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Participatory mapping of aquatic invasive species: a demonstration in a coastal lagoon

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Abstract

Aquatic Invasive species (AIS) are a growing driver of change across marine and freshwater ecosystems but spatially-explicit information is seldom available for supporting management actions and decision making. Here we conceived and tested a new participatory method to map the distribution of three invasive species (*Callinectes sapidus*, *Procambarus clarkii* and *Oreochromis niloticus*) in the coastal lagoon of Lesina (Italy). Local fishers were asked to draw the distribution of each species on pre-printed maps, indicating districts of the lagoon characterized by different abundance levels. Then, maps were converted to a lattice grid and a Bayesian hierarchical Generalized Additive Modeling was adopted to model species distribution in the lagoon, calculating the coefficient of variation for model fitted values to map fishers agreement about the distribution of each species.

The spatial gradient in the abundance of the three species in the lagoon aligned with their ecological requirements. *C. sapidus* was abundant throughout the whole lagoon, peaking in correspondence of saltmarsh vegetation, while *P. clarkii* and O. niloticus, were much less abundant and remained distributed near to freshwater inputs. Experts agreed about the spatial

distribution of *C. sapidus* in the lagoon, with a median coefficient of variation in model fitted values of 3.9%. On the other hand, the coefficient of variation was higher for *P. clarkii* (19.9%) *O. niloticus* (18.4%), indicating a higher level of uncertainty about their estimated distribution.

With this example, we provided new metrics to evaluate the quality of LEK-based participatory mapping in terms of agreement and consistency among experts. The resulting information provides new insights for spatially informed management across aquatic realms in relation to the increasing ecological and socio-economical pressures posed by biological invaders.

1 Introduction

Participatory mapping refers to a wide range of methodologies, whose general objective is to engage indigenous people in the elicitation of spatial information, compared to conventional cartography, where such information is derived from field measurements [1]. Participatory maps are increasingly employed for a variety of different applications, not only in natural resource management but also in many other domains [2]. Their outcomes can be particularly valuable to investigate patterns and processes fast enough to outrun large-scale ecological surveys, especially in contexts of limited data availability. These conditions are common in conservation sciences, which have recently witnessed an outburst of participatory mapping initiatives throughout the world, in both developing and developed countries [2][3][4]. In fact, information extracted from the knowledge of people living in close relationship with the natural environment can complement, or even surrogate, ecological sampling, at various spatial and temporal scales [5][6][7]. This expert knowledge, often reported as 'Local Ecological Knowledge' (LEK) is currently accessed to estimate a variety of biological and ecological parameters [8][9][10] in both terrestrial and aquatic systems, where ecological monitoring is particularly demanding [11]. LEK-based surveys indeed overcome the pragmatical constraints that hamper investigating the distribution of aquatic organisms [12], including AIS [13][14]. These methodologies provide fresh new inputs to conventional cartography [15] and may truly serve the needs of Marine Protected Areas [16], coral reef management [17]; fishing management [18] and provide key information for the conservation of marine [19] and freshwater [20] ecosystems.

Nevertheless, although LEK has been employed to reconstruct invasion dynamics and to investigate temporal variations in invasive species [5][14][21], participatory mapping is seldom applied to invasive species [22][23], especially in aquatic systems were, to the best of our knowledge, really few experiences exist. This absence probably stems from the skepticism of many conservationists about LEK itself and by their limited experience with these approaches: LEK-based studies, although growing, are relatively recent and minoritarian in conservation. Local experts are often perceived as less "objective" than ecological surveys and many researchers tend to adopt LEK only to complement "real" data obtained from the field. Moreover, participatory mapping also requires experience with cartography and research methods from the social sciences (e.g. interviews), a combination which further constrained its adoption by the scientific community.

This gap is worth to be filled, particularly for Invasive species that are a major driver of change [24] and knowing their distribution is considered a priority for conservation planning and adaptation in both terrestrial [25][26] and aquatic systems [27].

A further problem is that, whilst the potential of eliciting information from single experts appears to be large, the quality and validity of the observational data needs to be properly addressed through structured elicitation protocols and appropriate data processing. This aspect is of key importance to improve the accuracy and transparency of the resulting judgments when expert judgments are used to inform science [28][29].

In this study, we aim to offer a first answer to this need. We tested a participatory mapping methodology with the aim of providing spatially-explicit information on the distribution and abundance of three AIS occurring in a Mediterranean coastal lagoon: *C. sapidus*, *P. clarkii* and *O. niloticus*. In absence of complementary field data, statistical modeling is employed to measure agreement among experts, providing a first assessment for self-reported spatial data.

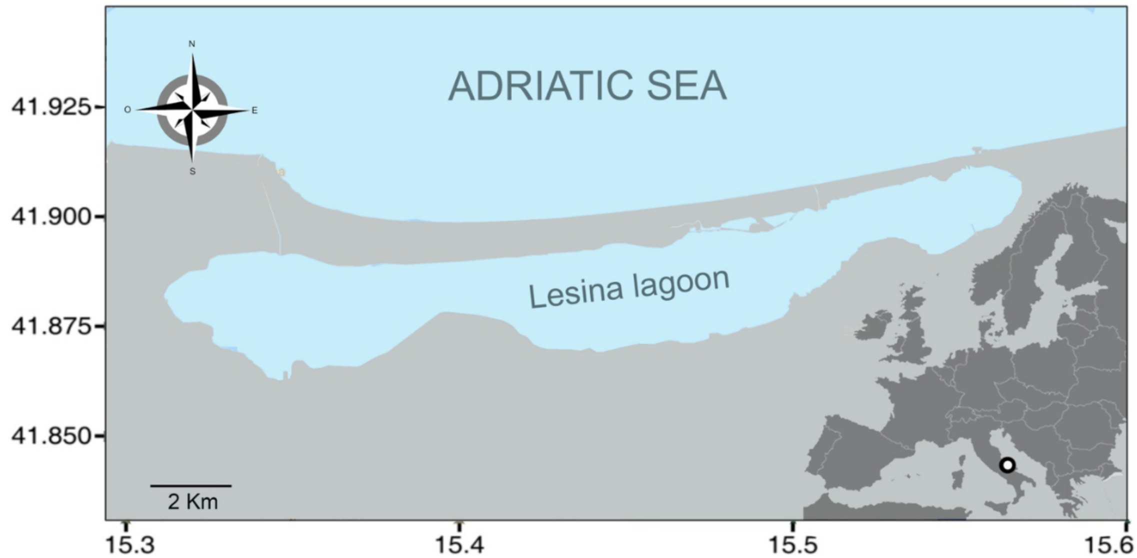

Figure 1 | Map of the study area in the Apulia region (Italy): the Lesina lagoon.

2 Methods

2.1 Study area and target species

The Lesina lagoon (Fig. 1), located along the south-western Adriatic coasts (Apulia region, Italy) is a micro-tidal coastal lagoon, characterized by brackish waters (area: 51. 4 km^2; average depth: 0.7 m; salinity: 11 – 34 psu; temperature: 7-26°C) and surrounded by a mosaic of intensive farmlands, urbanized areas, salt marshes and coastal dunes. The lagoon hosts a little community of small-scale fishers that once relied mostly on the European eel (*Anguilla anguilla*) [30], while today they mostly exploit sea breams (*Sparus aurata*) and the sea bass (*Dicentrarchus labrax*) [31][32].

Various AIS are currently established in the lagoon, notably the Atlantic blue crab (*Callinectes sapidus*), the red swamp crayfish (*Procambarus clarkii*) and the Nile tilapia (*Oreochromis niloticus*)[33]. All these three species can develop abundant populations, with severe ecological and economical impacts [34][35][36][37][38], but spatial-explicit information is currently unavailable for the Lesina lagoon [33].

2.2 Data collection

Interviews were carried out from February to April 2018. Expert fishers, operating in the Lesina lagoon, were identified through snowballing and recruited only after having evaluated their knowledge [39], their interest to the topic and their availability to share knowledge. At the beginning of each interview, the interviewer explained the aims of the study, and respondents agreed to provide information for scientific purposes.

The interview focused on two invasive crustaceans, *C. sapidus*, *P. clarkii* and one invasive fish *O. niloticus*, checking for their correct identification through pictures and field guides. Spatial information was extracted through a sketch mapping approach [40], sometimes referred as mental mapping, a method for representing "free drawing" from memory [41]. Fishers were provided with pre-printed maps of the lagoon and they were asked to draw were each species was distributed, indicating with demarcation lines districts of the lagoon characterized by homogeneous levels of abundance. The abundance of each species was rated on an ordered scale, ranging from 0 (absent) to 5 (dominant).

In the second part of the interview, we used a semi-structured protocol [14], to assist respondents in the retrospective elicitation of the abundance of each species across time but this information was not included in the present study. Participatory mapping took approximately 15 minutes, and time series elicitation took about 20 minutes.

2.3 Geographical representations and statistical analysis

Each sketch map drawn by the fishers on paper was georeferenced by overlaying a lattice grid (N. 248 cells of 500 x 500 m), obtaining a regular grid of cells with associated values of perceived abundance for the three species.

We mapped perceived abundances of the three species, and also evaluated the quality of information at hand by means of Bayesian hierarchical models. Notably, we fit a Generalized Additive Mixed Model (GAMM), accounting for differences between fishers in the perceived average abundance of each species, through a random intercept term. Following Plant (2012) [42], we modeled the spatial variation in perceived abundances by de-trending for the effect of the latitude and longitude of each cell through a nonparametric random walk term, and then by accounting for the similarity between neighboring cells through a Besag-York-Mollié structure [43][44]. Although our data were measured through an ordinal scale, we treated them as if they were generated by a continuous Skewed-Gaussian distribution. We mapped predicted abundances for each cell of the grid, to assess the perceived distribution and abundances of each species in the lagoon.

To measure the level of uncertainty in fishers' evaluation of abundances, as well as about their spatial distribution, we calculated the coefficient of variation (CV) for the predicted values of the model, expressed as the ratio between the standard deviation of predicted values and their average value, for each cell of the grid. The coefficient indicated the relative uncertainty about the abundance of the various species in each cell, ranging between 1 an 100. We plotted CV for each cell of the grid, to map spatial gradients in uncertainty about species abundances and we compared the distribution of the CV between the three species, to appreciate species-specific differences in fishers uncertainty. Distribution maps were digitalized with QGis [45] and statistical analysis were carried out with R [46] and INLA [47]. A complete reproducible dataset and a software code is available on OSF.

3 Results

Overall, we recruited a total of 25 expert fishers, who unambiguously identified the three species and were able to draw their spatial distribution over the maps. Considering that the fishing community of the Lesina lagoon is estimated in approximately 40 people [30], our interviews covered more than half of the available sample. They were 88% professional and 12% recreational fishers, all men, and their age was 50.48 ± 15.69 years (mean ± sd). Taken together, respondents' experience accounted for a total of 914 years of observations in the lagoon, and average experience was 36.56 ± 15.18 years (mean ± sd). Three main fishing gears were used by the respondent, mostly trammel nets (92% of respondents); traps (84%) and fish weirs locally called '*bertovelli*' (36%).

Overall, predicted values from the model (Table 1, 2) show that the Atlantic blue crab *C. sapidus* is deemed to have colonized the entire lagoon, with high abundances (Absent = 0%, Rare = 4.6%, Occasional = 11.0%, Common =25.8%, Abundant =37.4%, Dominant = 21.2%) and with a prevalence for the northern coasts (Fig. 2). The crayfish *P. clarkii* occurs at very low densities (Absent = 77.6%, Rare = 1.3%, Occasional = 10.1%, Common = 4.0%, Abundant = 3.6%, Dominant = 3.4%), mostly on the internal part of the lagoon (Fig. 2). Finally, the

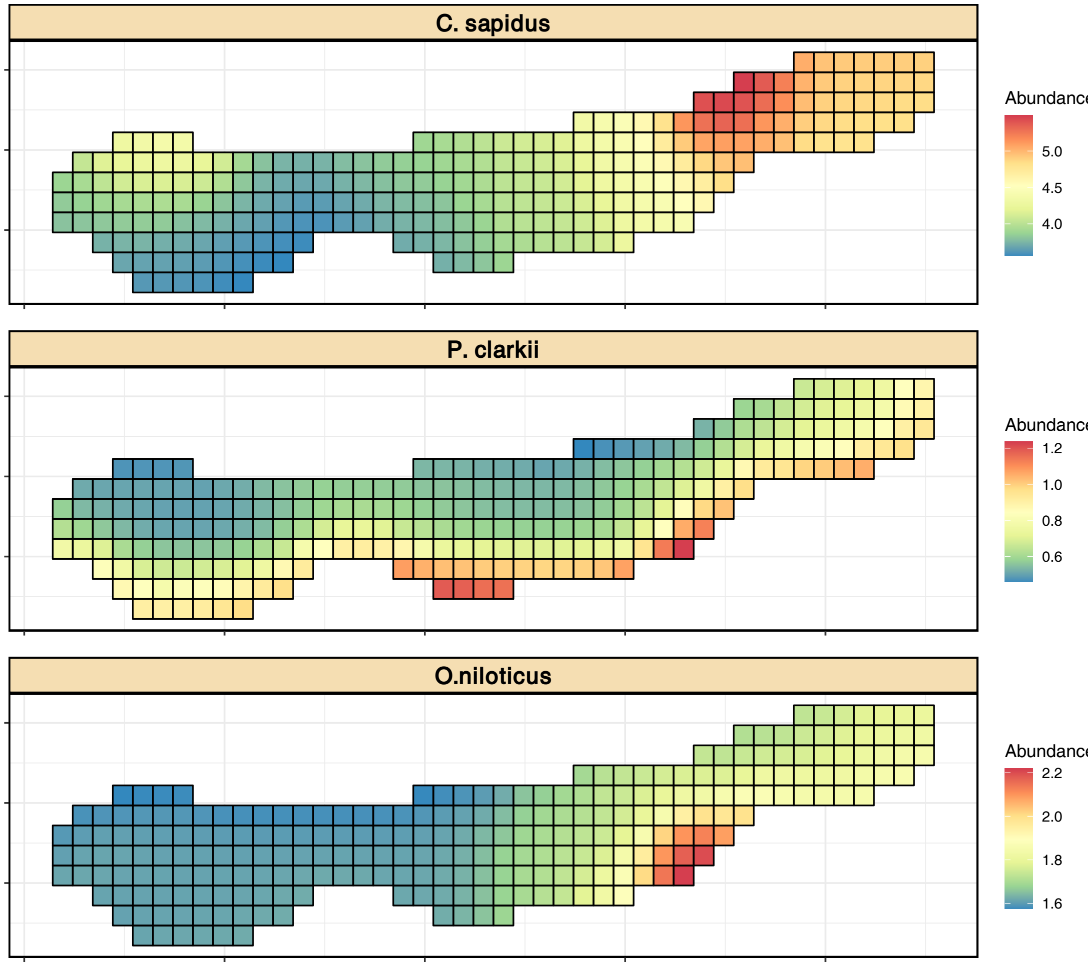

Figure 2 | Abundances of the three species in the lagoon, predicted values from the spatially-correlated models: *C. sapidus* (a), *P. clarkii* (b) and *O. niloticus* (c). Abundances ranged from 1 = "Absent", 2 = "Rare", 3 = "Occasional", 4 = "Common", 5 = "Abundant" to 6 = "Dominant".

Nile tilapia *O. niloticus* resulted distributed with low densities (Absent = 51.1%, Rare = 13.1%, Occasional = 13.2%, Common = 3.9%, Abundant = 11.6%, Dominant = 7.1%) and mostly near to freshwater inputs from karst springs on the internal part of the lagoon (Fig. 2).

The analysis of the spatial distribution of the CV also indicates that fishers became more uncertain about the species abundances, when considering those part of the lagoon where species were less abundant (Fig. 3). For example, uncertainty about the abundances of *O. niloticus* peaked for that part of the lagoon which was far away from the freshwater inputs were the species was believed to occur.

The analysis of the distribution of CV of the various cells, also revealed differences in fishers uncertainty about the abundance of each species (Fig. 4): respondents had little uncertainty about the abundances of *C. sapidus* (median CV = 3.9%), but they were more uncertain about *P. clarkii* (median CV =19.9%) and even more about *O. niloticus* (median CV = 18.4%).

4 Discussion

This study constitutes a first application of LEK as a source of information for the participatory mapping of AIS and for non indigenous species in general. It shows how spatially-explicit LEK, collected from multiple experts without deliberation, can be evaluated by researchers, in terms of its ecological plausibility and in terms of differences in expert evaluations.

We adopted the practice of mental mapping, which plays an important role in geography [48], but which was never applied before to the study of biological invaders. Through vis-a-vis interviews, we facilitated local experts to project their mental maps into a georeferenced space. Drawing demarcation lines on a pre-printed map of the lagoon was a very easy task for the small-scale fishers of Lesina, requiring minimum assistance from researchers. We believe that, due to its simplicity, this approach can be suitable for a broad adoption across different cultures and social contexts (including those with reduced literacy), being this aspect is a key requisite for large scale monitoring and planning [49]. For these reasons, participatory mapping is worth to be explored in those aquatic environments where tracing the abundance and the spatial distribution of species is particularly difficult [50][51] and where biological invasions typically outrun ecological sampling with consequent lags in the information chain (sensu Azzurro et al., 2016)[52]. Another benefit of this method is that participants were actively involved in the research framework, which is one of the core themes for co-management and informational governance [53][54].

Our study took sketch mapping one step further, as we decomposed a handwritten map into a discrete grid of values, which could be analyzed quantitatively as lattice data to: *i*) summarize fishers' judgments through statistical modeling, testing for the ecological significance of spatial patterns and *ii*) highlight species-specific differences and spatial patterns in fishers' uncertainty.

Summarizing experts' judgments through statistical modeling was a parsimonious approach to explore spatial patterns of abundance. Fitting a hierarchical model provided us with a map of fitted values for the abundance of the three species, enabling us to test if these patterns aligned with species-specific ecological requirements. This praxis can be the only way to the reliability of LEK data, in absence of other kind of spatial information about the distribution of a certain species and it requires summarizing observed data with a statistical model. In this study, the spatial distribution and the abundance of the three species in the lagoon aligned well with their ecological requirements. Indeed *C. sapidus* was reported to be generally widespread, as expected from a marine species in a brackish lagoon, and more abundant close to the area of the lagoon with a salt-marsh, rich in aquatic plants that are important as nurseries [55]. On the contrary, *P. clarkii* and *O. niloticus* were reported to occur at low abundances and only close to freshwater inputs from the inland, as it would be expected given their low tolerance to high salinities which in the lagoon exceed the limits of the two species (*P. clarkii*: https://www.cabi.org/isc/datasheet/67878; *O. niloticus*: https://www.cabi.org/isc/datasheet/72086). Analyzing the CV of model predictions also revealed differences in expert judgments about the three species. Appreciating these differences might be important to quantify the reliability of abundance estimates and decide whether to adopt the extracted knowledge as a source of information. We found that the agreement was maximum for *C. sapidus*, while it significantly decreased for *P. clarkii* and *O. niloticus*. We therefore considered as highly reliable *C. sapidus* maps and at the same time, provided appropriate metrics to evaluate if using or not the information related to *P. clarkii* and *O. niloticus*. These species-specific differences in expert evaluations can have multiple explanations, which could be addressed by acting on the study design. For example, we should consider that different species could be characterized by different levels of detectability, like the use of different fishing gears [14]. Considering that our sample of experts was homogeneous with respect to possible

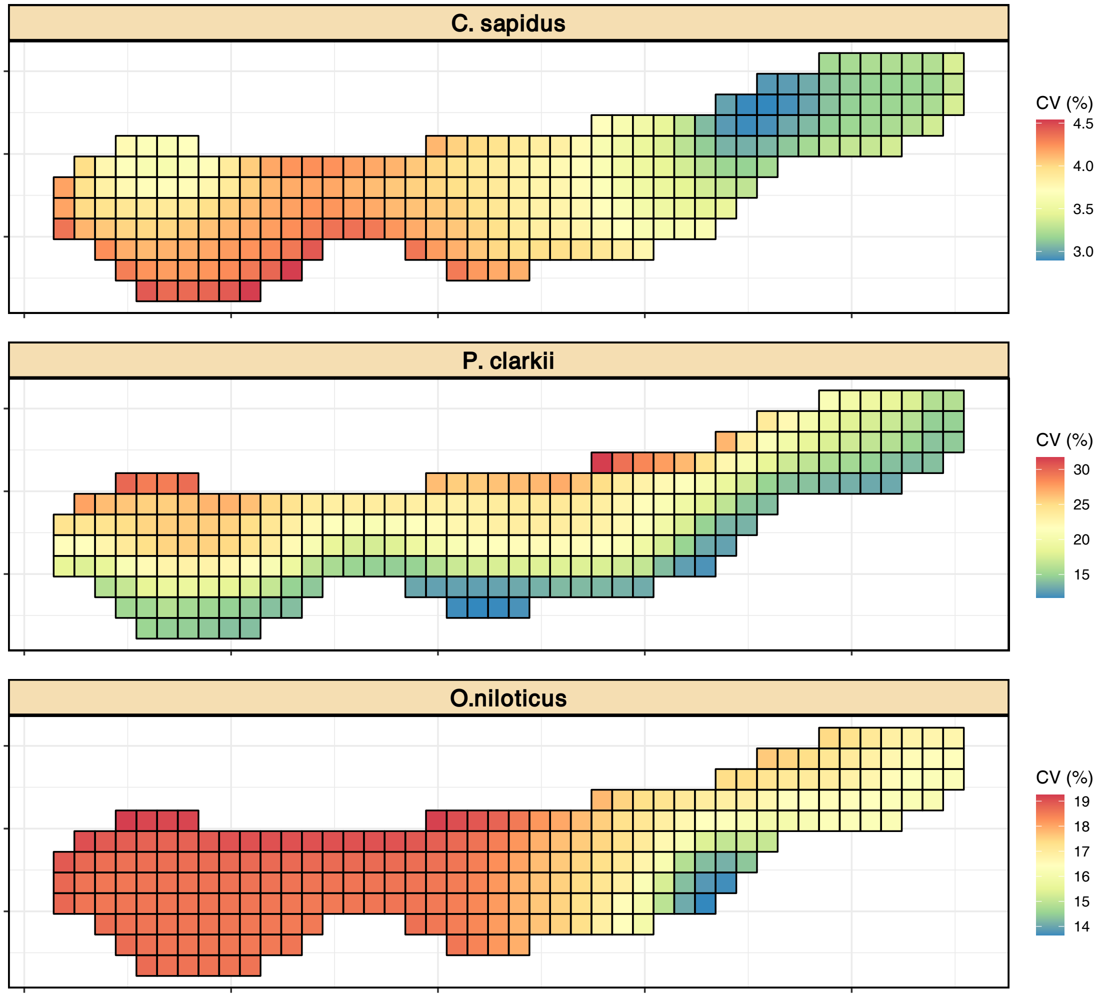

Figure 3 | Coefficient of variation of predicted values from the spatially correlated models: *C. sapidus* (a), *P. clarkii* (b) and *O. niloticus* (c). The coefficient of variation ranges between 0% and 100%.

gear-related bias (the used almost entirely set nets and traps), the observational processes could be influenced by other behavioral and on-ground conditions affecting individual's ecological knowledge [56]. Also, as a hierarchical model produces higher values of the CV for those cells where abundance scores were more heterogeneous, mapping the spatial distribution of the CV of model prediction can highlight spatial patterns in expert disagreement. Few LEK-based studies focus on expert disagreement, which could nevertheless be fundamental for assessing the quality of LEK [6]. In participatory mapping, identifying those areas where respondent's evaluation differ, might be highly informative about the observational process behind LEK and important for its integration with ecological surveys. In our case study, the CV of model predictions had a relatively scarce spatial variation, because the lagoon was shallow and small, with respondents that moved across it homogeneously. However, larger areas, deeper waters or heterogeneous seabeds, could lead fishers exploiting different habitats and using different fishing gears with consequent variation in individual knowledge and appreciation of fishing resources [57]. This would result in variable levels of disagreement about species distribution and abundances, and in higher values of the CV.

Our approach also mitigates one major flaw of interviews and questionnaires, for expert elicitation, namely the lack of deliberation between experts. Deliberation is fundamental to understand if, how much, and why experts agree over a certain topic [8][28]. Unfortunately, when experts are not gathered together, like in many LEK studies based on interviews, deliberation does not occur and most researchers deem impossible to evaluate the information at hand. We showed that this idea is misleading: through statistical modeling it is possible to partially evaluate what is elicited from experts. In our case we found coherent spatial patterns in the evaluation of the abundance of the three species in the lagoon which, for C. sapidus, also had relatively modest errors of prediction. The quality of LEK about C. sapidus was therefore deemed to be highly reliable for ecological mapping. Our case study focused on participatory mapping but we believe that a similar approach can also be potentially useful for evaluating time-series [21][58] and other kind of LEK-generated information.

It must be clear that our case study also has some clear simplifications. First and foremost, the scale and the accessibility of the study area: the Lesina lagoon is relatively small (51.4 km^2) and shallow, with no boundaries. Fishermen therefore move across the entire area. This enabled us to easily combine multiple distribution maps and to compare expert LEK, but future research could develop participatory mapping protocols combining experts with partially overlapped fishing areas. These studies should also explore the extent to which confidence in LEK varies at increasing distances from the core fishing area.

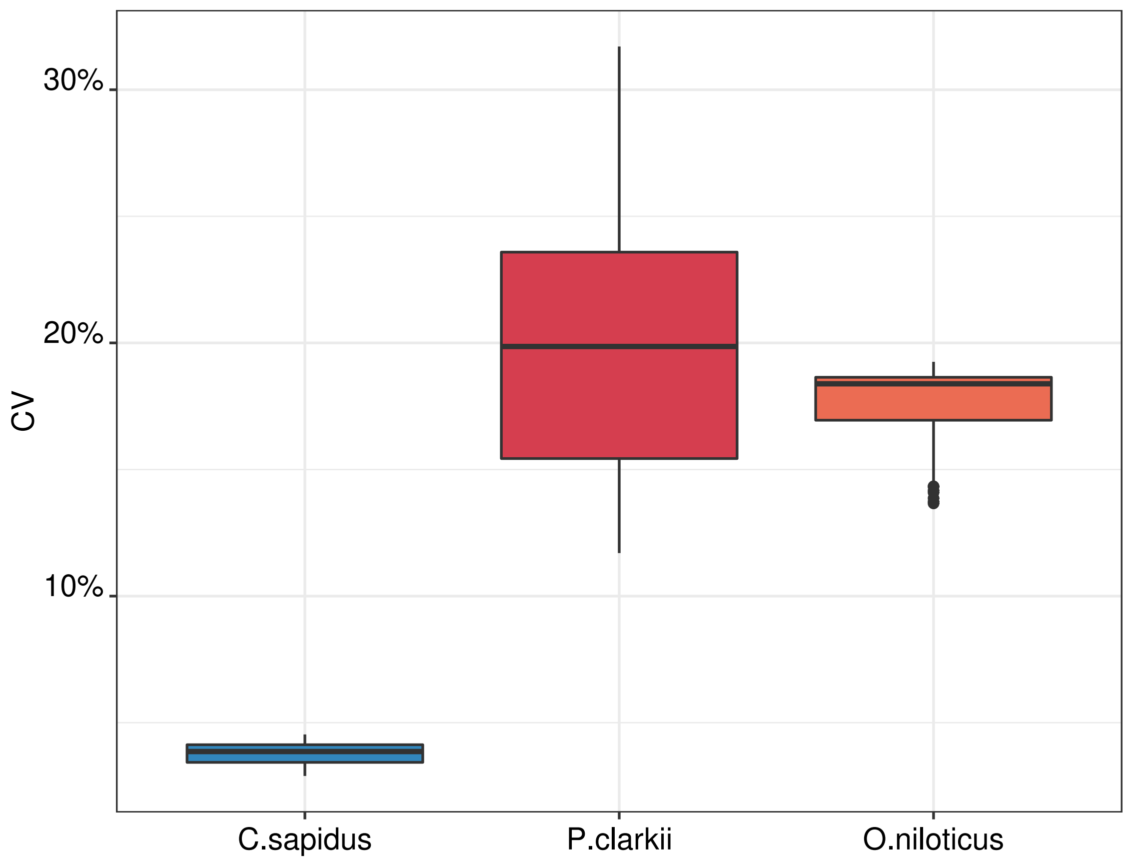

Figure 4 | Distribution of the coefficient of variation (CV) of predicted values from the spatially correlated models for the three species. The coefficient of variation ranges between 0% and 100%.

5 Conclusions

Yet, much has evolved in the theory and practice of participatory science and expert engagement in conservation biology [59][60]. Many different methods, like matrix scoring, causal-linkage or diagramming, have been adopted and used by conservationists all over the world. Due to the need for spatial-explicit information in invasive species monitoring and management, our experience highlights the potential benefits that could result from a structured participatory mapping methodology based on a rigorous and transparent evaluation of LEK-generated information. Improving the scientific quality of spatial representations, such kind of practices could be better and more widely used for the needs of research, conservation, resource management and decision-making.

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Table 1. Fitness indexes of the models without spatial correlation and with a Besag-York-Mollié (BYM) correlation structure: widely applicable information criterion (WAIC), deviance information criterion (DIC).

	WAIC (non spatial model)	WAIC (BYM model)	DIC (nonspatial model)	DIC (BYM model)
C. sapidus	11439.75	11364.08	11434.77	11341.43
P. clarkii	11005.16	10951.95	11025.91	11002.19
O. niloticus	10670.90	10609.98	10692.33	10659.49

Table 2. Coefficients of the generalized additive models for the three species.

C. sapidus			
Variable	Mean	0.025 quantile	0.975 quantile
Intercept	4.25	3.97	4.59
Precision:longitude	6.85	0.89	0.19
Precision:latitude	17900.00	1296.70	66500.00
Precision:respondent	2.24	1.736	3.07
P. clarkii			
Variable	Mean	0.025 quantile	0.975 quantile
Intercept	0.72	0.503	0.935
Precision:longitude	13500.00	463.570	55800.00
Precision:latitude	367.00	29.476	1800.00
Precision:respondent	5.07	2.280	8.80
O. niloticus			
Variable	Mean	0.025 quantile	0.975 quantile
Intercept	1.706	1.117	1.294
Precision:longitude	13800.00	293.089	57400.00
Precision:latitude	6870.00	725.930	21300.00
Precision:respondent	0.48	0.24	0.78

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