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How are the Mediterranean islands polluted by artificial light at night?

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ABSTRACT

The Mediterranean is considered as a World Biodiversity Hotspot because of the significant reservoir of endemics, which are threatened with destruction. Island ecosystems have special importance for biodiversity conservation in this region. However, most of them are under strong anthropogenic influences: recreational pressures, infrastructure development, fires etc. At the same time, new types of anthropogenic pressures have developed, one of which is the preponderance of artificial light at night (ALAN) and sky glow. This factor has not been perceived as dangerous for people and biodiversity until recently. However, the latest researches show the opposite conclusion: ALAN has a significant influence on reproduction, navigation, behavior, foraging, habitat selection, communication, and social interactions of all living organisms. Therefore, we have estimated the level of light pollution on the fifteen biggest islands of the Mediterranean using tools available from Google Earth Pro, and the New World Atlas of Artificial Sky Brightness in the form of a kmz layer created by Falchi et al. (2016). In addition, islands or their parts without ecological light pollution have been selected. The obtained results argue that light pollution is extremely high on these larger islands; there are no areas with zero-level of ecological light pollution. As well it has been found that the level of light pollution of these islands correlates with their human population density. Nevertheless, there are 49 small islands or their parts with "pristine" skies, and their total area is 118.67 km^2. Also, four dark sky refugia (Western (313,593 km^2), Adriatic (331 km^2), Aegean (12,448 km^2), and Eastern (841,195 km^2)) were highlighted within the territory of the Mediterranean Sea. That is 46,61% of its total area. Special attention has been paid to protected areas of the region in the context of combating light pollution, as well as the potential for astro-tourism development. Recommendations for changing of the current ALAN-related situation are given.

1. Introduction

The Mediterranean is considered a World Biodiversity Hotspot because of the significant reservoir of endemics and the fact that many are threatened with extinction (Myers et al., 2000). Its local flora is rich containing about 24000–25000 species with a high degree of endemism, up to 63.5% (Greuter, 1991; Heywood, 2002). The local fauna is also characterized by its richness and its high level of endemism. There are 298 species (of which 38 are endemic) of mammals (Temple and Cuttelod, 2009), 534 species of birds including 63 endemics (Blondel et al., 2010), 299 species (117 endemics) of reptiles (Cox et al., 2006), 109 species (54 endemics) of amphibians (Cox et al., 2006), 622 species (280 endemics) of freshwater fish (The Critical Ecosystem Partnership Fund, 2017), and 600 species of marine fish with approximately 74 endemic species (Abdul Malak et al., 2011). Invertebrates are highly diverse in the Mediterranean region: anthozoans are represented by 151 species (Coll et al., 2010) with approximately 26 endemic species amongst them (del Mar Otero et al., 2017); freshwater mollusks account for 629 species, including 384 endemic species (The Critical Ecosystem Partnership Fund, 2017); there are 61 species of damselflies and 104 species of dragonflies, 23 of them are endemic (Riservato et al., 2009); 463 species of butterflies (98 endemic species) (Numa et al., 2016); about 580 species of dung beetles occur in the region, of which approximately 150 are endemic; at least 576 species of saproxylic beetles represented here with approximately 338 endemic species (The Critical Ecosystem Partnership Fund, 2017). This rich and unique biodiversity has been formed to a large extent due to island isolation over a long period of time in the Mediterranean (Blondel et al., 2010; Greuter, 2001; Thompson, 2005). As a result, the flora of Sicily has 305 species of vascular plants, with 11.3% being endemic, the flora of Crete – 165 species or 10.1% being endemic, the flora of Sardinia – 61 species of which 5.4% are endemic, and the flora of Corsica – 131 species with 4.5% being endemic (Junikka

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et al., 2006). Therefore, the islands have special value to this region; many of them belonging to the ten Mediterranean Basin hotspots based on plant endemism and richness (Medail and Quezel, 1999). However, there is a very strong anthropogenic influence on natural ecosystems, which is causing biodiversity loss in the Mediterranean (Coll et al., 2010; Greuter, 1991). Though the human impact on the Mediterranean islands, from early prehistoric settlements through antiquity to the Middle Ages, has been profound, the situation has been changing for the worse in the last few decades; the speed of deterioration of natural habitats has increased exponentially (Greuter, 2001). Moreover, new threats are appearing. One of these is ecological light pollution which is increasing rapidly on a global scale (Kyba et al., 2017). This has already been documented for the Mediterranean (Bennie et al., 2015b; Caruana et al., 2020; Peregrym et al., 2020a).

While the impact of artificial light at night (ALAN) is being ignored by decision-makers at local and national levels, as well as by related organizations and even by some scientists, the problem becomes more dangerous for ecosystems, species, and human health (Abraham et al., 2019; Dominoni et al., 2020; Falchi, 2018; Schroer and Hölker, 2017). However, the fact that 80% of the world and more than 99% of U.S. and European populations live under light-polluted skies shocks (Falchi et al., 2016). In addition, its consequences are deep and serious, because they have a significant influence on reproduction, navigation, behavior, foraging, habitat selection, communication, and social interactions of all living organisms. There is, already, a lot of published data about the ALAN and sky glow affecting plants (Bennie et al., 2018; Brelsford and Robson, 2018; ffrench-Constant et al., 2016; Giavi et al., 2020; Knop et al., 2017; and others), invertebrates (Ayalon et al., 2019; Davies et al., 2012; Grubisic et al., 2018; Macgregor et al., 2017; Owens et al., 2019; Underwood et al., 2017; van Grunsven et al., 2018; and others), and vertebrates (Grubisic et al., 2019; Schroer and Hölker, 2017; Touzot et al., 2020; and others), including humans (Cho et al., 2015; Dominoni et al., 2016; Johnson and Munshi-South, 2017; and others). Consequently, cascading effects with unpredictable results appear in terrestrial and water ecosystems (Bennie et al., 2015a; Bolton et al., 2017; Davies et al., 2020; Depledge et al., 2010; Garratt et al., 2019; Hölker et al., 2015; Maggi et al., 2020; Navarro-Barranco and Hughes, 2015; Perkin et al., 2011; Russo et al., 2019; Sanders et al., 2015; Sanders and Gaston, 2018; Spoelstra et al., 2015). Besides, ALAN can be a driver of evolution across urban-rural landscapes (Hopkins et al., 2018).

In considering the described situation where the Mediterranean islands are natural habitats for many unique species, and the ALAN impact increase on them, it was decided to estimate the strength of the impact of artificial light at night in these territories.

2. Material and methods

This research covers the Mediterranean Sea and its islands. However, our investigation has mostly been focused on the fifteen islands with the largest areas (Sicily (Italy), Sardinia (Italy), Cyprus (the Republic of Cyprus), Corsica (France), Crete (Greece), Euboea (Greece), Majorca (Spain), Lesbos (Greece), Rhodes (Greece), Chios (Greece), Kefalonia (Greece), Menorca (Spain), Corfu (Greece), Ibiza (Spain), Djerba (Tunisia)) (Fig. 1), as well as on islands with total area more than 0.01 km^2 with "pristine" night skies as stated by Falchi at al. (Falchi et al., 2016).

The methodology tested in our former researches has been used for this study (Peregrym et al., 2020a, 2019, 2018). It has been carried out using the available tools of Google Earth Pro (version 7.3.2.5776 – https://www.google.com/earth/). We used the New World Atlas of Artificial Sky Brightness in the form of a kmz layer which has been obtained by an international team under the supervision of Fabio Falchi (Falchi et al., 2016) and available through its 3D Globe version - https://cires.colorado.edu/Artificial-light. We juxtaposed natural borders of the Mediterranean Sea and its islands with the artificial sky brightness layer and counted the number of squares of each index level of artificial sky brightness according to the legend of the atlas (Falchi et al., 2016). An example of the process for Corsica is shown in Fig. 2.

3. Results

The Mediterranean Sea occupies about 2,510,000 km^2 (Salah and Boxer, 2019), but absolutely dark skies at night cover only 1,167,567 km2 or 46.61% of this territory. There are 4 dark sky refugia (Fig. 1): Western (313,593 km^2), Adriatic (331 km^2), Aegean (12,448 km^2), and Eastern (841,195 km^2). ALAN pollutes the remaining parts of this marine area.

We have established that there are only 49 non-polluted or partly non-polluted islands in the Mediterranean Sea. The total area is 118.67 km^2, and the biggest island is 32.79 km^2. Most of these islands belong to Greece, with four belonging to Tunisia. The location of these islands is shown in Fig. 3, and their names, geographic coordinates as well as areas

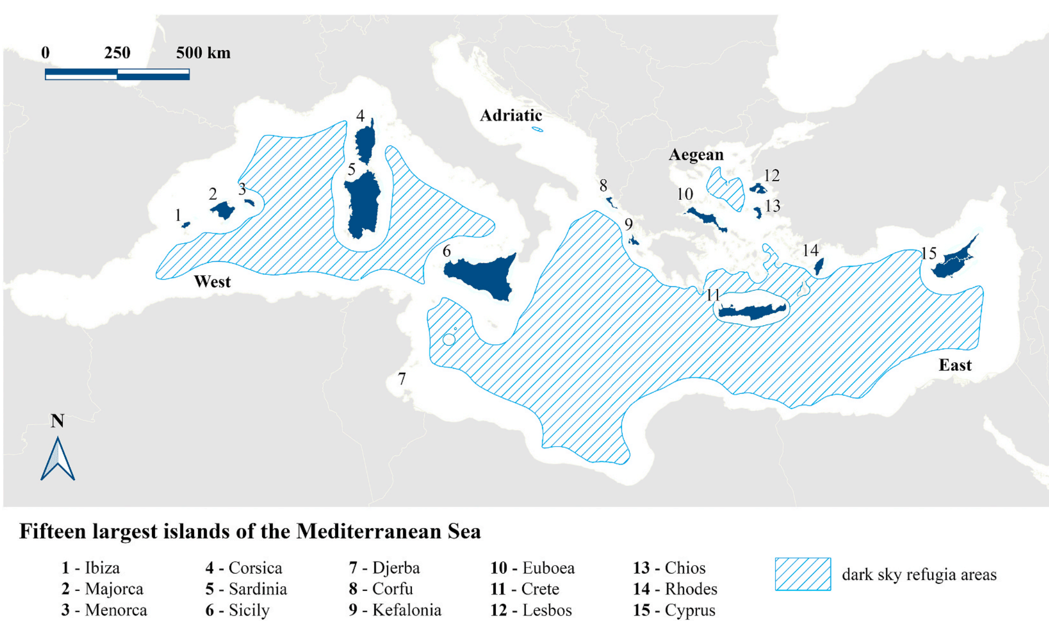

Fig. 1. The fifteen largest islands of the Mediterranean Sea and the areas with absolutely dark skies.

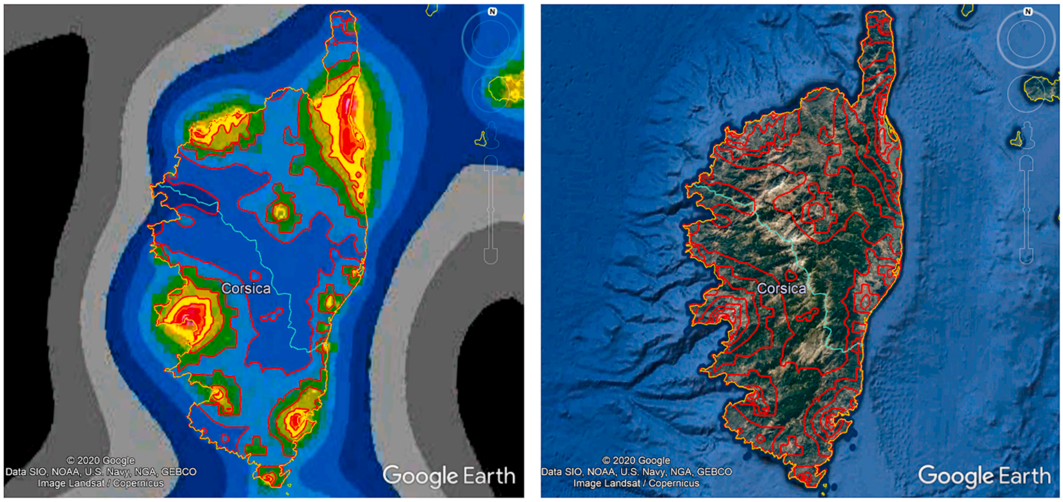

Fig. 2. An example of calculation of area (km^2) for every index of the level of artificial sky brightness using Google Earth Pro and the kmz layer obtained from Falchi et al. (2016).

are given in Supplementary material.

The results of calculations of artificial sky brightness levels for fifteen of the biggest Mediterranean islands are provided in Table 1. To quantify an error within the calculations, we have created two columns in this table: one column contains the calculated area, and the other one contains the official area of these islands (Pariona, 2017). The highlighted discrepancy is generally not more than 1–2% for studied areas, apart from Corfu and Ibiza with a discrepancy of 5.3% and 4.2% respectively. That could be a result of their intricate coastlines or from inaccurate official data of the countries areas. However, the obtained results show a common situation with the level of ecological light pollution for these two islands.

As seen from Table 1, there are no plots with zero-level of ecological light pollution. ALAN heavily pollutes all fifteen biggest Mediterranean islands. Using the scale provided by Falchi et al. (2016), it has been established that only 0.17% (157.33 km^2) of the total area of these islands can be considered non-polluted from an astronomical point of view, i.e. with artificial sky brightness less than 6.96 μcd/m^2 21.1% or 18,886.6 km^2 are polluted from an astronomical point of view (artificial sky brightness is from 6.96 to 55.7 μcd/m^2). The remaining parts of their territories have a higher level of ecological light pollution, up to the highest (>7130 μcd/m^2) being noted in Sicily.

4. Discussion

As seen from our results and data for the Maltese archipelago studied by Caruana et al. (2020) with other methodology, the largest part of the maritime areas of the Mediterranean Sea as well as all islands, exclude

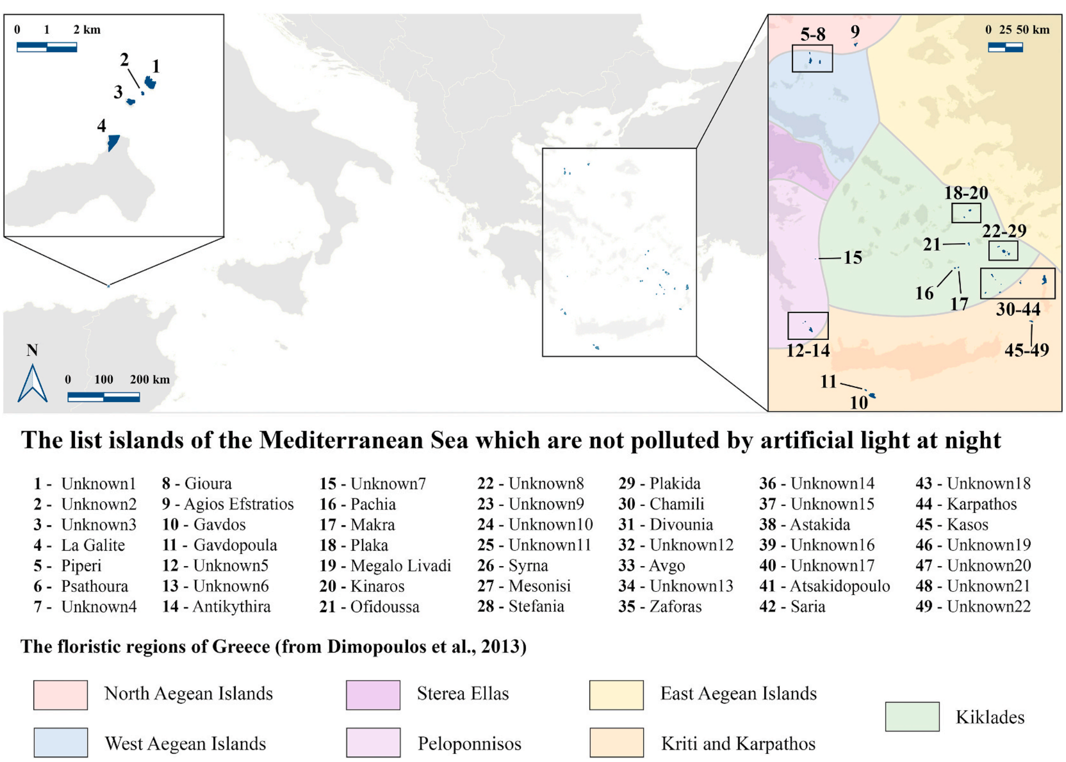

Fig. 3. The location of 49 non-polluted or partly non-polluted islands in the Mediterranean Sea.

Table 1
Squares of areas with different level of artificial sky brightness at 15 biggest Mediterranean islands.

Island	Square of areas with different level of artificial brightness (μcd/m²), km²														Calculated area, km²	Actual area, km²
	<1,74	1,74–3,48	>3,48–6,96	>6,96–13,9	>13,9–27,8	>27,8–55,7	>55,7–111	>111–223	>223–445	>445–890	>890–1780	>1780–3560	>3560–7130	>7130		
Sicily	–	–	–	–	–	–	1337.70	8412.54	9596.31	3893.94	1572.05	573.95	21.74	1.41	25,409.64	25,711
Sardinia	–	–	–	–	150.16	3108.41	8651.29	7195.72	3251.46	927.02	278.08	124.23	21.22	–	23,707.59	24,090
Cyprus	–	19.20	36.01	41.56	165.44	945.08	1461.98	2845.08	2068.79	1092.21	395.39	134.48	52.11	–	9257.33	9251
Corsica	–	–	–	199.31	2711.79	2837.61	1470.53	757.60	473.53	171.36	65.60	17.29	1.03	–	8705.65	8681
Crete	–	5.92	60.43	488.88	1694.26	2328.33	1985.23	997.83	439.98	157.29	57.81	15.42	2.21	–	8233.59	8336
Euboea	–	–	–	–	106.41	1228.2	1319.72	726.00	206.55	59.83	17.04	–	–	–	3663.75	3655
Majorca	–	–	–	–	–	17.29	271.46	1501.34	1110.44	423.18	170.59	74.01	40.35	–	3608.66	3640.11
Lesbos	–	–	3.84	155.51	244.02	604.61	381.34	135.47	56.71	13.50	3.71	–	–	–	1598.71	1632.8
Rhodes	–	–	31.93	202.49	239.93	288.70	183.50	147.20	166.42	90.27	51.57	2.07	–	–	1404.08	1401
Chios	–	–	–	76.78	197.61	215.23	230.38	62.87	44.39	6.62	–	–	–	–	833.88	842
Kefalonia	–	–	–	40.93	213.90	258.86	183.65	41.63	32.19	–	–	–	–	–	771.16	781
Menorca	–	–	–	–	–	71.32	274.97	209.79	91.50	38.26	6.15	3.95	–	–	695.94	694
Corfu	–	–	–	–	–	47.82	149.13	241.79	61.81	42.05	18.23	–	–	–	560.83	592
Ibiza	–	–	–	–	–	–	63.99	110.26	165.41	107.93	54.19	46.44	–	–	548.22	572
Djerba	–	–	–	–	–	6.16	59.50	176.14	190.23	61.95	17.75	4.82	–	–	516.55	523
TOTAL	0	25.12	132.21	1205.46	5723.52	11,957.62	18,024.37	23,561.26	17,955.72	7085.41	2708.16	996.66	138.66	1.41	89,515.58	
	0	0.03%	0.14%	1.35%	6.39%	13.36%	20.14%	26.32%	20.06%	7.92%	3.03%	1.11%	0.15%	0.00%	100%	

49 mentioned ones, are polluted by ALAN at the present time. However, at the moment our calculated data shows a static situation for the fifteen biggest Mediterranean islands from the New World Atlas of Artificial Sky Brightness publication (Falchi et al., 2016). Taking into account data concerning the global dynamics of light pollution increasing, which is about 2,2% (Kyba et al., 2017), we confidently assume that the current situation is significantly worse in the region studied. This means that the average level of artificial brightness will have gone up about 8–9% by 2020. As a result, the total area of polluted territories has increased alongside pollution intensity. It is unclear at the present time how deep are ALAN influences on biota in the sea. At the moment, here is no data for the Mediterranean Sea, but taking into account the latest facts documented by Berge et al. (2020) for Arctic latitudes, we presume that the ALAN impact is, at least, no less here, i.e. it disrupts behavior of fish and zooplankton living down to 200 m depth.

According to data from Table 1, the most polluted of the studied islands are Ibiza, Djerba, Sicily, and Majorca; the cleanest ones, although it is relative, are Corsica, Lesbos, Kefalonia, Chios, and Euboea. Because ALAN has only anthropogenic origin, it was logically to compare this result with the total number of human population of fifteen biggest Mediterranean islands ("List of islands in the Mediterranean," 2020): Sicily – 4,969,147 (data of 2019), Sardinia – 1,651,793 (2017), Cyprus – 1,189,265 (2019), Majorca – 896,036 (2019), Crete – 634,930 (2019), Corsica – 330,455 (2016), Euboea – 191,206 (2011), Djerba – 163,726 (2013), Ibiza – 147,914 (2019), Rhodes – 115,490 (2011), Corfu – 102, 071 (2011), Menorca – 93,397 (2019), Lesbos – 86,436 (2011), Chios – 51,390 (2011), and Kefalonia – 35,801 (2011). However, this information did not help to find any dependence in levels of light pollution on these islands. After that, we tried to compare data from Table 1 with human population density of the studied islands which was calculated using data about their official area and population number ("List of islands in the Mediterranean," 2020; Pariona, 2017): Djerba – 313 people/km², Ibiza – 259/km², Majorca – 246/km², Sicily – 193/km², Corfu – 172/km², Menorca – 135/km², Cyprus – 129/km², Rhodes – 82/km², Crete – 76/km², Sardinia – 69/km², Chios – 61/km², Lesbos – 53/km², Euboea – 52/km², Kefalonia – 46/km², and Corsica – 38/km². As seen, levels of light pollution of fifteen biggest Mediterranean islands mostly correlate with human population density of these islands. Though there are some minor deviations in it which could connected with relief features of the islands. It is only a visual observation (for example, see Fig. 2) which needs additional confirmations, however mountain areas are usually polluted less, than flat ones. Probably, the phenomenon arises because of light propagation features as well as less developed road and settlement infrastructure there.

Separately, it is worthwhile to note mild seasonal variability in the night sky brightness, with summer months exhibiting higher values, having been observed in the Maltese archipelago (Caruana et al., 2020). We imagine that this is a common tendency for all Mediterranean islands – a fact that should be taken into account in the future studies. Fortunately, the described predictions do not include the majority of non-polluted islands from Fig. 3, assuming that further lighting or road infrastructure has not been developed there during the last four years. Some negative changes could happen on these islands #4, 9, 14, 20, 44, 45, because these islands are only partially non-polluted.

Existence of these 49 non-polluted or partly non-polluted islands in the Mediterranean Sea is a positive finding for the current situation. Despite their small size, the majority of these islands have been recognized as Key Biodiversity Areas (The Critical Ecosystem Partnership Fund, 2017). In addition, in the main they have officially protected status as protected areas or parts: Nature Reserve "Archipel De La Galite" in Tunisia, the National Marine Park of Alonnisos Northern Sporades and Natura 2000 sites in Greece ("Protected Planet," 2014). Nonetheless, there is no doubting the unique value of the non-polluted territories for nature conservation, because of the absence of ALAN disturbance there. As a confirmation of this thesis, there is the case of nesting sea turtles in the Mediterranean; species that avoid night light intensity and concentrate in darker sections along the coast (Mazor et al., 2013). Unfortunately, night light pollution can reduce turtle population growth by more than 7%, as documented in Zakynthos Island (Dimitriadis et al., 2018).

Understandably, only a small part of Mediterranean biodiversity is represented on these 49 islands, because they are locally distributed. However, if we consider their location according to the floristic zoning of Greece (Dimopoulos et al., 2016; Strid and Tan, 1997), they are distributed in five of six floristic regions of the Aegean and Cretan areas (Fig. 3). This is positive in the context of representativeness of plant diversity. Islands # 5–8 from Fig. 3 are located in the West Aegean Islands floristic region, island # 9 is located in the North Aegean Islands region, islands # 10, 11, 42–49 are situated in the Crete and Karpathos region, islands # 12–15 are in the region of Peloponnisos, and islands # 16–41 are in the Kiklades region. The most important fact here is that the island populations of endemic plants are not affected by ALAN. Consequently, these islands are peculiar "night shelters" for those species with a narrow range.

Also these islands have all the prerequisites to be recognized as International Dark Sky Places (http://darksky.org/idsp/), or Starlight Areas (https://www.fundacionstarlight.org/en/section/what-are-they/284.html), that can give important benefits for astrotourism development. Today there are no recognized places in the framework of the International Dark Sky Places Program within the Mediterranean Sea. However, since 2001 it has been gaining recognition by the International Dark-Sky Association in the World (Barentine, 2016). Besides, the Starlight Foundation has an alternative certification program (https://www.fundacionstarlight.org/en/section/what-are-they/284.html) that supports efforts to develop recommendations aimed at preserving or restoring the quality of the night sky, taking into consideration the cultural, educational, scientific and environmental benefits (Varela et al., 2012). There are 9 Starlight Areas in territorial waters of Spain, but they all are light polluted. Thus, 49 non-polluted or partly non-polluted islands have great potential for development of these initiatives in the Mediterranean.

Besides, 4 Mediterranean Sea dark sky refugia (Fig. 1) together with these 49 non-polluted or partly non-polluted islands (Fig. 3) have to be recognized as 4 new Very Important Dark Areas (VIDAs), because they meet all criteria for it (Peregrym et al., 2020b). It means that the Western refugium together with islands #1–4, the Aegean one with islands #5–9, the Eastern one with islands #10–49, as well as the Adriatic refugium without islands are the most promising territories for the conservation of biodiversity with a dark sky at night. The recognizing of these VIDAs in the Mediterranean allows continuing the development of the VIDA Network globally, that has recently been beginning from Europe and the Caucasus.

Special attention should pay to the protected areas of the fifteen biggest Mediterranean islands and their neighborhoods, because these areas are an important *in situ* mechanism to conserve biodiversity and to buffer a wide range of anthropogenic pressures (Gaston et al., 2008). According to the "Protected Planet" database ("Protected Planet," 2014), different categories of protected areas are presented here: nature, wildlife and sea reserves, national as well as regional parks, Ramsar and Natura 2000 sites etc. However, it is most likely that their management plans do not include any actions directed towards combating light pollution, as it is common in the protected territories of the most European countries at the present time (Peregrym et al., 2020a, 2019, 2018). If this assumption is correct, then this situation must be changed in the near future.

Our research is the first step to change the current situation in the Mediterranean that is under a threat of by full loss of the night darkness with severe effects for natural ecosystems and local population. However, our results show only the present level of light pollution in the region. The next, it is important to start active actions for protection of the dark sky as well as for decreasing of the ALAN impact. These actions will have to be done on all levels: individual, local, regional, state and international. First of all, outdoor lighting systems should be improved that they keep lighting levels to the absolute minimum necessary for their tasks. There are many practical recommendations which will significantly help to decrease the ALAN level (Dick, 2018, 2014; Falchi, 2018; Hölker et al., 2010; Jechow and Hölker, 2019). Moreover, it is needed to pass regional and state laws against light pollution, as it has been done in Italy where 18 out of 20 regions (by the way, except Sicily) have them that allows protecting, more or less, most of the territory and population from this contamination (Falchi, 2018). Also, a lot of legislative shortcomings will have to be eliminated even in the European Union: while protection is predominantly provided for species with special protection status (protected by the Bern Convention on the Conservation of European Wildlife and Natural Habitats, the Flora-Fauna-Habitat Directive, the Wild Birds Directive, and National Red Data Lists, etc.) that reveal avoidance behavior of artificially lit landscapes and associated habitat loss, adverse effects on species and landscapes without special protection status are often unaddressed by existing regulations (Schroer et al., 2020). As well there are difficulties in proving adverse effects on the population level, detecting lighting malpractice, and applying the law to ALAN-related situations.

Certainly, the implementation of described actions will happen faster if influential international NGOs are involved in this process. There is a sense to create Mediterranean working groups at professional organizations specializing on decision of light pollution problems like the International Dark-Sky Association (https://www.darksky.org/) or the International Commission on Illumination (http://cie.co.at/). Besides, it is important to involve international conservation organizations for searching of optimal ways for rapid improvement of the current situation. It can be IUCN that has both the Centre for Mediterranean Cooperation (https://www.iucn.org/regions/mediterranean) and the Dark Skies Advisory Group (http://darkskyparks.org/dark-skies-and-nature-conservation/), or WWF Mediterranean (https://mediterranean.panda.org), as well as some regional ecological organizations like "PIM Initiative" (http://initiative-pim.org), SMILO (http://www.smilo-program.org) and others.

What is the final aim of these actions, except general decreasing of the level of light pollution in the Mediterranean? There is no doubt that it is impossible to restore the absolute darkness at night here at the present, because of human needs in artificial light for modern comfort life. Nevertheless, the most important task is to restore the absolute darkness at night at least on small plots with natural and/or semi-natural ecosystems on each largest islands as well as around them. Terrestrial and marine protected areas must be target objects for creation of these "night shelters" for reach local biodiversity and many migrated species.

5. Conclusion

Thus, we have adequately documented the fact that ALAN heavily pollutes the fifteen largest Mediterranean islands that are habitats for many endemic and rare species, and these islands do not have any plots with zero-level of light pollution. Also it has been found that the level of light pollution of the islands correlates with their human population density. Nevertheless, less than half of the marine area of the Mediterranean Sea is covered by completely dark skies at night, though this total area consists of four plots located in different parts of the sea. Also, only 49 non-polluted or partly non-polluted islands remain in the whole region. These islands of the Mediterranean Sea are very important dark areas where the living beings and their interactions, as yet, are not affected by ALAN. Although there is no exact data about the ALAN minimum level which influences organisms (Falchi, 2018), these places are unique in the context of both nature conservation and scientific investigations. Moreover, these areas can be used as the basic plots for comparative studies of biological, ecological and even evolutionary consequences of the ALAN impact, as well as for astrotourism development.

The results obtained must be a call for active measures to decrease ecological light pollution levels in the region, to restore the absolute night darkness within terrestrial and marine protected areas, as well as to accelerate new scientific research of the ALAN impact on all nature components of the Mediterranean, including endemic species.

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Declaration of competing interest

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Appendix A. Supplementary data

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