Advance View
https://doi.org/10.3354/meps14309

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

June 1, 2023

Contribution to the Theme Section 'Species range shifts, biological invasions and ocean warming'

Tracking ongoing transboundary marine distributional range shifts in the digital era

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ABSTRACT: The digitalization of society is providing new opportunities to track spatio-temporal redistribution of species across national boundaries in near real-time. This is particularly interesting for marine species for which dynamics are difficult to monitor. We took advantage of the ongoing northward distributional range shift of the white grouper *Epinephelus aeneus* in Italy, Spain and France (Mediterranean Sea) to test the performance and complementarity of 4 emerging digital methods: (1) local ecological knowledge of recreational fishers actively collected using social media; (2) passive data mining of recreational fishing on social media; (3) Wikipedia page views; and (4) Google search volumes. We compared the temporal changes in maximum latitude of occurrence of the species from local ecological knowledge, passive data mining and traditional scientific knowledge and matched it with the thermal habitat of the species. Moreover, we compared the Wikipedia page views and Google search volumes to assess whether societal interest has a relationship with the distributional range shift of the species. Local ecological knowledge and passive data mining on social media complement traditional scientific knowledge, but are more sensitive as suggested by their significant relationship with the thermal habitat of the species. Wikipedia page views and Google search volumes were higher in Italy where the species is more common, but temporal trends within countries did not agree with changes in the distribution, and likely reflect local societal interest. Digital methodologies can complement traditional scientific knowledge with limited associated costs and with the additional ability to provide social insights for species on the move.

KEY WORDS: Climate change · Local ecological knowledge · Social media · Wikipedia · Google search volume · iEcology · Culturomics · Remote sensing · *Epinephelus aeneus*

1. INTRODUCTION

Distributional range shifts of species represent one of the major ecological effects of climate change (Pecl et al. 2017). Marine ecosystems are especially sensitive to shifting distributions of species (Burrows et al. 2011, García Molinos et al. 2016, Poloczanska et al. 2016), and marine organisms better track climate warming than terrestrial ones (Lenoir et al. 2020). However, marine monitoring of climate change effects on species distribution is limited by insufficient resources, and by logistical and technological

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challenges to cover large-scale spatio-temporal dynamics (Painting et al. 2020). In addition, redistribution of marine species frequently occurs at a rate that is difficult to monitor with traditional methodologies, and near real-time monitoring is needed to develop effective mitigation and adaptation strategies (Pecl et al. 2017, Melbourne-Thomas et al. 2022). Moreover, redistributions are usually transboundary (Liu et al. 2020), which implies that nationwide monitoring efforts are not sufficient to capture and understand such large-scale processes. These limitations can negatively affect our capacity to effectively track and understand the redistribution of marine species.

The digitalization of our society may provide new possibilities to track spatio-temporal redistribution of species in near real-time and across national boundaries. Local ecological knowledge has proven to be an effective source of information for tracking redistribution of marine species (Azzurro et al. 2019), and the possibility to engage with fishers using social media provides enhanced potential for such applications (e.g. Sbragaglia et al. 2020a, Martelo et al. 2021). Additionally, passive data mining on digital platforms can be a powerful approach to characterize macroecological patterns (Jarić et al. 2020a) and human–nature interactions (Ladle et al. 2016). Such approaches are gaining momentum in aquatic ecological research (Jarić et al. 2020b), and they have been used to estimate species distributions based on a diverse range of online digital data, such as geotagged posts on social and news media platforms (Hong et al. 2017, McDavitt & Kyne 2020, Martelo et al. 2021), as well as spatially differentiated Internet search volumes (e.g. Google search volumes; Proulx et al. 2014, Schuetz et al. 2015, Jarić et al. 2021). Similarly, online digital data have been used to detect new introductions and range expansions of alien invasive species (Kalous et al. 2018, Schifani & Paolinelli 2018, Fukano & Soga 2019, Magalhães et al. 2021, Martelo et al. 2021), including new occurrences of marine fish species (Al Mabruk & Rizgalla 2019, Rothman et al. 2020). Despite such recent research interest, the performance and complementarity of these new data sources with respect to already available data or scientific records has been poorly explored, which prevents the operationalization of these methodologies at transboundary geographical scales (but see Martelo et al. 2021 for an example at national level).

Tracking distributional range shifts using digital approaches, especially using local ecological knowledge or passive data mining, is of particular interest in the context of marine recreational fisheries. First, social media are embedded in recreational fishers' culture and are used to share posts on fish catches (Sbragaglia et al. 2020b, Vitale et al. 2021, Lennox et al. 2022). Second, recreational fishers can be considered a widespread spatio-temporal network of samplers who can provide potentially valuable information on redistributions of species (Sbragaglia et al. 2020a, Martelo et al. 2021). In fact, recreational fishers can be the first to notice the arrival of new marine species (Townhill et al. 2019). Moreover, digital data from social media platforms can provide quantitative measures of human perception about ecological dynamics such as biological invasions (Sbragaglia et al. 2022). In a more general context, digital encyclopaedias such as Wikipedia can help measure public interest and perception of species, as well as spatially differentiated (i.e. language-based) data on page views and edits (Mittermeier et al. 2019, 2021, Correia et al. 2021). For example, Mittermeier et al. (2021) showed that the number of Wikipedia page views of migratory birds increased in specific languages with the arrival of birds in the areas represented by those languages, thus enabling tracking of phenological processes. Similarly, search-volume data from engines such as Google can provide spatially differentiated indices of species distributions (Schuetz & Johnston 2019, Jarić et al. 2020a, 2021). However, the potential use of such data to track distributional range shifts has thus far not been evaluated.

We took advantage of the ongoing northward distributional range shifts of marine species in the Northwestern Mediterranean Sea (Bianchi 2007, Lejeusne et al. 2010, Bianchi et al. 2012), which is a suitable case study to test the relative performance of emerging digital data sources and approaches, and evaluate their complementarity with traditional scientific knowledge in tracking transboundary distributional range shifts. We focused on the white grouper *Epinephelus aeneus*, which is a target species of recreational fishers and is highly valued as food in both national and international markets (Pollard et al. 2018). The northern limit of the geographical range of white grouper in the Northwestern Mediterranean Sea was considered to be around 40° N (i.e. central-western Italy; Pollard et al. 2018), but recent records indicate the species is expanding its distribution to the north (Ruitort 2012, Pollard et al. 2018, Bo et al. 2020), probably due to increasing water temperatures. Moreover, a previous study has shown that the ongoing change in the distribution of white grouper can be tracked using information shared by recreational fishers on social media and video-sharing platforms such as YouTube (Sbragaglia et al. 2021). Accordingly, the first objective of this study was to test complementarity in tracking the temporal changes on the maximum latitude of occurrence of the species using local ecological knowledge (i.e. observations of recreational fishers collected through online surveys distributed on social media), passive data mining on social media (i.e. catches of recreational fishers published on YouTube) and traditional scientific knowledge (i.e. occurrences of the species reported in the Global Biodiversity Information Facility [GBIF] and in peer-reviewed articles). Moreover, we tested the performance of these 3 data sources by assessing the relationship between the maximum latitude of occurrence and the maximum latitude of the optimal thermal habitat of the species, assessed using remote sensing of sea surface temperature. The second objective of the study was to compare the Wikipedia page views and Google search volumes to assess whether societal interest has a relationship with the distributional range shift of the species. Assessing the performance and complementarity of these methodologies represents an important step for operationalizing emerging digital methodologies to track distributional range shifts of marine species.

2. MATERIALS AND METHODS

2.1. Ethical and privacy aspects

The use of local ecological knowledge and social media data mining requires specific attention to ethical aspects and privacy issues. All respondents to the online local ecological knowledge questionnaire were over 18 yr old and informed about the scientific purposes and data treatment procedure adopted during the study. The data we mined from YouTube are publicly available. However, data privacy concerns and ethical principles associated with human-subject research must be carefully considered when using social media data (Zimmer 2010, Di Minin et al. 2021). We followed recent recommendations for responsible use of social media data in research (Monkman et al. 2018, Di Minin et al. 2021, Sbragaglia et al. 2021b), considering data privacy concerns and aiming to ensure compliance with the General Data Protection Regulation of the European Union. Specifically, we minimized the data by discarding all but the required information and pseudonymised the data by replacing IDs (e.g. channel title, channel ID). Additionally, we kept all data related to personal information in one dataset, while the rest of data presented in the paper were stored in a separate dataset. The white grouper is not a threatened species; therefore, we did not pay specific attention to providing evidence of its presence in new locations. The public information about the presence of white grouper in new areas could increase fishing pressure, but the resolution that can be obtained from the graphical material presented in this study does not allow retrieval of information on specific fishing spots.

2.2. Local ecological knowledge and social media data mining

We created an online survey in Google Forms following a similar approach to that described by Sbragaglia et al. (2020a). The aim of the survey was to collect local ecological knowledge of marine recreational fishers about the white grouper in Italy and along the Mediterranean coast of France and Spain. The survey was subdivided in 3 sections, with a total of 12 questions, including questions about the first sighting or capture of a white grouper, the location and the skills of and fishing strategy used by recreational fishers (Text S1 and Table S1 in the Supplement at www.int-res.com/articles/suppl/m14309_supp.pdf). Respondents were informed about the purpose of the study, and sharing of personal information such as an email address was voluntary. The survey was shared during February–April 2021 on the 5 most popular Facebook groups about recreational angling and spearfishing in Italy, France and Spain (those with the highest number of members; see also Sbragaglia et al. 2020a). We also shared it with associations affiliated to sport-fishing federations and other international NGOs involved in the sustainable management of recreational fishing.

We further explored recreational fishing of white grouper by systematically mining data on YouTube from 2010 to 2020. We collected the data using the YouTube Data API (v3), following the steps reported in previous studies (Sbragaglia et al. 2020b, 2021a, Correia et al. 2021). We extracted the data from YouTube's API in January 2021 for each country of interest (Italy, France and Spain) using the common name of the species in the 3 different languages (Italian: 'cernia bianca'; French: 'mérou blanc'; Spanish: 'mero blanco'). This approach helped to narrow the results to the study area, but also captured homonyms and other non-relevant content (Correia et al. 2017); thus, data required careful validation. We watched videos to validate the correct species identification and then used the video upload date as a proxy of the capture of the fish (Sbragaglia et al. 2020b). We used the title, description and comments of the videos to retrieve the location of the catch shown in the video, first at a general level (e.g. region within a country such as the Balearic Islands or Sardinia), and then, when possible, at the specific locations together with corresponding geographic coordinates. Data mining was done with R software (https://www.r-project.org/; version 4.0.3) using the packages 'jsonlite' (https://CRAN.R-project.org/package=jsonlite), 'lubridate' (Grolemund & Wickham 2011) and 'curl' (https://CRAN.R-project.org/package=curl/).

Moreover, we downloaded the occurrences of the species from GBIF.org (3 December 2021; https://www.gbif.org; DOI of the query: https://doi.org/10.15468/dl.npbj63) and added other relevant records published in peer-reviewed journals (Mas et al. 2006, Ruitort 2012, Bo et al. 2020). All GBIF occurrences that were already obtained from previous studies using YouTube data mining were removed (more details in Sbragaglia et al. 2021a).

2.3. Wikipedia page views and Google search volumes

We collected Wikipedia page view data for pages on white grouper in Italian and French language, while for Spain we only found a page in Catalan (Table 1). We obtained the page views for the 3 languages using the R package 'pageviews' (Keyes & Lewis 2016) from 15 July 2015 until 31 October 2021 (Wikipedia data are available from July 2015 in the current form). We focused on 3 time periods (2015, 2016–2018, 2019–2021) for each of the 3 languages. We normalized the data to account for differences in page-view volume among languages and time periods. In particular, for each language, we divided the species page views by the total page views of Wikipedia, and multiplied by the averaged total page views for all time periods (Eq. 1, where *i* is the language):

$$\frac{\text{Species page views } (i)}{\text{Total page views } (i)} \times \text{mean total page views } (i) \qquad (1)$$

This allowed us to obtain normalized values that were not influenced by different volumes across languages and time periods. In addition, we acquired data regarding the page edit history (date of creation, number of times edited and date when it was last edited).

We obtained the relative monthly Google search volumes from 1 January 2013 to 1 October 2021 for white grouper in Italy (including data at the regional level), France and Spain (Google search volumes are available since 2013 in its current form). We focused on 3 time periods (2013–2015, 2016–2018, 2019–2021), and obtained the search volumes for the topic 'white grouper'. Topics recognized by Google include in the search volume a collection of search terms such as synonyms, different spelling versions, misspellings and other related terms across languages, such as the species binomial in addition to its common name (Cooper et al. 2019). Data were obtained using the Google Health Trends API and a dedicated Python library (google-api-python-client; https://pypi.org/project/google-api-python-client/; see Vardi et al. 2021). The outputs were values calculated based on 10–15% of all searches (Green et al. 2018), and were normalized to all searches made in the country during the studied period. In those instances where the volume of available data allowed it (i.e. Italy), we analysed the data by regions within the same country. As it was based on a sample of searches, there was a threshold of searches under which zero was returned due to insufficiency of data.

Table 1. Summary of the results for the Wikipedia page views and Google search volumes for each of the 3 countries or regions (Italy, France, Spain–Catalonia), including names of each Wikipedia page, dates of page creation and last page edits, and the total number of edits. Dates are given as d/mo/yr

Variable	Country		
	Italy	France	Spain (Catalonia)
Wikipedia page name	*Epinephelus aeneus*	*Epinephelus aeneus*	Anfós blanc
Page creation	19/10/2008	11/11/2006	20/12/2008
Last edited	12/10/2021	16/12/2020	8/10/2021
Number of edits	44	42	54
Page views (Normalized)			
Total	33374	29398	1105
2015	2750	2337	99
2016–2018	15078	14085	512
2019–2021	15546	12977	494
Google search volume			
Total	1073	318	–
2013–2015	611	87	–
2016–2018	284	109	–
2019–2021	178	122	–

2.4. Matching occurrences with optimal thermal habitat

Marine organisms can track climate warming and redistribute following isotherm shifts towards higher and cooler latitudes (Pinsky et al. 2013, Lenoir et al. 2020). Here, we used long-term (1990–2020) spatially explicit (0.05° resolution) information on sea surface temperature (SST; Mediterranean Sea – High Resolution L4 Sea Surface Temperature Reprocessed; https://doi.org/10.48670/moi-00173; accessed in December 2021) to evaluate the shifting distribution in optimal thermal conditions for the white grouper. Data come from AquaMaps (www.aquamaps.org), which provides the probability of occurrence at particular locations (latitude and longitude) throughout the species distribution range, and associated SST (Kaschner et al. 2016). Here, we first subset AquaMaps occurrences within the Mediterranean Sea with probabilities of occurrence higher than 90%, and considered the minimum and maximum SST associated with the occurrence as the thresholds for the species' optimal thermal conditions. Information on the date on which the occurrences were recorded is not available. However, we exclusively used this information as a proxy for the thermal optimum of this species in the Mediterranean Sea. Absolute values for these thresholds may not necessarily reflect actual optimal thermal conditions for the white grouper in the Mediterranean. However, our approach is still useful for evaluating long-term, distributional shifts in the thermal optimum of a species. Pixels in yearly averaged maps of SST were subsequently reclassified as optimal or suboptimal according to the considered optimal thermal range (19.5–23.3°C). We identified marine areas encompassing optimal thermal conditions for the white grouper and overlapped them with the occurrence of the species per year. We then extracted the maximum latitude of the optimal thermal range of the species per year to further evaluate a possible relationship between the maximum latitude of the optimal thermal habitat and occurrence of the species.

2.5. Statistical analysis

We compared the performance of local ecological knowledge and passive data mining by testing the relationship of the maximum latitude of occurrence of the species with the maximum latitude of occurrence of the optimal thermal conditions across years. We also tested the complementarity of local ecological knowledge and passive data mining with traditional scientific knowledge by testing the relationship of the maximum latitude of occurrence of the species obtained from the different data sources across years. In both cases, we fitted a Gamma-family smoothing function and used the predicted values to estimate the correlation between the different variables (i.e. maximum latitude of occurrence and optimal thermal conditions) across years. The correlation was calculated with the nonparametric Kendall's coefficient of concordance. In all the cases, we used a 95% confidence interval. We ran all analyses in R (https://www.r-project.org/; version 4.0.3).

3. RESULTS

3.1. Local ecological knowledge and social media data mining

Scanning traditional scientific knowledge (i.e. peer-reviewed papers and GBIF), we found 108 records from 86 different locations spanning 1990 to 2020 (Fig. 1). We collected 133 observations of white grouper stemming from local ecological knowledge (108 from Italy, 23 from Spain and 2 from France) between 1992 and 2020 (Fig. 1). The median age of fishers was 42 yr, and 49% of them shared their email addresses for further collaboration. Importantly, 36% of recreational fishers declared to have recently changed fishing strategy (i.e. fishing deeper and/or using echo sounders to localize isolated fishing spots in the sand; see also Text S1 in the Supplement). Some of the most interesting comments that reinforce the quantitative replies were: 'only in 2020 I saw the first specimen of white grouper', 'I have only seen one white grouper in all my life, it was a juvenile specimen in 2017', and 'I started seeing white groupers when I started fishing in a specific part of the reef'. Regarding YouTube, we identified a total of 431 videos related to the capture of a white grouper between 2010 and 2020 (415 from Italy, 16 from Spain and none from France). This included 233 recreational spearfishing videos and 198 angling videos (in Spain, we only retrieved spearfishing videos; more information in Text S1). We were able to retrieve locations of the catches for 92 videos.

The occurrence of the species obtained from traditional scientific knowledge indicated a significant positive correlation in maximum latitude across years with both local ecological knowledge ($r_\tau = 0.35$; p <

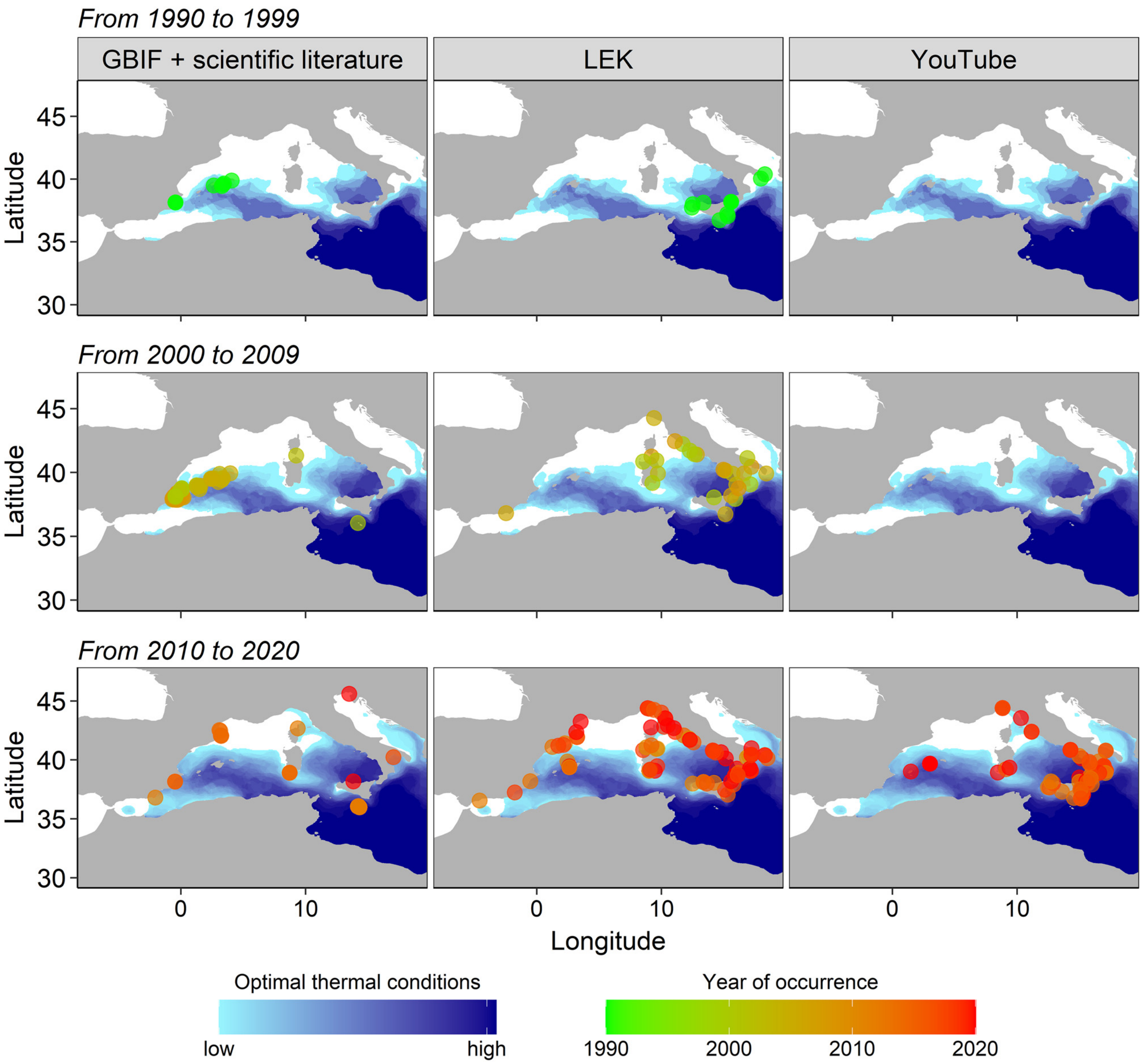

Fig. 1. Spatio-temporal occurrence of the white grouper *Epinephelus aeneus* coupled with its optimal thermal conditions for different time periods. Left column: GBIF data and additional records published in peer-reviewed journals (see Section 2 for more details). Centre column: local ecological knowledge (LEK) of recreational fishers who replied to the online questionnaire. Right column: passive mining of occurrences based on the catches of recreational fishers who posted videos on YouTube. The background illustrates spatio-temporal changes in optimal thermal conditions (blue gradient represents the number of years a particular pixel was categorized as optimal in terms of thermal conditions; see Section 2 for more details). Note that we did not report occurrence data for the non-Italian Adriatic Sea

0.01; Fig. 2) and YouTube data mining ($r_\tau = 0.95$; $p < 0.001$; Fig. 2). However, the maximum latitude obtained with traditional scientific knowledge was always lower than that obtained from local ecological knowledge and YouTube data mining across all years, except for 2020 where traditional scientific knowledge documented the northernmost occurrence of the species in the Adriatic Sea (Fig. 1). Moreover, maximum latitude of optimal thermal conditions showed a significant positive correlation with the maximum latitude of occurrence obtained from both local ecological knowledge ($r_\tau = 0.77$; $p < 0.001$; Fig. 2) and YouTube data mining ($r_\tau = 0.95$; $p < 0.001$; Fig. 2), while the correlation with maximum latitude from traditional scientific knowledge was not significant ($r_\tau = 0.21$; $p = 0.096$; Fig. 2).

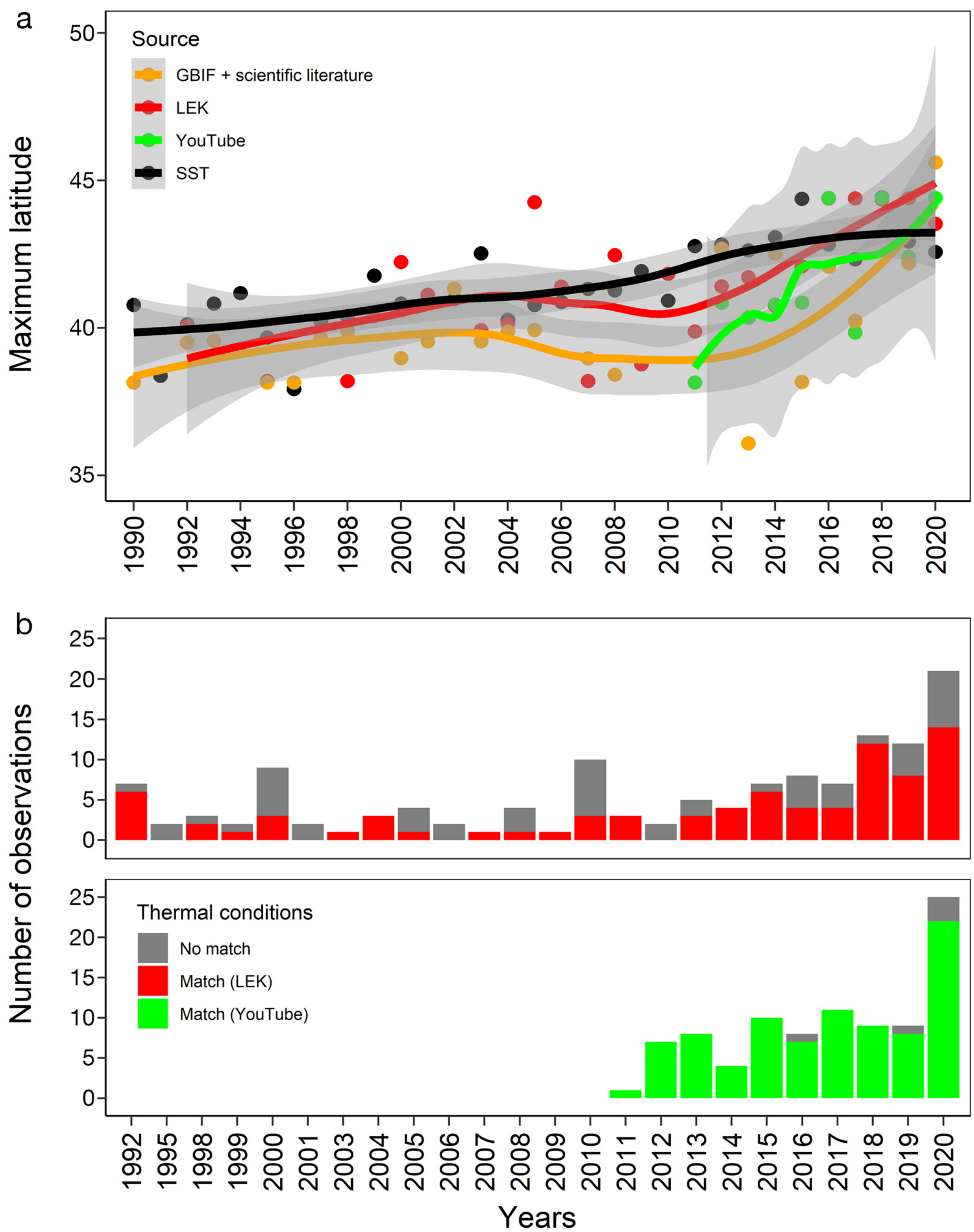

Fig. 2. Temporal patterns of occurrence of white grouper *Epinephelus aeneus* and its optimal thermal conditions. Maximum latitude of occurrence of the species according to local ecological knowledge (LEK) and YouTube data is reported together with its optimal thermal conditions. (a) Data are presented along with a Gamma-family smoothing function indicating means as lines and 95% confidence intervals as a shaded grey contours). SST: sea surface temperature. (b) Match between the occurrence of white grouper and optimal thermal conditions for both LEK and YouTube data

3.2. Wikipedia page views and Google search volumes

The Wikipedia pages for each language were created at different times (Italian: 19 October 2008; French: 11 November 2006; Catalan: 20 December 2008). The Italian page was the most visited (33 374 normalized views; 44 edits; Table 1), followed by the French (29 398 normalized views; 42 edits) and Catalan pages (1105 normalized views; 54 edits). Wikipedia page views originated mostly from within the country or region (Italy: 91.7%; France 68.4%;

Catalan: 71.1% from Spain). The Italian page showed an increasing trend in page views for the 3 time periods considered (2015, 2016–2018 and 2019–2021; Table 1, Fig. 3). The French and Catalan pages showed the highest number of page views for the period 2016–2018 (Table 1, Fig. 3). In terms of Google search volumes, white grouper was searched more in Italy (1073, normalized volume) than in France (318, normalized volume). The search volumes in Spain were insufficient to retrieve data. Search volumes in Italy had a decreasing trend for the 3 time periods considered (2013–2015, 2016–2018 and 2019-2021), while France showed an increasing trend (Table 1, Fig. 3). Among the Italian regions, Marche showed the highest search volume, followed by the southern regions of Sicilia and Calabria, and the western regions of Lazio and Toscana (Fig. 3; Table S2). Most of the regions showed a decreasing trend in search volumes for the 3 time periods considered (Fig. 3; Table S2).

4. DISCUSSION

4.1. Local ecological knowledge and social media data mining

Scientific projects based on the involvement of hobbyists (e.g. bird watchers) and recreationalists (e.g. divers or fishers) are widely recognized as effective actions for new discoveries and broader achievement of sustainability goals (Pecl et al. 2014, Sullivan

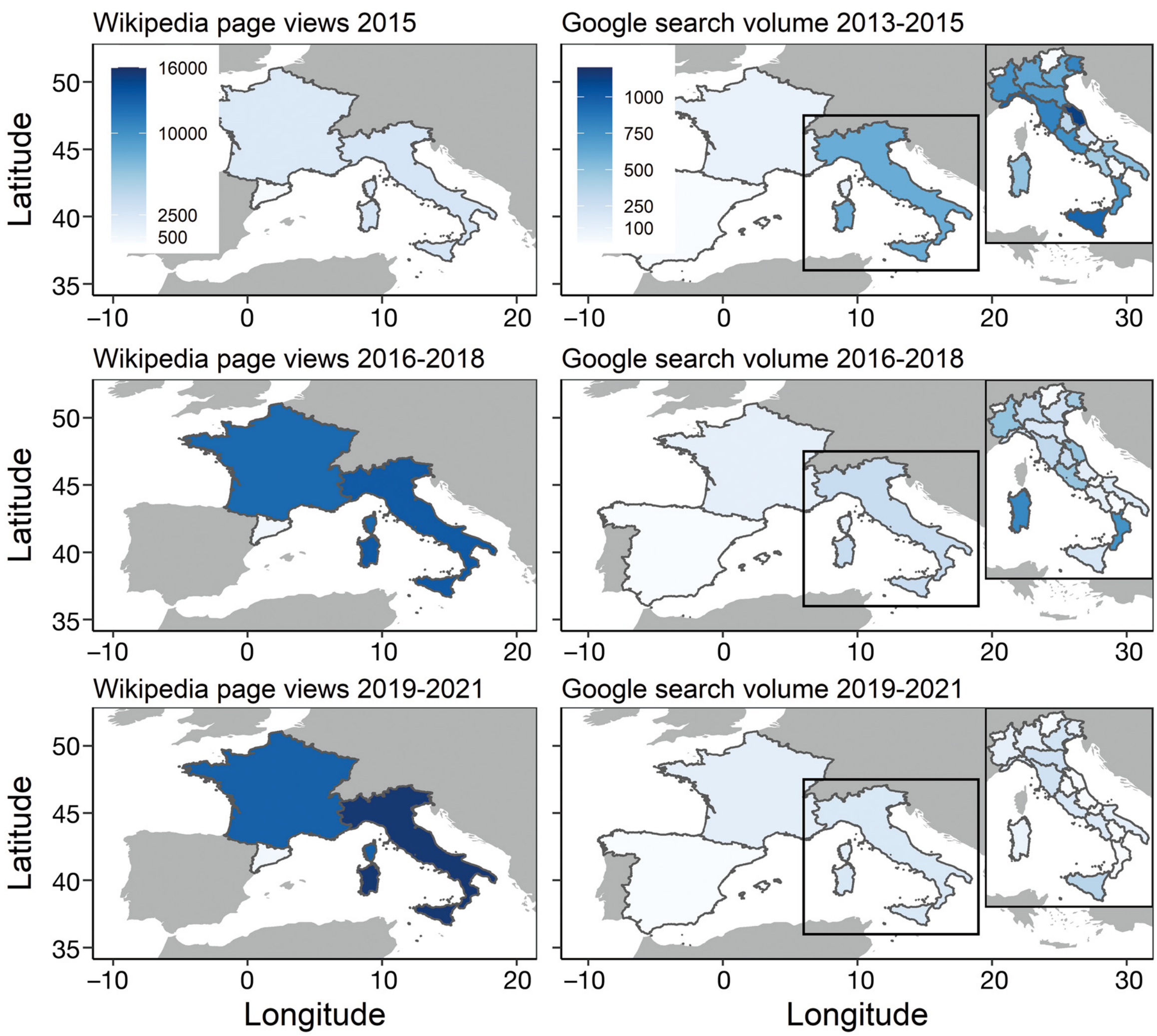

Fig. 3. Wikipedia page views (left column) and Google search volumes (right column) for white grouper *Epinephelus aeneus* in Spain (only the page in Catalan was retrieved), France and Italy according to the information presented in Table 1. Search volumes in Italy allowed for the presentation of regional data (insets)

et al. 2014, Fritz et al. 2019, Fraisl et al. 2020). Here, we demonstrated that local ecological knowledge, passive data mining on social media and traditional scientific knowledge complement each other in tracking the maximum latitude of occurrence of a northward-expanding species. Despite that, local ecological knowledge and passive data mining on social media seem more sensitive than traditional scientific knowledge in tracking the distributional range shifts as indicated by their significant relationship with the optimal thermal habitat of the species. It is important to note that although passive data mining has several caveats and limitations (Jarić et al. 2020b; see also Section 5), it has 2 major advantages over traditional local ecological knowledge approaches. First, passive data mining does not require engagement with and trust of hobbyists and recreationalists, which could be a limiting factor in many scenarios where response rate to surveys and general engagement decrease (e.g. recreational fishers may stop sharing information if they lose trust in local research activities). Second, the volume of data for passive mining is expected to increase in the future. For example, in 2020 we recorded more occurrences using social media data mining than local ecological knowledge (Fig. 2); therefore, passive data mining may have a strong potential for future applications (Jarić et al. 2020a).

4.2. Wikipedia page views and Google search volumes

Wikipedia page views and Google search volumes provided consistent information that generally agrees with white grouper being more common in Italy with respect to the other countries. However, such methodological approaches were not informative to track the spatio-temporal dynamics of the target species. One possible interpretation is that the decline in Google search volumes between 2019 and 2021 in Italy was due to restricted rules in the country resulting from the COVID pandemic, with recreational fishing — and many other outdoor activities — being forbidden (Pita et al. 2021). Alternatively, Wikipedia page views and Google search volumes might have been linked to local dynamics. This is particularly supported by the fact that Google search volumes for Italian regions showed the highest volume of searches for a region on the Adriatic coast (Marche), but according to the available knowledge, the white grouper has never been recorded there. A possible interpretation is that marine science institutions played a role in driving the search volume and page views at the local level, especially where overall volumes were not very high. In addition, such differences could be further explained by different societal aspects (e.g. cultural differences among regions or summer vacation destinations). For example, Mittermeier et al. (2019) showed an increase in Wikipedia page views of great white shark during 'Shark Week', and how such media exposure to local events can affect temporal and spatial patterns in these digital data sources. Nevertheless, although the use of Wikipedia page views and Google search volumes has certain challenges (Vardi et al. 2021; see also Section 5), they provide information that may reflect the level of societal attention the species received in each country (Millard et al. 2021, Mittermeier et al. 2021).

5. CONCLUSIONS, LIMITATIONS AND FUTURE DIRECTIONS

Many aspects of ecology are being revolutionized by emerging technologies, and emerging digital data sources will probably play a pivotal role in monitoring biodiversity in a society that is becoming increasingly digitalized (Jarić et al. 2020a). These digital opportunities can provide transboundary insights with quick data access and low associated costs because the data are already available on the internet. There are several considerations that we draw from our study that could have general validity in other contexts, which should be taken into consideration for future developments. First, it is likely that older people, who could have important historical memory of ecological processes, are not reached using emerging digital methodologies (i.e. recreational fishers who replied to our online questionnaire had a median age of 42 yr; see Vitale et al. 2021 for more details). This is not very important for tracking ongoing processes such as in our case study, but could be relevant for reconstructing historical processes. Second, new occurrences of species could be partially related to technological developments or behavioural changes of observers. This is an issue we specifically tackled in the local ecological knowledge questionnaire, and 36% of recreational fishers declared that they had recently changed fishing strategy (i.e. fishing deeper and/or using echo sounders to localize isolated fishing spots in the sand; see also Text S1). This could have increased the chances of catching and sighting white grouper, which inhabit isolated rocky areas in mud or sand (Heemstra 1993, Pollard et al. 2018). Third, there are sociocultural, ethical and intrinsic challenges and biases associated with social media data mining (Jarić et al. 2020b, Di Minin et al. 2021). For example, YouTube is a dynamic cultural system (Burgess & Green 2018), and algorithms managing the platform often change, while users also can modify or delete information. Using these methodologies in a systematic way (e.g. being explicit about the date of the mining and the key words used), may minimize such biases and provide snapshots of information to be used in the future. Fourth, different national management strategies can affect the sensitivity of the methodologies presented here. For example, in France (including Corsica), we only retrieved 2 occurrences of white grouper based on local ecological knowledge and no videos published on YouTube, even though the presence of the species has been described there (Pollard et al. 2018). Recreational fishing of groupers is not allowed in France (regulations 2013357-0004 and 2013357-0001 of 13 December 2013). Although these regulations do not explicitly address fishing of the white grouper, recreational fishers could have misunderstood their option to catch the species, and consequently avoided targeting white grouper. Nevertheless, this example highlights that nationwide regulations can be challenged by the distributional range shifts of species, which requires a transboundary approach to harmonize monitoring and understanding of such phenomena in fisheries and other contexts (Katsanevakis et al. 2015, Liu et al. 2020, Maureaud et al. 2021).

Redistribution of species in response to climate change is a major challenge for society (Pecl et al. 2017). We provided a snapshot of emerging digital methodologies that can advance our tracking capabilities and understanding of such phenomena from an ecological and social perspective. Our study showed that such methodologies can provide complementary and robust insight with respect to well-established biodiversity repositories such as GBIF or records retrieved from scientific publications. Future technical refinements of these digital methodological approaches such as automated data mining or automatic species identification (Jarić et al. 2020a, Correia et al. 2021) can further boost their operationalization. This could have an important impact in areas or taxonomic groups where biodiversity data are less available (Ramírez et al. 2022), or to track ecological and social dimensions of invasive alien species (Jarić et al. 2021).

Acknowledgements. We are extremely grateful to Ricardo A. Correia for developing the R script we used for mining data on YouTube, and to Carsten Riepe for helping with the development of the local ecological knowledge survey. V.S. is supported by a 'Juan de la Cierva Incorporación' research fellowship (IJC2018-035389-I), and he is now supported by a Ramón y Cajal research fellowship (RYC2021-033065-I) granted by the Spanish Ministry of Science and Innovation. F.R. was also funded by a Ramón y Cajal research fellowship (Spanish Ministerio de Ciencia e Innovación, RYC2020-030078-I). R.V. is partly supported by the George S. Wise post-doctoral fellowship. V.S., L.E., F.R. and M.C. acknowledge financial support from the European Union's Horizon 2020 project 'FutureMARES' (ID: 869300) and PRO-OCEANS (PID2020-118097RB-I00) by the Spanish Ministry of Economy and Competitiveness, Feder funds and the Spanish Research Agency. They also acknowledge the Spanish government through the 'Severo Ochoa Centre of Excellence' accreditation (CEX2019-000928-S).

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Editorial responsibility: Amanda E. Bates (Guest Editor), Victoria, British Columbia, Canada
Reviewed by: T. J. Bird, F. Ribeiro and 1 anonymous referee

Submitted: November 2, 2022
Accepted: April 11, 2023
Proofs received from author(s): May 25, 2023