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Research article

Mapping drivers of change for biodiversity risk assessment to target conservation actions: Human frequentation in protected areas

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ABSTRACT

Mapping the drivers of change that pose negative pressures or threats to biodiversity can help to identify where biodiversity is most threatened and can be used to determine priority sites to target conservation actions. Overlapping drivers of change maps with distribution maps of sensitive species provides valuable information to identify where and when it would be better to target actions to minimize the risk. The overall aim of this study was to develop a methodology for the integration of risk mapping associated with high human frequentation to guide conservation actions in two case study: the Kentish plover (*Charadrius alexandrinus*) and Posidonia meadows (*Posidonia oceanica*), both sensitive to human frequentation. To achieve this, we used two types of geolocated mobile phone information from the STRAVA platform: mapped paths and roads number of visitors at hourly precisions and a sporting activities heatmap representative of a wider period, together with species ecological information and complementary human frequentation data. The final, monthly risk maps identified the areas for Kentish plover with null, low, moderate, high, very high risk attributed to different aspects of the breeding biology of the species, nests, nestlings, and adults. The risk thresholds for nests are lower than for nestlings and adults, thought nestlings were generally less sensitive to human frequentation than adults. Visitors number ranges between 250 and 700 approximately suppose a moderate risk for the three assessed periods, and more than 1200 visitors appeared to prevent the nesting of the species completely. The final risk maps for Posidonia meadows determine the areas with low, moderate, hight and very high risk for human marine activities. Human frequentation values in this case study are scaled between 0 and 1, the results shows that values above 0.1 imply a high risk for the species. Both types of information can be used to target concrete, spatially explicit actions to

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minimize the risk caused by human frequentation. Furthermore, the first case study would allow to adapt the target actions to the species breeding phenology. The proposed risk assessment workflow is flexible and may be adjusted to match the available information and eventually could be adapted to other conservation objectives arising from different threats. In addition, data gathered from mobile mobility applications show great potential to accurately identify human frequentation, both spatially and temporally.

1. Introduction

Biodiversity has been declining rapidly the last decades, with the decline been accelerated further the recent years. The IPBES global report [1] describes that approximately 25 % of animal and plant species are seriously threatened with extinction, some in the next few decades. Similarly, the European Union report on the State of Nature shows that between 2013 and 2018 only half of the birds have good conservation status, and 70 % of species and 75 % of habitats listed in the Habitats Directive have poor or very poor conservation status [2,3]. These reports agree that the main drivers causing this decline are changes in use accelerated by human activity such as human intensification, overexploitation, leisure activities, unsustainable forestry, and agricultural practices, as well as invasive species and climate change. This drivers, strongly linked to human activities, cause biodiversity decrease in a variety of forms by altering or destroying the habitats in which biodiversity persists, by disturbing or causing direct mortality of species [4] or metropolitan areas in Europe [5–7].

Direct human disturbance of species linked to human frequentation is becoming increasingly intense. Specifically, human recreation threats near to a thousand species according to IUCN Red List of Threatened species [7] and is of particular concern in protected areas close to the most populated areas [8,9]. Humans particularly value these protected areas positively because they conserve landscapes of high natural value and provide physical and emotional well-being on one hand, and the possibility of observing species and habitats that can no longer be observed elsewhere [10]. It is, therefore, becoming increasingly urgent to plan and act including measures to reconcile biodiversity conservation and human activities within these protected areas. Due to their dynamism and singularity, and unlike other factors of environmental change that affect biodiversity, visitor impacts in protected areas may be anticipated, and effectively managed or planned with the aim to reduce their impact on biodiversity.

Mapping the drivers of change posing negative pressures or threats to biodiversity can help identify where biodiversity is most threatened and can be used to determine priority sites for conservation actions [11–14], especially when we can identify risk areas

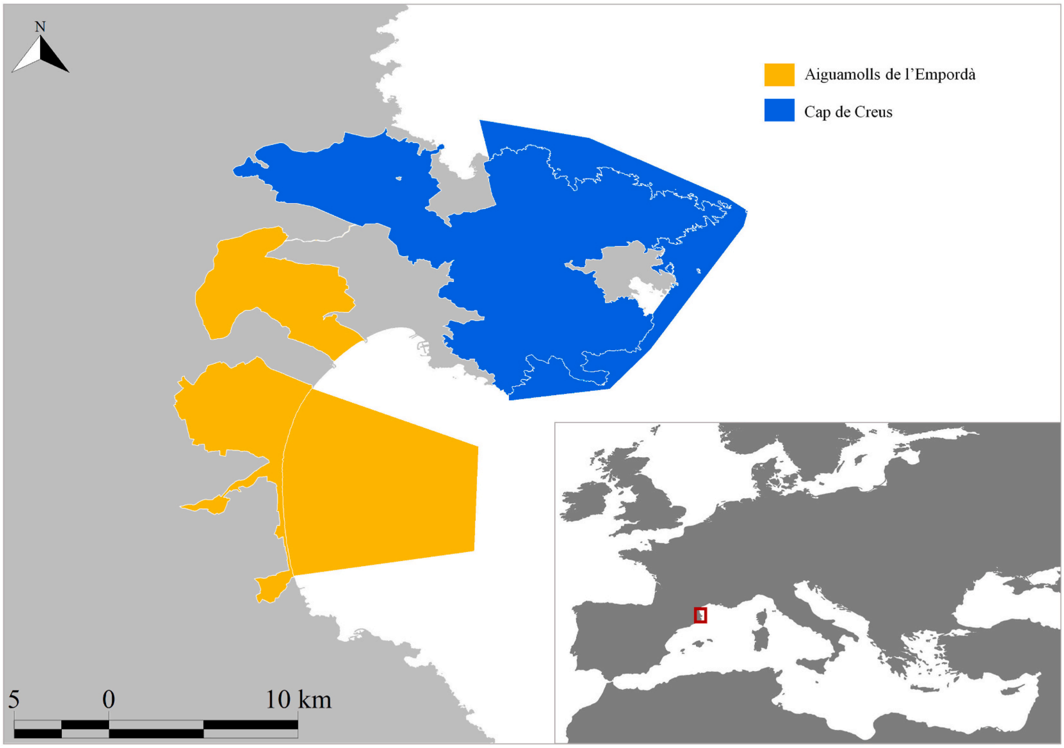

Fig. 1. The study area is situated on the west Mediterranean shore (red rectangle in the right-bottom figure). General figure: *Aiguamolls de l'Empordà* Natural Park in yellow and *Cap de Creus* Natural Park in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

through overlapping pressures and threats maps with distribution maps of sensitive species and habitats [15].

A first step to address the impacts of human frequentation on biodiversity in protected areas is to better understand human frequentation patterns and its geographical and temporal dynamics, to measure its real impacts on species and habitats. Human frequentation in natural areas can be described by direct visitors counting through traditional field sampling [4,16] or through pyroelectric sensors that detect the heat radiation emitted by human bodies [17]. However, both approaches are costly, and the information obtained is constrained to the sampling sites while the information needs to be estimated for larger areas. Therefore, human frequentation must often be inferred from proxies such as the degree of urbanisation of the landscape or accessibility from the main urban population centres [18]. Thus, obtaining explanatory information on human frequentation is still a challenge.

Recently, the availability of mobile phones and dedicated mobility applications capturing geographic locations allows to obtain detailed spatiotemporal human mobility data over large areas [19,20]. These are widely used for economical purposes to better understand consumer shopping patterns [21]. But due to the commercial purpose of collecting this data, this type of information is not freely available, and consequently it is not currently being used to analyse human distribution in wilderness areas. However, several citizen platforms that collect in a very precise way human leisure and sports activities throughout the territory have been recently launched. The increasingly extensive and intensive use of these platforms has led to their use as a source of information for estimating human visitation of natural areas [22,23].

The general objective of this study is to develop a methodology to integrate the drivers of change maps into decision-making flows for risk assessment to guide conservation actions. To achieve this, we focused on human frequentation and its temporal dynamics to identify where and when the sensitive species and habitats are at risk. Considering two case studies: Kentish plover (*Charadrius alexandrines*) and Posidonia meadows (*Posidonia oceanica*) within two protected areas in Catalonia, adapting the risk assessment methodology to both species' ecological characteristics and the available biodiversity data.

2. Material and methods

2.1. Case study region and species

This study focusses on two coastal protected areas in Catalonia, in the north-east of the Iberian Peninsula in the western Mediterranean Sea (Fig. 1): *Aiguamolls de l'Empordà* Natural Park (42.2°N, 3.1°E), characterized for being one of the most important wetlands in Catalonia; and *Cap de Creus* Natural Park (42.3°N, 3.2°E), with terrestrial and marine protected areas.

In *Aiguamolls de l'Empordà* Natural Park inhabits the Kentish Plover (*Charadrius alexandrinus*), a shorebird that breeds on sandy, pebble or silty banks of sea, estuaries, and river deltas with no or scarce low vegetation in immediate proximity to the water [24] has been assessed. Kentish plover is a sensible specie to human frequentation, especially during the breeding months [25] and despite being of Least Concern according to the Red List [26] its population is decreasing in the whole Europe. The intensive development of coastal habitats and increasing recreational and economic activity are the main factors for the decline in many areas, as well the presence and trampling of dogs in breeding areas may reduce breeding success [24]. Geolocated points of presence of adults, nestlings, and nests during the breeding months (from April to July) have been used for the years 2018–2021. The data come from the periodic field survey on the species carried out by the biologists of the natural park.

In *Cap de Creus* Natural Park, the Posidonia meadows (*Posidonia oceanica*) has been assessed. Posidonia meadows is a priority habitat listed in Annex I of the Habitats Directive, and listed as Least Concern [27]. Posidonia meadows perform a wide range of ecological functions and services: they protect the coastal zone, fix sediments, constitute refuge and breeding areas, host great biodiversity, are nutrient exporters, etc. Posidonia is mainly sensitive to fishing, anchoring, diving, and bathing, followed by the potential effects of climate change, acidification, and temperature [28]. The bionomic maps of the marine areas of the Parc Natural del *Cap de Creus* [29,30] was used to determine its distribution.

Both protected areas register at the park offices a mean value of 250,000 and 500,000 visitors respectively every year. These statistics do not include visitors who come to both parks without being registered at the park offices, nor do they include users of the beaches and coastline. Thus, the actual annual visitor count of the park may be much higher.

2.2. Human frequentation data

We used human frequentation data from the Strava platform [31]. This is a widely used platform to track outdoor activities, such as running and cycling that has been extended to other types of sports and leisure activities (hiking, motorcycling, swimming, sailing, kitesurfing, etc.). Strava offers free access to mapped paths or roads containing the number of visitors with hourly precision to support cycling and running planning to governmental administrations through the Strava Metro platform [32]. The Strava user's public outdoor activities are also shown by means of the global Strava heatmap (Strava, 2018a; Strava press 2018). Both types of information have been recently used for ecological studies and validated with [22,23], and high correlations with ground truth data have been reported [22,23,33]. Both types of information were used in the present work, and data processing was adapted to the ecological characteristics of each species, as explained below.

2.3. Case study 1: risk mapping for Kentish plover

In the Kentish plover case study in the *Aiguamolls de l'Empordà* Natural Park, it was used the Strava Metro data, which links individual activity events to nearby linear features (paths, roads etc.) in OSM [34]. Strava Metro data provides information on the number of people passing in each section. If a person passes twice or more, it is counted as 2 or more people. Monthly data were downloaded from April to July, corresponding to the of Kentish plover breeding months, for the available years: 2018 to 2021. Human activities corresponding to running, walking, hiking (defined as pedestrian) and riding, considering commute and leisure trips. The mean average for each month during the period was calculated. It should be noted that information for the year 2020 was excluded due to COVID-19 lockdowns in the study area as the data was significantly different from the rest of the years. It is important to note that in the absence of OSM linear features close to an activity event (or parts of it), that event (or parts of it) is not included in the aggregated version of the dataset. Further, to comply with privacy legislations, linear features with less than three unique users are removed and the number of activity events is rounded up to the nearest multiple of five [23]. As the OSM data do not consider routes on sandy beaches, where the Kentish Plover inhabits, it was extrapolated the original human frequentation data using a 500 × 500 m moving window mean filter (Fig. 2). The OSM routes near the beach are the main access routes to beaches, in consequence, we assumed that this extrapolation represents the real human frequency on the beaches. Human frequentation map was then combined with the species habitat, excluding the areas not inhabited by the species inside the park's boundaries. The habitats described as inhabited by the species were selected from the Habitat Map of Catalonia [35].

The next step was to classify each human frequentation driver of change map into risk levels for the Kentish plover. In this case, it was used the monthly Kentish plover presence data sampled between April and July for adults, nestlings, and nests. This information allowed accounting for the Kentish plover sensitivity to human frequentation and to define sensitivity thresholds to this driver of change. The human frequentation driver of change maps was combined with the corresponding Natural Park Kentish plover presence data separately for each month (from April to July) and each phenological moment (adults, nestlings, and nests) to know the human frequentation for each species presence. Distribution histogram of human frequentation (number of visitors) for each phenological moment, was produced and used to define the thresholds for classify the driver of changes maps in 6 risk levels for the specie: null, low, moderate, high, very high risk and unsuitable. There are different methods for defining the cut-off points, in the present work it has been used an objective method applied in the selection of marine IBAs (Important Bird Areas) in Spain [36,37], the Catalan Winter Bird Atlas [38] and also to define the risk attack areas for brown bear in Catalonia [39]. This method combines two simple and effective approaches with strong ecological components. First, from the habitat suitability models it was defined the species presence areas excluding areas with low suitability scores that could be caused by casual or occasional presences. Since the input information were the model habitat suitability scores for each actual species observation, the first threshold was calculated after ordering the suitability scores of each presence, cutting at the 10th percentile value. It was considered that the 10th percentile excluded the casual or occasional presences. Secondly, to define different levels of importance base on the average of suitability values within the area of presence. Applied to the present work case study, instead of the model habitat suitability values it was considered the human

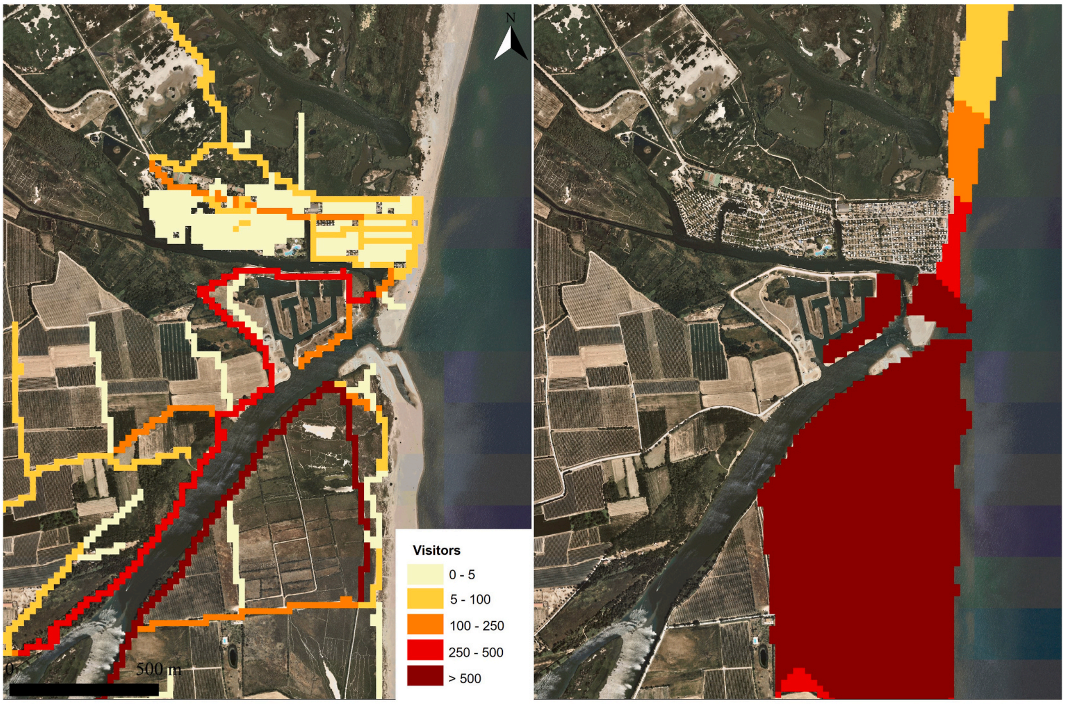

Fig. 2. Number of visitor (pedestrians and riders) on an area of *Aiguamolls de l'Empordà* Natural Park in June 2021, coloured from yellow to dark brown indicating 0 to 3000 visitors respectively. On the left, the image shows the Strava Metro data corresponding to the total visitors received in each Open Street Map (OSM) route fragment during June 2021. On the right, the image shows the extrapolation of the Strava Metro data to the rest of the protected area, using the same colour legend and clipped by the habitat occupied by the species. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

frequentation scores, equating areas of presence with the actual presence of the human frequentation risk. Although, after different tests and expert criteria, the 25th percentile was used instead of the 10th percentile to better represent most situations where the species coincides with visitors without significant disturbance to its survival, indicating that there is no risk to the species. Secondly, within the risk areas four human frequentation thresholds were defined to get five risk levels: the average mean of the human frequentation scores within the risk areas defined the low threshold risk, the average mean of the scores above the previous threshold defined the moderate threshold risk, and so on up to the third and fourth threshold to define the very high risk areas and the unsuitable areas where the threat do not allow for the species to be present.

2.4. *Case study 2: risk mapping for Posidonia meadows*

In the Posidonia meadows case study, we used the Strava Global Heatmap [40], which shows the last two years of STRAVA data [31], updating them monthly. Roads and trails with very little activity will not show "heat" until several different athletes upload activities in that area. The Strava Global Heatmap displays a colour gradient of outdoor activity tracks (rides, runs, water, and winter activities) recorded by users, where brighter tones represent an intense use [22]. The heatmap displays outdoor activity tracks as a 'pixel path' connecting consecutive GPS locations [22]. To this purpose, the recorded vector tracks were rasterized. The rasterized raw data was normalized between 0 to 1values using the CDF technique (cumulative distribution function) reaching a perfectly uniform distribution over the colour map. This causes the heatmap to convey information about relative heat values but makes it not absolutely quantitative, the same colour only locally represents the same level of heat data [40]. Focusing on water activities, Strava heatmap data contains specially movement from swimming, snorkelling, sport boats, or other activities.

The human frequentation driver of change map was produced by taking screenshots of the Strava heatmap web [22] to achieve in a GIS environment. Before taking screenshots, we set the Heatmap Colour to "blue", the desired Activity Type to "Marine", the Heat Opacity to 100 %, and we removed all background layers. The raster image in a GIS environment was georeferenced using seven control points. The WGS 84/Pseudo-Mercator Coordinate system (EPSG: 3857) was used, as it was the projected coordinate system used to build the Global Heatmap [22]. The terrestrial area from local geographic layers was masked (Fig. 3-A). Single pixels as a 256-element colour spectrum array were displayed, which perfectly matches the blue colour spectrum of an RGB colour model (0, 255). The values were rescaled between 0 and 1. But, according to expert knowledge, the mooring of recreational boats in coastal coves, which is the most important impact activity for Posidonia meadows, is being underestimated. Consequently, marine sampling data on the number of boats moored within the boundaries of the protected area captured by the *Cap de Creus* Natural Park rangers were used as complementary information to weight the human frequentation data from STRAVA. The Natural Park information on human frequentation was not geo-referenced, only the names of the main coves were informed. The coves were geolocated, corresponding surfaces were mapped and the number of boats that moor in each cove were digitised. Finally, it was rasterized at the same

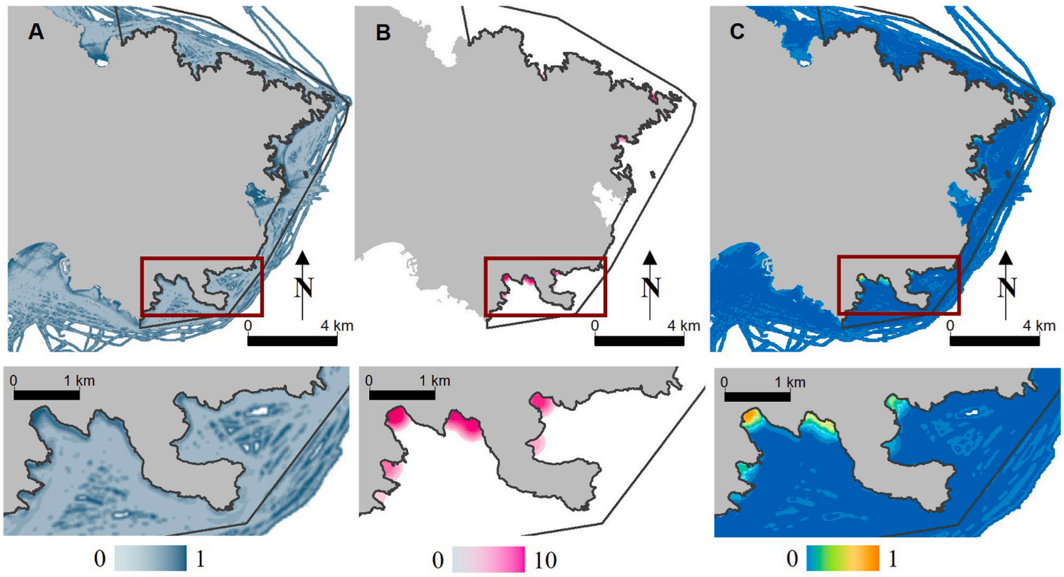

Fig. 3. The upper figures show the human driver of change map for marine activities in *Cap de Creus* Natural Park extracted from Global Strava Heatmap, scaled from 0 to 1 representing from null to high pressure (A); moored boats mapping in Natural Park coves from Natural Park information scaled from 0 to 10 representing from zero to the high number of moored boats (B); human driver of change map in *Cap de Creus* weighted with information on boats moored in the Natural Park, scaled from 0 to 1 representing from null to high pressure (C). The corresponding bottom figures are a zoom from a little Natural Park surface, represented by a red rectangle. The terrestrial area is grey, and the marine protected area is represented with a black line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

resolution as STRAVA data (10 m resolution) and scaled from 1 to 10 (Fig. 3-B). Both maps were multiplied to obtain a weighted human frequentation driver of change map and rescaled between 0 and 1 (Fig. 3-C). This final human frequentation driver of change map contained information from boat moorings in the coves and the routes of the boats between these coves. The combination of both sources of information improved the human frequentation heatmap from Strava (Fig. 3-C).

The final human marine frequentation map (Fig. 3-C) in the *Cap de Creus* Natural Park was combined with the Posidonia presence map and classified in different risk levels. In this case, the Posidonia meadows ecology did not allowed to directly relate the presence of the specie with the human frequentation data to infer sensitivity. Consequently, statistics criteria based on the mean and the standard deviation of marine human frequentation values was used to classify the risk levels. The values between 0 to mean minus the standard deviation were classified as low risk. Moderate risk corresponded to values between mean minus the standard deviation to mean values. High risk corresponded to values between mean to mean plus standard deviation. Very high values corresponded to values between mean plus standard deviation to 1. In this case study, due to the ecological characteristics of the Posidonia meadows, the category "Unsuitable" was not calculated because we focused on quantifying the risk of human frequentation in the areas where the species was already present, making this category meaningless.

3. Results

3.1. Risk maps for Kentish plover

The histograms resulting from the combination of presence data for Kentish plover nests, nestlings, and adults with the human frequentation driver of change maps, shows a decreasing species frequency with an increasing number of visitors (Fig. 4). Nests were only presents in beaches with visitor numbers below 250, the adults seem to tolerate higher human pressures up to visitor numbers slightly above 500.

The 25th quartile threshold for nests, nestlings and adults corresponds to 18, 11 and 10 visitors respectively. So, these values determine the null risk threshold for each phenological moment (Table 1). When the number of visitors is higher than this value, there may be a low to very high risk or become unsuitable for the species. Table 1 shows the human frequentation risk thresholds derived from the statistical analysis of the number of visitors combined with species presence in each phenological moment based on the mean human frequentation values supported by the species described above. The human frequentation driver of change map for each month and phenological moment has been reclassified into these 6 risk levels using these thresholds to obtain a monthly risk map (April to July) for nests, nestlings, and adults. As Table 1 shows the risk thresholds for nests are lower than for nestlings and adults, thought nestlings seem to support slightly higher levels of frequentation than adults.

The final classified risk maps for nest, nestlings, and adults (Fig. 5), indicate the areas where there is a higher risk of disturbance due to human frequentation. This final risks maps show respectively which areas of the park are unsuitable areas for the specie in each period due to the high human frequentation. The level of risk at each phenological stage is quite similar in all three cases, but the level of risk varies over time.

3.2. Risk maps for posidonia meadows

The human frequentation values in Posidonia meadows, which were scaled from 0 to 1, had a mean value of 0.0619 with a standard deviation of 0.0418. These values were used to identify the different thresholds to classify the human frequentation in four categories (Table 2). The final risk map shows (Fig. 6) where the Posidonia meadows are from low to very high risk. The most part of the Posidonia meadows in marine coves are in high and very high risk. Very few surfaces are in moderate risk. In this case, as the human

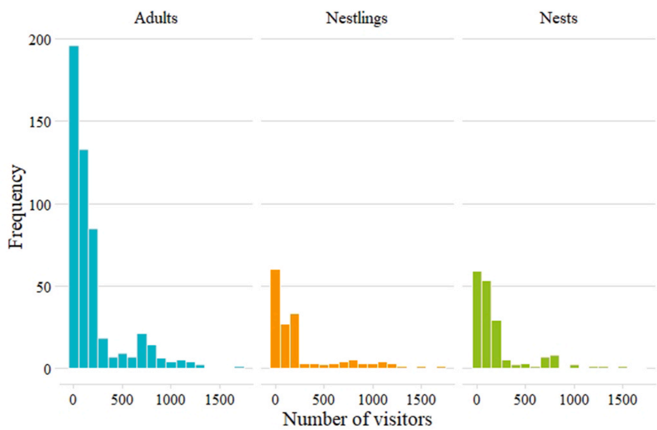

Fig. 4. Distribution histogram of human frequentation (number of visitors) for adults, nestlings, and nests during the whole study period. The most part of presences correspond to less than 250 visitors, nest and nestlings are more sensitive to human frequentation than adults.

Table 1
Human frequentation risk thresholds for nests, nestlings and adults defined from the combination of the number of visitors and species presence.

Risk	Nests	Nestlings	Adults
Null	0–18	0–11	0–10
Low	18–254	11–332	10–252
Moderate	254–698	332–855	252–674
High	698–905	855–1122	674–884
Very high	905–1201	1122–1286	884–1127
Unsuitable	>1201	>1286	>1127

frequentation data in marine areas from the Strava Heatmap corresponds to the aggregation of a long period, it is not possible to generate different drivers of change maps and, in consequence it is not possible to elaborate temporal risk maps.

4. Discussion

The mapping of drivers of environmental change, such as human frequentation, together with additional information on species sensitives to these specific changes provide a valuable starting point to elaborate specific risk maps. Recent works underpin the importance of including driver of change maps, also referred to as pressures or threats maps, in the decision-making flows to determine where species are at risk [14,15]. Traditionally, the human frequentation information has been used to define carrying capacity of protected areas, specifically, by using indirect estimates of human visitation such as the number of visitors to the park, the population of surrounding towns, distances to human infrastructure, etc. [41]. Recent works use geolocated human frequentation data such as STRAVA to better understand biodiversity distribution [22,23] as an adaptation response to human activity. In the present work, also based on geolocated human visitation data, we go further by creating risk maps to define where and how much two specific species are at risk and providing concrete information to guide actions such as restricting the number of visitors in the most sensitive areas. The present work, in addition to the detection of location where the species are at risk, in the Kentish plover case study, proposes a methodology for determining risk over different time periods when information is available. Such different periods risk maps provide valuable information to target concrete actions. In the case of the Kentish plover, the risk maps could help to relocate paths or increase the distance from the beach entrances and car parks for the most visited beaches, which has been shown to have a major influence on visitor numbers along the coastline and with positive effects on Kentish plover conservation [25]. Adapting both management proposals related to the species phenology. Biodiversity conservation in highly frequented areas can often conflict with leisure and sporting activities that are also part of the uses of these areas, so being able to focus conservation actions on the most critical periods for the species is key to reconciling both uses. In the case of Posidonia meadows, the risk maps could aim to provide guidance on where to prohibit anchoring by vessel recreational boating, which has been shown to have major negative impacts on influences on Posidonia meadows [42].

This study also defines a flowchart that could be applied to other drivers of change types, ecological species characteristics, and different regions (Fig. 7). First, the freely available human frequentation data can be broken down into different time periods, generating human frequentation driver of change maps for each defined period. These drivers of change maps can then be combined with available biological information (i.e., species distribution maps, species presence data for different phenological moments) as well as additional human frequentation information to weigh the initial frequentation data (i.e., field surveys or direct visitors counts from field monitoring). This combination finally produced the specific risk maps for each period.

In this sense, our approach could be automatized and easily incorporated into the park managers' decision-making flows, providing an easy method to update risk maps with different data types and at different moments of the year. Its automatization could also help to compare the results before and after the application of measures targeting the threat at stake. Our methodology can also be scalable and make use of different information on human frequentation, as well as more detailed or updated biological information on the target species. When available, new human frequentation data or species-specific sensitivity data can be incorporated to define new thresholds.

It is also important to point out the limitations of the human frequentation data used, especially potential biases towards certain types of sporting activities. In the case study of the Kentish plover in the *Aiguamolls de l'Empordà* Natural Park, the human frequentation sensibility histograms (Fig. 4) show similar results to those of other works on similar plover species [25]. Nevertheless, according to the expert knowledge of the area, the Strava Metro data could be underestimating leisure or birdwatching walks, people walking the dog, or campers from neighbouring campsites taking walks and baths on the nearby beaches where the Kentish plover inhabits. In consequence, it would be important to deepen in new human frequentation data less biased. In the case study of the *Cap de Creus* Natural Park, according to the available experts' knowledge, there is a clear underestimation of the number of visitors to the coves, so the Park's information on frequentation during the summer months was incorporated. This suggests that the limitations of STRAVA data may be dependent to each study region, for example in forest areas it would be underestimating the activity of the mushroom hunters, very frequent in the forests of Catalonia during the mushroom season. Since human frequentation is nowadays one of the main drivers of change that negatively impacts biodiversity [7] it is key to be able to have the most accurate information possible on this driver. The spatial and temporal precision STRAVA information, from mobile phones, has been shown as an important source of information, but with a bias to sport activities. In this sense, it would be interesting to be able to use information from mobile phones,

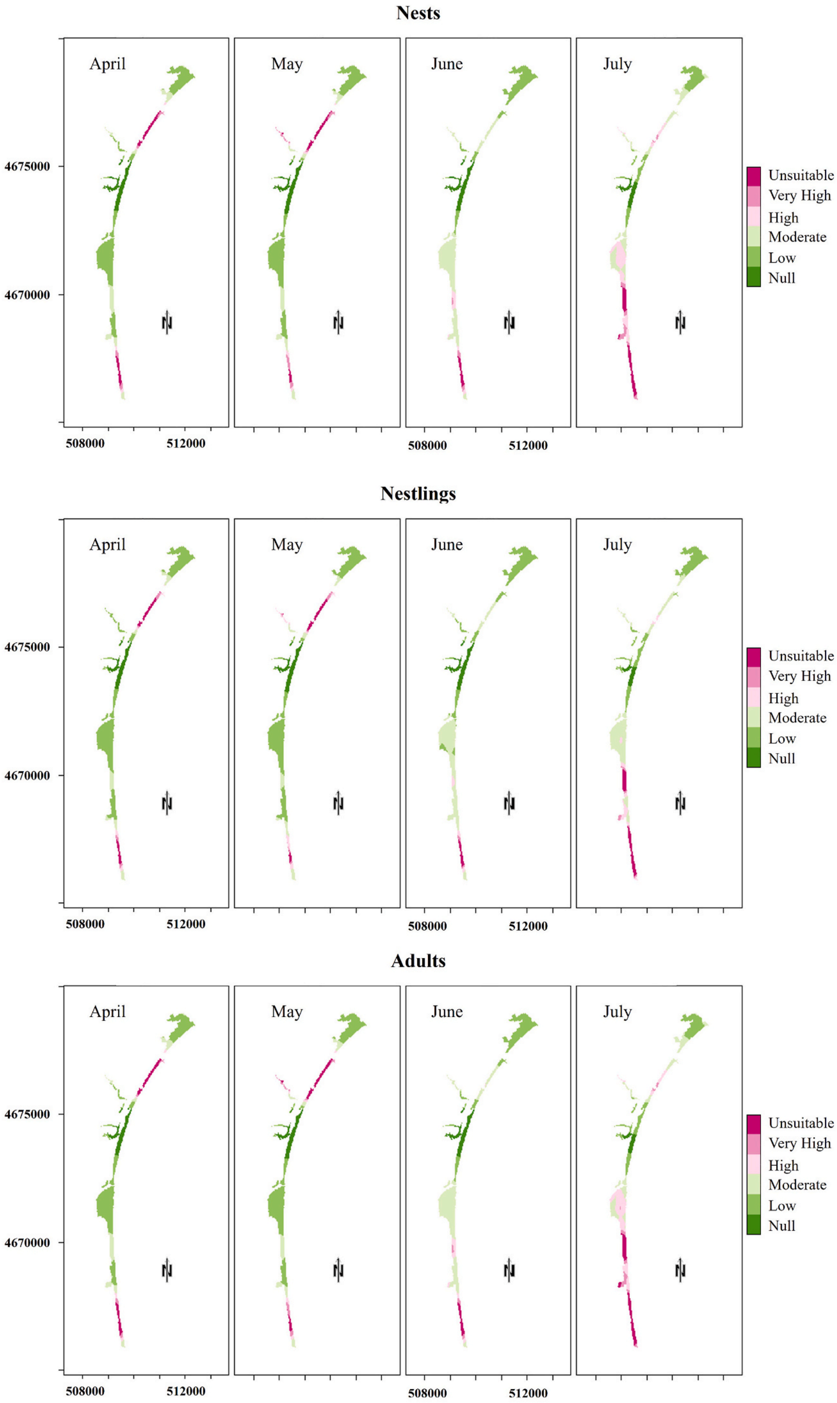

Fig. 5. Risk maps for Kentish plover to human frequentation inside *Aiguamolls de l'Empordà* boundaries from April to July for nests, nestlings, and adults. Coloured from green to pink indicating the null risk (dark green), low risk (light green) moderate and high risk (soft green and soft pink respectively), very high risk (light pink) and unsuitable (dark pink). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Human frequentation thresholds based in statistic criteria using mean and Standard deviation to classify into risk categories.

Human frequentation statistic thresholds	Values (*Mean=0.0619* *Standard deviation=0.0418)*	Risk
< Mean – Standard deviation	<0.0201	Low
Mean – Standard deviation to mean	0.0201 to 0.0619	Moderate
Mean to Mean + Standard deviation	0.0619 to 0.1037	High
> Mean + Standard deviation	>0.1037	Very high

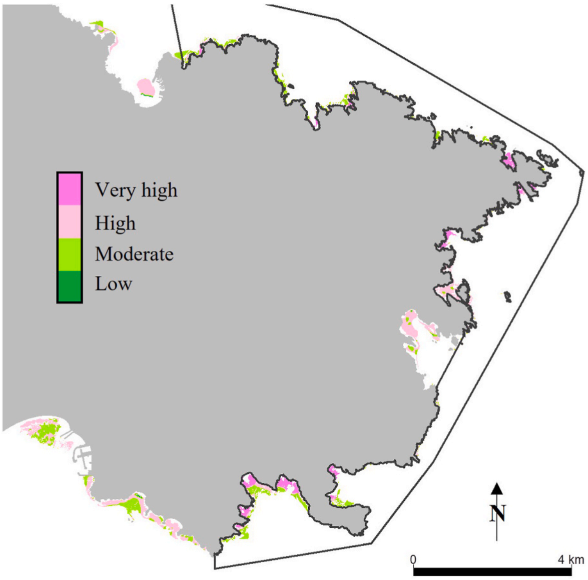

Fig. 6. Posidonia meadow risk to human frequentation in *Cap de Creus* Natural Park. The earth surface is grey, and the *Cap de Creus* Natural Park marine boundaries (black line). The dark green, light green, light pink and dark pink colours indicate the low, moderate, high, and very high risk, respectively, indicating the Posidonia meadows risk level to human frequentation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

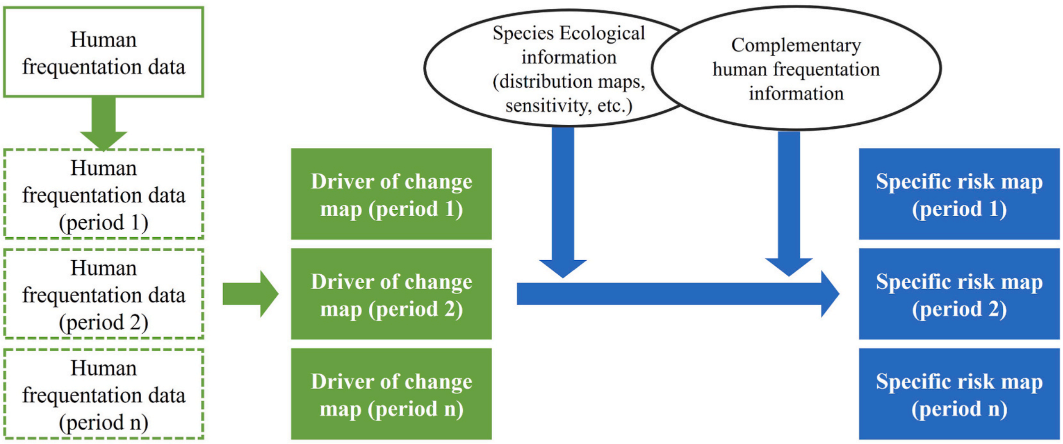

Fig. 7. Flowchart to elaborate specific risk maps: from left to right, the human frequentation data, disaggregated by time periods, is the base to map a driver of change map for each period. The combination of this drivers of change maps with species ecological distribution (i.e., distribution maps, sensitivity information) as well other complementary human frequentation data produces the final specific risk maps for each period.

as is already done to guide marketing decisions [43] adapting the technology and information flows to the management needs of protected areas.

5. Conclusions

The mapping of drivers of environmental change aimed at describing human frequentation impacts on a protected area provides a valuable starting point for risk assessment taking into account the coupled spatial and temporal dynamics of species and its threats. Our study highlights the effectiveness of incorporating complementary ecological information into the proposed information flow, which helps to direct specific conservation actions at different phenological moments of the species. Furthermore, in this particular case based on the assessment of human frequentation impacts, data from mobility applications used from mobile phones show great potential to accurately describe human activities, both spatially and temporally. More specifically, STRAVA proves to be a very powerful source of information despite its bias towards sporting activities.

Data availability statement

The data associated with the study will be made available on request.

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CRediT authorship contribution statement

Magda Pla: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Albert Burgas:** Supervision, Methodology, Data curation. **Gerard Carrion:** Supervision, Methodology, Data curation. **Virgilio Hermoso:** Writing – review & editing, Supervision, Conceptualization. **Ponç Feliu:** Supervision, Data curation. **Sergi Romero:** Supervision, Data curation. **Pilar Casanovas:** Methodology, Data curation. **Pau Sainz de la Maza:** Project administration, Methodology, Data curation. **Pedro Arnau:** Supervision, Methodology. **Joan Pino:** Supervision, Methodology, Investigation, Conceptualization. **Lluís Brotons:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] IPBES, in: E.S. Brondízio, J. Settele, S. Díaz, H.T. Ngo (Eds.), Global Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES secretariat, Bonn, 2019.

[2] European Environment Agency, State of Nature in the EU, Results from Reporting under the Nature Directives 2013-2018, 2020.

[3] L. Röschel, R. Noebel, U. Stein, S. Naumann, C. Romao, E. Tryfon, Z. Gaudillat, S. Roscher, D. Moser, T. Ellmauer, M. Löhnertz, L. Halada, Staneva, C. Rutherford, State of Nature in the EU - Methodological Paper. Methodologies under the Nature Directives Reporting 2013-2018 and Analysis for the State of Nature 2000, European Environment Agency, 2020.

[4] C. Kerbiriou, I. Leviol, F. Jiguet, R. Julliard, The impact of human frequentation on coastal vegetation in a biosphere reserve, J. Environ. Manage. 88 (2008) 715–728, https://doi.org/10.1016/j.jenvman.2007.03.034.

[5] L. Brotons, S. Herrando, Reduced bird occurrence in pine forest fragments associated with road proximity in a Mediterranean agricultural area, Landsc. Urban Plan. 57 (2001) 77–89, https://doi.org/10.1016/S0169-2046(01)00191-8.

[6] M. Guirado, J. Pino, F. Rodà, Understorey plant species richness and composition in metropolitan forest archipelagos: effects of forest size, adjacent land use and distance to the edge: edge distance, patch size and adjacent land use on forest understorey, Glob. Ecol. Biogeogr. 15 (2006) 50–62, https://doi.org/10.1111/j.1466-822X.2006.00197.x.

[7] S.L. Maxwell, R.A. Fuller, T.M. Brooks, J.E.M. Watson, Biodiversity: the ravages of guns, nets and bulldozers, Nature 536 (2016) 143–145, https://doi.org/10.1038/536143a.

[8] A.D. Baker, P.L. Leberg, Impacts of human recreation on carnivores in protected areas, PLoS One 13 (2018) e0195436, https://doi.org/10.1371/journal.pone.0195436.

[9] A. Semper-Pascual, D. Sheil, L. Beaudrot, P. Dupont, S. Dey, J. Ahumada, E. Akampurira, R. Bitariho, S. Espinosa, P.A. Jansen, M.G.M. Lima, E.H. Martin, B. Mugerwa, F. Rovero, F. Santos, E. Uzabaho, R. Bischof, Occurrence dynamics of mammals in protected tropical forests respond to human presence and activities, Nat. Ecol. Evol. 7 (2023) 1092–1103, https://doi.org/10.1038/s41559-023-02060-6.

[10] R. Naidoo, D. Gerkey, D. Hole, A. Pfaff, A.M. Ellis, C.D. Golden, D. Herrera, K. Johnson, M. Mulligan, T.H. Ricketts, B. Fisher, Evaluating the impacts of protected areas on human well-being across the developing world, Sci. Adv. 5 (2019), https://doi.org/10.1126/sciadv.aav3006 eaav3006.

[11] V. Hermoso, J. Salgado-Rojas, M. Lanzas, E. Álvarez-Miranda, Spatial prioritisation of management for biodiversity conservation across the EU, Biol. Conserv. 272 (2022) 109638, https://doi.org/10.1016/j.biocon.2022.109638.

[12] S. Ruitton, P. Astruch, A. Blanfuné, M. Cabral, T. Thibaut, C.-F. Boudouresque, Bridging Risk Assessment of Human Pressure and Ecosystem Status, Vie Milieu, 2020.

[13] J. Carwardine, T.G. Martin, J. Firn, R.P. Reyes, S. Nicol, A. Reeson, H.S. Grantham, D. Stratford, L. Kehoe, I. Chadès, Priority Threat Management for biodiversity conservation: a handbook, J. Appl. Ecol. 56 (2019) 481–490, https://doi.org/10.1111/1365-2664.13268.

[14] V.J. Tulloch, A.I. Tulloch, P. Visconti, B.S. Halpern, J.E. Watson, M.C. Evans, N.A. Auerbach, M. Barnes, M. Beger, I. Chadès, S. Giakoumi, E. McDonald-Madden, N.J. Murray, J. Ringma, H.P. Possingham, Why do we map threats? Linking threat mapping with actions to make better conservation decisions, Front. Ecol. Environ. 13 (2015) 91–99, https://doi.org/10.1890/140022.

[15] A. Ostwald, V.J.D. Tulloch, P.M. Kyne, N.J. Bax, P.K. Dunstan, L.C. Ferreira, M. Thums, J. Upston, V.M. Adams, Mapping threats to species: method matters, Mar. Policy. 131 (2021) 104614, https://doi.org/10.1016/j.marpol.2021.104614.

[16] J.P. Schägner, J. Maes, L. Brander, M.-L. Paracchini, V. Hartje, G. Dubois, Monitoring recreation across European nature areas: a geo-database of visitor counts, a review of literature and a call for a visitor counting reporting standard, J. Outdoor Recreat. Tour. 18 (2017) 44–55, https://doi.org/10.1016/j.jort.2017.02.004.

[17] O. Andersen, V. Gundersen, L.C. Wold, E. Stange, Monitoring visitors to natural areas in wintertime: issues in counter accuracy, J. Sustain. Tour 22 (2014) 550–560, https://doi.org/10.1080/09669582.2013.839693.

[18] J. Pino, C. Başnou, S. de, Anàlisi de les pressions sobre la biodiversitat a l'Àrea Metropolitana de Barcelona i de les seves tendències futures, (n.d.).

[19] A. Wang, A. Zhang, E.H.W. Chan, W. Shi, X. Zhou, Z. Liu, A review of human mobility research based on big data and its implication for smart city development, ISPRS Int. J. Geo-Inf. 10 (2020) 13, https://doi.org/10.3390/ijgi10010013.

[20] Z. Zhang, Y. Xiao, X. Luo, M. Zhou, Urban human activity density spatiotemporal variations and the relationship with geographical factors: an exploratory Baidu heatmaps-based analysis of Wuhan, China, Growth Change 51 (2020) 505–529, https://doi.org/10.1111/grow.12341.

[21] V. Shankar, Big data and analytics in retailing, NIM Mark. Intell. Rev. 11 (2019) 36–40, https://doi.org/10.2478/nimmir-2019-0006.

[22] A. Corradini, M. Randles, L. Pedrotti, E. van Loon, G. Passoni, V. Oberosler, F. Rovero, C. Tattoni, M. Ciolli, F. Cagnacci, Effects of cumulated outdoor activity on wildlife habitat use, Biol. Conserv. 253 (2021) 108818, https://doi.org/10.1016/j.biocon.2020.108818.

[23] N.H. Thorsen, R. Bischof, J. Mattisson, T.R. Hofmeester, J.D.C. Linnell, J. Odden, Smartphone app reveals that lynx avoid human recreationists on local scale, but not home range scale, Sci. Rep. 12 (2022) 4787, https://doi.org/10.1038/s41598-022-08468-7.

[24] V. Keller, S. Herrando, P. Voříšek, M. Franch, M. Kipson, P. Milanesi, D. Martí, M. Anton, A. Klvaňová, M.V. Kalyakin, H.-G. Bauer, R.P.B. Foppen, European Breeding Bird Atlas 2: Distribution, Abundance and Change, European Bird Census Council & Lynx Edicions, Barcelona, 2020.

[25] J.A. Tratalos, A.P. Jones, D.A. Showler, J.A. Gill, I.J. Bateman, R. Sugden, A.R. Watkinson, W.J. Sutherland, Regional models of the influence of human disturbance and habitat quality on the distribution of breeding territories of common ringed plover Charadrius hiaticula and Eurasian oystercatcher Haematopus ostralegus, Glob. Ecol. Conserv. 28 (2021) e01640, https://doi.org/10.1016/j.gecco.2021.e01640.

[26] BirdLife International, Charadrius alexandrinus (amended version of 2016 assessment), The IUCN Red List of Threatened Species (2019) e.T22727487A155485165, https://doi.org/10.2305/IUCN.UK.2019-3.RLTS.T22727487A155485165.en. (Accessed 25 September 2023).

[27] G. Pergent, C. Pergent-Martini, V. Gerakaris, Y. Fernandez Torquemada, Y. Ramzi Sghaier, R. Zakhama-Sraier, Posidonia oceanica (errata version published in 2018). The IUCN Red List of Threatened Species 2016: e.T153534A135156882., IUCN Red List Threat, SPECIES (2016). https://www.iucnredlist.org/en. (Accessed 25 September 2023).

[28] J.M. Gili, T. Madurell, S. Requena, C. Orejas, A. Gori, A. Purroy, C. Domínguez, C. Lo Iacono, E. Isla, J.P. Lozoya, C. Carboneras, J. Grinyó, Caracterización Física y ecológica del área marina del Cap de Creus, Informe final área LIFE+INDEMARES (LIFE07/NAT/E/000732)., Instituto de Ciencias del Mar/CSIC, Barcelona, 2011.

[29] Ecohidros, Cartografia bionòmica i batimetria dels àmbits del Parc Natural del Cap de Creus, fora de les zones de reserva natural (inèdit), Ports de la Generalitat, Parc Natural del Cap de Creus, 2017.

[30] S.A. Entorn, Typsa, CartCartografia bionòmica i batimetria de la Reserva Natural Integral de Cap de Creus i de les dues reserves naturals parcials de Cap Gros-Cap de Creus i Cap Norfeu(inèdit), Ports de la Generalitat, Parc Natural del Cap de Creus, 2014.

[31] STRAVA Inc, San Francisco, CA, USA, 2019. https://www.strava.com/about.

[32] S. Metro, StravaInc. https://metro.strava.com/, 2023. (Accessed 10 May 2022).

[33] Z.S. Venter, D.N. Barton, V. Gundersen, H. Figari, M. Nowell, Urban nature in a time of crisis: recreational use of green space increases during the COVID-19 outbreak in Oslo, Norway, Environ. Res. Lett. 15 (2020) 104075, https://doi.org/10.1088/1748-9326/abb396.

[34] Open Street map. https://www.openstreetmap.org/about, 2019. (Accessed 1 May 2022).

[35] A. Ferré, J. Font, J. Gesti, L. Vilar, A. Curcó, M. Guardiola, A. Salvat, Manual dels hàbitats de Catalunya. Volum IIa 1-Ambients litorals i salins.Hàbitats terrestres, Jordi Carreras, Albert Ferré, Josep Vigo, Barcelona, 2020. http://atzavara.bio.ub.edu/ManualCORINE/Volum_IIa_2a.pdf.

[36] J.M. Arcos, J. Bécares, D. Villero, L. Brotons, B. Rodríguez, A. Ruiz, Assessing the location and stability of foraging hotspots for pelagic seabirds: an approach to identify marine Important Bird Areas (IBAs) in Spain, Biol. Conserv. 156 (2012) 30–42.

[37] J. Arcos, J. Bécares, B. Rodríguez, A. Ruiz, Áreas Importantes para la Conservación de las Aves Marinas en España, 2009.

[38] S. Herrando, L. Brotons, J. Estrada, S. Guallar, M. Anton, Atles dels ocells de Catalunya a l'hivern 2006-2009, Institut Català d'Ornitologia, Lynx Edicions, Barcelona, 2011.

[39] D. Villero, M. Pla, D. Camps, J. Ruiz-Olmo, L. Brotons, Integrating species distribution modelling into decision-making to inform conservation actions, Biodivers. Conserv. 26 (2017) 251–271, https://doi.org/10.1007/s10531-016-1243-2.

[40] STRAVA global HeatMap. https://www.strava.com/heatmap, 2018. (Accessed 1 April 2022).

[41] S. Kostopoulou, I. Kyritsis, A tourism carrying capacity indicator for protected areas, Anatolia 17 (2006) 5–24, https://doi.org/10.1080/13032917.2006.9687024.

[42] C. Pergent-Martini, B. Monnier, L. Lehmann, E. Barralon, G. Pergent, Major regression of Posidonia oceanica meadows in relation with recreational boat anchoring: a case study from Sant'Amanza bay, J. Sea Res. 188 (2022) 102258, https://doi.org/10.1016/j.seares.2022.102258.

[43] D. Zaim, A. Benomar, M. Bellafkih, Developing A geomarketing solution, Procedia Comput. Sci. 148 (2019) 353–360, https://doi.org/10.1016/j.procs.2019.01.043.