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Updating the occurrences of *Pterois miles* in the Mediterranean Sea, with considerations on thermal boundaries and future range expansion

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Abstract

Here we present an update of the Mediterranean distribution of the lionfish *Pterois miles,* based on a comprehensive list of geo-referenced occurrences up to October 2019. New data were provided by multiple reporting tools and citizen science initiatives. Our findings suggest that well established populations of *P. miles* exist in the Levantine Sea, in the southern and central Aegean Sea, as well as in the Greek Ionian Sea, whilst so far, only a few individuals were reported from Tunisia and southern Sicily (Italy). We also argue about the future expansion of this invasive species in the Mediterranean region and about the role of climate change by projecting the limits of winter isotherms under different climate change scenarios. Under the assumption that the mean winter sea surface temperature is the main limiting factor of the range expansion of the species (i.e. 15.3°C winter isotherm), *P. miles* could substantially expand in the Mediterranean Sea, except the coolest northernmost regions, under future climatic scenarios. These results were discussed in comparison to published outcomes of species distribution modelling.

Keywords: *Pterois miles*; species invasion; climatic change.

Introduction

One of the most ecologically harmful and well documented invasions in the marine realm around the world can be considered that of the Indo-Pacific lionfish (*Pterois volitans/miles* complex, Scorpaenidae) (Sutherland *et al*., 2010; Albins & Hixon, 2013). The lionfish *P. miles* and the invasive *P. volitans* in western Atlantic (which recent molecular studies consider it as a hybrid between *P. miles* and *P. russelii*; Wilcox *et al*., 2018) are regarded as among the most invasive species worldwide, severely impacting the invaded ecosystems and the native biota, but also affecting ecosystem services and human health (Albins & Hixon, 2008; Sutherland *et al*., 2010). Several ecological traits such as early maturity, high growth rates, generalist diet, high reproductive rate, long range larval dispersion and defensive structures have been listed to explain the great invasiveness of this species, which is capable to destabilize coastal marine communities through cascading effects (Albins & Hixon, 2013; Ballew *et al*., 2016; Zannaki *et al*., 2019).

The common lionfish *P. miles*, after its recent re-appearance in the eastern Mediterranean Sea (easternmost Levantine sector) (Bariche *et al*., 2013), has started to rapidly expand both westwards and northwards thus raising concerns for an incipient "lionfish invasion" with considerable conservation challenges (Azzurro *et al*., 2017). Here our main goal is to provide a detailed update of *P. miles* occurrences in the Mediterranean Sea (up to October 2019) based on multiple reporting tools, citizen science initiatives (i.e. scientific surveys, citizen science reporting platforms, social media forums, alert campaigns) and published scientific papers. In addition, we investigated the future expansion of this invasive species in the Mediterranean region under climate change scenarios by considering the winter isotherm of 15.3°C, which is considered to be a distribution limit for *P. volitans* across the North Carolina (USA) continental shelf (Whitfield *et al*., 2014).

Materials and Methods

We compiled a geo-referenced data set on the occurrence of *P. miles* in the Mediterranean Sea from 1991 to 2019. The data set updated the dataset of Azzurro *et al*. (2017), which included published observations in the scientific literature until 2017, amended by confirmed observations of *P. miles* from scientific surveys, citizen science reporting platforms, social media forums, alert campaigns and published scientific papers between 2012 to 2019 (Appendix 1).

The potential distribution of *P. miles* in the Mediterranean under current and future climate conditions was explored and discussed on the basis of the notion of minimum thermal tolerance, which has been used in the past to identify the geographical limits of the species (Côté & Green, 2012; Morris & Whitfield, 2009; Whitfield *et al.,* 2014). According to experiments conducted by Kimball *et al.* (2004), the lionfish (*P. volitans/miles*) cannot tolerate temperatures below 9.5-10°C and on average stop feeding at 15.3°C. These thermal limits correspond well to the geographical limits of the lionfish in the Atlantic invaded range: i.e. along the east US coast, established lionfish populations are consistently found at mesophotic depths in areas that maintain winter mean temperatures of ≥15.3°C (Whitfield *et al.,* 2014). Thus, the mean isotherm of 15.3°C during the winter period (December to February) was traced through three time periods as a possible limiting factor for the current distribution of *P. miles*.

The mean monthly Sea Surface Temperature (SST) fields for the period 1987-2017 were provided at a horizontal resolution 1/16º x 1/16º by the Copernicus Marine Environment Monitoring Service (CMEMS) through the Mediterranean Sea Physical Reanalysis product (medsea_reanalysis_phy_006_004 or dataset 1; Simoncelli *et al*., 2014; Fratianni *et al*., 2018). This dataset covers the Eastern Mediterranean Transient or EMT period 1987-1996 (e.g. Roether *et al*., 1996; von Schuckmann *et al*., 2016) and the post-EMT period 1997-2017. Additionally, a second reanalysis dataset covering the period 1955-2015 (medsea_reanalysis_phy_006_009 or dataset 2) that was produced with the same methodology and spatial resolution (Fratianni *et al*., 2015; 2017) was adopted by CMEMS in order to extend our view of the estimated SST variability prior 1987. Subsequently, mean seasonal SST fields were computed over the Central Mediterranean area for the winter period (December to February - DJF), for three different periods: a pre-EMT decadal period or period A (1975-1985) and the EMT period B (1987-1996) based on dataset 1, and the post-EMT period C (1997-2017) based on dataset 2.

As future projections of sea temperature are not available within this suite of datasets, potential future distribution under climate change was estimated with the use of the BIO-ORACLE dataset (Assis *et al*., 2018). BIO-ORACLE provides present (2000–2014) and future (2040–2050 and 2090–2100) marine environmental conditions both at the surface and the seabed for four future climate scenarios under the Representative Concentration Pathways (RCPs), developed for the IPCC AR 5 (Moss *et al*., 2010). Of these four scenarios, we employed two in our study: a) the RCP4.5 pathway, representing a stabilization scenario, assuming reductions in greenhouse gas emissions and b) the RCP8.5 pathway, which is a worst-case scenario, representing increasing greenhouse gas emissions combined with limited mitigation policies (Van Vuuren *et al.,* 2011). BIO-ORACLE does not include in its data layers mean winter temperatures, but it provides the average temperature of the coldest month, which is February in the Mediterranean, according to the CMEMS 1997-2017 dataset. Based on the simple linear regression of the grid values for the two data layers (Fig. 1), the 15.3°C mean winter temperature of the 1997-2017 CMEMS dataset corresponds to 14.3°C average temperature of the coldest month under current conditions (i.e. 2000-2014) in the respective BIO-ORACLE data layer. This value (14.3°C), was considered as the February temperature threshold for establishment of *P. miles*, under

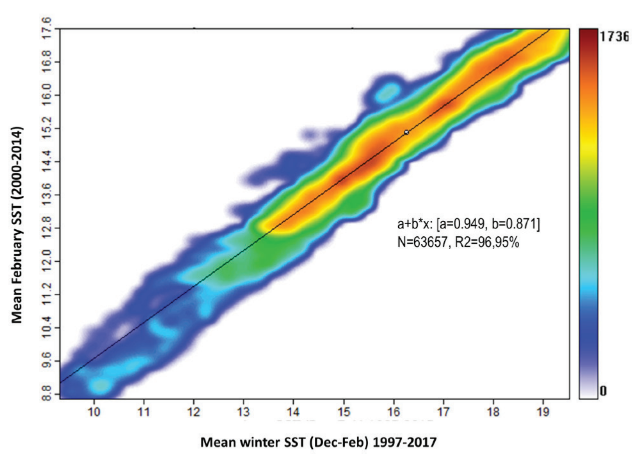

Fig. 1: Scatterplot of the grid values of Sea Surface Temperature (SST) for the average winter temperature between 1997-2017 calculated from the CMEMS dataset against the corresponding values of the average temperature of the coldest month between 2000-2014 from the BIO-ORACLE dataset. The linear regression line (in black) and equation are also displayed. The scale bar represents the density of data points.

future climate conditions. Subsequently, the isotherm of 14.3°C was traced under the two scenarios for the time periods of 2040-2050 and 2090-2100.

Results

A total of 447 distinct sightings of *P. miles* were included in the current study from 1991 until October 2019 (Fig. 2), with the vast majority of records being reported by citizen science initiatives. Overall, 52.5% of our records derived from citizen science reporting platforms (i.e. iSea– Is it alien to you? Share it!!!; ELNAIS; MedMIS), 39.5% from published scientific papers, 6% from Facebook forums (i.e. ODDFISH), media and alert campaigns established by research centers and marine protected areas (i.e. ISPRA and National Marine Park of Zakynthos, respectively) and 2.9% from unpublished observations by scientists. Our dataset included sightings from Turkey, Syria, Israel, Lebanon, Cyprus, Greece, Italy, Tunisia and Libya. The habitats of occurrence of *P. miles* were predominantly rocky reefs (84%), followed by underwater caves and rock slits (7%) and to a lesser extent by muddy and sandy bottoms, seaweed beds, algal patches and coralligenous formations (5.5%) (number of records reporting habitat: 186). Yet, the average depth of the sightings was 14.1 m (range: 0-110 m; number of records reporting depth: 278). The majority of the reported sightings originated by underwater observations from scuba divers and snorkelers (65.5%) followed by observations from artisanal and recreational fishers (including spear fishers) (30.3%) (number of records reporting the observation type: 218).

Our data set revealed a fast range expansion of *P. miles* which was restricted in the Levantine Sea by 2014 (with the exception of a record from the Aegean sea – Kalymnos in 2008), towards the south Aegean Sea during 2015 (two specimens were also reported in the Gulf of Tunis), and the southern Peloponnese Peninsula and Southern Sicily during 2016. During 2017 and 2018 *P. miles* continued to expand in the south Aegean Sea and two additional records from Southern Sicily were reported by local sea users within the framework of a national alert campaign in Italy (http://www.isprambiente.gov.it/files/comunicati-stampa/2016/Locandina_Pterois_miles.pdf). These additional Italian records were considered as 'valid' by the receiving scientists (EA, MF, LC), even if not supported by photographic material. Moreover, additional records from Libya were also reported.

In 2019, a rapid northward expansion in the Ionian Sea was evidenced, when *P. miles* got established in the entire Greek Ionian coastline and reached Corfu Island. As regards the cumulative density of sightings and the total number of specimens per sighting for the period 1991 to 2019 the highest values were calculated at Lebanon (e.g. 43 sightings / 70 km radius), southeastern Cyprus Island (e.g. 44 sightings / 70 km radius and 15 individuals per reporting), southeastern Aegean Sea (e.g. 25 sightings / 70 km radius), and Crete Island (e.g. 20 individuals per reporting) (Fig. 3).

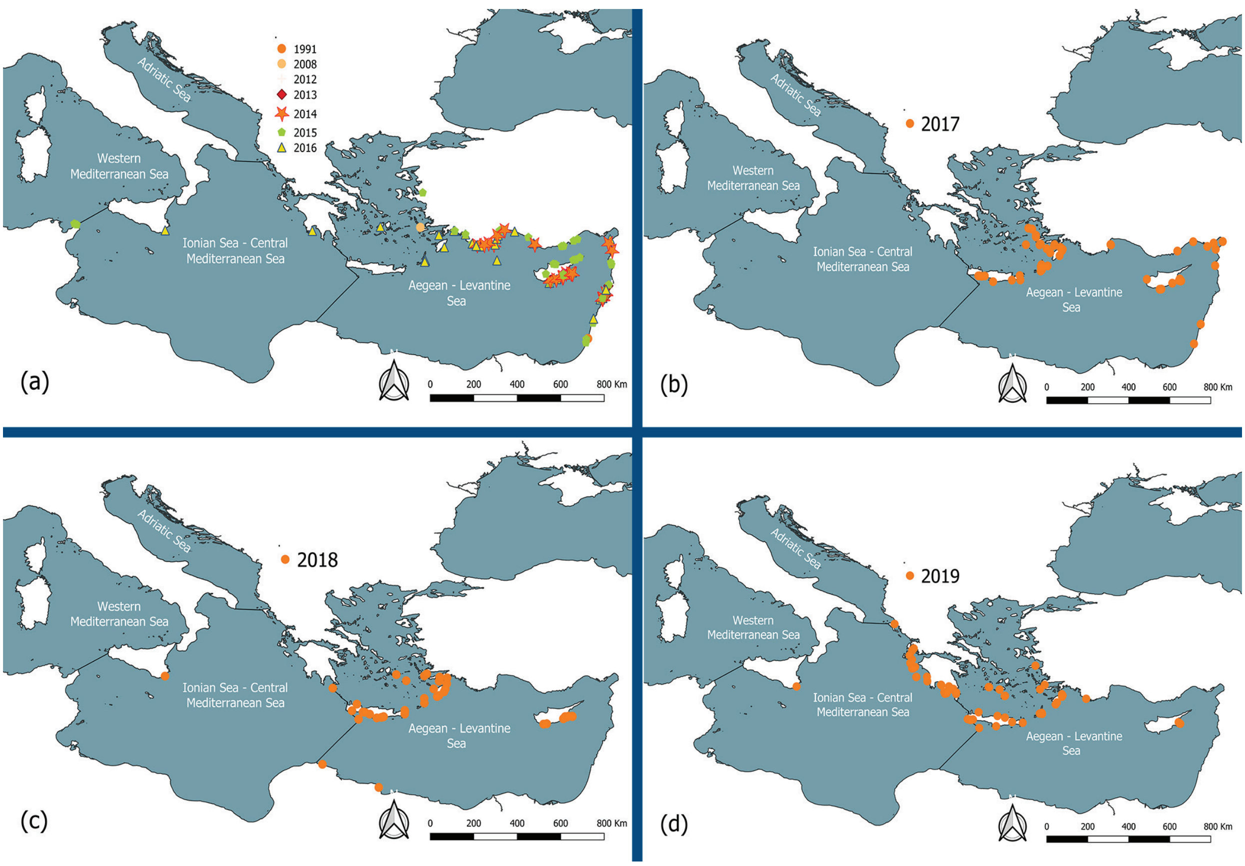

Fig 2: Reporting of *Pterois miles* in the Mediterranean Sea (a) from 1991 to 2016 (the year of first record in selected locations is depicted in the map); (b) in 2017, (c) in 2018 and (d) in 2019 (up to October 2019). MSFD marine subregions are also delineated (Jensen *et al*., 2017).

The 15.3°C mean winter isotherm displays a relatively good correspondence with the 14.3°C isotherm for the average temperature of the coldest month in most areas of the Mediterranean (Fig. 4), with the exception of the south and south-west of Italy, where future climate projections of *P. miles* establishment with the currently employed approach will contain higher uncertainty. Currently, the expansion of the species falls within the 15.3°C thermal limit, both at the northern (Corfu) and the western (Sicily, Tunisia) reaches of the Ionian and the Central Mediterranean Sea. Following to this criteria, future climate projections of SST would suggest that by the end of the century and under the moderate RCP4.5 scenario, the only areas not susceptible to a *P. miles* invasion will be the northern Aegean, northern Adriatic and the northwestern parts of the Western Mediterranean, whereas with the most extreme RCP8.5 scenario, only the northern Adriatic will remain unaffected. Even the most moderate of the scenarios examined, i.e. RCP4.5 by 2050, indicates a risk of considerable expansion towards the middle Adriatic and the Western Mediterranean.

Discussion

Soon after its re-appearance in the Mediterranean in 2012 (after a single report at 1991 – Israel and 2008 - Greece), *P. miles* was considered as established across the Aegean-Levantine region, spatially restricted though to the Levantine Sea and the southeastern Aegean Sea until 2015 (Bariche *et al*., 2013; Turan *et al*., 2014; Crocetta *et al*., 2015; Kletou *et al*., 2016; Mytilineou *et al*., 2016; Karachle *et al*., 2017), and further expanded to the central and southern Aegean Sea as well as Libyan Sea (southern Crete) in 2016-2018 (Dailianis *et al*., 2016; Giovos *et al*., 2018; Al Mabruk & Rizgalla, 2019). Here we provide further information regarding the rapid westward and northward spreading and establishment of this species in the Mediterranean complementing the recent sighting of *P. miles* in southern Italian waters (Azzurro *et al*., 2017) and the southern Ionian Sea (Yokeş *et al*., 2018; Vavasis *et al*., 2019). Therefore, our findings highlight that in 2019, *P. miles* has further advanced both northwards and westwards to the central and southern Aegean Sea, and has expanded its distribution range to the northernmost limit of the Ionian Sea (close to the border with the Adriatic Sea). The isolated individuals found up to Southern Sicily and Gulf of Tunis can be considered as the westernmost limits of its current distribution. It has to be stressed, though, that our social media search mainly focused in Greece, Cyprus, Italy, Lebanon and Libya, and hence the available information from other Mediterranean countries deriving from this source is rather limited. Moreover, the published scientific data from the easternmost areas of the Levant tend to decline, as upon first records of an alien species in a given area, additional records are rarely reported in the scientific literature. Yet additional limitations in the reporting and retrieving information of invasive species from this area could also arise from language barriers and political issues. Hence, we consider that, despite the fact that in our dataset *P. miles*' presence in the east Levant is generally low, this is an underestimate and the species should also be considered well-established in the entire Levant coastline (e.g. Israel: Stern *et al*., 2018) in the shallows and down to depths of 150 m or more (Jimenez *et al*., 2019; Orejas *et al*., 2019).

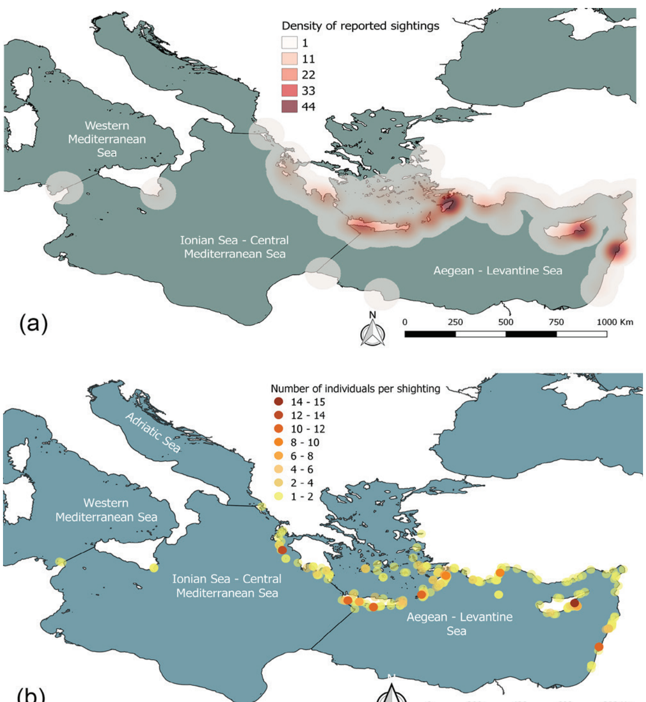

Fig. 3: (a) Heat map of the density of the reported sightings (radius = 70 km) and (b) the number of total individuals per sighting for the period 1991 to 2019.

Our results illustrate that the current distribution of *P. miles* falls within the limits of the winter isotherm of 15.3°C, as also reported by Whitfield *et al.* (2014) for *P. volitans* across the North Carolina (USA) continental shelf. Nevertheless, due to the recent and rapid invasion of the species in the Mediterranean, we cannot truly assess if the lionfish thermal niche is filled or not in this basin. It is also worth noting that the potential expansion dynamics of the species in the Mediterranean may differ from what is observed along the east USA coast, due to: 1) different thermal tolerance between *P. miles* and the complex *P. miles/volitans* and 2) not conserved thermal niches between two distinct geographical regions (Parravicini *et al*., 2015). We may also consider that Cape Hatteras in North Carolina represents a sharp biogeographic boundary, where warmer Gulf Stream waters diverge eastwards towards the Atlantic, while winter temperatures of inshore areas to the north of the Cape drop dramatically due to the influence of cooler Labrador current waters flowing south (Atkinson *et al*., 1983). In contrast, winter temperatures below 15.3°C in the Mediterranean are characterised by a much smoother gradient (see Fig. 4), such that yearly variations in the position of the thermal limit may facilitate over-wintering survival at new locations, northward spread and possible adaptations that can potentially lead to niche expansion. It is noteworthy that, in the USA invaded range, there have been reports of *P. volitans* as far north as Rhode Island

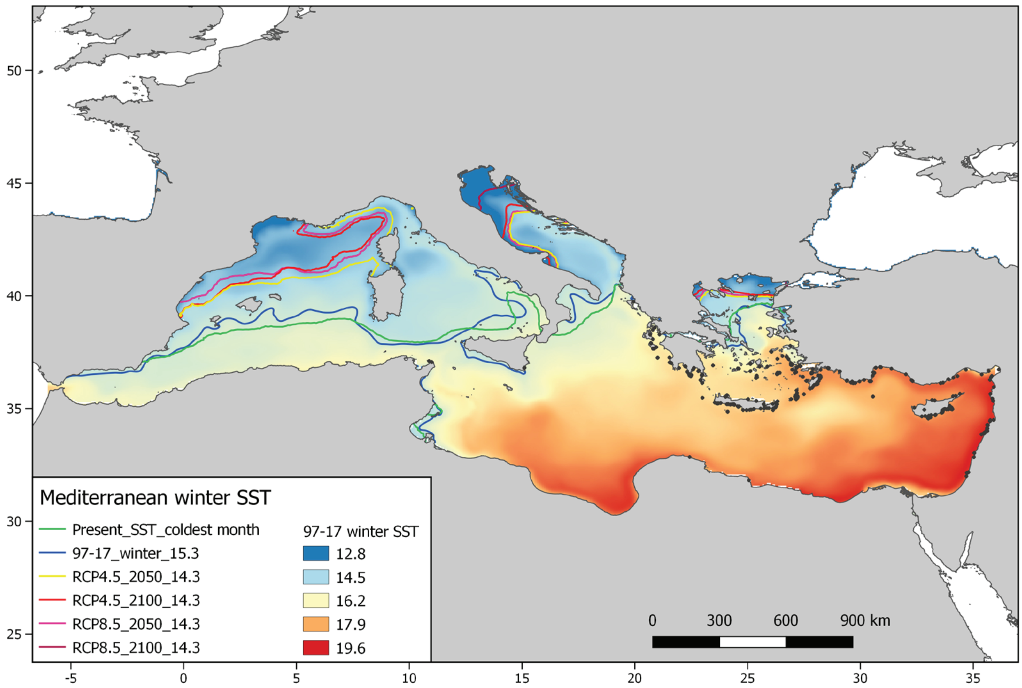

Fig. 4: Mean winter (December to February) Sea Surface Temperature (SST) between 1997-2017 with overlaid contour lines for the 15.3°C isotherm during that period (CMEMS dataset – see Methods) as well as the corresponding average temperature of the coldest month (=14.3°C) under present conditions and under two climate change scenarios, RCP4.5 and RCP8.5, for the periods 2040-2050 and 2090-2100 (BIO-ORACLE datasets). Black dots represent *Pterois miles* presence records.

and New Jersey waters in the summer months, at temperatures of 13.8°C (Meister *et al*., 2005) and 13.3°C (Gardner, pers. comm. in Schofield *et al*., 2019). These reports refer mainly to juveniles that were presumably carried over as larvae during suitable thermal conditions but failed to survive the low winter temperatures in these regions (Evangelista *et al*., 2016).

Our future predictions under climate change scenarios, based on the winter isotherms, differ from the ones provided by recent modelling approaches (D'Amen & Azzurro, 2020), which predicted the current and future areas of climate suitability in the Mediterranean Sea for nine invasive fishes, including *P. miles*. These authors used an ensemble of three SDM techniques, data pooled across invaded and native ranges, four different climate change scenarios by 2050 and six environmental predictors: pH, salinity (mean and range), SST (mean and range), and mean primary productivity. According to that study, *P. miles* was predicted to find suitable habitats only in the eastern Mediterranean sector, without significantly expanding its range of suitable environments due to climate change. According to these results, a further expansion of the species toward the western sectors of the Mediterranean wouldn't be possible based on the currently modelled niche, but only in the condition of niche unfilling, which is a plausible condition to be carefully considered in forecast exercises (Parravicini *et al*., 2015; D'Amen & Azzurro, 2020). Similarly, Poursanidis (2015), based on a MaxEnt model, concluded that the lionfish would be restricted in the eastern Mediterranean, especially the Levantine and the southeastern Aegean Sea.

The different predictions between the present study and the two previous studies are due to the different modelling approaches and the different assumptions on the role of temperature. Our study is based on the assumption of the 15.3°C winter isotherm being the sole limiting factor for the lionfish geographical expansion, whilst D'Amen & Azzurro (2020) assessed the variable importance on a large set of environmental marine layers and finally retained six predictors, including mean SST and SST range, but not the minimum winter temperature. A similar approach was used by Poursanidis (2015) who used nine predictor variables, among which SST but not the minimum winter temperature (the other variables were: silicate, phosphate and calcite concentrations, salinity, pH, photosynthetically available radiation, dissolved oxygen and chlorophyll A concentration). Yet Johnston & Purkis (2014) used a biophysical model and predicted that particular parts of the western Mediterranean will be susceptible to lionfish invasion with low connectivity among potential lionfish habitats based, however, on past and current oceanographic features of the Mediterranean.

Therefore, we highlighted the differences between the 15.3°C winter isotherm approach (whose output is essentially binary maps, i.e. maps where a condition is either met or not) and SDMs. This comparison is particularly useful to better evaluate the uncertainties related to both, the validity of the 15.3°C winter isotherm approach and the possibility of niche unfilling. Thermal niche approaches are widely applied, particularly with regards to projections of species' range shifts with climate change (Sunday *et al*., 2012; Stuart-Smith *et al*., 2017; Morley *et al*., 2018). For marine species, geographic ranges seem to conform closely to their thermal limits (Sunday *et al*., 2012; Payne *et al*., 2016; Fredston-Hermann *et al*., 2020), and seasonal extremes often appear to have a high predictive capacity (e.g. Langer *et al*., 2013; Reyna *et al*., 2018), with species possessing wide thermal niches usually exhibiting higher plasticity at their lower thermal limits (Stuart-Smith *et al*., 2017). Lionfish can survive at considerably lower temperatures than what their current distribution indicates and, despite they may not be able to feed below a certain temperature range (see Methods section), they have an exceptional tolerance for food deprivation for up to three months (Fishelson, 1997; Côté & Smith, 2018). Hence, our predictions for the expansion of the lionfish in the Mediterranean, based on the mean winter isotherm approach, can be considered as conservative, due to niche unfilling (D'Amen & Azzurro, 2020) or a further expansion of its climatic niche in the Mediterranean Sea (Parravicini *et al*., 2015).

Thus, our study summarized the available knowledge, providing new perspectives on the thermal boundaries and future range expansion of *P. miles* in the Mediterranean Sea. We presented possible knowledge gaps and limits of the various approaches that can be used for assessing the risk of the Mediterranean lionfish invasion. Future studies could certainly ameliorate our predictive abilities by considering the importance of biotic interactions (Azzurro *et al*., 2014) and by investigating the physiological performances of the Mediterranean lionfish in relation to water temperature (e.g. Marras *et al*., 2015). Based on empirical observations, we also suggest to carefully consider minimum winter temperature and evaluate the importance of this variable in future SDMs, together with the other environmental predictors. Still the relation of the bathymetric distribution of the lionfish and the winter minimum temperatures across depths may lead to more accurate predictions regarding the potential regional expansion of this species in the Mediterranean.

In conclusion, our findings suggest that *P. miles* can be considered as well established in the Levantine Sea, the southern and central Aegean Sea, as well as the Greek Ionian Sea, whilst population status should be closely monitored at its invasion front (Sicily and Otranto Straits). Our study also highlights the added value of citizen-science and public engagement for the monitoring of marine invasions, if data collected by citizens are properly managed and validated (Giovos *et al*., 2019). Hence citizen science networks can provide valuable information overcoming funding and time restrictions of scientific surveys, and supplementing information derived by targeted research surveys (Azzurro *et al*., 2018; Giovos *et al*., 2019).

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APPENDIX is available on line.