Received: 19 October 2017 | Revised: 31 May 2018 | Accepted: 13 June 2018

DOI: 10.1111/conl.12591

LETTER

WILEY Conservation Letters Open Access
A journal of the Society for Conservation Biology

Efficiency of species survey networks can be improved by integrating different monitoring approaches in a spatial prioritization design

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Funding information
Spanish Ministry of Economy, Industry and Competitiveness. Grant ref: CGL2017-89999-C2.

Abstract

Public participation to monitoring programs is increasingly advocated to overcome scarcity of resources and deliver important information for policy-making. Here, we illustrate the design of optimal monitoring networks for bird species of conservation concern in Catalonia (NE Spain), under different scenarios of combined governmental and citizen-science monitoring approaches. In our case study, current government efforts, limited to protected areas, were insufficient to cover the whole spectrum of target species and species-threat levels, reinforcing the assumption that citizen-science data can greatly assist in achieving monitoring targets. However, simply carrying out both government and citizen-science monitoring *ad hoc* led to inefficiency and duplication of efforts: some species were represented in excess of targets while several features were undersampled. Policy-making should concentrate on providing an adequate platform for coordination of government and public-participatory monitoring to minimize duplicated efforts, overcome the biases of each monitoring program and obtain the best from both.

KEYWORDS

biodiversity monitoring, citizen science, EU Birds Directive, Europe, MARXAN, optimisation, participatory monitoring, spatial conservation planning, species distributions, species threats, threatened species

1 | INTRODUCTION

Biodiversity monitoring provides vital information to guide conservation management and eventually improve its effectiveness (Nichols & Williams, 2006). Recognizing such importance, legislation increasingly sets explicit targets for monitoring. For example, the EU Birds and Habitat directives require Member States to monitor the conservation status and trends of species and habitats of Community interest and report it to the Commission every six years (Art. 12 2009/147/EC and Art. 17 92/43/EEC, respectively).

The effectiveness of monitoring is generally constrained by limited resources, requiring optimal planning from individual surveys (e.g., Pierce & Gutzwiller, 2004) to large-scale programs (Ficetola, Romano, Salvidio, & Sindaco, 2017; Guillera-Arroita, Ridout, & Morgan, 2010). Within this effort to reconcile monitoring targets and resource constraints, the potential contribution of public participation is increasingly considered (Silvertown, 2009) to complement efforts coordinated by public authorities (Dickinson, Zuckerberg, & Bonter, 2010; Schmeller et al., 2009). A range of combinations are possible between monitoring carried out by the public, governmental authorities, local agencies, NGOs, and other stakeholders (Danielsen et al., 2009).

However, simply adding public participation to other monitoring schemes may not be an efficient way of addressing resource constraints. Citizen-science monitoring might introduce specific spatial or taxonomic biases (Crall et al., 2011; Tiago, Ceia-Hasse, Marques, Capinha, & Pereira, 2017). Monitoring carried out by professionals is more expensive (Danielsen, Burgess, & Balmford, 2005), and therefore especially limited by available resources at large scales and often restricted to protected areas or highly endangered species. Even where professional and participatory monitoring are similarly effective, simply doing both in parallel can lead to redundancies while still leaving coverage gaps. Therefore, combined planning may be needed to obtain the full potential of public participation, but policies promoting this combination remain to be developed.

In other areas of conservation, such as spatial reserve design, issues of complementarity, adequacy, and representativeness are increasingly solved by adopting systematic conservation planning (Margules & Pressey, 2000). Recent studies have illustrated the application of those principles and tools to the design of monitoring networks (Amorim, Carvalho, Honrado, & Rebelo, 2014; Carvalho, Gonçalves, Guisan, & Honrado, 2016). Here, we demonstrate how they can also be used for planning monitoring networks that combine monitoring schemes with different level of local participation. We used an optimization tool to explore the advantages and limitations of combining government-led and participatory monitoring schemes in a European region where both are well established. Our results highlight the benefits and trade-offs of such combined programs, and the need for policy that allows integrated planning, rather than the simple *post hoc* aggregation of independent monitoring outcomes, to overcome specific biases and avoid inefficiencies.

2 | METHODS

2.1 | Case study and data

Our case study illustrates the design of a monitoring network for bird species in Catalonia (NE Spain). The study area covers 0.7% of the total EU area (32,108 km^2) but regularly hosts almost 50% of the bird species included in Annex 1 of the EU Birds Directive (2009/147/EC). Consequently, 73 terrestrial Special Protection Areas have been designated, covering more than 836,000 ha (25.9% of the total area of Catalonia). We focused on all bird species of Community Interest listed in the EU Birds Directive occurring in Catalonia (97 species), for which EU regulations (Art. 12 2009/147/EC) request the Spanish government to report status and population trends. We excluded vagrant, marine and migratory species, retaining 62 species (Table S1) for which distribution maps of breeding and wintering grounds within the study area were available (continuous probability distributions at 1 km resolution, derived from presence-only species distribution models; Estrada et al., 2004; Herrando et al., 2011). To ensure only areas with likely species presence were selected within the monitoring network, we removed pixels with probability of species presence below the 10th percentile of predicted probabilities across the 1 km pixels used as training presences. We classified each species within one of the four dominant terrestrial habitat types in the study area (forests, natural open habitats, farmlands, wetlands/riverine environments), following the species and habitat linkages to the MAES ecosystems (Maes et al., 2015) proposed by the European Environmental Agency (https://www.eea.europa.eu/data-and-maps/data/linkages-of-species-and-habitat/).

2.2 | Species pressures

We sought to design a monitoring network representative not only of the bird species in Catalonia of conservation concern for the EU, but also of the range of species-specific threats, since the ability to link detected negative trends to potential drivers would make monitoring data more directly useful for policy decisions. We mapped (at 1 km^2) five environmental drivers/pressures threatening the status of the 62 species selected (BirdLife International, 2015; Table 1): intensification of farming activities (affecting farmland species), closure of open habitats (natural open habitats species), forest

TABLE 1 Main pressures/threats for birds identified in the study area

Name of threat	Rationale	Indicator used	Indicator details and data source
Agricultural intensification	The intensification of farming activities due to either land consolidation or intensive use of fertilizers and pesticides threatens farmland birds across Europe (Donald, Green, & Heath, 2001; Guerrero et al., 2012).	Proportion of agricultural fields within a 3 × 3 km window of each pixel, weighted by the maximum nitrogen loads of each agricultural crop.	This indicator integrates information of both the spatial aggregation of crops (indirect measure of land consolidation) and the use of fertilizers. Source: Crops map of Catalonia 2015 (Department of Agriculture, Livestock, Fisheries and Food production. Catalonian Government)
Loss of open habitats	Land abandonment and forest expansion are the main causes of habitat loss for open-habitat species (Herrando et al., 2014).	Proportion of young forest (< 15 years) in a 3 × 3 km window of each pixel.	Open areas at risk of encroachment by forest. The main tree species in the region reach maturity and start recolonising open spaces on average 15 years after a stand-replacing perturbation such as wildfire (the most common disturbance in the study area; Pausas, Carbó, Neus-Caturla, Gil, & Vallejo, 1999). Source: forest age map developed by Gil-Tena et al. (2016), measuring the years since last fire for recently burnt forests and shrublands, and the age of unburnt forests.
Forest immaturity	Forest immaturity threatens forest-dependent species that require a given stand structure to find feeding and nesting resources (e.g., closer canopies, larger tree diameters). Old-growth and mature forests are an exception across the long heavily managed Mediterranean basin (Gauquelin et al., 2018).	Proportion of forest ≤30 years old in a 3 × 3 km window of each pixel.	Immature forest areas derived from the forest age map developed by Gil-Tena et al. (2016), measuring the years since last fire for recently burnt forests and shrublands, and the age of unburnt forests. Forest seral stage evolution was assessed according to the time required for canopy closure after fire disturbance in Mediterranean forests, which has been set at 30 years (Broncano, Retana, & Rodrigo, 2005; Retana, Espelta, Habrouk, Ordóñez, & de Solà-Morales, 2002).
Linear infrastructure (public use) and urban areas (urban pressure)	Urban development and public land use are key components of anthropogenic disturbance, which we assume affects species across all habitats.	Proportion of urban areas and linear infrastructure (impervious surface) within each 1 km^2 pixel.	Density of highways, tracks, trails, footpaths, cycle paths and other road-type features, as elements that facilitate people access to natural environments, was sourced from the OpenStreeMap (https://www.openstreetmap.org) downloaded on 13 October 2016. Data on urban areas was sourced from the land cover map of Catalonia 2009 (Ibáñez & Burriel, 2010); https://www.creaf.uab.es/mcsc/.
Water pollution	Pollution and loss of water quality are one of the main drivers of freshwater biodiversity declines (Dudgeon et al., 2006), affecting waterbirds in our analysis.	Index of Ecologic Condition of freshwater systems. Five classes (very good, good, average, poor, very poor).	The indicator integrates information about the physic–chemical, biological and flow conditions of the freshwater habitats (including rivers, estuaries, wetlands, reservoirs, and lakes). Catalan Water Agency (ACA; Department of Territory and Sustainability of the Catalonian Government)

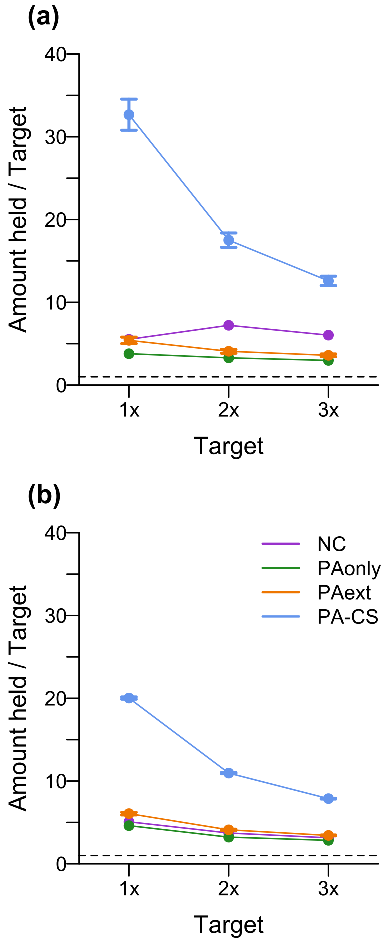

FIGURE 1 Mean achievement of monitoring targets across the 671 monitoring features, for the optimal solution under each scenario, at different target levels (x-axis), with and without connectivity penalty (a and b, respectively). The dashed horizontal line indicates a reference condition in which the monitoring target achieved equals the target set in each simulation ($1x$, $2x$, or $3x$). Therefore, any value above this dashed line indicates the best Marxan solution for a given scenario exceeds (on average) the monitoring target set. Results of $\mathbf{PA_{EXT}}$ and **PA-CS** refer to simulations assuming existing monitoring efforts within protected areas consist of three monitoring units per protected area (points and error bars indicate mean, minimum, and maximum number of planning units over 100 randomized runs). Scenario acronyms: NC, *no constraints*; PA_{ONLY}, *protected areas-only*; PA_{EXT}, *protected areas-extended*; and PA-CS *protected areas-citizen science.* See Figure S2 for solutions of the $\mathbf{PA_{EXT}}$ and **PA-CS** scenarios when other already-existing monitoring efforts were applied (6, 9, 12, 15, 18, 21, 24 monitoring units per protected area)

immaturity (forest species), freshwater pollution (wetlands/riverine species), and urban development (all species). We standardized the mapped pressure values and classified them into low-pressure (< 25th percentile or very good quality, depending on the original classification), mid-pressure (25–75th percentile or average quality) or high-pressure (> 75th percentile or low/very low quality). Given the dominant habitat type and the ecology of species, we crossed the occurrence map for each species with the maps of pressures that affect its terrestrial habitat group, for a total of 671 species–pressures combinations. These combinations are the units of our monitoring network (hereafter “monitoring features”).

2.3 | Spatial prioritization of a monitoring network in Catalonia

We used Marxan (Ball, Possingham, & Watts, 2009) to design an optimal monitoring network covering the distribution of all 671 monitoring features across Catalonia (the distribution of species for which there are reporting duties to Europe, under different pressure levels), under four scenarios:

No constraints **(NC)** simulating a monitoring network built *ex novo*, assuming no prior monitoring efforts and no spatial constraints to the selection of monitoring sites.

Protected areas-only $\mathbf{(PA_{ONLY})}$ here, monitoring would occur *exclusively* within protected areas where resources from the Catalonian Administration exist—for example, personnel—that could be mobilized for monitoring surveys (Figure S1a). We represented this in Marxan by locking out of the analysis all nonprotected areas in Catalonia and those protected areas without a functioning management structure. For consistency, hereafter only areas with a functioning management structure are referred to as “protected areas.”

Protected areas-extended $\mathbf{(PA_{EXT})}$, recognizing existing monitoring efforts within protected areas, and allowing Marxan to complement them by adding pixels outside protected areas to achieve the targets for the bird species. Although we know there are ongoing monitoring efforts in protected areas, we could not source information about the exact amount and location of effort invested (in number of monitoring units). Therefore, we performed sensitivity analysis by locking in the solutions different numbers of monitoring units (3, 6, 9, 12, 15, 18, 21, 24) within each protected area, simulating increasing levels of monitoring effort. To address the lack of information about where these monitoring efforts occur within each protected area, we ran each simulation 100 times, placing randomly the monitoring units to be locked in. Marxan then searched for the optimal set of additional monitoring units outside protected areas that are needed to complement those locked-in units to achieve the targets.

Protected areas-citizen science **(PA-CS)** recognizing both existing monitoring within protected areas and existing participatory bird monitoring programs. We based the participatory component on the Catalan Common Bird Survey (SOCC; Herrando, Brotons, Estrada, & Pedrocchi, 2008). Since 2002, a total of 580 SOCC transects of 3 × 1 km have been surveyed, with variable consistency, for monitoring common birds across Catalonia. Surveyors, mainly volunteers, monitor each transect four times a year (twice each breeding and wintering season). We considered only the 363 transects that were continuously sampled between 2012 and 2014, excluding inactive or recently started transects (Figure S1a). In Marxan, this scenario used the same settings and procedure as the $\mathbf{PA_{ONLY}}$ scenario, adding the SOCC monitoring transects to the locked-in units. Since the SOCC protocol is not suitable for monitoring all species of EU concern, we limited the input data passed to Marxan so that the locked-in SOCC monitoring units only contained species that can actually be monitored within that protocol (37 out of 62 species; Table S1).

For each scenario, we ran Marxan 100 times to find the optimal solution which minimized the following Objective Function across *I* monitoring units and *J* monitoring features:

$$OF = \sum\nolimits_i^I Cost_i + \sum\nolimits_j^J SPF^* Feature\ Penalty_j + CSM \sum\nolimits_i^I Connectivity\ Penalty_i \qquad (1)$$

We calculated *Cost* as the inverse of the density of species observations uploaded by contributors to the biodiversity repository Ornito (https://www.ornitho.cat) between 2012 and 2015, rasterized and rescaled to a 0–1 interval (Figure S1b). We assumed this variable to indicate the accessibility of each pixel and thus the potential costs of surveying there for the general public (Boakes et al., 2016). We repeated the analyses assuming even costs across the study area. The *Feature Penalty* in Equation (1) is applied for not achieving the target for each monitoring feature; we set a high penalty (SPF = 10) to ensure the optimal solution tries to achieve the targets for all monitoring features. Finally, the *Connectivity Penalty* in Equation (1) forces the selection of spatially aggregated sets of monitoring units (boundary length modifier setting in MARXAN). We derived connectivity penalties from the geographic distance d_{ij} to the nearest 8-neighbours of each monitoring unit (penalty = d_{ij}^{-2}). We repeated all analyses without and with aggregation, to simulate a situation in which carrying out surveys in neighboring areas would be preferred for efficiency. Finally, we ran all scenarios for three monitoring targets (1, 2, or 3), the target being the minimum number of monitoring units in the network (1 km pixels) in which each monitoring feature is represented.

We used standard Marxan parameters for all scenarios: 2,500,000 iterations and 10,000 temperature decreases per Marxan run. We calibrated the CSM (Equation (1)) for each monitoring scenario and target following Hermoso, Linke, Prenda, and Possingham (2011). We compared the optimal solutions of all scenarios using three metrics: the average number of times features were represented in the monitoring network (ability to reach targets), the proportion of features that achieved the target (coverage), and the number of units required by the optimal solution (reflecting total monitoring costs).

3 | RESULTS

All scenarios achieved more than the target set across all management features; in other words, when set a target of, for example, two monitoring features, they achieved more than that *on average across all features*. For a target level of one, the **PA-CS** scenario exceeded the monitoring targets by a minimum of twentyfold (Figures 1 and S2). However, several scenarios failed to cover all features. In the $\mathbf{PA_{ONLY}}$ solution, 12% of monitoring features did not achieve the target (Table 2), mostly because some species–pressure levels combinations are not found in protected areas (e.g., there is little overlap between protected areas and high levels of agriculture intensification). Moreover, some species listed in the Birds Directive mainly occur outside managed protected areas in Catalonia (e.g., the calandra lark, *Melanocorypha calandra*, the little bustard *Tetrax tetrax,* the pin-tailed sandgrouse *Pterocles alchata*). The choice of cost layer had only marginal influence on the ability to meet targets of all scenarios (Figure S2).

Scenarios required markedly different numbers of monitoring units ("cost"; Figures 2 and S3), with $\mathbf{PA_{ONLY}}$ the

TABLE 2 Percentage of monitoring features that do not achieve the targets under the different monitoring scenarios. Scenario acronyms: NC, *no constraints*; PA_{ONLY}, *protected areas-only*; PA_{EXT}, *protected areas-extended*; and PA-CS, *protected areas-citizen science.* Results of $\mathbf{PA_{EXT}}$ and **PA-CS** refer to simulations assuming existing monitoring efforts within protected areas consist of three monitoring units per protected area

		Monitoring scenarios			
Target	**Connectivity penalty applied?**	**NC**	$\mathbf{PA_{ONLY}}$	$\mathbf{PA_{EXT}}$	**PA-CS**
1	Yes	0.3	12.37	0	1.04
2	Yes	3.58	14.9	3.13	4.17
3	Yes	4.77	17.14	4.62	5.16
1	No	1.19	12.37	0	1.04
2	No	3.43	14.9	3.13	4.17
3	No	4.92	17.44	4.62	5.16

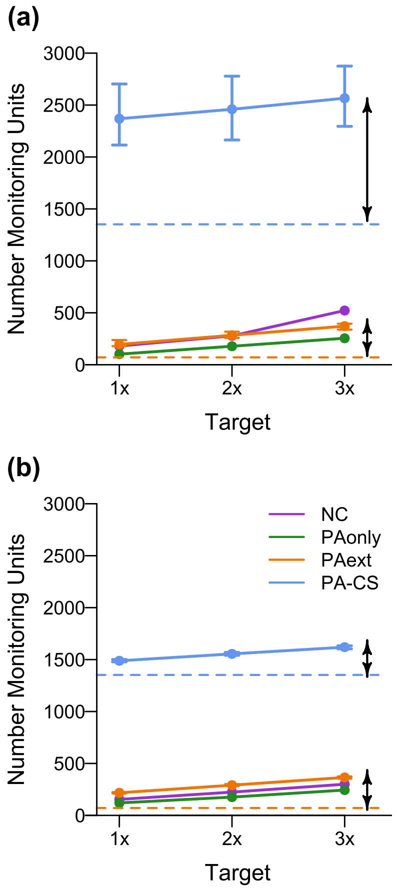

FIGURE 2 Number of planning units required by the best optimal monitoring network identified under each monitoring scenario, at different target levels (*x*-axis), with and without connectivity penalty (a and b, respectively). The dashed lines indicate the total *current* monitoring efforts assumed in the **PA$_{\mathrm{EXT}}$** (three monitoring units per protected area; dashed orange) and **PA-CS** (three monitoring units per protected area *plus* SOCC transects; dashed blue). The actual number of *additional* monitoring units required under these two scenarios is the difference between the values of the respective solid and dashed lines (marked by arrows). Results of **PA$_{\mathrm{EXT}}$** and **PA-CS** refer to simulations assuming existing monitoring efforts within protected areas consist of three monitoring units per protected area (points and error bars indicate mean, minimum and maximum number of planning units over 100 randomized runs). Scenario acronyms: NC, *no constraints*; PA$_{\mathrm{ONLY}}$, *protected areas-only*; PA$_{\mathrm{EXT}}$, *protected areas-extended*; and PA-CS, *protected areas-citizen science.* See Figure S3 for solutions of the **PA$_{\mathrm{EXT}}$** and **PA-CS** scenarios when other already-existing monitoring efforts were applied (6, 9, 12, 15, 18, 21, 24 monitoring units per protected area)

“cheapest,” followed by **NC**, **PA$_{\mathrm{EXT}}$**, and **PA-CS**. These results were consistent with and without forced aggregation (Figures 2a,b). Within each scenario, spatially aggregated solutions had greater costs. The **PA$_{\mathrm{ONLY}}$** scenario required the least monitoring units, reflecting the smaller area available for sampling. Discounting the current monitoring efforts assumed in protected areas (since these are already locked in the solution), the **PA$_{\mathrm{EXT}}$** scenario required fewer additional units than the total required in the **NC** scenario. This suggests the design of an optimal aggregated monitoring network benefits from considering existing efforts within protected areas (Figure 2a). The **PA-CS** scenario always required more monitoring units, but it was the cheapest nonaggregated solution if the existing monitoring efforts assumed in this scenario are discounted (i.e., monitoring efforts in protected areas and SOCC transects locked in the solution; Figure 2b).

The spatial outputs of the best solutions differed especially between the **NC** scenario and the rest, since the latter were constrained by the distribution of protected areas and SOCC transects (Figures 3 and S4). All scenarios where monitoring units could be selected outside protected areas (**NC**, **PA$_{\mathrm{EXT}}$**, and **PA-CS)** included some important monitoring units from the western part of the study area in the optimal solutions (Figures 3 and S4). This suggests the existing efforts we incorporated (within protected areas and SOCC transects) are not sufficient to fulfill our monitoring objectives (sampling all species and pressure levels), mostly because the optimal solutions of the **NC**, **PA$_{\mathrm{EXT}}$**, and **PA-CS scenarios** include some species-pressure combinations absent from protected areas.

4 | DISCUSSION

The results of our optimal design of a bird monitoring network for Catalonia confirm both the benefits of systematic conservation planning for monitoring networks and the challenges to its implementation (McIntosh, Pressey, Lloyd, Smith, & Grenyer, 2017). In our case, results confirmed the intuitive advantage of combining government-led monitoring and a participatory scheme: expanding limited resources would be beneficial regardless of the specific limitations such as the need for locating monitoring sites close to each other. However, we also found some subtle trade-offs that should be accounted for.

While all scenarios achieved good average results, monitoring efforts that focused exclusively on protected areas (where most monitoring resources available to public agencies are typically concentrated) fell short of coverage targets when compared with an ideal, unconstrained scenario. However, simply adding a citizen-science scheme and government-led monitoring led to inefficiencies. For example, all scenarios identified important areas for the reporting of the birds’ status outside current protected areas, e.g. cereal steppes in western Catalonia. However, that region was not sufficiently covered by ongoing citizen-science and government monitoring, the latter most likely reflecting the spatial bias of protected areas (mostly concentrated in the Pyrenees or coastal areas; Figure S1a).

Merging monitoring frameworks that have been planned mostly independently of each other is bound to create some duplication. In our case, incorporating current participatory

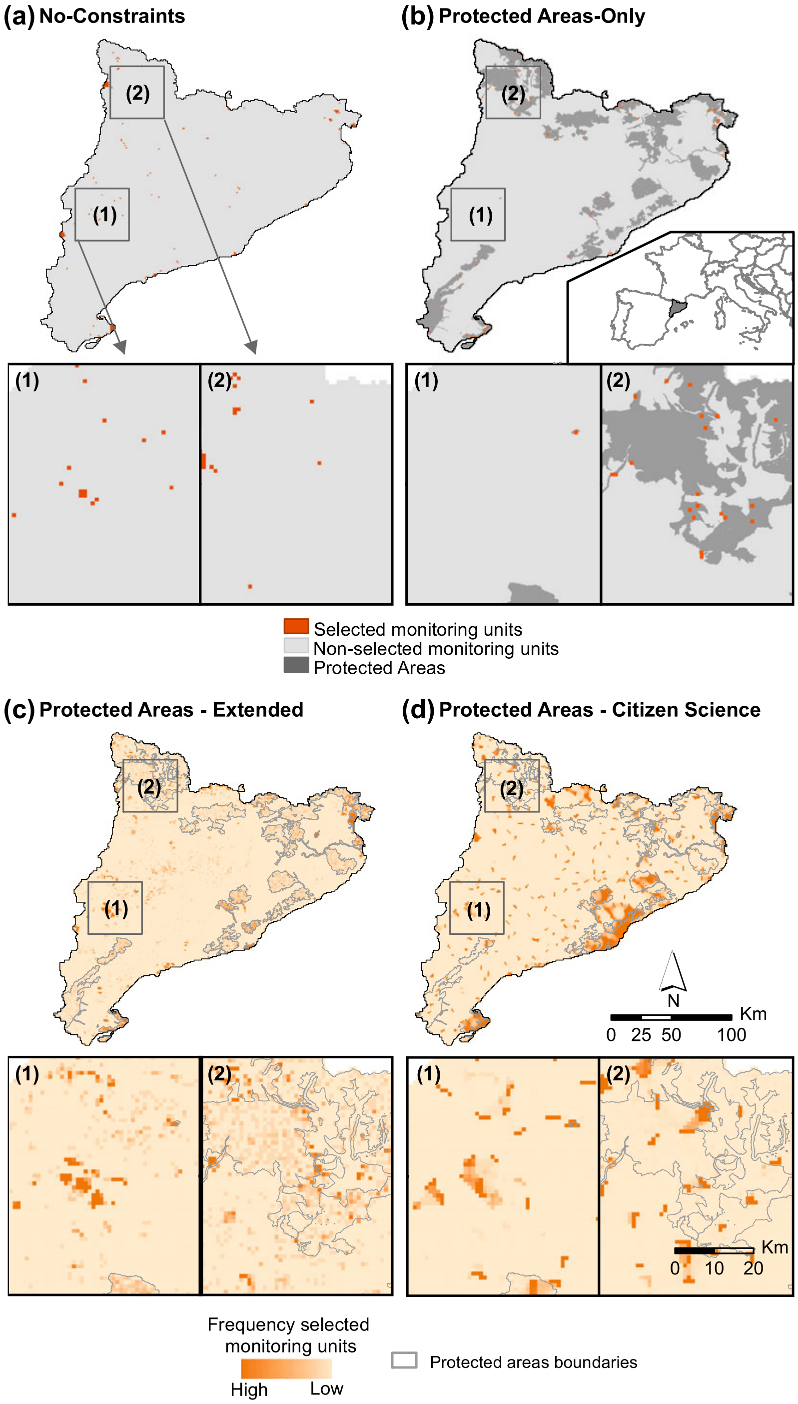

FIGURE 3 Optimal monitoring network under each proposed monitoring scenario (optimal solution): (a) *no-constraints* (**NC**); (b) *protected areas-only* (**PA**$_{\mathbf{ONLY}}$); (c) *protected areas-extended* (**PA**$_{\mathbf{EXT}}$); and (d) *protected areas-citizen science* (**PA-CS**). For every scenario, darker colors indicate the optimal location of monitoring units. For ease of comparison, a zoom of two different areas of each solution is shown under each of the main maps (insets 1 and 2). Results of **PA**$_{\mathbf{EXT}}$ and **PA-CS** (plots c and d, respectively) show the frequency of selection of each monitoring unit across the 100 randomization runs (assuming three units in each protected area), to reflect the lack of information about the exact location of current monitoring within protected areas. A higher frequency of selection indicates a greater importance of that unit to achieve the monitoring target. The map inset under panel (b) shows the location of the study area. Maps show the scenario solution when the connectivity penalty is applied (i.e., the solution forces the aggregation of monitoring units) and the monitoring target equals one (i.e., within the monitoring network, there is at least one monitoring unit–1 km pixel–with presence of each of the 671 monitoring features); see Figure S4 for the nonaggregated solution

TABLE 3 List of practical considerations to help developers of biodiversity monitoring networks to achieve monitoring objectives, through integration of the different sources of already existing monitoring efforts

Questions	Practical aspects to consider
1) Which species should be monitored, how much and why?	• Set the list of species to monitor (e.g., species listed in the annex of Birds Directive). • Objectives: for example, assess population trends in the study area. • Set monitoring targets. Determine how many monitoring units are required per species (e.g., sensitivity or statistical power analyses to detect change in trend and to link change to threat level).
2) Which data are available about monitoring features?	• Collect spatial data about distribution of monitoring features: species (e.g., species distribution models, atlases, biodiversity repositories), threats/pressure levels, environmental gradients, climatic gradients, etc.
3) Are there existing monitoring efforts ongoing in the study area?	• Collect data about existing monitoring efforts within the study area. Identify the species and sites currently monitored (by local stakeholders, citizens, NGOs, government, scientific programs, others). • Evaluate how each already existing monitoring scheme can contribute to the monitoring goals given the expertise of the observers, the survey technique (e.g., visual or audio), the ecology of the target species (e.g., diurnal vs. nocturnal), among others, given that not all monitoring options would be suitable in all cases.
4) Are there monitoring objectives not adequately covered by current monitoring efforts?	• Understand which monitoring features (e.g., species-pressure/threat combinations) exist in practice. • Identify the monitoring features that are not covered by current monitoring efforts.
5) Where should new monitoring be located?	• Set the minimum number of monitoring units required for monitoring feature (e.g., the minimum number of units in which each species-pressure/threat level should be represented across the network). • Determine whether units should be aggregated and the aggregation criteria (neighborhood, accessibility, etc.) • Set monitoring costs across space (multiple criteria possible: accessibility, existing monitoring resources, etc.) • Solve the optimization problem (e.g., spatial prioritization using Marxan)
6) How can the current gaps in the monitoring network be covered?	• Identify locations in the optimal solution that are not currently covered by monitoring efforts. • Assess participatory options available, the extent to which professional input is required, and whether specific objectives of the participatory monitoring (e.g., community building) are compatible with reporting needs.

efforts while trying to spatially aggregate them to government efforts (PA-CS aggregated; Figure 2a) led to particularly high duplication, greatly increasing the number of monitoring units. Optimal planning can indicate where such duplication occurs; planners then need to consider specific objectives and constraints to determine whether it can be removed, and which combination of professional researches and local people is most suited for a given feature (Danielsen et al., 2009). For example, duplication may be justified by practical constraints: sensitive features, such as restricted areas or rare species, may need specific skills (Roy, Baxter, Saunders, & Pocock, 2016). Moreover, duplication does not necessarily correspond to increased costs, since the respective funding sources may not overlap (in our case, SOCCs are partly funded by the Catalonian administration). Finally, different schemes may serve different objectives: public participation may be driven by multiple motivations (Chase & Levine, 2016; Domroese & Johnson, 2017) and provide benefits beyond the simple collection of data, such as improving links to local decision-making and empowering local constituencies (Danielsen et al., 2005).

Adopting a systematic planning approach helps in considering such issues explicitly and, by removing truly unnecessary redundancies, can save resources that can be reinvested to establish the extra monitoring units that are needed using the most suitable level of local participation. Although we combined two monitoring schemes that are clearly different in terms of public involvement, spatial conservation planning methods such as our Marxan-based approach can be adapted to a wide range of monitoring schemes, as long as the specific objectives, suitability and limitations of each are adequately represented in the optimization. Spatial conservation planning is a well-established field with a wealth of accessible resources (see for example resources available for Marxan, https://marxan.net/ and ZONATION, https://www.helsinki.fi/en/researchgroups/metapopulation-research-centre/software#section-14300); in Table 3, we provide an overview of practical considerations specific to the design of integrated monitoring schemes.

A key advantage of integration was highlighted by our choice of individual combinations of species and pressure levels as the monitoring feature. Monitoring should directly address management-specific questions, rather than blindly collecting potentially useful data (Donald et al., 2007; Nichols & Williams, 2006). Carvalho et al. (2016) demonstrated that optimal planning can assist in obtaining useful stratified monitoring data; Tulloch, Possingham, Joseph, Szabo, and Martin (2013) suggested longitudinal, stratified monitoring schemes are a more cost-effective application for citizen science programs. Applying such a stratified approach, we found that simply focusing on protected areas, although it may better match existing resources, was insufficient to cover the full range of species and threat levels and could even introduce bias, since species trends in protected areas may not be representative of the general situation in a country/region. Monitoring combinations of species and pressures requires a more realistic coverage of the environmental space, and reduces potential time lags between observation of species trends, identification of possible drivers and implementation of responses. Planned integration again becomes especially important since public participation may not cover all species, and monitoring of extant protected areas may not cover all features (as illustrated respectively by the SOCC and protected areas in our study).

In spite of the intuitive advantages, effectively integrating monitoring schemes with different degrees of public participation will still require a significant policy effort. Most importantly, it needs fluent communication and coordination between monitoring programs directed by the public administration and the NGOs and other citizen-science communities willing to contribute to long-term monitoring of species trends. Our results suggest that, to better cover the needs of reporting on EU Directives, part of the overall monitoring effort of more or less participatory monitoring schemes should target areas with combinations of species–pressures not present in the current monitoring network. Moreover, in our study area there are more bird monitoring programs than the one we considered. For example, we could not include an ongoing annual census of wintering water birds, nor the specific monitoring schemes currently in place for some highly threatened species, most of which would be difficult to replace with participatory schemes, because we could not retrieve the spatially explicit information required for our analysis. Data exchange and coordination thus become necessary for integrated programs (Crall et al., 2010). Finally, the scale at which monitoring data are collected and reported is also important (Devictor, Whittaker, & Beltrame, 2010); in our case, monitoring for the Birds Directive targets is implemented subnationally (in each autonomous community independently), data are then aggregated at the national level and reported to the EU. The methodology presented here represents an innovation of the usual mechanisms of informing policy makers and general audiences on the state of nature. Ideally, it should integrate the broad range of ongoing monitoring schemes and should be scaled up to the Spanish and European levels, accounting for the full distribution of species and pressures at the national and continental scales, while considering the crucial role of subnational and local stakeholders that make possible the data collection and subsequent reporting.

ACKNOWLEDGMENTS

We thank the Department of Territory and Sustainability of the Catalan government, and Marc Antón and David García from the Catalan Institute of Ornithology for detailed information about protected areas (spatial data and management status) and SOCC transects (spatial data and species recorded), respectively. AMO is supported by the Spanish Government through the project INMODES (CGL2017-89999-C2-2-R). SC is supported by the Research Foundation Flanders (FWO16/PDO/019). VH is supported by the Ramón y Cajal program funded by the Spanish Ministry of Science and Innovation (RYC-2013-13979).

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SUPPORTING INFORMATION

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

How to cite this article: Morán-Ordóñez A, Canessa S, Bota G, Brotons L, Herrando S, Hermoso V. Efficiency of species survey networks can be improved by integrating different monitoring approaches in a spatial prioritization design. *Conservation Letters*. 2018;11:e12591. https://doi.org/10.1111/conl.12591