



HAL
open science

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

S. Adamantopoulou, A A Karamanlidis, P. Dendrinou, O. Gimenez

► **To cite this version:**

S. Adamantopoulou, A A Karamanlidis, P. Dendrinou, O. Gimenez. Citizen science indicates significant range recovery and defines new conservation priorities for Earth's most endangered Pinniped in Greece. *Animal Conservation*, 2022, 10.1111/acv.12806 . hal-03718409

HAL Id: hal-03718409

<https://hal.science/hal-03718409>

Submitted on 8 Jul 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Title:** Citizen science indicates significant range recovery and defines new conservation
2 priorities for Earth's most endangered Pinniped in Greece

3

4 S. Adamantopoulou^{1,#}, A.A. Karamanlidis^{1,*}, P. Dendrinou¹, O. Gimenez²

5

6 ¹MOm/Hellenic Society for the Study and Protection of the Monk seal, Solomou Str. 18,
7 Athens, Greece

8 ²CEFE, University of Montpellier, CNRS, EPHE, IRD, Montpellier, France

9 [#]S. Adamantopoulou and A.A. Karamanlidis contributed equally to this study.

10

11 *Correspondence

12 Email: akaramanlidis@gmail.com

13

14 **Running head** Citizen science informs marine mammal conservation

15 **Abstract**

16 Conservation actions for endangered species often require detailed data over large temporal
17 and spatial scales, which are usually hard to obtain from traditional scientific surveys that
18 operate at localized scales. In contrast to the terrestrial conservation world where citizen
19 science has become nowadays a highly-relevant and useful tool to overcome such
20 difficulties, Marine Citizen Science is still highly underrepresented. Using a dataset of 20
21 years of citizen science data and appropriate statistical modelling we developed a
22 methodological approach to monitor the presence of the endangered, notoriously-elusive
23 Mediterranean monk seal *Monachus monachus*. We used sighting data collected in Greece
24 from 2000 – 2020 and fitted dynamic occupancy models that allow inferring range dynamics
25 while accounting for species imperfect detectability to estimate species occupancy.
26 Occurrence of Mediterranean monk seals of all age categories combined, and pups
27 separately, increased during the study period. Mediterranean monk seal occurrence
28 increased also spatially: the distribution of the species in Greece increased by approximately
29 12.5% for seals of all age categories and by approximately 185% for monk seal pups. Most of

1 this distribution (i.e., 67 and 72% of the distribution of seals of all age categories and of pups
2 respectively) was located within the boundaries of the network of protected areas in the
3 country. These results indicate a significant range recovery of the Mediterranean monk seal
4 in Greece over the last two decades and facilitate the prioritization of conservation actions
5 for the species in the country. We demonstrate how occupancy modelling and citizen science
6 can be used to evaluate the distribution of an endangered species and become a highly-
7 relevant and reliable tool in marine mammal conservation. We advocate the increased use of
8 citizen science in the conservation of the Mediterranean monk seal in the eastern
9 Mediterranean Sea.

10

11 **Keywords** Hellenic Mediterranean Monk Seal Rescue and Information Network, marine
12 mammal conservation, *Monachus monachus*, presence-only data, site-occupancy models,
13 species range

1 **Introduction**

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

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

24 Reliable data obtained from citizen science programs are particularly relevant to
25 endangered species, because information on presence, abundance and habitat associations
26 is hard to obtain (Wiley & Simpfendorfer, 2010), due to the often cryptic and solitary nature
27 of such species and their relatively low density of occurrence over large areas (Kindberg *et al.*,
28 *et al.*, 2009). More specifically, opportunistic, presence-only data of citizen science projects
29 may produce reliable estimates of wildlife distribution trends, if properly analysed with
30 relevant statistical tools (van Strien *et al.*, 2013b). In particular, site-occupancy models
31 (MacKenzie *et al.*, 2017) are increasingly used to map species range dynamics while

1 accounting for observation bias inherent in opportunistic data (van Strien *et al.*, 2013a,
2 Ruete *et al.*, 2017, Louvrier *et al.*, 2018, Erickson & Smith, 2021).

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

11 The Mediterranean monk seal (*Monachus monachus*) is the sole member of the genus
12 *Monachus* and the only seal living in the Mediterranean Sea. Once abundant throughout the
13 Black and Mediterranean Sea and the coasts of North Africa, the species experienced a
14 (series of) severe population decline(s) during historical times, mainly due to human
15 persecution and habitat destruction. This resulted in the extinction of the species from the
16 biggest part of its historical range and ultimately led to a severe population collapse
17 (Karamanlidis *et al.*, 2016). Acknowledging the dire situation for the species, the IUCN
18 classified the Mediterranean monk seal as “Critically Endangered” towards the end of the
19 previous century (Aguilar & Lowry, 2008). At the same time the countries with the last
20 remaining seal populations initiated systematic monitoring and/or
21 management/conservation efforts to reverse the plight of the species (Karamanlidis *et al.*,
22 2016).

23 Despite the ongoing and increasing exploitation of coastal ecosystems and numerous
24 negative seal - fishery interactions (Karamanlidis *et al.*, 2008, Karamanlidis *et al.*, 2020),
25 Mediterranean monk seals throughout their range, and in the eastern Mediterranean in
26 particular, have been showing encouraging signs of population recovery in recent years (i.e.,
27 after approximately the year 2000), resulting in the IUCN delisting the species and classifying
28 it as “Endangered” (Karamanlidis & Dendrinis, 2015, Karamanlidis *et al.*, 2019).
29 Circumstantial evidence suggests that this recovery is associated with the presence and
30 pupping of Mediterranean monk seals in areas in Greece from which the species was long
31 considered to be extinct (Dendrinis *et al.*, 2020); however, no thorough, nation-wide study

1 has been conducted as yet to substantiate this fact. This incomplete understanding of the
2 current distribution of Mediterranean monk seals in Greece may hinder their effective
3 conservation, which in turn may compromise the ongoing recovery of the species in the
4 country.

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

19 **Materials and methods**

20 **Data collection**

21 Data on Mediterranean monk seal presence were used from 2000 – 2020 within the
22 framework of a citizen science program, the “Hellenic Mediterranean Monk Seal Rescue and
23 Information Network” (HMSRINT), established by the non-governmental organization
24 MOm/Hellenic Society for the Study and Protection of the Monk seal. Information on seal
25 presence (i.e., opportunistic observations, damage to fishing gear) was received from the
26 general public through the post, telephone or email and was evaluated (i.e., on a scale from
27 1 – 3, 1 being the most reliable information) and verified, either on site by a field team or
28 through the examination of the information provided (e.g., photographs and videos). In the
29 study we used only information that was related to live seals and information that we
30 considered to be reliable (i.e., evaluated as 1 – 2). Because of their importance in the
31 recovery potential of a population (de Larrinoa *et al.*, 2021) and the increased management

1 and conservation efforts required to effectively protect them, pup (i.e., an animal
2 approximately 0 – 3 months old that has not undergone the first moult) presence was
3 examined separately from the general seal presence.

4 **Studying Mediterranean monk seal presence in Greece**

5 In order to gain insights on the presence of Mediterranean monk seals in Greece, we
6 mapped seal records from the HMSRINT using R version 4.1.0 (R Core Team, 2021) and the
7 packages tidyverse v1.3.1 (Wickham *et al.*, 2019) and sf v1.0-2 (Pebesma, 2018). We
8 considered and compared two eight-year study periods, one from 2000-2007 and one from
9 2013-2020.

10 *Modelling framework*

11 To estimate monk seal presence, we fitted dynamic occupancy models that allow inferring
12 range dynamics while accounting for species imperfect detectability (MacKenzie *et al.*, 2017).
13 We used a state-space model formulation to separate the state process (i.e., whether monk
14 seals are present) from the observational process (i.e., whether monk seals are detected
15 given present) (Royle & Kéry, 2007). We followed Molinari-Jobin *et al.* (2012) and considered
16 two primary occasions corresponding to the two study periods 2000-2007 ($t = 1$) and 2013-
17 2020 ($t = 2$). We used a 10×10 km grid ([https://www.eea.europa.eu/data-and-](https://www.eea.europa.eu/data-and-maps/data/eea-reference-grids-2)
18 [maps/data/eea-reference-grids-2](https://www.eea.europa.eu/data-and-maps/data/eea-reference-grids-2)) to define the distribution units over Greece. We
19 overlapped this grid with a buffer around coastlines, 20 km distance from the coast, and
20 selected grid cells (sites hereafter) that intersected with this buffer. After this procedure, not
21 all sites had the same size, a fact which we accounted for in the state and observation
22 process (see below). There were also a few small sites (approximately 5% or 166 out of 3016
23 sites that were less than 10km^2) which we ignored in the analysis to avoid numerical
24 instabilities. We defined $z_{i,t}$ as the latent occupancy state for site i at time t with $z_{i,t} = 1$ for
25 presence, and $z_{i,t} = 0$ for absence. The state process starts with initial occupancy probability
26 ($\psi_{i,1}$) for site i in period 1 and its dynamics are governed by colonization probability γ_i – the
27 probability that a site i that is not occupied at $t = 1$ will become occupied at $t = 2$, and
28 extinction probability ε_i – the probability that an occupied site i at $t = 1$ will become
29 unoccupied at $t = 2$. We modelled $z_{i,1}$ as a draw from a Bernoulli distribution with probability
30 $\psi_{i,1}$. Latent states $z_{i,2}$ were drawn from a Bernoulli distribution that combined possible
31 extinction and colonization events $z_{i,2}|z_{i,1} \sim \text{Bernoulli}(z_{i,1}(1 - \varepsilon_i) + (1 - z_{i,1})\gamma_i)$. If a site is

1 occupied at t , it will still be occupied at $t+1$ with probability $1-\epsilon_i$ or if it is unoccupied, it will
2 become occupied with probability γ_i . Dynamic occupancy models assume closure (i.e., no
3 change in occupancy state) within primary periods. The closure assumption may have been
4 violated in that the monk seal distribution within each of the two periods may have changed,
5 and as a consequence occupancy should be interpreted as the area of use rather than as the
6 area of actual presence. In addition to the state process, the observation process involves
7 the data $y_{i,j,t}$, i.e., the observed state of site i during a year j (a secondary occasion in the
8 terminology of occupancy modelling) within each 8-year period t (a primary occasion). Here,
9 $y_{i,j,t} = 0$ denotes no detection, and $y_{i,j,t} = 1$ a detection, and we used $y_{i,j,t} | z_{i,t} \sim \text{Binomial}(8, z_{i,t}$
10 $p_{i,t})$ where $p_{i,t}$ is the species detection probability in site i during period t . Given the constant
11 human presence along the Greek coasts, we assumed that an empty cell in a given year was
12 a non-detection in that cell, and not a site where there was no sampling at all. We modelled
13 time and site variation in the model parameters as follows: We used site random effects to
14 allow for heterogeneity among sites in species detection because, for example, of
15 geographical variation in abundance across the species' range. We also considered fixed
16 period effects on the detection probabilities. To account for spatial autocorrelation in
17 occupancy, we considered the improper intrinsic Gaussian conditional autoregressive (ICAR)
18 model to capture dependence among sites. Finally, we used the (log-transformed) area of a
19 site i denoted area_i as an offset in models for occupancy, extinction and colonization
20 probability to accommodate differences in areas among sites. To include an offset on the
21 probability of a binary event, the complementary log-log link is usually preferred over the
22 standard logit link. Preliminary analyses suggested that extinction and colonization could be
23 considered homogeneous. We used vague priors for all parameters, and ran two Markov
24 chain Monte Carlo chains with 50,000 iterations and 10,000 burn-in in the R package NIMBLE
25 (de Valpine *et al.*, 2017) to get numerical summaries of posterior distributions (posterior
26 means and 95% credible intervals). All details of the analyses, including model code with
27 priors, are available at <https://github.com/oliviergimenez/monkseal-occupancy>.

28 We adopted a diachronic approach to assess the species recovery, in which we estimated
29 occupancy for two 8-year periods and accounted for the dynamic between these periods by
30 considering local colonization and extinction events. An alternative approach would consist
31 in modelling each year separately and link annual occupancy estimates with a random walk
32 (Isaac *et al.*, 2014, Outhwaite *et al.*, 2018) or splines (Rushing *et al.*, 2019) to account for

1 temporal autocorrelation. Although we had to discard some data to separate the two
2 periods, our standard dynamic occupancy model is less complex in terms of number of
3 parameters and easier to implement.

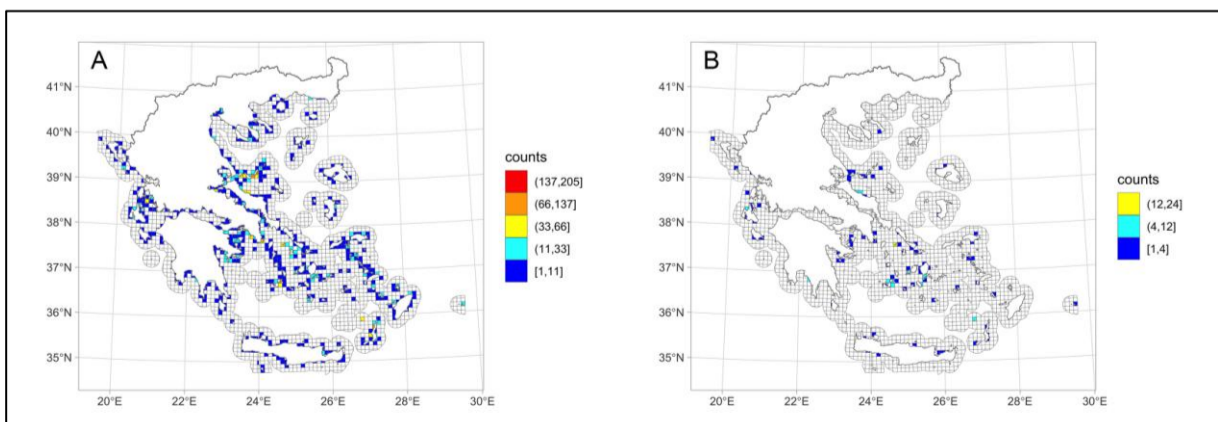
4 *Comparison of the predicted monk seal distribution and protected area distribution in Greece*

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

15 To assess trends in monk seal presence, we derived and compared occupancy probabilities
16 between both periods. A positive change in occupancy probability was considered as an
17 increase, regardless of the magnitude of the change.

18 **Results**

19 From 2000–2020 the HMSRINT recorded the presence of Mediterranean monk seals on 4039
20 occasions [all age categories N = 4039; pups N = 386]. Mediterranean monk seal sightings of
21 all age categories were recorded throughout most of the coastline of continental and insular
22 Greece (Fig. 1A), whereas pups were recorded primarily at coastal areas of insular Greece
23 (Fig. 1B).



24

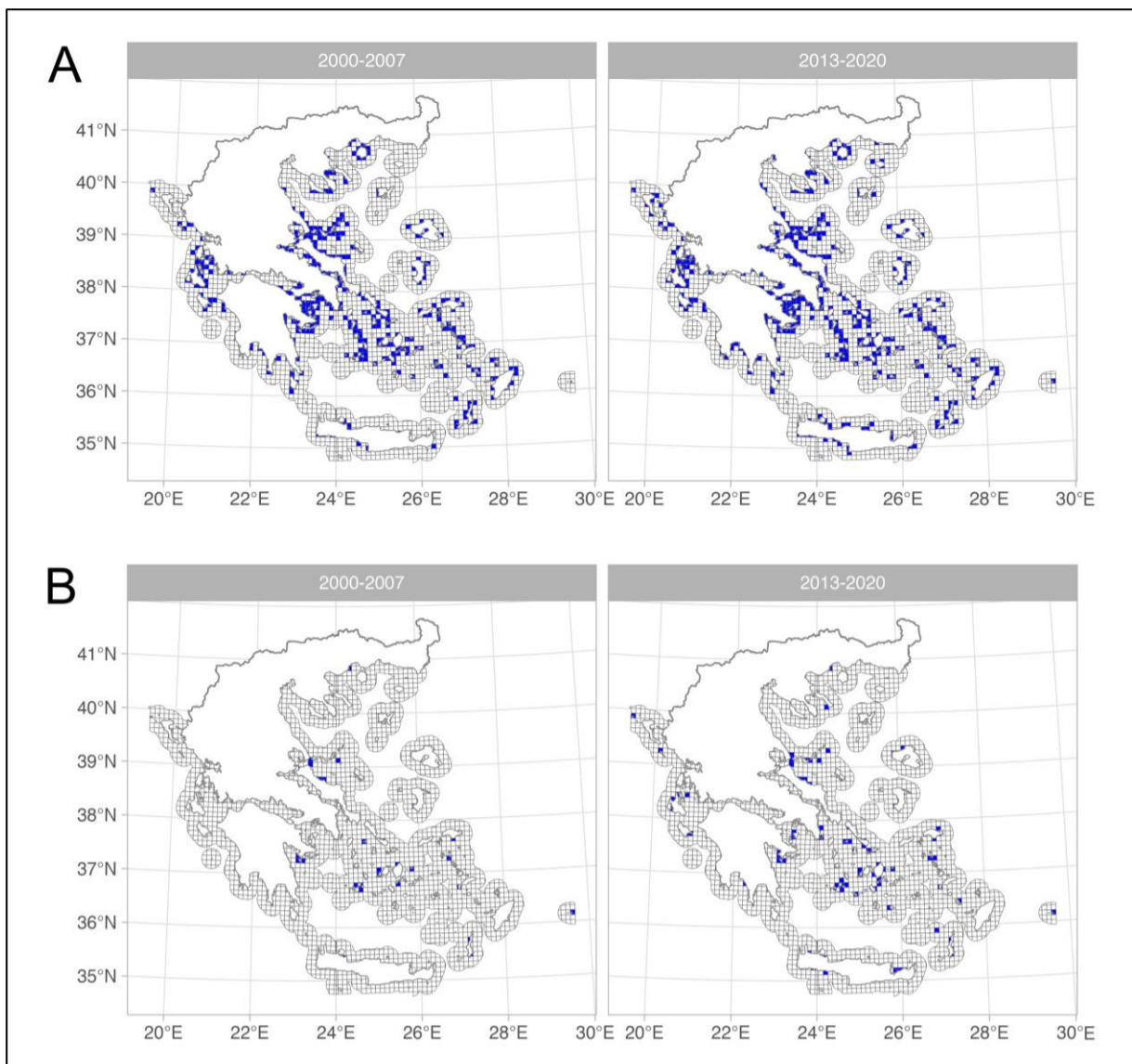
1 **Figure 1** Map of Greece indicating the distribution of Mediterranean monk seal sightings
2 collected by the HMSRINT between 2000–2020. A) Sightings of Mediterranean monk seals of
3 all age categories; B) Sightings of Mediterranean monk seal pups.

4

5 **The trend of Mediterranean monk seal presence in Greece**

6 1369 seal sightings of all age categories and 71 pups were recorded during the first study
7 period (2000–2007) and 1684 seal sightings of all age categories and 192 pups were
8 recorded during the second study period (2013–2020). The occupancy probability of
9 Mediterranean monk seals of all age categories increased between the two study periods
10 (Suppl. Fig. 1). From a total of 2,850 grid cells examined, our model estimated that 2,437
11 cells showed an increase in the probability of occupancy of seals of all age categories, 252
12 cells showed a decreased probability of occupancy, while 161 cells remained stable (Suppl.
13 Fig. 1A). A similar, general increase was recorded in the occupancy of monk seal pups in
14 Greece: From a total of 2,850 grid cells examined, our model estimated that 2,819 cells
15 showed an increase in the probability of occupancy, 18 cells showed a decreased probability
16 of occupancy, while 13 cells remained stable (Suppl. Fig. 1B).

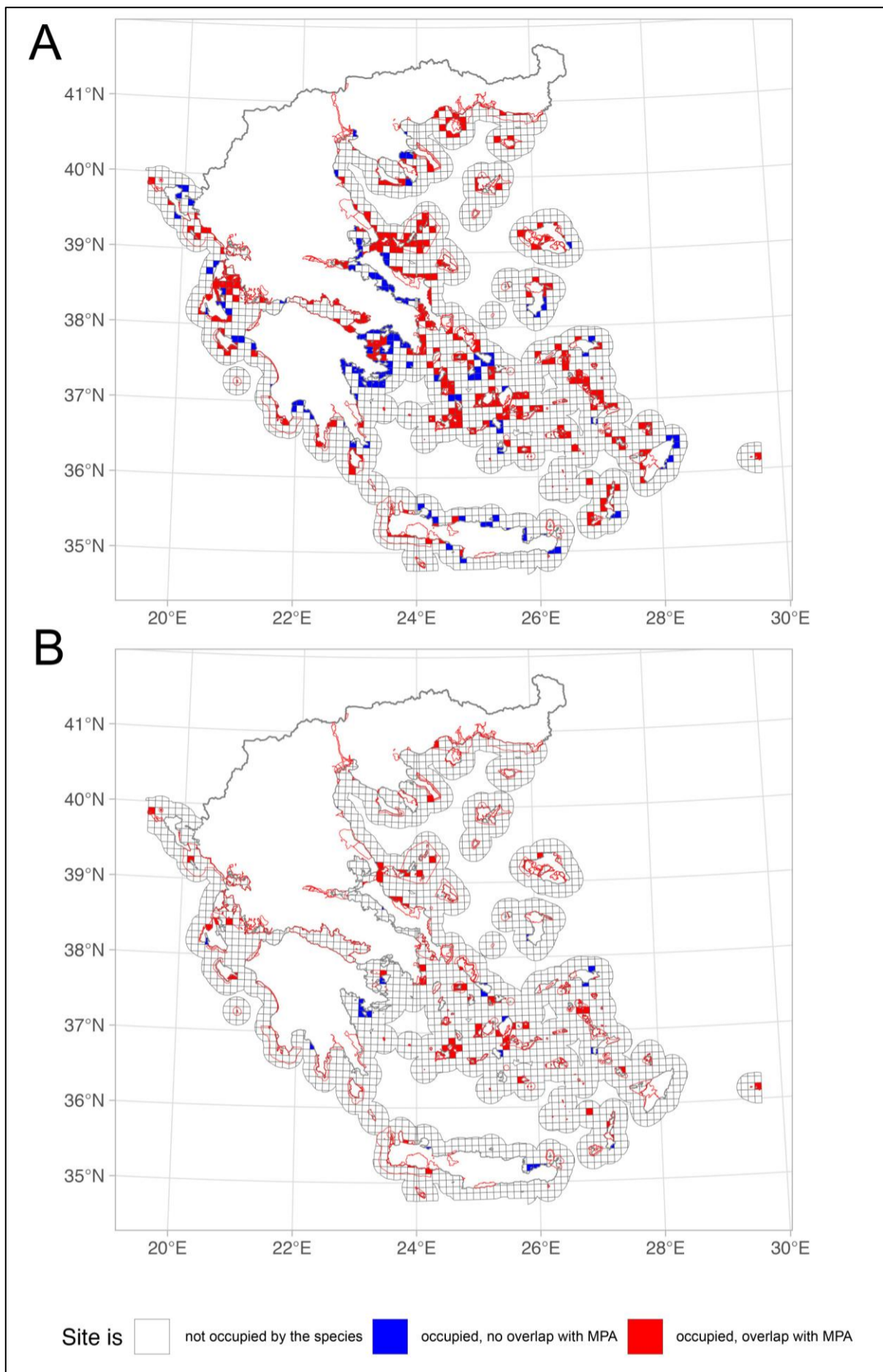
17 The occupancy of Mediterranean monk seals increased also spatially. The number of
18 grid cells estimated to be occupied (i.e., have occupancy probability > 0.25) by seals of all age
19 categories increased from 386 [363,413] in 2000-2007 to 449 [440,493] in 2013-2020 (Fig.
20 2A). Similarly, the number of grid cells estimated to be occupied by monk seal pups
21 increased from 42 [35,53] in 2000-2007 to 86 in 2013-2020 [79,104] (Fig. 2B). The
22 distribution of the Mediterranean monk seal in Greece, defined as the marine area of the
23 occupied cells, increased during the study period by approximately 12.5%, from 39,419 km²
24 to 44,334 km², for seals of all age categories and by approximately 185%, from 2,992 km² to
25 8,532 km², for monk seal pups.



1
 2 **Figure 2** Map of Greece indicating the location of grid cells estimated to be occupied (i.e.,
 3 have an occupancy probability > 0.25) by Mediterranean monk seals in 2000-2007 (left) and
 4 in 2013-2020 (right). A) Mediterranean monk seals of all age categories; B) Mediterranean
 5 monk seal pups. These maps are based on estimates from a dynamic occupancy model we
 6 fitted to citizen science data.

7
 8 **Identifying new priority areas for Mediterranean monk seal conservation in Greece**

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



1

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

8 **Discussion**

1 Understanding wildlife range expansions and population recoveries is important for
2 mitigating potential conflicts with humans (Marucco & McIntire, 2010) and essential for
3 protecting critical habitat and implementing effective conservation policies (Cianfrani *et al.*,
4 2010). Given the lack of information on the conservation status of the majority of marine
5 species, increased citizen science efforts have been suggested if conservation policies are to
6 be successful and extinctions minimised (Edgar *et al.*, 2017). We used data from a citizen
7 science project in Greece and occupancy modelling to understand the spatial processes
8 associated with the trend in time of the distribution of one of the most important
9 Mediterranean monk seal (sub)populations globally, and to identify critical areas and priority
10 actions for conservation.

11 Range contraction due to various factors, such as habitat destruction and conflicts with
12 humans, appears to be a common characteristic of endangered species, both terrestrial
13 (Rodríguez, 2002) and marine (Rugh *et al.*, 2010). This has been the case also with the
14 Mediterranean monk seal. Once common throughout its historical range the species ended
15 up at the end of the previous century occupying a small number of sites (i.e., 3 – 4), widely
16 separated from each other (Karamanlidis *et al.*, 2016). In one of the last strongholds of the
17 species in the eastern Mediterranean Sea, in Greece, Goedicke (1981) estimated range
18 contraction and population decline to be so severe that he predicted that “...no seals will be
19 left in Greece by the year 2000, and many colonies will have ceased to exist by 1990”
20 (Goedicke, 1981)! The results of the present study show clearly that this not only has not
21 occurred, but that in the last twenty years Mediterranean monk seals have exhibited a
22 significant range recovery. This is evident by the increase in the probability of occurrence
23 and in the increase of the number of grid cells estimated to be occupied by seals of all age
24 categories, which has translated in a range increase during the study period of
25 approximately 12.5%. However, more important for the future of the species as a whole (de
26 Larrinoa *et al.*, 2021) are the results of the study pertaining to the occurrence of
27 Mediterranean monk seal pups. We recorded an increase in the probability of occurrence
28 and an increase in the number of grid cells estimated to be occupied by pups, which
29 translated in an approximately three-fold range expansion during the study period. The
30 results of the study and the range increase of the Mediterranean monk seal in Greece are
31 even more evident if compared with previous research efforts in the country (i.e., Sergeant
32 *et al.*, 1978, Marchessaux, 1989, Adamantopoulou *et al.*, 1999, Panou *et al.*, 1999). Although

1 the results of previous research efforts are not directly comparable, due to significant
2 differences in methodology and effort invested, we believe that the overall trend of the
3 range recovery of the Mediterranean monk seal in Greece is clear.

4 Understanding (range) recovery has been instrumental in defining effective
5 conservation strategies for endangered species (Carroll *et al.*, 2006). The reasons of the
6 range recovery of the Mediterranean monk seal in Greece are not a subject of the present
7 study and are not fully understood yet. We speculate, however, that this range recovery is
8 related to a combination of the implementation of effective conservation measures that
9 have resulted in the decrease of habitat destruction, deliberate killing and accidental
10 entanglement, and changes in basic socioeconomic parameters of coastal areas in Greece.
11 Whatever the reasons of this range recovery might be, its effects in the country and abroad
12 are evident. In Greece, the number of sightings of Mediterranean monk seal using open
13 beaches (Dendrinou *et al.*, 2008) and areas in general that were not used by the species in
14 the recent past has steadily increased over the past twenty years (Dendrinou *et al.*, 2020). On
15 a wider scale, we believe that the range recovery of the Mediterranean monk seal in Greece
16 is directly linked to evidence of species recovery in Turkey (Kıraç & Savaş, 2019), the re-
17 establishment of the species in Cyprus (Nicolaou *et al.*, 2019) and the increase of extralimital
18 sightings of seals in the eastern Mediterranean Sea (Alfaghi *et al.*, 2013, Bundone *et al.*,
19 2019). Consequently, the range recovery of the Mediterranean monk seal in Greece (and in
20 the eastern Mediterranean Sea in general) opens up a number of interesting research
21 questions common among Pinnipeds, such as the role of dispersal in disease transmission,
22 population management and species recovery (Robertson *et al.*, 2006). Preliminary findings
23 indicate that dispersal in the Mediterranean monk seal is female mediated (Karamanlidis *et al.*
24 *et al.*, 2021), but this fact needs to be further investigated before it can contribute to effective
25 conservation planning.

26 The results of the study indicate that Mediterranean monk seals appear to be widely
27 distributed throughout, mainly, the coastal areas of Greece. This is consistent with previous
28 studies on the distribution (Adamantopoulou *et al.*, 1999) and behavior of the species in the
29 country (Karamanlidis *et al.*, 2014). A large percentage of this range (i.e., 67%) is formally
30 protected within the framework of the Natura 2000 network of protected areas. However, a
31 part of the current range of the species still does not receive any kind of protection,
32 including areas throughout Crete, the southern Peloponnese (MOM, 2018), the Island of

1 Kythera (MOM, 2016) and the Island of Evia (Karamanlidis *et al.*, 2015), where important
2 monk seal sub-populations have been identified. Similarly, Mediterranean monk seal pup
3 range is also covered to a large extent (i.e., 72%) by the Natura 2000 network of protected
4 areas, but leaving some important pupping areas, for example in Crete and the southern
5 Peloponnese, unprotected. The results of the study should be used in order to address these
6 shortcomings in the conservation of the Mediterranean monk seal in Greece.

7 Citizen science has become nowadays highly relevant in the study of terrestrial
8 biodiversity (Lloyd *et al.*, 2020). The development and refinement of site-occupancy models
9 that account for observation bias (imperfect and possibly heterogeneous detection) has
10 provided an additional impetus for the application of such efforts, as in combination with
11 appropriate statistical modelling, citizen science is capable of delivering information on
12 range dynamics that would be otherwise hard to obtain (van Strien *et al.*, 2013b) and that is
13 indispensable for the effective conservation planning of endangered species. For this reason
14 citizen science and appropriate statistical modelling are increasingly used in the conservation
15 of endangered terrestrial wildlife, such as large carnivores, and in areas with limited logistic
16 and financial resources for more extensive biological surveys (Farhadinia *et al.*, 2018, Bonnet
17 Lebrun *et al.*, 2019). Our study demonstrates that citizen science and appropriate statistical
18 modelling is highly relevant also in the conservation of marine biodiversity. The HMSRINT
19 managed to collect reliable data on occupancy for an endangered marine mammal, the
20 Mediterranean monk seal. The species is notoriously difficult to monitor, due to its
21 distribution in Greece along a coastline exceeding 16,000km, its cryptic nature and
22 inaccessible habitat (Dendrinis *et al.*, 2007), its low population density (Karamanlidis *et al.*,
23 2019) and logistic constraints and financial limitations (Dendrinis *et al.*, 2020). The HMSRINT
24 collected this information, while benefiting at the same time from the inherent advantages
25 of citizen sciences projects (i.e., low cost, ease and amount of data collected; Dickinson *et*
26 *al.*, 2012), and without the need for dedicated, trained observers that are often required in
27 citizen science-related marine mammal surveys (Pirodda *et al.*, 2020).

28 **Management implications**

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

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

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

26 **Conclusions**

27 This study demonstrates how citizen science and appropriate statistical modelling (here,
28 occupancy modeling) can inform conservation management of endangered marine
29 mammals as they recolonize historical habitat. In the present case of the Mediterranean
30 monk seal in Greece the findings of the study have provided evidence of potentially new
31 priority areas for conservation and highlighted the need for the continued operation of the

1 HMSRINT as the only reliable tool to monitor the distribution of the Mediterranean monk
2 seal in Greece.

3 Finally, Mediterranean monk seal distribution is listed as one of the important
4 descriptors (GR.1.1.1. of Descriptor 1: Biodiversity) for assessing the level of Good
5 Environmental Status (GES) in a number of European Union States (e.g., Portugal, Italy,
6 Greece, Croatia, Cyprus), as defined by the Marine Strategy Framework Directive (Directive
7 2008/56/EC) of the European Parliament and of the Council (Palialexis & Boschetti, 2018).
8 We believe that the information provided by citizen science efforts, such as the HMSRINT, in
9 combination with data collected through *in situ* monitoring efforts of important pupping
10 areas can provide the necessary data for assessing the GES in the Member States.
11 Considering the effectiveness of the HMSRINT in Greece, an international management and
12 conservation priority for the Mediterranean monk seal should be the establishment of
13 citizen science projects similar to the HMSRINT in the countries neighboring Greece. So far,
14 the challenges of transboundary citizen science programs (i.e., raising adequate financial and
15 human resources, training, generating long-term commitment amongst participants, and
16 database support, including appropriate quality control processes; Edgar *et al.*, 2017) are
17 being addressed in Cyprus (Nicolaou *et al.*, 2019), the countries of the eastern Adriatic (i.e.,
18 Albania, Montenegro, Croatia; Eastern Adriatic Monk seal Project), Turkey (Kaboğlu *et al.*,
19 2007) and Italy (Mo, 2011). It is important for the remaining countries in the region to follow
20 suit in this respect, in order to enhance the survival chances for the Mediterranean monk
21 seal in the eastern Mediterranean Sea.

22 **Acknowledgements**

23 We thank all the members of the RINT that participated in the data collection. The study
24 received funding from the Green Fund, EAAM, Acquario di Genova, the Thalassa Foundation
25 and the Mohamed Bin Zayed Foundation and was carried out within the framework of the
26 research permits 184316/4337, 165523/88 and 118956/3033 of the Hellenic Ministry of
27 Environment & Energy. The authors declare that they have no conflict of interest. Dr. Elina
28 Rantanen, Dr. Rahel Sollmann, Dr. Devin Johnson and an anonymous reviewer provided
29 comments that improved the quality of the manuscript.

30 **Data availability statement**

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

3 **Author Contributions Statement**

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

8 **References**

- 9 Adamantopoulou, S., Androukaki, E. & Kotomatas, S. (1999). The distribution of the
10 Mediterranean monk seal in Greece based on an information network. *Contr.*
11 *Zoogeogr. Ecol. East. Medit. Reg.* **1**, 399-404.
- 12 Aguilar, A. & Lowry, L. (2008). www.iucn.org
- 13 Alfaghi, I. E., Abed, A. S., Dendrinou, P., Psaradellis, M. & Karamanlidis, A. A. (2013). First
14 confirmed sighting of the Mediterranean monk seal (*Monachus monachus*) in Libya
15 since 1972. *Aqua. Mamm.* **39**, 81-84.
- 16 Araujo, G., Ismail, A. R., McCann, C., McCann, D., Legaspi, C. G., Snow, S., Labaja, J., Manjaji-
17 Matsumoto, M. & Ponzio, A. (2020). Getting the most out of citizen science for
18 endangered species such as whale shark. *J. Fish Biol.* **96**, 864-867.
- 19 Barnas, K. & Katz, S. L. (2010). The challenges of tracking habitat restoration at various
20 spatial scales. *Fisheries* **35**, 232–241.
- 21 Bonnet Lebrun, A.-S., Karamanlidis, A. A., De Gabriel Hernando, M., Renner, I. & Gimenez, O.
22 (2019). Identifying priority conservation areas for a recovering brown bear population
23 in Greece using citizen science data. *Anim. Conserv.* **23**, 83-93.
- 24 Brambilla, M., Casale, F., Bergero, V., Matteo Crovetto, G., Falco, R., Negri, I., Siccardi, P. &
25 Bogliani, G. (2009). GIS models work well, but are not enough: habitat preferences of
26 *Lanius collurio* at multiple levels and conservation implications. *Biol. Conserv.* **142**,
27 2033–2042.
- 28 Bruce, E., Albright, L., Sheehan, S. & Blewitt, M. (2014). Distribution patterns of migrating
29 humpback whales (*Megaptera novaeangliae*) in Jervis Bay, Australia: A spatial analysis
30 using geographical citizen science data. *Appl. Geog.* **54**, 83-95.

- 1 Bundone, L., Panou, A. & Molinaroli, E. (2019). On sightings of (vagrant?) monk seals,
2 *Monachus monachus*, in the Mediterranean Basin and their importance for the
3 conservation of the species. *Aquat. Cons. Mar. & Freshw. Ecos.* **29**, 554-563.
- 4 Carroll, C., Phillips, M. K., Lopez-Gonzalez, C. A. & Schumaker, N. H. (2006). Defining recovery
5 goals and strategies for endangered species: the wolf as a case study. *Bioscience* **56**,
6 25-37.
- 7 Chase, S. K. & Levine, A. (2016). A framework for evaluating and designing citizen science
8 programs for natural resources monitoring. *Conserv. Biol.* **30**, 456-466.
- 9 Cianfrani, C., Le Lay, G., Hirzel, A. H. & Loy, A. (2010). Do habitat suitability models reliably
10 predict the recovery areas of threatened species? *J. Appl. Ecol.* **47**, 421-430.
- 11 de Larrinoa, P. F., Baker, J. D., Cedenilla, M. A., Harting, A. L., Haye, M. O., Munoz, M.,
12 M'Bareck, H., M'Bareck, A., Aparicio, F., Centenera, S. & Gonzalez, I. M. (2021). Age-
13 specific survival and reproductive rates of Mediterranean monk seals at the Cabo
14 Blanco Peninsula, West Africa. *End. Spec. Res.* **45**, 315-329.
- 15 de Valpine, P., Turek, D., Paciorek, C., Anderson-Bergman, C., Temple Lang, D. & Bodik, R.
16 (2017). Programming with models: writing statistical algorithms for general model
17 structures with NIMBLE. *Journal of Computational and Graphical Statistics* **26**, 403-413.
- 18 Dendrinou, D., Karamanlidis, A. A., Adamantopoulou, S., Koemtzopoulos, K., Komninou, A. &
19 Tounta, E. (2020). LIFE-IP 4 NATURA: Integrated actions for the conservation and
20 management of Natura 2000 sites, species, habitats and ecosystems in Greece.
21 Deliverable Action A.1: Action Plan for the Mediterranean monk seal (*Monachus*
22 *monachus*). 1-105; Annexes 112p): Hellenic Ministry of Environment and Energy.
- 23 Dendrinou, P., Karamanlidis, A. A., Kotomatas, S., Legakis, A., Tounta, E. & Matthiopoulos, J.
24 (2007). Pupping habitat use in the Mediterranean monk seal: a long-term study. *Mar.*
25 *Mamm. Sci.* **23**, 615-628.
- 26 Dendrinou, P., Karamanlidis, A. A., Kotomatas, S., Paravas, V. & Adamantopoulou, S. (2008).
27 Report of a new Mediterranean monk seal (*Monachus monachus*) breeding colony in
28 the Aegean Sea, Greece. *Aqua. Mamm.* **34**, 355-361.
- 29 Dickinson, J. L., Zuckerberg, B. & Bonter, D. N. (2010). Citizen science as an ecological
30 research tool: challenges and benefits. *Ann. Rev. Ecol., Evol. and Syst.* **41**, 149-172.

- 1 Dickinson, J. L., Shirk, J., Bonter, D., Bonney, R., Crain, R. L., Martin, J., Phillips, T. & Purcell, K.
2 (2012). The current state of citizen science as a tool for ecological research and public
3 engagement. *Front. Ecol. Environ.* **10**, 291-297.
- 4 Edgar, G. J., Stuart-Smith, R. D., Cooper, A., Jacques, M. & Valentine, J. (2017). New
5 opportunities for conservation of handfishes (Family Brachionichthyidae) and other
6 inconspicuous and threatened marine species through citizen science. *Biol. Conserv.*
7 **208**, 174-182.
- 8 Erickson, K. D. & Smith, A. B. (2021). Accounting for imperfect detection in data from
9 museums and herbaria when modeling species distributions: combining and
10 contrasting data-level versus model-level bias correction. *Ecography* **44**, 1341-1352.
- 11 Farhadinia, M. S., Moll, R. J., Montgomery, R. A., Ashrafi, S., Johnson, P. J., Hunter, L. T. &
12 Macdonald, D. W. (2018). Citizen science data facilitate monitoring of rare large
13 carnivores in remote montane landscapes. *Ecol. Indic.* **94**, 283-291.
- 14 Goedicke, T. R. (1981). Life expectancy of monk seal colonies in Greece. *Biol. Conserv.* **20**,
15 173-181.
- 16 Gooliaff, T. J., Weir, R. D. & Hodges, K. E. (2018). Estimating bobcat and Canada lynx
17 distributions in British Columbia. *J. Wildl. Manag.* **82**, 810-820.
- 18 Hanski, I. (1998). Metapopulation dynamics. *Nature* **396**, 41-49.
- 19 Isaac, N. J., van Strien, A. J., August, T. A., de Zeeuw, M. P. & Roy, D. B. (2014). Statistics for
20 citizen science: extracting signals of change from noisy ecological data. *Meth. Ecol.*
21 *Evol.* **5**, 1052-1060.
- 22 Issaris, Y., Katsanevakis, S., Salomidi, M., Tsiamis, K., Katsiaras, N. & Verriopoulos, G. (2012).
23 Occupancy estimation of marine species: dealing with imperfect detectability. *Mar.*
24 *Ecol. Prog. Ser.* **453**, 95-106.
- 25 Kaboğlu, G. K., Güclüsoy, H., Biszsel, K. C., Eronat, H., Kiraç, C. O. & Savaş, Y. I. (2007).
26 Information technology for endangered marine species management: AFBİKA goe-
27 database. *R. Comm. Inter. Mer Med.* **38**, 507.
- 28 Karamanlidis, A. A., Dendrinis, P., Tounta, E. & Kotomatas, S. (2004). Monitoring human
29 activity in an area dedicated to the protection of the endangered Mediterranean monk
30 seal. *Coast. Manage.* **32**, 293-306.
- 31 Karamanlidis, A. A., Androukaki, E., Adamantopoulou, S., Chatzistryrou, A., Johnson, W. M.,
32 Kotomatas, S., Papadopoulos, A., Paravas, V., Paximadis, G., Pires, R., Tounta, E. &

- 1 Dendrinos, P. (2008). Assessing accidental entanglement as a threat to the
2 Mediterranean monk seal *Monachus monachus*. *End. Spec. Res.* **5**, 205-213.
- 3 Karamanlidis, A. A., Curtis, J. P., Hirons, A. C., Psaradellis, M., Dendrinos, D. & Hopkins III, J. B.
4 (2014). Stable isotopes confirm a coastal diet for critically endangered Mediterranean
5 monk seals. *Isot. Environ. & Health Stud.* **50**, 332-342.
- 6 Karamanlidis, A. A., Dendrinos, D. & Adamantopoulou, S. (2015). Discovery of an important
7 monk seal colony at the island of Evia, Greece. In *13th International Congress on the*
8 *Zoogeography and Ecology of Greece and Adjacent Regions*: 130. Poulakakis, N.,
9 Antoniou, A., Karameta, E. , Psonis, N. (Eds.). Irakleio, Crete, Greece.: Hellenic
10 Zoological Society.
- 11 Karamanlidis, A. A. & Dendrinos, P. (2015). *Monachus monachus*. *The IUCN Red List of*
12 *Threatened Species 2015: e.T13653A45227543*.
- 13 Karamanlidis, A. A., Dendrinos, P., Fernández de Larrinoa, P., Gücü, A. C., Johnson, W. M.,
14 Kiraç, C. O. & Pires, R. (2016). The Mediterranean monk seal *Monachus monachus*:
15 status, biology, threats, and conservation priorities. *Mamm. Rev.* **46**, 92-105.
- 16 Karamanlidis, A. A., Adamantopoulou, S., Tounta, E. & Dendrinos, D. (2019). *Monachus*
17 *monachus* Eastern Mediterranean subpopulation. *The IUCN Red List of Threatened*
18 *Species 2019*, e.T120868935A120869697.
- 19 Karamanlidis, A. A., Adamantopoulou, S., Kallianiotis, A., Tounta, E. & Dendrinos, D. (2020).
20 An interview-based approach to assess seal – small-scale fishery interactions informs
21 the conservation strategy of the endangered Mediterranean monk seal. *Aquat. Cons.*
22 *Mar. & Freshw. Ecos.* **30**, 928-936.
- 23 Karamanlidis, A. A., Skrbinišek, T., Amato, G., Dendrinos, D., Gaughran, S., Kasapidis, P.,
24 Kopatz, A. & Vik Stronen, A. (2021). Genetic and demographic history define a
25 conservation strategy for Earth’s most endangered Pinniped, the Mediterranean monk
26 seal *Monachus monachus*. *Sc. Rep.* **11**, 373.
- 27 Kelly, R., Fleming, A., Pecl, G. T., von Gönner, J. & Bonn, A. (2020). Citizen science and marine
28 conservation: a global review. *Phil. Trans. R. Soc. B* **375**, 20190461.
- 29 Kindberg, J., Ericsson, G. & Swenson, J. E. (2009). Monitoring rare or elusive large mammals
30 using effort-corrected voluntary observers. *Biol. Cons.* **142**, 159-165.
- 31 Kiraç, C. O. & Savaş, Y. (2019). Assessments for threats and ecological needs of monk seal
32 populations in Turkish Aegean and the Sea of Marmara. In *Presentation at the 5th*

1 *International Conference on Marine Mammal Protected Areas: 8-12 April 2019*). Costa
2 Navarino, Messinia, Greece: ICMMPA5.

3 Kosmala, M., Wiggins, A., Swanson, A. & Simmons, B. (2016). Assessing data quality in citizen
4 science. *Front. Ecol. Environ.* **14**, 551–560.

5 Lauret, V., Labach, H., Authier, M. & Gimenez, O. (2021). Using single visits into integrated
6 occupancy models to make the most of existing monitoring programs. *Ecology* **102**,
7 e03535.

8 Lloyd, T. J., Fuller, R. A., Oliver, J. L., Tulloch, A. I., Barnes, M. & Steven, R. (2020). Estimating
9 the spatial coverage of citizen science for monitoring threatened species. *Glob. Ecol.*
10 *Conserv.* **23**, e01048.

11 Louvrier, J., Duchamp, C., Lauret, V., Marboutin, E., Cubaynes, S., Choquet, R., Miquel, C. &
12 Gimenez, O. (2018). Mapping and explaining wolf recolonization in France using
13 dynamic occupancy models and opportunistic data. *Ecography* **41**, 647-660.

14 MacKenzie, D. I., Nichols, J. D., Royle, J. A., Pollock, K. H., Bailey, L. & Hines, J. E. (2017).
15 *Occupancy estimation and modeling: inferring patterns and dynamics of species*
16 *occurrence*: Elsevier.

17 Marchessaux, D. (1989). Distribution et statut des populations du phoque moine *Monachus*
18 *monachus* (Hermann, 1779). *Mammalia* **53**, 621-642.

19 Marucco, F. & McIntire, E. J. B. (2010). Predicting spatio-temporal recolonization of large
20 carnivore populations and livestock depredation risk: wolves in the Italian Alps. *J. Appl.*
21 *Ecol.* **47**, 789–798.

22 McKinley, D. C., Miller-Rushing, A. J., Ballard, H. L., Bonney, R., Brown, H., Cook-Patton, S. C.,
23 Evans, D. M., French, R. A., Parrish, J. K., Phillips, T. B. & Ryan, S. F. (2017). Citizen
24 science can improve conservation science, natural resource management, and
25 environmental protection. *Biol. Conserv.* **208**, 15-28.

26 Mo, G. (2011). Mediterranean Monk Seal (*Monachus monachus*) Sightings in Italy (1998-
27 2010) and implications for conservation. *Aqua. Mamm.* **37**, 236-240.

28 Molinari-Jobin, A., Kéry, M., Marboutin, E., Molinari, P., Koren, I., Fuxjäger, C., Breitenmoser-
29 Würsten, C., Wölfel, S., Fasel, M., Kos, I., Wölfel, M. & Breitenmoser, U. (2012).
30 Monitoring in the presence of species misidentification: the case of the Eurasian lynx in
31 the Alps. *Anim. Conserv.* **15**, 266-273.

1 MOm (2016). The Mediterranean monk seal *Monachus monachus* returns to the coasts of
2 the Argosaronic Gulf. In *Final unpublished report of a project supported by the Stavros*
3 *Niarchos Foundation: 1-52*). Athens, Greece: MOm/Hellenic Society for the Study and
4 Protection of the Monk seal.

5 MOm (2018). Status report of the Mediterranean monk seal population at the Peloponnese,
6 Kythira, Antikythira and the Golf of Corinth. In *Final unpublished report to Grant*
7 *provided by the Thalassa Foundation: 1-29*). Athens, Greece: MOm/Hellenic Society for
8 the Study and Protection of the Monk seal.

9 Nicolaou, H., Dendrinou, D., Marcou, M., Michaelides, S. & Karamanlidis, A. A. (2019). Re-
10 establishment of the Mediterranean monk seal *Monachus monachus* in Cyprus:
11 priorities for conservation. *Oryx* **55**, 526-528.

12 Outhwaite, C. L., Chandler, R. E., Powney, G. D., Collen, B., Gregory, R. D. & Isaac, N. J.
13 (2018). Prior specification in Bayesian occupancy modelling improves analysis of
14 species occurrence data. *Ecol. Indic.* **93**, 333-343.

15 Palialexis, A. & Boschetti, S. T. (2018). Review and analysis of Member States' 2018 reports.
16 Descriptor 1: Species biological diversity, EUR 30664 EN.). Luxemburg: Publications
17 Office of the European Union.

18 Panou, A., Alimantiri, L., Aravantinos, P. & Verriopoulos, G. (1999). Distribution of the
19 Mediterranean Monk Seal (*Monachus monachus*) in Greece: Results of a Pan-Hellenic
20 Questionnaire Action, 1982-1991. *Contr. Zoogeogr. Ecol. East. Medit. Reg.* **1**, 421-428.

21 Pebesma, E. (2018). Simple Features for R: Standardized Support for Spatial Vector Data. *The*
22 *R Journal* **10**, 439–446.

23 Pereira, H. M., Leadley, P. W., Proença, V., Alkemade, R., Scharlemann, J. P., Fernandez-
24 Manjarrés, J. F., Araujo, M. B., Balvanera, P., Biggs, R., Cheung, W. W. L., Chini, L.,
25 Cooper, H. D., Gilman, E. L., Guenette, S., Hurtt, G. C., Huntington, H. P., Mace, G. M.,
26 Oberdorff, T., Revenga, C., Rodrigues, P., Scholes, R. J., Sumaila, U. R. & Walpole, M.
27 (2010). Scenarios for global biodiversity in the 21st century. *Science* **330**, 1496-1501.

28 Pirotta, V., Reynolds, W., Ross, G., Jonsen, I., Grech, A., Slip, D. & Harcourt, R. (2020). A
29 citizen science approach to long-term monitoring of humpback whales (*Megaptera*
30 *novaeangliae*) off Sydney, Australia. *Mar. Mamm. Sci.* **36**, 472-485.

31 R Core Team (2021). R: A language and environment for statistical computing.). Vienna,
32 Austria: R Foundation for Statistical Computing.

1 Robertson, B. C., Chilvers, B. L., Duignan, P. J., Wilkinson, I. S. & Gemmell, N. J. (2006).
2 Dispersal of breeding, adult male *Phocarctos hookeri*: implications for disease
3 transmission, population management and species recovery. *Biol. Conserv.* **127**, 227-
4 236.

5 Rodríguez, J. P. (2002). Range contraction in declining North American bird populations. *Ecol.*
6 *Appl.* **12**, 238-248.

7 Royle, J. A. & Kéry, M. (2007). A Bayesian state-space formulation of dynamic occupancy
8 models. *Ecology* **88**, 1813-1823.

9 Ruete, A., Pärt, T., Berg, Å. & Knape, J. (2017). Exploiting opportunistic observations to
10 estimate changes in seasonal site use: An example with wetland birds. *Ecol. & Evol.* **7**,
11 5632– 5644.

12 Rugh, D. J., Shelden, K. E. & Hobbs, R. C. (2010). Range contraction in a beluga whale
13 population. *End. Spec. Res.* **12**, 69-75.

14 Rushing, C. S., Royle, J. A., Ziolkowski, D. J. & Pardieck, K. L. (2019). Modeling spatially and
15 temporally complex range dynamics when detection is imperfect. *Sc. Rep.* **9**, 12805.

16 Sandahl, A. & Tøttrup, A. P. (2020). Marine citizen science: recent developments and future
17 recommendations. *Cit. Scie: Theo. Pract.* **5**, 24.

18 Sergeant, D., Ronald, K., Boulva, J. & Berkes, F. (1978). The recent status of *Monachus*
19 *monachus*, the Mediterranean Monk seal. *Biol. Conserv.* **14**, 259-287.

20 Sun, Y., Wang, T., Skidmore, A. K., Palmer, S. C., Ye, X., Ding, C. & Wang, Q. (2016). Predicting
21 and understanding spatio-temporal dynamics of species recovery: implications for
22 Asian crested ibis *Nipponia nippon* conservation in China. *Divers. Distrib.* **22**, 893-904.

23 Thorson, J. T., Scheuerell, M. D., Semmens, B. X. & Pattengill-Semmens, C. V. (2014).
24 Demographic modelling of citizen science data informs habitat preferences and
25 population dynamics of recovering fishes. *Ecology* **95**, 3251-3258.

26 van Strien, A. J., Termaat, T., Kalkman, V., Prins, M., De Knijf, G., Gourmand, A. L., Houard, X.,
27 BNelson, B., Plate, C., Prentice, S., Regan, E., Smallshire, D., Vanappelghem, C. &
28 Vanreusel, W. (2013a). Occupancy modelling as a new approach to assess
29 supranational trends using opportunistic data: a pilot study for the damselfly
30 *Calopteryx splendens*. *Biodivers. Conserv.* **22**, 673-686.

- 1 van Strien, A. J., van Swaay, C. A. & Termaat, T. (2013b). Opportunistic citizen science data of
2 animal species produce reliable estimates of distribution trends if analysed with
3 occupancy models. *J. Appl. Ecol.* **50**, 1450-1458.
- 4 Votsi, N. E. P., Zomeni, M. S. & Pantis, J. D. (2016). Evaluating the effectiveness of Natura
5 2000 network for wolf conservation: A case-study in Greece. *Environ. Manage.* **57**, 257-
6 270.
- 7 Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D. A., François, R., Golemund,
8 G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, t. L., Miller, E. H., Bache, S. M.,
9 Muller, K., Ooms, J., Robinson, D., Seidel, D. P., Spinu, V., Takahashi, K., Vaughan, D.,
10 Wilke, C., Woo, K. & Yutani, H. (2019). Welcome to the Tidyverse. *J. Open Sourc. Softw.*
11 **4**, 1686.
- 12 Wiley, T. R. & Simpfendorfer, C. A. (2010). Using public encounter data to direct recovery
13 efforts for the endangered smalltooth sawfish *Pristis pectinata*. *End. Spec. Res.* **12**, 179-
14 191.