species recorded in the Mediterranean Sea. This endemic Mediterranean cubozoan has been registered in Spain, Italy, Malta, the northern Adriatic coastline and Algeria (Acevedo et al., 2019). In Tunisia, the species has been observed only in the TP, specifically in Hammamet (Gueroun et al., 2015a) in 2014 and later in Sousse (Fig. 5). *C. marsupialis* distribution is usually associated with shallow (0.5–10 m) coastal sandy beaches, with a gentle slope where *Posidonia oceanica* meadows and *Caulerpa prolifera* coexist with rocky and sandy bottoms (Bordehore et al., 2011; Acevedo et al., 2013; Gueroun et al., 2015a). This spatial distribution associated with the summer occurrence of the species constitutes a genuine socioeconomic concern. In Spain, jellyfish stinging incidences increased dramatically in 2008, coinciding with the *C. marsupialis* outbreak (Bordehore et al., 2011). *C. marsupialis* sting causes severe pain, a burning sensation, erythematous-vesicular eruption, local oedema and systemic effects (Peca et al., 1997; Bordehore et al., 2015).

#### Ctenophora

Only two ctenophores' species have been observed in Tunisia, namely the Nuda *Beroe* sp. in Bizerte (March 2018) (Daly-Yahia, personal observation) and *Leucothea*



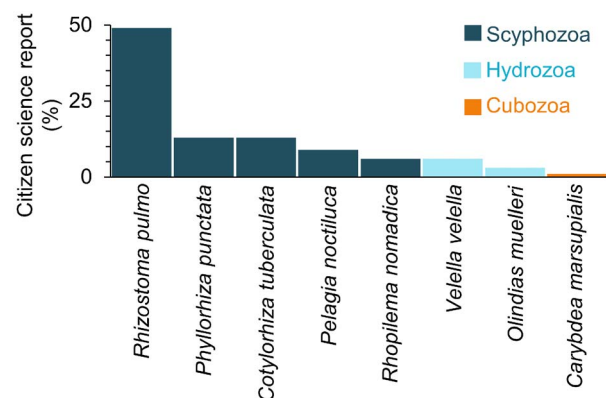
**Fig. 7.** Temporal variability (month/year) of citizen science reports between 2013 and 2020.

sp. in Sousse (2014) and off Djerba Island (at 5 m depth, March 2018) (Gueroun, personal observation) (Fig. 5). Ctenophores are one of the most understudied jellyfish phyla. This lack of knowledge of their diversity, distribution and ecology is related to these organisms’ fragility. Classical zooplankton sampling tools (nets) destroy ctenophores, making the observation, identification and quantification challenging.

### Citizen science contribution

The number of Citizen science reports *via* the social media platform depended on the season and tourist activities. Most of the records were collected during the summer (77.2%), with a peak in July (48.1%) (Fig. 7). The absence of records coincided with the late-autumn and winter periods (November–January). The second observed trend was in the species records proportion. *R. pulmo* was the most reported species (49%), followed by *P. punctata* (13%) and *P. noctiluca* (13%) (Fig. 8). The records trend was size- & abundance-dependent, as *R. pulmo* and *P. punctata* are large scyphozoans (adult bell diameter reaching 50 cm with the capacity to often occur in high densities. All their respective records on the citizen science platform corresponded to blooms or unusual high abundance. Small and transparent species such as *O. muelleri* and *C. marsupialis* are usually difficult to spot by non-trained observers, resulting in few records.

Citizen science’s contribution efficiency in tracking jellyfish diversity, spatial distribution and phenology was demonstrated in the Mediterranean Sea (Deidun, 2011; Leoni *et al.*, 2021; Marambio *et al.*, 2021). Although data collected by CS in the present study allowed to extend



**Fig. 8.** Relative abundance of reported species by citizen science between 2013 and 2020.

the geographic distribution of some jellyfish species, the data input suffered from inconsistency. As the frequency of the records received through the social media platform is highly dependent on the seasons, the strategy of the scientific campaign needs, therefore, to be adapted to cover the periods with few observations (winter). Moreover, links and collaborations with sea-related professionals (e.g. fishers, coast guards, offshore aquacultures) and environment associations must be strengthened. To assure the constant flow of data, especially during the non-bloom periods, citizen science network activities must be carried out continuously (Liu *et al.*, 2021), according to the general principle: “*out of sight, out of mind*”. These constant network activities can be done through regular social media publications and organizing events such as workshops, training and contests (e.g. photography). Citizen science has a long history in the ecological sciences (Katrin *et al.*, 2021). It made substantial contributions to science, policymakers, education and society (Roche *et al.*, 2020). However, citizen science application in Tunisia is recent (Lamine *et al.*, 2018; Fehri *et al.*, 2020a, b) but represents a fruitful tool to assess the diversity state of different taxa across the country.

### CONCLUSION

The present study constitutes the first complete update on jellyfish diversity and phenology across Tunisian coastal waters. This pioneering step forward will be a baseline study for future research on the biodiversity, temporal occurrence and spatial distribution patterns of jellyfish assemblages in Tunisia and other Mediterranean ecosystems. It revealed the establishment and the expansion of some NIS scyphozoans (*R. nomadica* and *P. punctata*) in the

SW Mediterranean Sea and a change in their known phenology, likely related to global warming, which will induce repercussions in the ecosystems. On the other hand, other NIS (*A. solida*), failed to extend its geographical distribution likely due to the population's ecophysiology, albeit its long-term establishment. Under the context of global warming numerous jellyfish appear to be increasing in several marine ecosystems globally, leading to various changes in the ecosystem structure and functioning (i.e. the trophic webs (Pitt *et al.*, 2007), altering the biogeochemical cycle (Sweetman *et al.*, 2016) and altering ecosystem services (Graham *et al.*, 2014). Additionally, these gelatinous organisms are also affected by regional hydroclimate (Lynam *et al.*, 2005; Daly Yahia *et al.*, 2010) and human activities (Lo *et al.*, 2008). Jellyfish outbreak's repercussions are likely to vary regionally, and ecosystem management would benefit from considering this regional variability. Finally, the present study showed the advantage of citizen science programs tracking jellyfish dynamics when scientific field works are restricted. However, the public's engagement needs constant visibility of the program to ensure continuous data flow.

## SUPPLEMENTARY DATA

Supplementary data can be found at *Journal of Plankton Research* online.

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## AUTHOR'S CONTRIBUTION

Conceptualization, S.K.M.G. and M.N.D.Y.; methodology, S.K.M.G. and M.N.D.Y.; formal analyses and investigation, S.K.M.G. and M.N.D.Y. writing original draft preparation, S.K.M.G.; writing-review and editing, S.K.M.G., S.P., O.K.D.Y. and M.N.D.Y.; funding acquisition, S.P., O.K.D.Y. and M.N.D.Y. All authors have read and agreed to the published version of the manuscript.

## DATA ARCHIVING

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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