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Review Article

Invasive Macrophyte Species in the Mediterranean Sea: An Update

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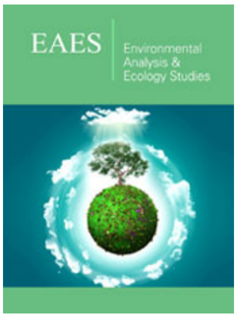

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Abstract

This study aims to summarize the history of biological invasions by alien macrophytes in the Mediterranean Sea from 1880 to 2020 years on a decadal basis. At the same time, it has been analyzed the impacts of sea warming and the increasing trend of sea surface temperature affecting invasive processes. The high number of Not-Indigenous Species and Invasive Alien Species, widespread in the basin, needs a continuous and updated monitoring of the process. In this way, the traditional recording methods, realized by scientific surveys are, actually, improved by Citizen Science activities very useful to study and update the presence of invasive allochthonous macrophytes widespread in the Mediterranean. From the resulting data, it has been highlighted the large diffusion of thermophilic and invasive alien macrophytes, by tropical and subtropical origin, coming from Indo-Pacific regions. Finally, to manage this invasive process, it is necessary to have a close collaboration between Science, Policy, and Citizenship.

Keywords: Biological invasions; Macrophytes; Warming; Non-Indigenous species; Invasive alien species; Citizen science

Introduction

In the anthropocene era, characterized by human-driven processes [1], biological invasions are becoming one of the most important issues affecting terrestrial and aquatic ecosystems worldwide [2-5]. This phenomenon is a serious threat to the sensitive balance of marine ecosystems in the Mediterranean Sea [6]. Nevertheless, global warming, Sea Surface Temperature (hereafter, SST) and the introduction of alien species in a climate change scenario, are actually increasing but the link between these trends is still unclear and very debated in the scientific community. Indeed, in these last decades it has been observed a coupled increase of SST and bio invasions [7]. So, it has been suggested that such thermal rise could support, in time, the spread of Not-Indigenous Species (hereafter NIS) in the Mediterranean [8]. European Union has defined NIS as species able to spread outside their native biogeographic regions to new areas [9]. However, the introduction of NIS species into a new marine environment is not directly related to their success in diffusion and establishment. The outcome of an invasive process depends on the interactions between the biological characteristics of what we refer to as invasive species and the species indicated as indigenous. Really, the establishment of NIS species depends on their potential to settle, spread and colonize local biotopes [10]. At the end of the process, some NIS become stable and widespread in the Mediterranean Sea changing their status to Invasive Alien Species (hereafter IAS), as a subset of NIS. IAS are defined by IAS Regulation, issued by the European Union [11], as alien species whose spreading could threaten marine biodiversity and the right functioning of ecosystem services [12-14].

More generally, this invasive trend may cause, also, social and economic impacts [15,16]. Worldwide, the financial costs of biological invasions have been estimated to be US $1.288 trillion in the period 1970-2017 [17]. The high number of NIS and IAS species, actually widespread in the basin, makes the Mediterranean Sea a real hotspot for bio invasions [18-21]. Amongst the main abiotic factors influencing the evolution of this invasive process, temperature is certainly one of the most important driving forces affecting the success or the failure of NIS invasion because all these species thrive within their thermal niches [22,23]. Since the 1980s, the Mediterranean Sea has become warmer, according to an increasing trend twice than ocean seawaters [24,25]. However, just 10% of the whole scientific literature analyses the relationship between the progressive warming of Mediterranean Sea and the present trend of biological invasions occurring in the basin [26]. In particular, SST is one of the most important thermal variables to value the present climate conditions of the basin and to foresee the future impacts of climate changes on global and regional scales, in this way, it has been highlighted that SST, in the period 1985-2011, increased +0.25 °C decade-1 in the western sub-basin and +0.65 °C decade-1 in the eastern one [27]. This growing trend has determined, over time, the spread of Indo-Pacific species of tropical and subtropical origin, with a slow and gradual tropicalization of the basin [28,29], which is becoming more sensitive to the establishment of a termophilic biota. Indeed, many of these tropical and subtropical invaders have reached, in time, the northern sectors of the basin [30,31], causing their meridionalization [32]. To the considerations just made, it is necessary to add the human factor. In fact, what is known as Citizen Science, in the last two decades, has taken up an important factor in the identification of alien species, initially understood as NIS and which then took on the role of IAS [33-36].

The Mediterranean Sea holds about 1500 species of macrophytes [37], including macroalgae and marine plants, with a rate of endemism of about 20% [38,39]. In particular, alien macrophytes represent a rate between 20% and 29% of the total number of NIS species living in the Mediterranean seawaters [40-42]. These invasive species may cause negative impacts at ecological levels inducing possible reductions of local biota [43-46]. A lot of lists, regarding NIS and IAS species have been published for the Mediterranean Sea [47-51]. Furthermore, recent studies, through an in-depth review of historical data on NIS and IAS species, have shown that their number, considerably, increased over time [52]. Indeed, Citizen Science activities have considerably contributed to the knowledge of invasive processes through active information and training channels between the academic world and ordinary citizens. This close collaboration between scientists and people has, more and more, increased the number of NIS reports, as summarised in [53]. Our investigation aims to suggest an updated list of NIS and IAS macrophytes living in the Mediterranean Sea through a specific database of these invasive and alien species, excluding cryptogenic and questionable records [53]. This list is the final result of a long set of reports conducted by scientists and citizens from 1880 to 2020 years. The research analyzes, also, the warming trend of Mediterranean seawaters in these last decades and its effect on the invasive process of NIS macrophytes widespread in the basin.

Methodology

The high number of alien macrophyta species, widespread in the Mediterranean Sea, requires a constant and updated control of invasive processes. However, the traditional methods of mapping and monitoring are long, expensive and limited in space and time. In this critical context, Citizen Science, despite all its limitations, has become a useful tool to study the widespread distribution of NIS and IAS species in the Mediterranean seawaters. So, it has been utilized the reports supplied by the activities of fishermen, divers, tourists and citizens to collect temporal and spatial information about these invasive species, side by side with the study, distribution, abundance and spread of allochtonous macroalgae widespread in the basin. The present study aims to follow on a decadal basis, the history of this invasive process, performed by alien marine macrophytes from 1880 to 2020. In parallel, it has been valued the warming impact of Mediterranean seawaters through satellite data, on a decadal basis, issued by Copernicus Marine Monitoring Service (CMMS), for the period between 1982 and 2020 years.

To date NIS and IAS lists, it has been consulted scientific literature, updated to 2023 year, using the main databases drawn by some digital platforms such as: Google Scholar, Web of Science, Scopus and Research Gate. The bibliographic search has been realized according to the following keywords: Citizen Science, Mediterranean Sea, non-indigenous species, invasive alien species, macrophytes and macroalgae. The lists of NIS and IAS species have been realized through the informations supplied by citizen scientists and by an informative bibliographic search. All these data have been updated by scientists and validated by taxonomists according to the World Register of Marine Species (WoRMS) (Figure 1). The roles of citizen scientists and taxonomists are clearly differentiated because the first ones have the main function to point out the presence of alien species in Mediterranean coastal seawaters while the second ones perform the important role to establish their systematic position. The criteria to assess the status of NIS and IAS species and to assign their biogeographical origin have been drawn by [11]. Finally, the species with a doubtful origin or with an uncertain systematic position have been defined as "uncertain".

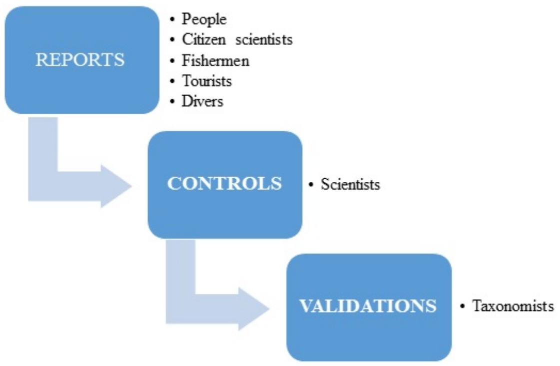

Figure 1: The pattern of validation of NIS and IAS species.

Results

The resulting data are shown in two databases of alien macrophytes, including macroalgae and marine plants, widespread in the Mediterranean Sea. The first directory includes 92 NIS (Table 1), while the second one shows just 26 IAS (Table 2). This information are drawn by scientific and popular records conducted from 1880 to 2020 years and summarized in two lists including altogether 118 allochtonous macrophyta species.

Table 1: List of NIS and their first years of detection at region levels in Mediterranean basin (legends: WAO=Western Atlantic Ocean; NAO=Northeast Atlantic Ocean; IPO/RS=Indo-Pacific/Read Sea; NPO=Northwest Pacific Ocean; A=Australasia; U=Uncertain). [The taxa nomenclature is updated according to www.algaebase.org consulted on 18 June 2024].

N.	Not-Indigenous Species (NIS)	Origin	Years	Countries
1	*Acanthosiphonia echinata* (Harvey) Savoie & G.W.Saunders 2018	WAO	2018	Italy
2	*Acrothamnion preissii* (Sonder) E.M. Wollaston 1968	IPO/RS	1968	Italy
3	*Agardhiella subulata* (C. Agardh) Kraft & M.J. Wynne 1979	U	1984	France
4	*Agarophyton vermiculophyllum* (Ohmi) Gurgel, J.N. Norris & Fredericq 2018	NPO	2008	Spain
5	*Aglaothamnion halliae* (Collins) Aponte, D.I. Ballantine & J.N. Norris 1997	WAO	2016	Italy
6	*Ahnfeltiopsis flabelliformis* (Harvey) Masuda 1993	NPO	1994	France
7	*Antithamnion hubbsii* E.Y. Dawson 1962	WAO	1987	Italy
8	*Antithamnion amphigeneum* A. Millar 1990	A	1982	France
9	*Antithamnionella ternifolia* (Hooker F. & Harvey) Lyle	A	1981	France
10	*Ascophyllum nodosum* (Linnaeus) Le Jolis 1863	NAO	2009	Italy
11	*Asparagopsis taxiformis* (Delile) Trevisan 1845	A	1992	Spain
12	*Asparagopsis armata* Harvey 1855	A	1880	Spain
13	*Batophora occidentalis* var. *largoensis* (J.S.Prince & S.Baker) S.Berger & Kaever ex M.J.Wynne 1998	WAO	2020	Italy
14	*Bonnemaisonia hamifera* Hariot 1891	NPO	1932	Tunisia
15	*Botryocladia wrightii* (Harvey) W.E.Schmidt, D.L.Ballantine & Fredericq 2017	NPO	1978	Spain
16	*Botryocladia madagascariensis* G. Feldmann 1945	IPO/RS	1978	Turkey
17	*Botrytella parva* (Takamatsu) H.S. Kim 1996	NPO	1996	Italy
18	*Caulacanthus okamurae* Yamada 1933	NPO	2002	France
19	*Caulerpa cylindracea* Sonder 1845	A	1991	Tunisia
20	*Caulerpa lamourouxii* (Turner) C. Agardh 1817	IPO/RS	1956	Italy
21	*Caulerpa taxifolia* (M. Vahl) C. Agardh 1817	A	1984	Monaco
22	*Caulerpa taxifolia* var. *distichophylla* (Sonder) Verlaque, Huisman & Procaccini 2013	IPO/RS	2007	Italy
23	*Ceramium bisporum* D.L. Ballantine 1990	WAO	1980	Italy
24	*Ceramium strobiliforme* G.W. Lawson & D.M. John 1982	NAO	1991	Italy
25	*Chondria pygmaea* Garbary & Vandermeulen 1990	WAO	1974	Italy
26	*Chondria curvilineata* F.S. Collins & Hervey 1917	WAO	1981	Greece
27	*Chondrus giganteus* f. *flabellatus* Mikami 1965	NPO	1994	France
28	*Chrysonephos lewisii* (W.R.Taylor) W.R.Taylor 1952	WAO	1988	Italy
29	*Cladophora patentiramea* (Montagne) Kützing 1849	IPO/RS	1991	Cyprus
30	*Codium arabicum* Kützing 1856	IPO/RS	2006	Israel
31	*Codium fragile* subsp. fragile (Suringar) Hariot 1889	NPO	1946	France
32	*Colaconema codicola* (Børgensen) H. Stegenga, J.J. Bolton & R.J. Anderson 1997	IPO/RS	1952	France
33	*Colpomenia peregrina* Sauvageau 1927	NPO	1918	Spain
34	*Dasya sessilis* Yamada 1928 as a synonymus of *Dasysiphonia sessilis* (Yamada) M.M.Cassidy, C.W.Schneider & G.W.Saunders 2022	NPO	1984	France
35	*Dasysiphonia japonica* (Yendo) H.S. Kim 2012	NPO	1998	Spain
36	*Derbesia rhizophora* Yamada 1961	NPO	1984	France
37	*Dictyota cyanoloma* Tronholm, De Clerck, Gòmez-Garreta & Rull Llluch 2010	A	1935	Spain
38	*Goniotrichopsis sublittoralis* G.M. Smith 1943	NPO	1989	Spain
39	*Grateloupia asiatica* S. Kawaguchi & H.W. Wang 2001	NPO	1984	France
40	*Grateloupia patens* (Okamura) Kawaguchi & H.W. Wang 2001	NPO	1994	France
41	*Grateloupia subpectinata* Holmes 1912	NPO	1990	France
42	*Grateloupia turuturu* Y. Yamada 1941	NPO	1982	France

43	*Grateloupia yinggehaiensis* H.W. Wang & R.X. Luan 2012	NPO	2008	Italy
44	*Halimeda incrassata* (J. Ellis) J.V. Lamouroux 1816	WAO	2011	Spain
45	*Halophila stipulacea* (Forsskàl) Ascherson 1867	IPO/RS	1894	Rodi island
46	*Herposiphonia parca* Setchell 1926	A	1997	France
47	*Hypnea anastomosans* Papenfuss, Lipkin & P.C. Silva 2002	IPO/RS	2008	Israel
48	*Hypnea cervicornis* J. Agardh 1851	U	2009	Israel
49	*Hypnea cornuta* (Kützing) J. Agardh 1851	IPO/RS	1894	Greece
50	*Hypnea spinella* (C. Agardh) Kützing 1847	WAO	1977	Greece
51	*Hypnea valentiae* (Turner) Montagne 1841	IPO/RS	1996	France
52	*Kapraunia schneideri* (Stuercke & Freshwater) A.M. Savoie & G.W. Saunders 2018	WAO	2016	Spain
53	*Laurencia caduciramulosa* Masuda & M. Kawaguchi 1997	A	1991	Spain
54	*Laurencia okamurae* Yamada 1931	NPO	1984	France
55	*Leathesia marina* (Lyngbye) Decaisne 1942	NPO	1905	France
56	*Lithophyllum yessoense* Foslie 1909	NPO	1994	France
57	*Lomentaria flaccida* Tak. Tanaka 1944	NPO	2002	France
58	*Lomentaria hakodatensis* Yendo 1920	NPO	1978	France
59	*Lophocladia lallemandii* (Montagne) F. Schmitz 1893	IPO/RS	1908	France
60	*Melanothamnus harveyi* (Bailey) Diaz-Tapia & Maggs 2017	NPO	1958	France
61	*Melanothamnus japonicus* (Harvey) Diaz-Tapia & Maggs 2017	NPO	2016	France
62	*Nemalion vermiculare* Suringar 1874	NPO	2005	France
63	*Nitophyllum stellatumcorticatum* Okamura 1932	NPO	1984	France
64	*Pachymeniopsis gargiuloi* S.Y. KIm, Manghisi, Morabito & S.M. Boo 2014	NPO	1968	Italy
65	*Pachymeniopsis lanceolata* (Okamura) Yamada ex Kawabata 1954	NPO	1982	Italy
66	*Padina boergesenii* Allender & Kraft 1983	IPO/RS	1965	Israel
67	*Phrix spatulata* (E.Y. Dawson) M.J. Wynne, M. Kamiya & J.A. West 2018	U	1992	Turkey
68	*Plocamium secundatum* (Kützing) Kützing 1866	A	1991	Spain
69	*Polysiphonia paniculata* Montagne 1842 as a synonym of *Eutrichosiphonia paniculata* (Montagne) D.E. Bustamante & T.O. Cho 2021	U	1967	Italy
70	*Polysiphonia morrowii* Harvey 1857	NAO	1997	France
71	*Pyropia yezoensis* (Ueda) M.S. Hwang & H.G. Choi 2011	NPO	1975	France
72	*Pyropia suborbiculata* (Kjellman) J.E. Sutherland, H.G. Choi, M.S. Wang & W.A. Nelson 2011	NPO	2014	Spain
73	*Rugulopteryx okamurae* (E.Y. Dawson) I.K. Hwang, W.J. Lee & H.S. Kim 2009	NPO	2002	Italy
74	*Saccharina japonica* (J.E. Areschoug) C.E. Lane, C., Mayes, Druehl & G.W. Saunders 2006	NPO	1976	France
75	*Sarconema filiforme* (Sonder) Kylin 1932	IPO/RS	1990	Israel
76	*Sarconema scinaioides* Børgensen 1934	IPO/RS	1980	Israel
77	*Sargassum muticum* (Yendo) Fensholt 1955	NPO	1980	Spain
78	*Scytosiphon dotyi* M.J. Wynne 1969	NPO	1968	Italy
79	*Solieria filiformis* (Kützing) P.W. Gabrielson 1985	WAO	1922	Italy
80	*Spermothamnion cymosum* (Harvey) De Toni 1903	A	2010	Italy
81	*Sphaerotrichia firma* (E.S. Gepp) A.D. Zinova 1958	NPO	1981	Turkey
82	*Spongoclonium caribaeum* (Børgensen) M.J. Wynne 2005	IPO/RS	1974	Spain
83	*Stypopodium schimperi* (Kützing) Verlaque & Boudouresque 1991	IPO/RS	1990	Turkey
84	*Symphyocladia marchantioides* (Harvey) Falkengerg 1897	A	1984	Italy
85	*Symphyocladiella dendroidea* (Montagne) D. Bustamante, B.Y. Won, S.C. Lindstrom & T.O. Cho 2019	U	1993	France
86	*Ulva australis* Areschoug 1854	A	1984	Spain
87	*Ulva californica* Wille 1899	IPO/RS	2011	Italy
88	*Ulva ohnoi* Hiraoka & S. Shimada 2004	NPO	2011	Italy

89	*Ulvaria obscura* Kützing 1843 as a synonym of *Ulva obscura* (Kützing) P. Gayral ex Bliding 1869	U	1985	Spain
90	*Undaria pinnatifida* (Harvey) Suringar 1873	NPO	1971	France
91	*Uronema marinum* Womersley 1984 as a synonym of *Okellya marina* (Womersley) Wetherbee 2024	U	1989	France
92	*Womersleyella setacea* (Hollenberg) R.E. Norris 1992	U	1986	Italy

Table 2: List of IAS and their first years of detection at regional levels in Mediterranean basin (legends: WAO=Western Atlantic Ocean; NAO=Northeast Atlantic Ocean; IPO/RS=Indo-Pacific/Read Sea; NPO=Northwest Pacific Ocean; A=Australasia; U=Uncertain). [The taxa nomenclature is updated according to www.algaebase.org consulted on 18 June 2024].

N.	Invasive Alien Species (IAS)	Origin	Years	Countries
1	*Asparagopsis taxiformis* (Delile) Trevisan 1845	A	1993	Spain
2	*Bonnemaisonia hamifera* Hariot 1891	NPO	1909	Tunisia
3	*Caulerpa cylindracea* Sonder 1845	A	1985	Tunisia
4	*Chondria curvilineata* F.S. Collins & Hervey 1917	WAO	1980	Greece
5	*Cladophora patentiramea* (Montagne) Kützing 1849	IPO/RS	1991	Cyprus
6	*Codium fragile* subsp. fragile (Suringar) Hariot 1889	NPO	1946	France
7	*Codium taylorii* P.C. Silva 1960	U	1955	Israel
8	*Colaconema codicola* (Børgensen) H. Stegenga, J.J. Bolton & R.J. Anderson 1997	IPO/RS	1952	France
9	*Derbesia rhizophora* Yamada 1961	NPO	1984	France
10	*Galaxaura rugosa* (J. Ellis & Solander) J.V. Lamouroux 1816	IPO/RS	1990	Syria
11	*Hypnea anastomosans* Papenfuss, Lipkin & P.C. Silva 2002	IPO/RS	1972	Israel
12	*Hypnea cornuta* (Kützing) J. Agardh 1851	IPO/RS	1994	Greece
13	*Hypnea valentiae* (Turner) Montagne 1841	IPO/RS	1996	France
14	*Laurencia okamurae* Yamada 1931	NPO	1984	France
15	*Leathesia marina* (Lyngbye) Decaisne 1942	NPO	1905	France
16	*Lomentaria hakodatensis* Yendo 1920	NPO	1978	France
17	*Plocamium secundatum* (Kützing) Kützing 1866	A	1976	Spain
18	*Polysiphonia morrowii* Harvey 1857	NAO	1997	France
19	*Pterosiphonia tanakae* Uwai & Masuda 1999	NPO	1993	France
20	*Sarconema filiforme* (Sonder) Kylin 1932	IPO/RS	1944	Israel
21	*Sarconema scinaioides* Børgensen 1934	IPO/RS	1945	Israel
22	*Scytosiphon dotyi* M.J. Wynne 1969	NPO	1960	Italy
23	*Spatoglossum variabile* Figari & De Notaris 1853	IPO/RS	1944	Egypt
24	*Sphaerotrichia firma* (E.S. Gepp) A.D. Zinova 1958	NPO	1970	Turkey
25	*Ulva ohnoi* Hiraoka & S. Shimada 2004	NPO	2011	Italy
26	*Uronema marinum* Womersley 1984 as a synonym of *Okellya marina* (Womersley) Wetherbee 2024	U	1989	France

Most of the reports regards the coastline of France (34.7%) followed by Italy (26.3%), Spain (16.8%), Israel (6.6%), Turkey (4.2%), Greece (3.2%), Tunisia (2.1%), Egypt (2.1%) and other Mediterranean regions with low percentages (Figure 2). The geographic distribution of the reports could be explained by two different factors that interacted one each other. On one hand, the nations with the highest percentages of collected NIS are those in which the study of marine biology shows an older tradition. Another reason, for the high number of records, regarding marine alien species, is certainly linked to the spread of recreational diving activities which were born in France immediately after the Second War World (WWII) and, subsequently, began to spread also in Italy and in Spain.

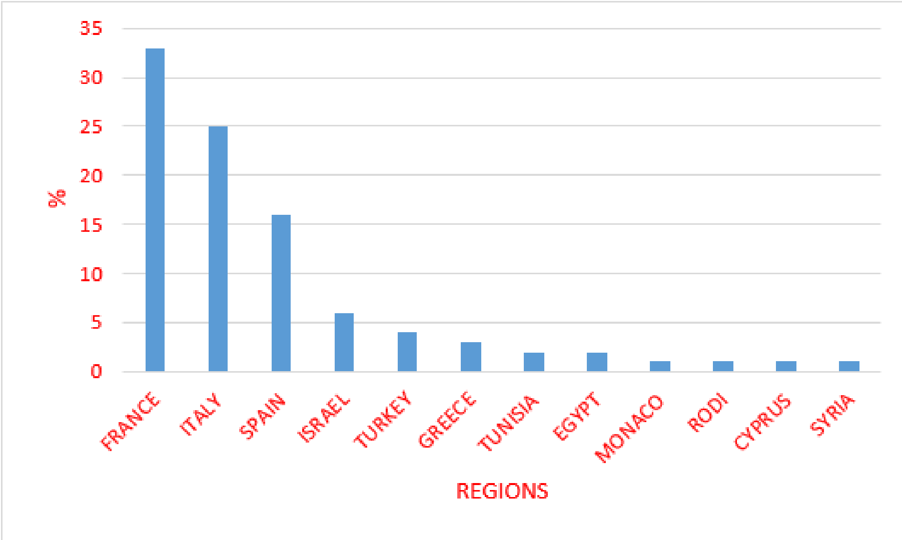

Figure 2: Regional percentages of NIS and IAS macrophyta species reported for Mediterranean regions.

From a careful analysis of the temporal records, it is possible to observe that the trend of this invasive process is rather unstable and strongly fluctuating decade after decade. In fact, in the first period, between 1880 and 1950, a small number of reports were recorded with only eleven alien species identified (Figure 3). This condition was probably caused by the long period of conflicts that affected the European continent, culminating in the first War World (WWI) and in the Second War World (WWII), leading to some indifference in this type of scientific research. In the following period, between 1950 and 2000, when the socio-economic conditions of European countries enjoyed a period of relative wellbeing, with a resulting increase in the tourist industry linked to underwater activities, the number of NIS reports increased strongly up to a maximum value of twenty-five NIS in the decade 1980/1990. This growing trend significantly decreased in the decades 2000-2010 and 2010-2020 with eleven and ten NIS records respectively (Figure 4 & 5). Also in this case, socio-economic reasons could have affected research activities linked to marine biology. Really, the low number of NIS recorded in these last decades is, probably, caused by the declining survey efforts, as stated by the Kumminga Montreal Global Biodiversity Framework (GBF) that calls for a 50% reduction of monitoring efforts by 2030 [54]. However, in these last years, there is a higher number of tropical and subtropical thermophilic macrophytes than temperate and cosmopolitan ones (Figure 6 & 7). In fact, from the collecting data, it is highlighted a clear drop of these last species since 2000 year [55].

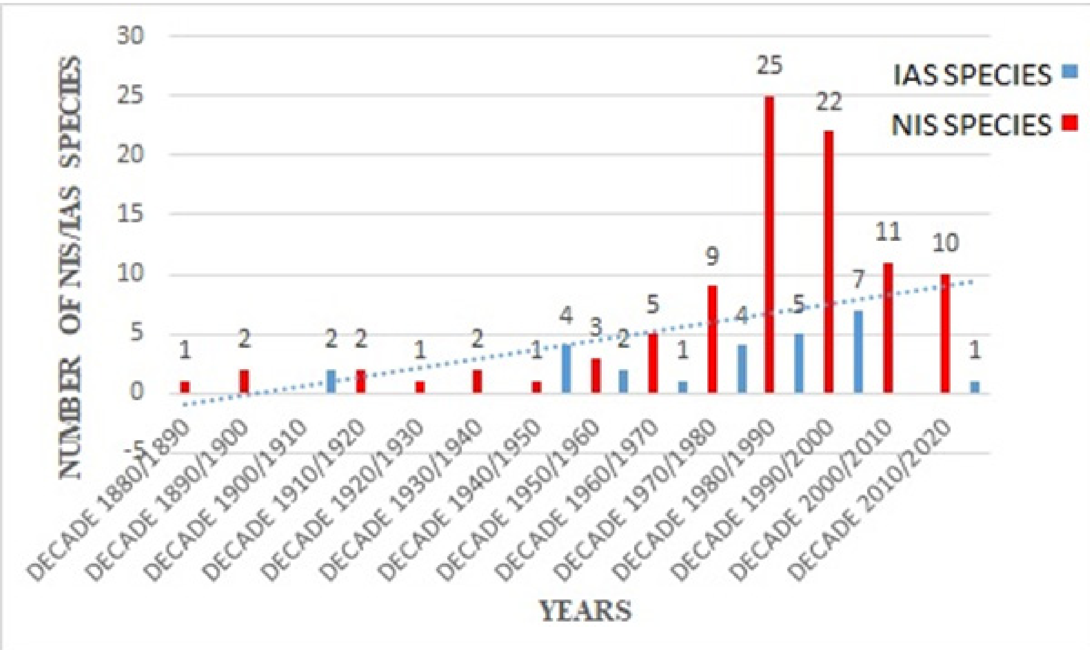

Figure 3: The temporal trend of the invasive process of NIS and IAS from 1880 to 2020 years on a decadal basis.

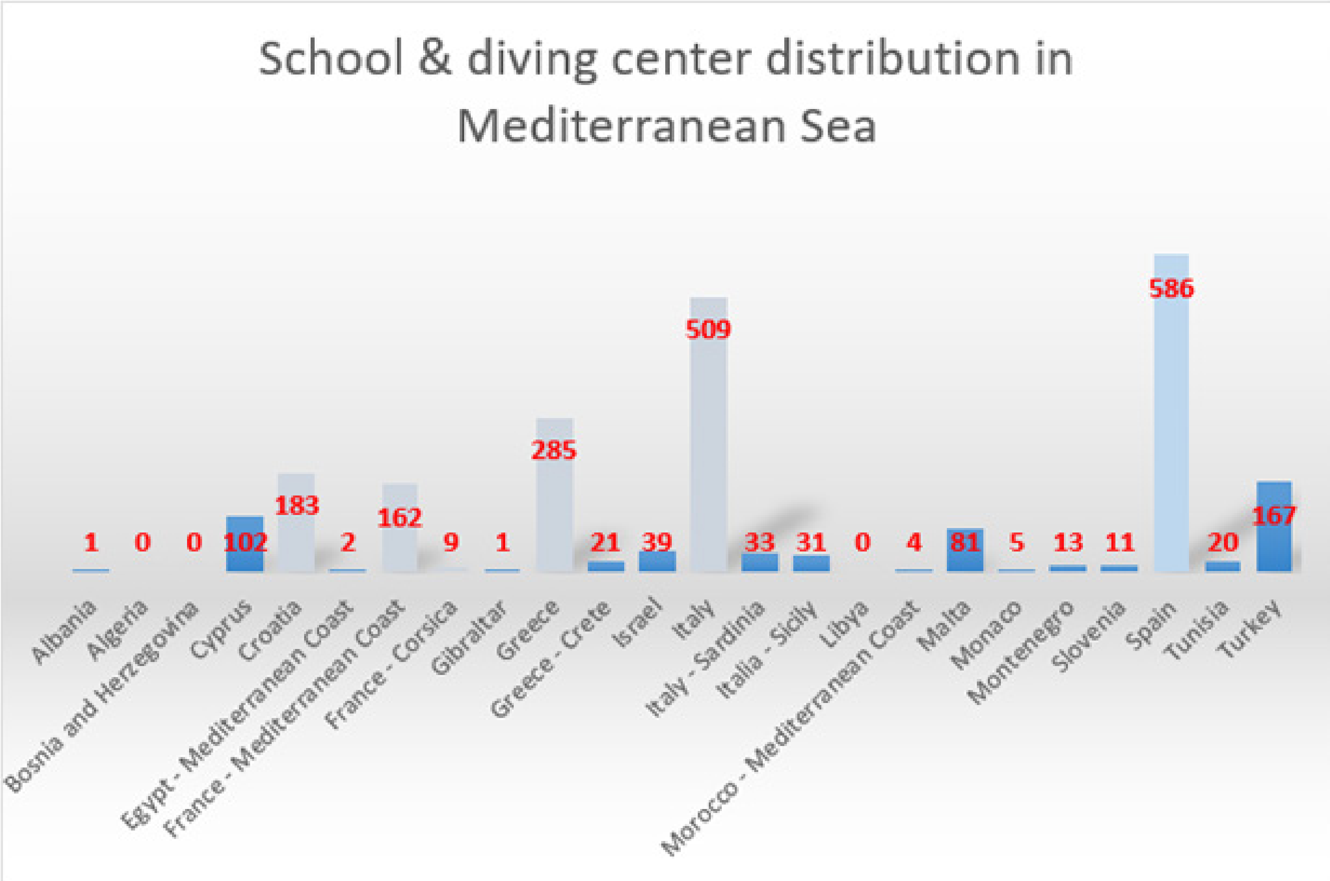

Figure 4: Geographic distribution of school and diving centers in Mediterranean countries (from: Scuba Diving centers and diving sites, https://www.divescover.com).

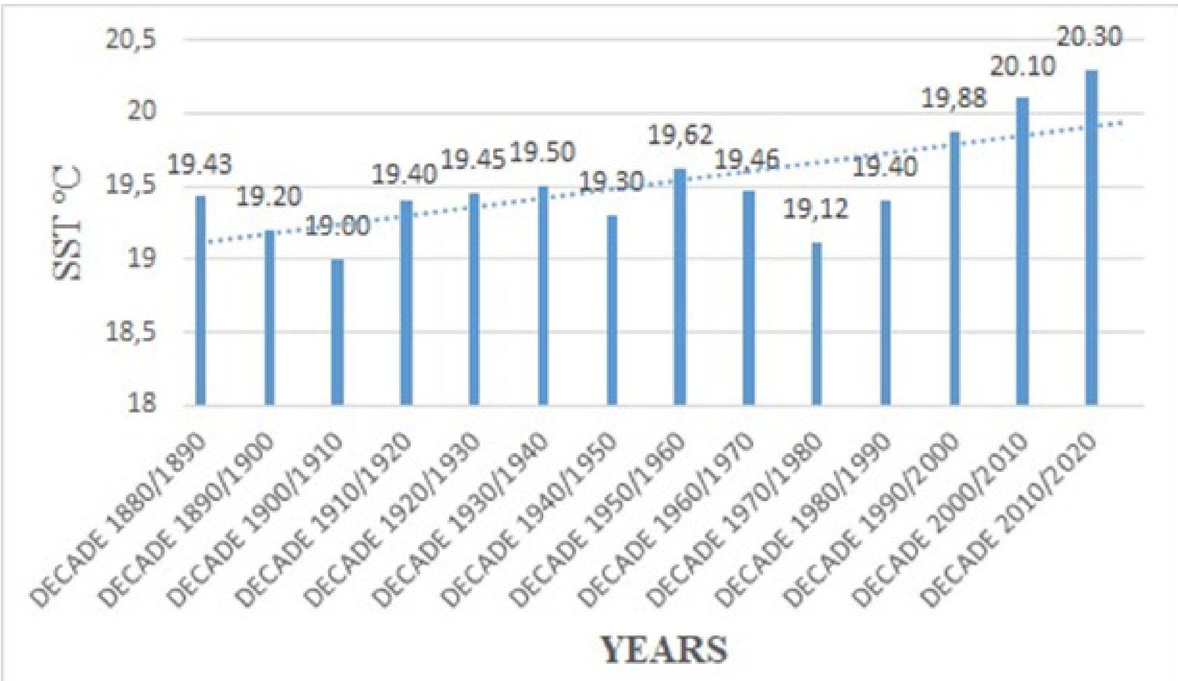

Figure 5: The increasing trend of SST in Mediterranean seawaters.

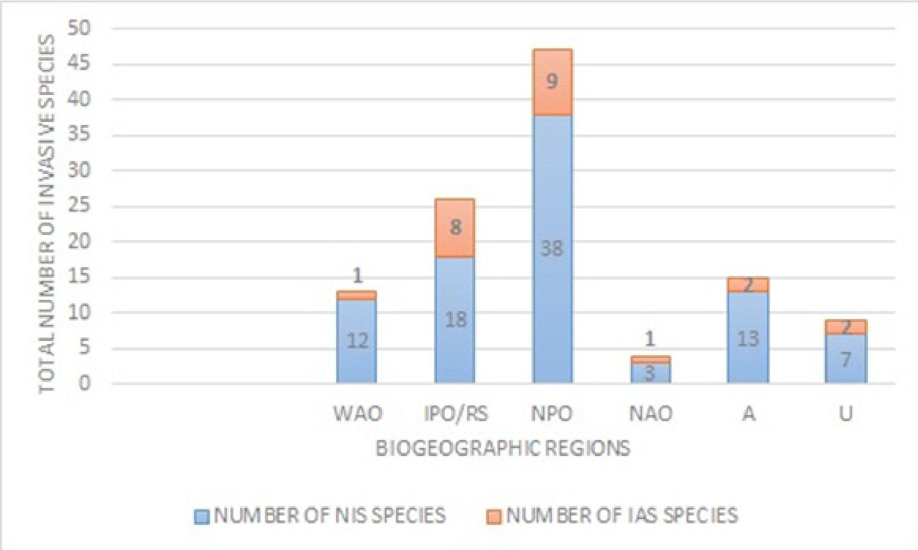

Figure 6: Number of NIS and IAS macrophytes distinguished by their biogeographic origins (legends: WAO=Western Atlantic Ocean; NAO=Northeast Atlantic Ocean; IPO/RS=Indo-Pacific/ Read Sea; NPO=Northwest Pacific Ocean; A=Australasia; U=Uncertain).

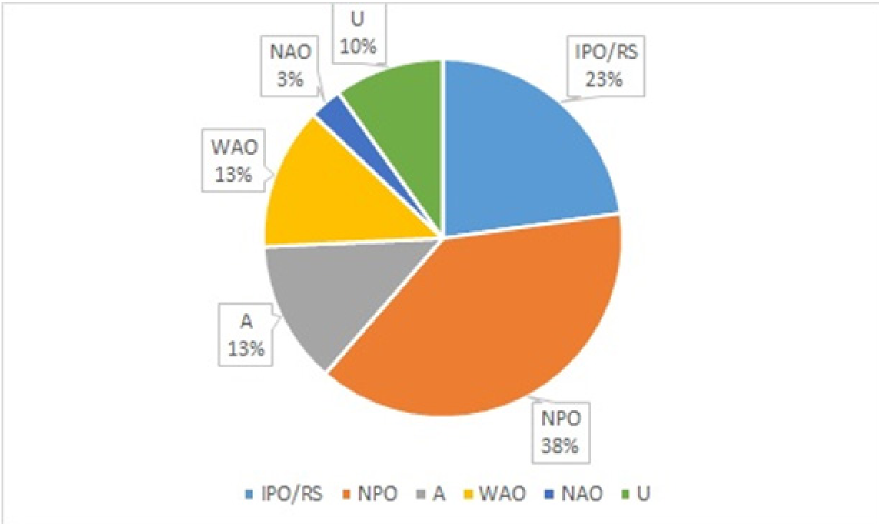

Figure 7: Pie chart detailing the percentages of NIS and IAS macrophytes distiguished by their biogeographic origins (legends: WAO=Western Atlantic Ocean; NAO=Northeast Atlantic Ocean; IPO/RS=Indo-Pacific/ Read Sea; NPO=Northwest Pacific Ocean; A=Australasia; U=Uncertain).

At the same time, there was a clear drop in the industry of underwater tourism with the closure of dozens of school and diving centers previously widespread along the coastlines of Mediterranean Sea (Figure 4). The different number of invasive macrophytes from tropical and temperate NIS is becoming more evident in the last decades. Really, in Mediterranean seawaters the global media of SST rised of about 1 °C since 1980s and such increasing trend is actually ongoing (Figure 5).

So, these conditions have caused, in time, ideal thermic values for the growth and the expansion of thermophilic macrophytes by Indo-Pacific regions. In a climate change scenario, SST appears strictly connected with the increasing trend of Marine Heatwaves (MHWs), as highlighted also by scientific literature [56]. The coupled effects of these climate factors can increase the spreading of tropical and subtropical species in the Mediterranean seawaters [57]. Globally, the non-indigenous macrophytes are about the 10% of the whole Mediterranean marine flora but these data must be distinguished according to the biogeographic origins of NIS and IAS macroalgae. In this way, a greater number of tropical and subtropical thermophilic macrophytes, coming from NPO, IPO/RS and A regions, arrived at the basin, compared to cosmopolitan and temperate species native of WAO and NAO regions (Figure 6). In particular, NIS and IAS, coming from NPO, IPO/RS and A regions are prevailing with respective percentages of 38%, 23% and 13%, while the cosmopolitan and temperate species, by WAO and NAO regions, show respectively rates of 13% and 3% of the whole (Figure 7).

Discussion

Mediterranean Sea has become, in time, very sensitive to biological invasions, leading to a gradual change of its marine biota. This growing trend leads to the introduction of many alien algal species coming from Indian, Pacific and Atlantic oceans through two marine corridors, as are the Strait of Gibiltrar and the Suez Canal. There are two driving forces supporting the process of bio invasions. Firstly, the increasing commercial trade by maritime traffic into the basin has caused the introduction of many macrophyta species through ballast waters and biofouling [58,59]. Secondly, the opening of Suez Canal in 1880, the reduction of salinity levels in bitter lakes since 1960s and the late doubling of this corridor in 2015, have established a steady sea-level waterway for thermophilic species including animals, plants, fungi, bacteria, etc., by Indo-Pacific origin, into the Mediterranean Sea [60]. To the databases presented here, most of NIS and IAS macrophytes belong to the systematic division of *Rhodophyta* with respective percentages of 68.0% and 53.8%, while lower rates are represented by *Ochrophyta* (23.1% and 16.3%) and *Chlorophyta* (23.1% and 15.5%) of the whole marine invasive flora (Figure 8).

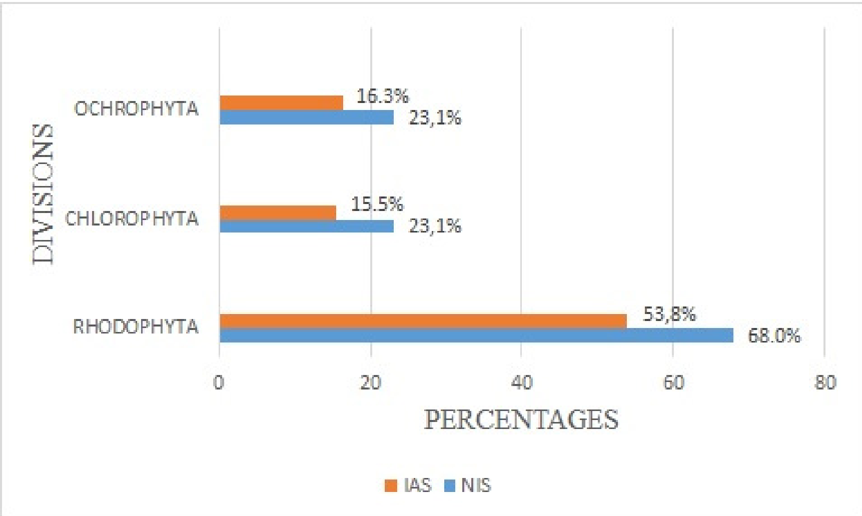

Figure 8: Bar chart representing NIS and IAS percentages within macroalgal divisions.

Generally speaking, the increasing introduction of NIS and IAS is leading to the tropicalization of the basin [61]. Indeed, the Mediterranean regions more affected by invasive processes are French and Italian coastlines (Figure 2), as confirmed by the presence of two important hotspots for the introduction of alien macrophytes. The main area prone to invasive processes is the Thau Lagoon (France) where 58 macroalgal NIS, as the 63% of the whole number of alien marine flora, are well established [62]. The second zone, sensitive to bio invasions, is the Venice Lagoon, where 14 macroalgal NIS, as the 15% of the whole, are reported by scientific literature [63-65]. So, Mediterranean is actually exposed to a gradual and steady warming of its seawaters at a rate 2/3 times faster than ocean ones [66]. This warming trend, inserted in a climate change scenario, supports the introduction and the establishment of thermophilic tropical and subtropical alien macrophytes coming from Indo-Pacific regions [67].

In this way, NIS and IAS macroalgae are characterized by thermal ranges higher than those of indigenous species, showing a greater capacity to adapt quickly to the increasing temperatures of the basin [68,69]. Therefore, NIS are able to maintain their populations alive within a wider thermal niche. So, the higher number of alien tropical and subtropical macroalgal species could be related to their better resistance towards the lowest temperatures of the basin, enabling them to widespread in the Mediterranean Sea. On the contrary, the lower introduction rates of temperate and cosmopolitan alien species, reported in these last decades, could be ascribed to the highest summer values of Mediterranean SST (Figure 5). Indeed, MHWs could have caused a lower rate in the spreading of invasive temperate macrophytes and, in some serious cases, large-scale mortality events [70-72]. From the resulting data, it is possible to assert that most of NIS and IAS macrophytes, spreading in Mediterranean seawaters, come from the warmer waters of Pacific and Indian oceans with respective percentages of 38% and 23% of the whole invasive macroalgal division (Figure 6 & 7).

After all, the success of thermophilic macrophytes is supported, also, by their greater capacity in the interactions with other indigenous macroalgal species. In fact, Indo-Pacific NIS, accustomed to a great species richness and to high levels of interspecific competition in their native environments [73,74], might have great advantages invading Mediterranean temperate seawaters for the lower or absent mutual contest. In a climate change scenario, the native biodiversity levels could suffer a clear drop caused by the negative effects of marine global warming, so affecting the right functioning of ecosystem services. These data confirm that Mediterranean marine flora is gradually changing its composition from temperate and cosmopolitan species, by Atlantic origin, to tropical and subtropical ones, coming from the warmer waters of Indo-Pacific oceans.

Finally, a lot of reports, supporting decision-making processes, come from Citizen Science [75]. Also in this study, the information collected by citizen scientists on some NIS and IAS macrophytes, by special importance, has supplemented the scientific monitoring according to other surveys conducted worldwide [76,77]. In this way, Citizen Science has become an important tool not only to counterbalance the limited financial means available to researchers, but also to generate greater public awareness towards possible solutions and political actions.

Conclusion

This study highlights the successful invasive process and the widespread diffusion of thermophilic NIS macrophytes by tropical and subtropical origins, from the southeastern areas of Mediterranean towards the northwestern ones. The increasing trend in the introduction of NIS macrophytes, the warming of Mediterranean seawaters and the rise of commercial trade by maritime transport make the basin a real hotspot for biological invasions. Indeed, the environmental impacts of NIS and IAS on coastal ecosystems could be more marked in the present context of climate change [78]. So, cold water macrophytes could be replaced by warm water ones while the impacts of MHWs on vegetal communities could lead to the disappearance of canopy-forming species and to the prevalence of turf ones. An effective management of invasive processes requires a prompt report of NIS and IAS and their continuous monitoring in time and in space involving tourists, fishermen, divers and citizens in data collection.

All this, however, could lead to a wrong perception, evaluating the presence of exotic species marked as NIS. Therefore, it is suggested that, in studies concerning the spread of exotic species, it is necessary to carefully value the relative SST components, the migratory routes of NIS and IAS and the contribution of Citizen Science. Only in this case, it is possible to avoid false beliefs relating the invasiveness of species which, despite being NIS, do not have the typical characteristics of IAS. Anyhow, in these last years the interest of the whole scientific community towards this complementary tool is, remarkably, increased [79-81] not only to point out the presence of NIS and IAS macrophytes, but also to increase a public awareness about this important topic. In conclusion, it is necessary to counteract the negative effects of bio invasions through a sound coastal governance and coordinate actions at international level so to prevent NIS introductions and to manage IAS establishment, reducing their impacts at ecological and economic levels.

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