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Citizen science indicates significant range recovery and defines new conservation priorities for Earth's most endangered pinniped in Greece

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Abstract

Conservation actions for endangered species often require detailed data over large temporal and spatial scales, which are usually hard to obtain from traditional scientific surveys that operate at localized scales. In contrast to the terrestrial conservation world where citizen science has become nowadays a highly relevant and useful tool to overcome such difficulties, Marine Citizen Science is still highly underrepresented. Using a dataset of 20 years of citizen science data and appropriate statistical modelling, we developed a methodological approach to monitor the presence of the endangered, notoriously elusive Mediterranean monk seal *Monachus monachus*. We used sighting data collected in Greece from 2000 to 2020 and fitted dynamic occupancy models that allow inferring range dynamics whilst accounting for species imperfect detectability to estimate species occupancy. The occurrence of Mediterranean monk seals of all age categories combined, and pups separately, increased during the study period. Mediterranean monk seal occurrence increased also spatially: the distribution of the species in Greece increased by approximately 12.5% for seals of all age categories and by approximately 185% for monk seal pups. Most of this distribution (i.e. 67 and 72% of the distribution of seals of all age categories and of pups, respectively) was located within the boundaries of the network of protected areas in the country. These results indicate a significant range recovery of the Mediterranean monk seal in Greece over the last two decades and facilitate the prioritization of conservation actions for the species in the country. We demonstrate how occupancy modelling and citizen science can be used to evaluate the distribution of an endangered species and become a highly relevant and reliable tool in marine mammal conservation. We advocate the increased use of citizen science in the conservation of the Mediterranean monk seal in the eastern Mediterranean Sea.

Introduction

Conservation actions are of utmost importance in halting the declines in biodiversity that have been projected for the 21st century (Pereira *et al*., 2010). Effective conservation actions require, however, a thorough understanding of the basic life-history traits of endangered species, in order to evaluate their extinction risk and recovery potential (Hanski, 1998; Brambilla *et al*., 2009), and consequently identify conservation priorities. Understanding, for example, the distribution of an endangered species is essential in defining the scope and scale of research questions and management actions (Gooliaff, Weir & Hodges, 2018). Conservation actions for endangered species often require detailed data over large spatial and temporal scales, which are usually hard to obtain from traditional scientific surveys, which often operate at localized scales (Thorson *et al*., 2014). Monitoring endangered species distribution over such scales is typically expensive, whilst long-term funding for such monitoring activities undertaken by government agencies or academic scientists is often unstable (Barnas & Katz, 2010).

As new technologies emerge that make it easier to collect and transmit information on one's location, volunteer participation in data collection is becoming increasingly more important as an ecological research tool (Dickinson *et al*., 2012; Chase & Levine, 2016). Volunteers participating in citizen science programmes can collect more data and cover wider areas faster than researchers alone would, all of this at a lower cost (Dickinson, Zuckerberg & Bonter, 2010; Dickinson *et al*., 2012). Although concerns have been expressed over the reliability of citizen science data (Kosmala *et al*., 2016), if properly designed, carried out and evaluated, citizen science can provide sound science, efficiently generate high-quality data and help solve conservation problems (McKinley *et al*., 2017).

Reliable data obtained from citizen science programmes are particularly relevant to endangered species because information on presence, abundance and habitat associations is hard to obtain (Wiley & Simpfendorfer, 2010), due to the often cryptic and solitary nature of such species and their relatively low density of occurrence over large areas (Kindberg, Ericsson & Swenson, 2009). More specifically, opportunistic, presence-only data of citizen science projects may produce reliable estimates of wildlife distribution trends, if properly analysed with relevant statistical tools (van Strien, van Swaay & Termaat, 2013). In particular, site-occupancy models (MacKenzie *et al*., 2017) are increasingly used to map species range dynamics whilst accounting for observation bias inherent in opportunistic data (van Strien *et al*., 2013; Ruete *et al*., 2017; Louvrier *et al*., 2018; Erickson & Smith, 2021).

Whilst citizen science has now become highly relevant in the terrestrial conservation world (Lloyd *et al*., 2020), in contrast, Marine Citizen Science (MCS) is still highly underrepresented (Sandahl & Tøttrup, 2020; see however Bruce *et al*., 2014). This is despite the call for using site-occupancy models in the field (Issaris *et al*., 2012; Lauret *et al*., 2021) and the development of new technologies (e.g. underwater cameras, smartphones) that can generate a considerable number of observations that would otherwise not be feasible through conventional research (Araujo *et al*., 2020), and the resulting benefits and prospects for marine conservation (Kelly *et al*., 2020).

The Mediterranean monk seal *Monachus monachus* is the sole member of the genus *Monachus* and the only seal living in the Mediterranean Sea. Once abundant throughout the Black and Mediterranean Sea and the coasts of North Africa, the species experienced a (series of) severe population decline(s) during historical times, mainly due to human persecution and habitat destruction. This resulted in the extinction of the species from the biggest part of its historical range and ultimately led to a severe population collapse (Karamanlidis *et al*., 2016). Acknowledging the dire situation for the species, the IUCN classified the Mediterranean monk seal as 'Critically Endangered' towards the end of the previous century (Aguilar et al., 2010). At the same time, the countries with the last remaining seal populations initiated systematic monitoring and/or management/conservation efforts to reverse the plight of the species (Karamanlidis *et al*., 2016).

Despite the ongoing and increasing exploitation of coastal ecosystems and numerous negative seal–fishery interactions (Karamanlidis *et al*., 2008, 2020), Mediterranean monk seals throughout their range, and in the eastern Mediterranean in particular, have been showing encouraging signs of population recovery in recent years (i.e. after approximately the year 2000), resulting in the IUCN delisting the species and classifying it as 'Endangered' (Karamanlidis & Dendrinos, 2015; Karamanlidis *et al*., 2019). Circumstantial evidence suggests that this recovery is associated with the presence and pupping of Mediterranean monk seals in areas in Greece from which the species was long considered to be extinct (Dendrinos *et al*., 2020); however, no thorough, nationwide study has been conducted as yet to substantiate this fact. This incomplete understanding of the current distribution of Mediterranean monk seals in Greece may hinder their effective conservation, which, in turn, may compromise the ongoing recovery of the species in the country.

Because of its endangered status and its highly charismatic nature, the Mediterranean monk seal has become a flagship species for marine conservation in the Mediterranean Sea, thus attracting a lot of public attention and increasing the chances that seal sightings would be reported, and consequently, making the species particularly suitable for citizen science programmes. The aims of this study were to take advantage of a large citizen science dataset to: (1) study the recent trend of Mediterranean monk seal distribution in Greece and (2) assess how efficiently the NATURA 2000 network of protected areas covers the species' current distribution in the country. The first aim was achieved by analysing citizen science data with site-occupancy models and assessing the change in species occupancy between the beginning and the end of our study; the second aim was achieved by comparing the predictions of our site-occupancy models with the current distribution of protected areas in Greece. This comparison allowed us to obtain new, valuable insights into the spatial recovery and identify new priority conservation actions that will promote the continued survival of the Mediterranean monk seal in Greece.

Materials and methods

Data collection

Data on Mediterranean monk seal presence were used from 2000 to 2020 within the framework of a citizen science programme, the 'Hellenic Mediterranean Monk Seal Rescue and Information Network' (HMSRINT), established by the non-governmental organization MOm/Hellenic Society for the Study and Protection of the Monk seal. Information on seal presence (i.e. opportunistic observations, damage to fishing gear) was received from the general public through the post, telephone or email and was evaluated (i.e. on a scale from 1 to 3, 1 being the most reliable information) and verified, either on site by a field team or through the examination of the information provided (e.g. photographs and videos). In the study, we used only information that was related to live seals and information that we considered to be reliable (i.e. evaluated as 1–2). Because of their importance in the recovery potential of a population (de Larrinoa *et al*., 2021) and the increased management and conservation efforts required to effectively protect them, pup (i.e. an animal approximately 0–3-month old that has not undergone the first moult) presence was examined separately from the general seal presence.

Studying Mediterranean monk seal presence in Greece

In order to gain insights into the presence of Mediterranean monk seals in Greece, we mapped seal records from the HMSRINT using R version 4.1.0 (R Core Team, 2021) and the packages tidyverse v1.3.1 (Wickham *et al.*, 2019) and sf v1.0-2 (Pebesma, 2018). We considered and compared two 8-year study periods, one from 2000 to 2007 and one from 2013 to 2020.

Modelling framework

To estimate monk seal presence, we fitted dynamic occupancy models that allow inferring range dynamics whilst accounting for species imperfect detectability (MacKenzie *et al.*, 2017). We used a state-space model formulation to separate the state process (i.e. whether monk seals are present) from the observational process (i.e. whether monk seals are detected given present) (Royle & Kéry, 2007). We followed Molinari-Jobin *et al.* (2012) and considered two primary occasions corresponding to the two study periods 2000–2007 ($t = 1$) and 2013–2020 ($t = 2$). We used a 10 × 10 km grid (https://www.eea.europa.eu/data-and-maps/data/eea-reference-grids-2) to define the distribution units over Greece. We overlapped this grid with a buffer around coastlines, 20 km distance from the coast, and selected grid cells (sites hereafter) that intersected with this buffer. After this procedure, not all sites had the same size, a fact which we accounted for in the state and observation process (see below). There were also a few small sites (approximately 5% or 166 out of 3016 sites that were less than 10 km^2) which we ignored in the analysis to avoid numerical instabilities. We defined $z_{i,t}$ as the latent occupancy state for site i at time t with $z_{i,t} = 1$ for presence, and $z_{i,t} = 0$ for absence. The state process starts with initial occupancy probability ($\psi_{i,1}$) for site i in period 1 and its dynamics are governed by colonization probability γ_i – the probability that a site i that is not occupied at $t = 1$ will become occupied at $t = 2$, and extinction probability ε_i – the probability that an occupied site i at $t = 1$ will become unoccupied at $t = 2$. We modelled $z_{i,1}$ as a draw from a Bernoulli distribution with probability $\psi_{i,1}$. Latent states $z_{i,2}$ were drawn from a Bernoulli distribution that combined possible extinction and colonization events $z_{i,2}|z_{i,1} \sim$ Bernoulli $(z_{i,t}\ (1 - \varepsilon_i) + (1 - z_{i,t})\ \gamma_i)$. If a site is occupied at t, it will still be occupied at $t + 1$ with probability $1 - \varepsilon_i$ or if it is unoccupied, it will become occupied with probability γ_i. Dynamic occupancy models assume closure (i.e. no change in occupancy state) within primary periods. The closure assumption may have been violated in that the monk seal distribution within each of the two periods may have changed, and as a consequence, occupancy should be interpreted as the area of use rather than as the area of actual presence. In addition to the state process, the observation process involves the data $y_{i,j,t}$, that is, the observed state of site i during a year j (a secondary occasion in the terminology of occupancy modelling) within each 8-year period t (a primary occasion). Here, $y_{i,j,t} = 0$ denotes no detection, and $y_{i,j,t} = 1$ a detection, and we used $y_{i,j,t}|z_{i,t} \sim$ Binomial $(8,\ z_{i,t}\ p_{i,t})$ where $p_{i,t}$ is the species detection probability in site i during period t. Given the constant human presence along the Greek coasts, we assumed that an empty cell in a given year was a non-detection in that cell, and not a site where there was no sampling at all. We modelled time and site variation in the model parameters as follows: We used site random effects to allow for heterogeneity amongst sites in species detection because, for example, of geographical variation in abundance across the species' range. We also considered fixed period effects on the detection probabilities. To account for spatial autocorrelation in occupancy, we considered the improper intrinsic Gaussian conditional autoregressive (ICAR) model to capture dependence amongst sites. Finally, we used the (log-transformed) area of a site i denoted area_i as an offset in models for occupancy, extinction and colonization probability to accommodate differences in areas amongst sites. To include an offset on the probability of a binary event, the complementary log–log link is usually preferred over the standard logit link. Preliminary analyses suggested that extinction and colonization could be considered homogeneous. We used vague priors for all parameters and ran two Markov chain Monte Carlo chains with 50 000 iterations and 10 000 burn-in in the R package NIMBLE (de Valpine *et al.*, 2017) to get numerical summaries of posterior distributions (posterior means and 95% credible intervals). All details of the analyses, including model code with priors, are available at https://github.com/oliviergimenez/monkseal-occupancy.

We adopted a diachronic approach to assess the species recovery, in which we estimated occupancy for two 8-year periods and accounted for the dynamic between these periods by considering local colonization and extinction events. An alternative approach would consist in modelling each year separately and link annual occupancy estimates with a random walk (Isaac *et al.*, 2014; Outhwaite *et al.*, 2018) or splines (Rushing *et al.*, 2019) to account for temporal autocorrelation. Although we had to discard some data to separate the two periods, our standard dynamic occupancy model is less complex in terms of number of parameters and easier to implement.

Comparison of the predicted monk seal distribution and protected area distribution in Greece

The Natura 2000 (N2K) network is a European network of protected areas (http://ec.europa.eu/environment/nature/natura2000/db_gis/index_en.htm). To compare the estimated presence of monk seals and the distribution of protected areas in Greece, we mapped all the N2K sites in Greece (http://www.ekby.gr/ekby/en/Natura2000_main_en.html; last updated in 2012) and identified the sites included in the dedicated network for the protection of monk seals in Greece and those which were not. For this, we mapped the cells/areas with a predicted occupancy level above the 0.25 probability; these cells/areas are referred to as estimated to be occupied hereafter. We checked that ecological inference was little sensitive to the choice of the 0.25 probability threshold.

To assess trends in monk seal presence, we derived and compared occupancy probabilities between both periods. A positive change in occupancy probability was considered as an increase.

Results

From 2000 to 2020, the HMSRINT recorded the presence of Mediterranean monk seals on 4039 occasions (all age categories $N = 4039$; pups $N = 386$). Mediterranean monk seal sightings of all age categories were recorded throughout most of the coastline of continental and insular Greece (Fig. 1a), whereas pups were recorded primarily in coastal areas of insular Greece (Fig. 1b).

The trend of Mediterranean monk seal presence in Greece

A total of 1369 seal sightings of all age categories and 71 pups were recorded during the first study period (2000–2007) and 1684 seal sightings of all age categories and 192 pups were recorded during the second study period (2013–2020). The occupancy probability of Mediterranean monk seals of all age categories increased between the two study periods (Supporting Information Figure S1). From a total of 2850 grid cells examined, our model estimated that 2437 cells showed an increase in the probability of occupancy of seals of all age categories, 252 cells showed a decreased probability of occupancy, whereas 161 cells remained stable (Supporting Information Figure S1a). A similar, general increase was recorded in the occupancy of monk seal pups in Greece: From a total of 2850 grid cells examined, our model estimated that 2819 cells showed an increase in the probability of occupancy, 18 cells showed a decreased probability of occupancy, whereas 13 cells remained stable (Supporting Information Figure S1b).

The occupancy of Mediterranean monk seals increased also spatially. The number of grid cells estimated to be occupied (i.e. have occupancy probability >0.25) by seals of all age categories increased from 386 [363, 413] in 2000–2007 to 449 [440, 493] in 2013–2020 (Fig. 2a). Similarly, the number of grid cells estimated to be occupied by monk seal pups increased from 42 [35, 53] in 2000–2007 to 86 in 2013–2020 [79, 104] (Fig. 2b). The distribution of the Mediterranean monk seal in Greece, defined as the marine area of the occupied cells, increased during the study period by approximately 12.5%, from 39 419 to 44 334 km^2, for seals of all age categories and by approximately 185%, from 2992 km^2 to 8532 km^2, for monk seal pups.

Identifying new priority areas for Mediterranean monk seal conservation in Greece

Our modelling analysis identified 449 grid cells that were estimated to be occupied by Mediterranean monk seals of all age classes (Fig. 2a) in the period between 2013 and 2020. Of these 449 grid cells, 299 (67%) cells were located within the boundaries of a protected area of the Natura 2000 network (Fig. 3a). Similarly, of the 86 cells estimated to be occupied by Mediterranean monk seal pups between 2013 and 2020 (Fig. 2b), 62 (72%) were located within the boundaries of a protected area of the Natura 2000 network (Fig. 3b).

Discussion

Understanding wildlife range expansions and population recoveries is important for mitigating potential conflicts with humans (Marucco & McIntire, 2010) and essential for protecting critical habitat and implementing effective conservation policies (Cianfrani *et al.*, 2010). Given the lack of information on the conservation status of the majority of marine species, increased citizen science efforts have been suggested if conservation policies are to be successful and extinctions minimized (Edgar *et al.*, 2017). We used data from a citizen science project in Greece and occupancy modelling to understand the spatial processes associated with the trend in time of the distribution of one of the most important Mediterranean monk seal (sub)populations globally and to identify critical areas and priority actions for conservation.

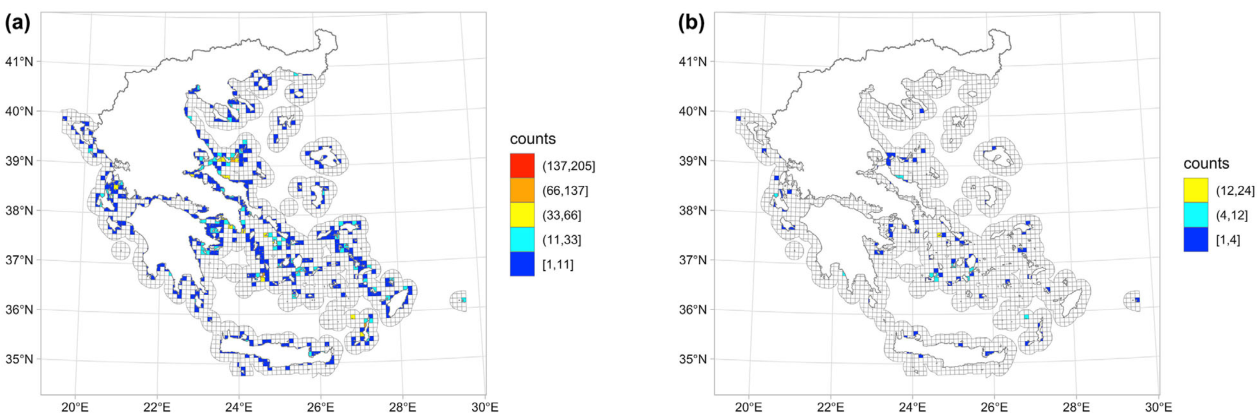

Figure 1 Map of Greece indicating the distribution of Mediterranean monk seal sightings collected by the HMSRINT between 2000 and 2020. (a) Sightings of Mediterranean monk seals of all age categories; (b) Sightings of Mediterranean monk seal pups. HMSRINT, Hellenic Mediterranean Monk Seal Rescue and Information Network.

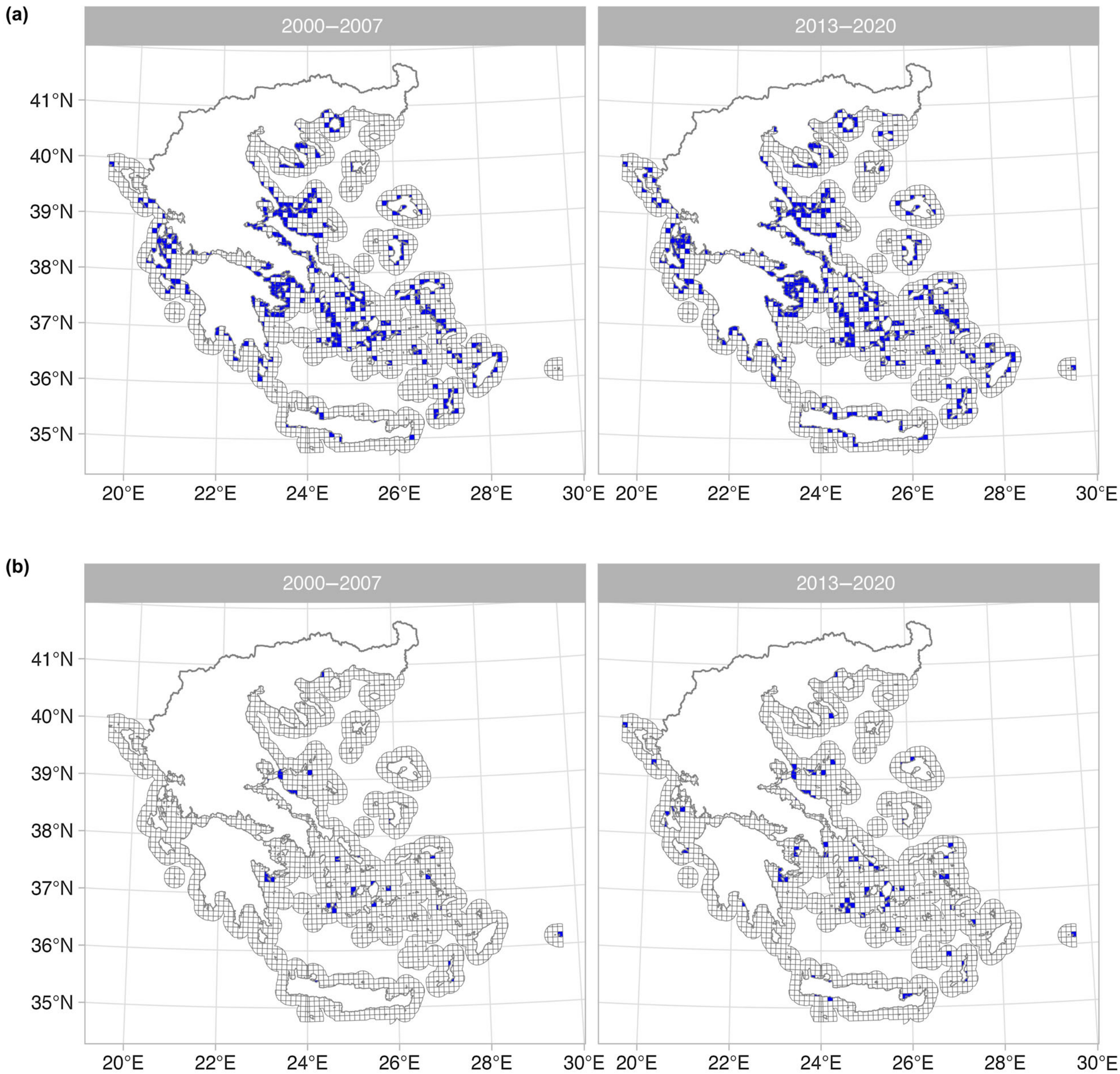

Figure 2 Map of Greece indicating the location of grid cells estimated to be occupied (i.e. have an occupancy probability >0.25) by Mediterranean monk seals in 2000–2007 (left) and in 2013–2020 (right). (a) Mediterranean monk seals of all age categories; (b) Mediterranean monk seal pups. These maps are based on estimates from a dynamic occupancy model we fitted to citizen science data.

Range contraction due to various factors, such as habitat destruction and conflicts with humans, appears to be a common characteristic of endangered species, both terrestrial (Rodríguez, 2002) and marine (Rugh, Shelden & Hobbs, 2010). This has been the case also with the Mediterranean monk seal. Once common throughout its historical range, the species ended up at the end of the previous century occupying a small number of sites (i.e. 3–4), widely separated from each other (Karamanlidis *et al*., 2016). In one of the last strongholds of the species in the eastern Mediterranean Sea, in Greece, Goedicke (1981) estimated range contraction and population decline to be so severe that he predicted that '. . .no seals will be left in Greece by the year 2000, and many colonies will have ceased to exist by 1990' (Goedicke, 1981)! The results of the present study show clearly that this not only has not occurred, but that in the last 20 years, Mediterranean monk seals have exhibited a significant range recovery. This is evident by the increase in the probability of occurrence and in the increase in the number of grid cells estimated to be occupied by seals of all age categories, which has translated in a range increase during the study period of approximately 12.5%. However, more

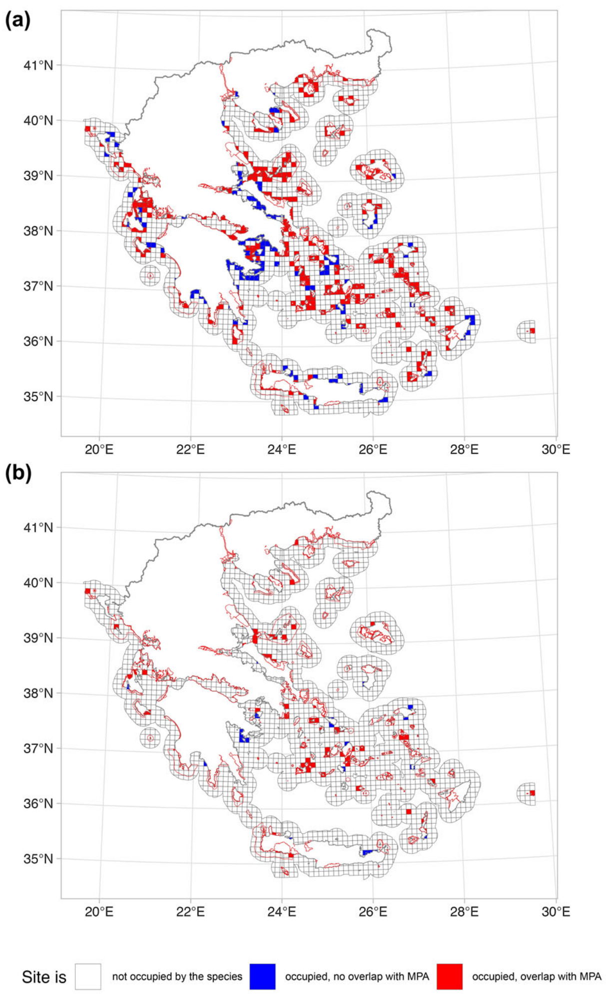

Figure 3 Map of Greece highlighting the overlap between the grid cells estimated to be occupied by Mediterranean monk seals between 2013 and 2020 and the protected areas in Greece established within the framework of the Natura 2000 ecological network of protected areas. (a) Mediterranean monk seals of all age categories; (b) Mediterranean monk seal pups. These maps are based on estimates from a dynamic occupancy model we fitted to citizen science data.

important for the future of the species as a whole (de Larrinoa *et al.*, 2021) are the results of the study pertaining to the occurrence of Mediterranean monk seal pups. We recorded an increase in the probability of occurrence and an increase in the number of grid cells estimated to be occupied by pups, which translated in an approximately threefold range expansion during the study period. The results of the study and the range increase in the Mediterranean monk seal in Greece are even more evident if compared with previous research efforts in the country (i.e. Sergeant *et al.*, 1978; Marchessaux, 1989; Adamantopoulou, Androukaki & Kotomatas, 1999; Panou *et al.*, 1999). Although the results of previous research efforts are not directly comparable, due to significant differences in methodology and effort invested, we believe that the overall trend of the range recovery of the Mediterranean monk seal in Greece is clear.

Understanding (range) recovery has been instrumental in defining effective conservation strategies for endangered species (Carroll *et al.*, 2006). The reasons of the range recovery of the Mediterranean monk seal in Greece are not a subject of the present study and are not fully understood yet. We speculate, however, that this range recovery is related to a combination of the implementation of effective conservation measures that have resulted in the decrease of habitat destruction, deliberate killing and accidental entanglement, and changes in basic socioeconomic parameters of coastal areas in Greece. Whatever the reasons of this range recovery might be, its effects in the country and abroad are evident. In Greece, the number of sightings of Mediterranean monk seal using open beaches (Dendrinos *et al.*, 2008) and areas in general that were not used by the species in the recent past has steadily increased over the past 20 years (Dendrinos *et al.*, 2020). On a wider scale, we believe that the range recovery of the Mediterranean monk seal in Greece is directly linked to evidence of species recovery in Turkey (Kiraç & Savaş, 2019), the re-establishment of the species in Cyprus (Nicolaou *et al.*, 2019) and the increase in extralimital sightings of seals in the eastern Mediterranean Sea (Alfaghi *et al.*, 2013; Bundone, Panou & Molinaroli, 2019). Consequently, the range recovery of the Mediterranean monk seal in Greece (and in the eastern Mediterranean Sea in general) opens up a number of interesting research questions common amongst pinnipeds, such as the role of dispersal in disease transmission, population management and species recovery (Robertson *et al.*, 2006). Preliminary findings indicate that dispersal in the Mediterranean monk seal is female mediated (Karamanlidis *et al.*, 2021), but this fact needs to be further investigated before it can contribute to effective conservation planning.

The results of the study indicate that Mediterranean monk seals appear to be widely distributed throughout, mainly, the coastal areas of Greece. This is consistent with previous studies on the distribution (Adamantopoulou *et al.*, 1999) and behaviour of the species in the country (Karamanlidis *et al.*, 2014). A large percentage of this range (i.e. 67%) is formally protected within the framework of the Natura 2000 network of protected areas. However, a part of the current range of the species still does not receive any kind of protection, including areas throughout Crete, the southern Peloponnese (MOm, 2018), the Island of Kythera (MOm, 2016) and the Island of Evia (Karamanlidis, Dendrinos & Adamantopoulou, 2015), where important monk seal subpopulations have been identified. Similarly, the Mediterranean monk seal pup range is also covered to a large extent (i.e. 72%) by the Natura 2000 network of protected areas, but leaving some important pupping areas, for example, in Crete and the southern Peloponnese, unprotected. The results of the study should be used in order to address these shortcomings in the conservation of the Mediterranean monk seal in Greece.

Citizen science has become nowadays highly relevant in the study of terrestrial biodiversity (Lloyd *et al.*, 2020). The development and refinement of site-occupancy models that account for observation bias (imperfect and possibly heterogeneous detection) has provided an additional impetus for the application of such efforts, as in combination with appropriate statistical modelling, citizen science is capable of delivering information on range dynamics that would be otherwise hard to obtain (van Strien, van Swaay & Termaat, 2013) and that is indispensable for the effective conservation planning of endangered species. For this reason, citizen science and appropriate statistical modelling are increasingly used in the conservation of endangered terrestrial wildlife, such as large carnivores, and in areas with limited logistic and financial resources for more extensive biological surveys (Farhadinia *et al*., 2018; Bonnet Lebrun *et al*., 2019). Our study demonstrates that citizen science and appropriate statistical modelling is highly relevant also in the conservation of marine biodiversity. The HMSRINT managed to collect reliable data on occupancy for an endangered marine mammal, the Mediterranean monk seal. The species is notoriously difficult to monitor, due to its distribution in Greece along a coastline exceeding 16 000 km, its cryptic nature and inaccessible habitat (Dendrinos *et al*., 2007), its low population density (Karamanlidis *et al*., 2019) and logistic constraints and financial limitations (Dendrinos *et al*., 2020). The HMSRINT collected this information whilst benefiting at the same time from the inherent advantages of citizen sciences projects (i.e. low cost, ease and amount of data collected; Dickinson *et al*., 2012), and without the need for dedicated, trained observers that are often required in citizen science-related marine mammal surveys (Pirotta *et al*., 2020).

Management implications

Based on the results of our study, we identify the following priority management and conservation actions for the Mediterranean monk seal in Greece:

1. An important part of the current Mediterranean monk seal range (including important reproductive sites) in Greece is located within the Natura 2000 network of protected areas, thus providing excellent prospects for the long-term survival of the species in the country. However, the management of the Natura 2000 areas in Greece is considered to be still insufficient, a fact that negatively impacts the future of other endangered species in the country as well (Votsi, Zomeni & Pantis, 2016; Bonnet Lebrun *et al*., 2019). Effective management of all Natura 2000 areas in the country should be a priority for the conservation of biodiversity in Greece in general. For the Mediterranean monk seal in particular, the results of the study may act as a roadmap for the inclusion of new areas in the Natura 2000 network, which is in line with the international commitments of Greece regarding the protection of marine biodiversity.
2. Within the Natura 2000 areas, special attention should be given into protecting important pupping sites, that is, by restricting human access to marine caves. Currently, human access to marine caves important for the Mediterranean monk seals is controlled in only one site, the National Marine Park of Alonnisos, Northern Sporades (Karamanlidis *et al*., 2004).
3. The results of the study indicate that a significant part of the current, and if the current trend continues, the future range of the Mediterranean monk seal in Greece will be located beyond the boundaries of the organized network of marine protected areas in the country. Consequently, management and conservation measures are/will be required that are implemented on a national scale. Based on previous experience, these conservation measures should include: (i) Public awareness campaigns, (ii) Operation of a Stranding and Rehabilitation system for injured, sick and orphan seals and (iii) Mitigating negative fishery–seal interactions (Karamanlidis *et al*., 2020).

These priority management and conservation actions have been included in the new Action Plan for the Mediterranean monk seal in Greece (Dendrinos *et al*., 2020).

Conclusions

This study demonstrates how citizen science and appropriate statistical modelling (here, occupancy modelling) can inform the conservation management of endangered marine mammals as they recolonize historical habitat. In the present case of the Mediterranean monk seal in Greece, the findings of the study have provided evidence of potentially new priority areas for conservation and highlighted the need for the continued operation of the HMSRINT as the only reliable tool to monitor the distribution of the Mediterranean monk seal in Greece.

Finally, Mediterranean monk seal distribution is listed as one of the important descriptors (GR.1.1.1. of Descriptor 1: Biodiversity) for assessing the level of Good Environmental Status (GES) in a number of European Union States (e.g. Portugal, Italy, Greece, Croatia, Cyprus), as defined by the Marine Strategy Framework Directive (Directive 2008/56/EC) of the European Parliament and of the Council (Palialexis & Boschetti, 2018). We believe that the information provided by citizen science efforts, such as the HMSRINT, in combination with data collected through *in situ* monitoring efforts of important pupping areas can provide the necessary data for assessing the GES in the Member States. Considering the effectiveness of the HMSRINT in Greece, an international management and conservation priority for the Mediterranean monk seal should be the establishment of citizen science projects similar to the HMSRINT in the countries neighbouring Greece. So far, the challenges of transboundary citizen science programmes (i.e. raising adequate financial and human resources, training, generating long-term commitment amongst participants and database support, including appropriate quality control processes; Edgar *et al*., 2017) are being addressed in Cyprus (Nicolaou *et al*., 2019), the countries of the eastern Adriatic (i.e. Albania, Montenegro, Croatia; Eastern Adriatic Monk Seal Project), Turkey (Kaboğlu *et al*., 2007) and Italy (Mo, 2011). It is important for the remaining countries in the region to follow suit in this respect, in order to enhance the survival chances for the Mediterranean monk seal in the eastern Mediterranean Sea.

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Author contributions

SA, AAK, PD and OG conceived the ideas and designed methodology; SA, AAK and PD collected the data; SA, AAK, PD and OG (main) analysed the data; SA and AAK led the writing of the paper. All authors contributed critically to the drafts and gave final approval for publication.

Data availability statement

All data and codes used to carry out the analyses and generate the maps are provided at https://github.com/oliviergimenez/monkseal-occupancy.

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Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Map of Greece indicating the probability of occupancy of Mediterranean monk seals in 2000–2007 (left) and in 2013–2020 (right). (A) Mediterranean monk seals of all age categories; (B) Mediterranean monk seal pups. These maps are based on estimates from a dynamic occupancy model we fitted to citizen science data.