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Spatial prioritisation of management for biodiversity conservation across the EU

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ABSTRACT

The last report on the State of the Nature in the European Union (EU), a periodic monitoring exercise at continental scale, shows that biodiversity continues to decline, despite the efforts done in the last decades. Urgent action is, therefore, needed to reverse this trend. Effective conservation must rely on careful planning and strategic investment of limited resources to maximise efficiency of conservation efforts.

Here, we carry out a gap analysis to identify pressures and threats with no reported management action over the period 2013–2018 and identify priorities to close this gap. We use information from the State of Nature report to identify combinations of species/habitats × pressures/threats affecting them with no management action reported. We finally prioritise the selection of pressures and threats to be addressed for all species and habitats collectively.

We found that 2/3 of all combinations of species/habitat × pressure/threat did not have management actions reported. Management gaps were especially large for birds, amphibians and reptiles and marine bioregions in northern EU. This management gap affects 98 % of Natura 2000 sites, with at least one species/habitat with no management action reported for one or more pressures/threats. The spatial prioritisation analyses showed that all species and habitats could benefit collectively from a reduction in 30 % of pressures/threats incidence by targeting a small proportion of pressures/threats and Natura 2000 sites.

The prioritisation approach that we demonstrate here could be valuable to plan investment to close the current management gap and inform conservation across the EU.

1. Introduction

Biodiversity conservation is an increasingly global priority given the widespread decline in populations of many species (WWF, 2020) and the resulting increase in extinction risks. Current extinction rates are 100 times higher than background (Ceballos et al., 2015), with up to 1 million of species facing risk of extinction, many within decades (IPBES, 2019). There is a complex combination of threats behind this situation, including habitat modification and loss, invasive species, pollution, overexploitation, and climate change (IPBES, 2019). Effective conservation requires the adequate management of these threats (Game et al., 2013). Knowing where biodiversity is impacted and by what pressures (current impacts) and threats (expected future impacts) is essential to plan management effort and implement effective conservation (Tulloch et al., 2015¸ Bowler et al., 2020).

The European Union (EU) and its Member States have made a significant collective conservation effort over the last decades to try to halt biodiversity loss. These efforts have been led by the adoption of policy like the Birds and Habitats Directives and guided by commitments in the successive EU Biodiversity Strategies (EC, 2011, 2020a). As a result of the application of the Birds and Habitats Directives, the Member States have designated >27,800 protected areas: the Natura 2000 network (Evans, 2012). The designation of protected areas is accompanied by funding mechanisms to support the implementation of management actions and monitoring to periodically assess the status of biodiversity in the EU and effectiveness of conservation policy and action. The Member

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States must report on the trends of populations of species and habitats of conservation concern, the pressures and threats affecting them and the conservation actions implemented every six years, under articles 12 and 17 of the Birds and Habitats Directives respectively. This report is, therefore, a key management instrument to evaluate the incidence of pressures and threats and act accordingly.

The last report on the State of Nature in the EU that summarises the results from the last periodic monitoring effort (2013–2018), shows that only 27 % of species and 15 % of habitats listed in the Habitats Directive and 47 % of species listed in the Birds Directive are under no foreseeable risk of extinction (EC, 2020b). These numbers are far from the targets set for 2020 (EC, 2011). Although agriculture-related are the most commonly reported pressures for habitats and species in the EU (EC, 2020b), there are differences across taxa and realms. For example, modifications to hydrological flow and physical alterations to water bodies are important for freshwater fish, overexploitation (hunting and illegal killing) for wintering and passage birds, or pollution and climate change (droughts and decreases in precipitation) for amphibians (EC, 2020b).

A commonly cited reason behind this limited impact of conservation efforts on the EU is the insufficient budgets available (Hermoso et al., 2019). The investment made in maintaining the Natura 2000 network in the period 2007–2013 ranged between €550 and €1150 million annually, which only represents between 9 and 19 % of the financing needs (Kettunen et al., 2011). Moreover, these budgets have not been adequately distributed to cover the species that are most in need. This is the case, for example, of the LIFE program, which is the main direct financial tool for biodiversity conservation in the EU. Despite increasing budgets over time, these have been mostly directed towards species under lower risk of extinction, while those most in risk have been underfunded (Hermoso et al., 2017; Giakoumi et al., 2019). The new EU Biodiversity Strategy for 2030 aims to reduce this funding gap by securing at least 20 euro billion/year investment in biodiversity conservation actions within this coming decade (EC, 2020a). However, even this increase in financial resources might be insufficient to address the magnitude of the problem with pressures to species and habitats widely distributed across the Natura 2000 network (EC, 2020b). It will be, therefore, crucial to plan how to invest in biodiversity conservation to overcome past inefficiencies and achieve the goal of halting biodiversity loss (EC, 2020a). Prioritizing locations for management action can help direct conservation efforts where those actions are likely to achieve the greatest benefits to species when funding is limited (e.g., Wilson et al., 2007). There has been a growing body of research that focuses on how to prioritise threat management through cost-effectiveness analysis to support decision-making under limited budgets (e.g., Carwardine et al., 2012; Auerbach et al., 2014; Cattarino et al., 2015). However, some of these approaches are limited to a reduced number of species, threats or locations where those threats need to be addressed.

Here, we aim to contribute to a better-informed distribution of management efforts, to address some of the issues behind the insufficient effectiveness of past conservation action in the EU for all species and habitats of conservation concern according to the Birds and Habitats Directives and across the whole Natura 2000 network. With this aim, we first carry out a gap analysis to identify combinations of species/habitats × pressures/treats that did not have management actions reported (management-gaps hereafter), by using information from the last State of the Nature in the EU report (EC, 2020b). This information is only available at coarse spatial resolution (bioregion or country), while management occurs at finer resolution. To address this, we translate these management-gaps into a more adequate resolution for prioritizing management efforts: the Natura 2000 network. We then prioritise the selection of pressures/threats × Natura 2000 site that would need to be addressed so all species and habitats benefit from a reduction in the impacts they currently withstand. The prioritisation demonstrated here could be also carried out at regional or national scales and elsewhere to inform decision-making on the distribution of management effort for biodiversity conservation.

2. Methods

2.1. Distribution of pressures and management actions

We sourced the distribution of pressures and the management actions from the last report on articles 12 and 17 of the Birds and Habitats Directives, respectively (period 2013–2018; EC, 2020b). These are periodic reports on the status of populations of species and habitats of conservation concern that all Member States must submit every six years. Among other information, the reports include data on the trends of populations of species and habitats over the reported period, main pressures affecting each species and habitat and the management actions that have been implemented to address those pressures (EC, 2020b). We acknowledge that this source of information on pressures and threats is subject to potential spatial inconsistencies or incompleteness due to differences across Member States. However, this database still represents the most complete and updated source of information available at continental scale and has been used for the elaboration of the official State of the Nature report (EC, 2020b). Reports on article 12 for birds include the information at the country scale, differentiating breeding, wintering, and migrating periods. So, for a given bird species, three different pieces of information could be available at each country. Reports on article 17 for habitats and species in the Habitats Directive contain information at bioregions level (N = 14 bioregions, 9 of them terrestrial; available at: www.eea.europa.eu/data-and-maps) within each country. So, in case of a country covered by different bioregions, information for each species and habitats was available for each bioregion individually. The final database from both reports contains 155,262 evaluations for 1991 species and habitats × bioregions/seasons and incidence of 221 pressures (referred to as fine-resolution pressures). These pressures are nested within 15 broader classes (e.g., agriculture, silviculture, or transportation infrastructure), referred to as coarse-resolution pressures hereafter. This terminology of coarse and fine relates only to the thematic resolution of these different hierarchical levels, rather than their spatial resolution (the same in both cases).

2.2. Assessment of management gaps

We used the reference list of management actions suitable to address each pressure to evaluate whether pressures reported for each individual species and habitats at each combination of country-bioregion in the case of the Habitats Directive or country-season for the Birds Directive had been addressed through at least one suitable management action. The reference list of management actions contains 100 actions and 301 unique combinations of actions-pressures/threats (some actions are considered suitable for multiple pressures/threats). For this gap analysis, we use the fine-resolution pressure classification. A management gap was, therefore, identified whenever no suitable management action could be found on the list of actions reported within a country-bioregion or country-season for a specific pressure impacting a species or habitat. Management-gaps were recorded as the proportion of all records for each species or habitat (country × bioregion for species and habitats listed in the Habitats Directive and country × season for species listed in the Birds Directive) that did not have adequate management actions reported in the State of Nature report (EC, 2020b). We calculated two alternative management-gaps: i) 1—the proportion of records for each species or habitat that had all pressures addressed, and ii) 1—the proportion of records for each species or habitats where at least one pressure had been addressed with management actions.

2.3. Downscaling management-gaps

Conservation action usually occurs at smaller scales than the available for the management-gap analysis (e.g., individual Natura 2000 site), so the prioritisation of management effort would benefit from a finer resolution dataset. We therefore translated the information from bioregional/seasonal-country scale at the Natura 2000 resolution (N = 27,852 sites). We first identified the country and the dominant bioregion for each Natura 2000 site. We then linked each Natura 2000 site to the list of pressures/threats included in the management-gap identified previously, by assigning all pressures/threats with no actions in the bioregion × country/season × country to all Natura 2000 sites that occurred within that bioregion × country/season × country. We finally used the list of species and habitats in the Standard Data Forms of each Natura 2000 site to further assess which species and habitats could be affected by those management gaps. These forms convey general information on each Natura 2000 site, including a list of habitats included in Annex I of the Habitats Directive and all species in Annex I of the Birds Directive and Annex II of the Habitats Directive. This is not an exhaustive inventory of all habitats and species present in each Natura 2000, but it does convey those for which the protected area was designated and, therefore, priority for management. The final database contained information on the species and habitats × pressures/threats with no action reported for each Natura 2000 site individually. For example, this database contained 335 records of *Anaecypris hispanica*, a critically endangered freshwater fish species endemic to the SW Iberian Peninsula. These records correspond to 13 pressures/threats that have no reported management action in 46 Natura 2000 sites in Spain and Portugal. Given the large number of combinations of Natura 2000 sites and pressures/threats at fine-resolution, we used the coarse-resolution pressures classification resulting in 235,268 unique records of pressures × Natura 2000 site, where at least one species or habitat did not have management actions reported. Moreover, not all 1991 species/habitats with information in the reports had spatial data in the Standard Data Forms, so the prioritisation analyses at the Natura 2000 scale were constrained to 1473 species/habitats, resulting in 1,897,423 unique combinations of species/habitats × pressure/threat × Natura 2000 site, for which no management action had been reported. We acknowledge that this downscaled dataset might be an overestimation of the real management-gap, as pressures were assumed to be homogeneously distributed across Natura 2000 sites within a given country × bioregion. However, this was the best available and updated knowledge at continental scale for demonstration purposes, and finer resolution data would be needed if the results were to be used to inform decision-making.

2.4. Spatial prioritisation of management actions

We sought to identify what pressures/threats (hereafter referred to only as pressures for conciseness) should be addressed across Natura 2000 sites to fill the management gaps identified previously and collectively reduce the impacts of these pressures on species and habitats. We used a Mixed Integer Programming (MIP) mathematical model (Salgado-Rojas et al., 2020) to identify an optimal combination of pressures and Natura 2000 sites where they occur that if addressed would help reduce the management gap for all species and habitats simultaneously. The optimisation problem we addressed was to try to minimise the total cost needed to address pressures selected to reduce the management gap:

$$min\sum_{i\in I}\sum_{k_i\in K}c_{ik}x_{ik}$$

where, I is the set of all individual i Natura 2000 sites; K is the set of k pressures; c_{ik} is the cost of addressing pressure k in Natura 2000 site i; and x_{ik} is a binary control variable that takes a value of 1 if pressure k has been selected in Natura 2000 site i or 0 otherwise. There were no estimates of potential costs of actions needed to address each pressure available, so we assigned a constant cost to all pressures (cost = 1). In this way, the optimisation problem we addressed was to try to minimise the number of pressures selected across Natura 2000 sites to reduce the management gap. We set this "recovery" target as the proportion of management-gap that would need to be addressed:

$$\text{s.t.}\sum_{i\in I_s}\frac{\sum_{k\in K_I\cap K_s}x_{ik}}{|k_i\cap k_s|}>t_s\forall s\in \text{S}$$

where, S is the set of s species and habitats considered in this study; $|K_i\cap K_s|$ is the set of all k pressures that impact species or habitat s in Natura 2000 site i, being always >0 as we only included in the analyses sites where at least one species had one pressure reported with no action; t_s is the target for each s species or habitat. The recovery target, therefore, represents the proportion of all existing pressures/threats that a species is subject to across Natura 2000 sites that would need to be addressed. To demonstrate our approach, we assume that a pressure or threat can be abated if managed (similar to Auerbach et al., 2014, Cattarino et al., 2015). We run the analyses for 6 different target levels, between 5 and 30 % at 5 % incremental steps across all species for the sake of simplicity. However, this target could be set individually for each species according to their particular conservation needs.

We used Gurobi (2021) to solve the mathematical problem, using the branch and bound strategy on an Intel Core i7-4712Q 2.30 GHz of 16.0 GB RAM. The solver was parameterized to stop once the execution time reached 10,000 s (or earlier if an optimal solution was found). We recorded the gap of solutions reported by Gurobi, as a measure of quality of solutions (hereafter quality-gap). This quality-gap is defined as the percentage difference between the relaxed (lower bound) and best (upper bound) solutions found by Gurobi, being 0 when the optimum is reached (Salgado-Rojas et al., 2020).

We also recorded the number of Natura 2000 sites where at least one pressure was selected, the total number of pressures selected across all Natura 2000 sites and the combination of species/habitats × pressures that would benefit from that selection. We finally summarised the benefit across species and habitats for different solutions (measured as $\sum_{i\in I_s}\frac{\sum_{k\in K_I\cap K_s}x_{ik}}{|k_i\cap k_s|}$) and measured the proportion of the Natura 2000 sites where each species/habitat was initially impacted by at least one pressure that was either partially addressed (not all pressures in that Natura 2000 site impacting the species/habitat selected) or fully addressed (all pressures selected).

We compared the performance of the optimisation algorithm against 1000 random allocations of the same effort (n pressures × Natura 2000 sites) for each solution and measured the average benefit for each species and the number of times that a given species would have achieved the desired target across random allocations and their cost.

3. Results

3.1. Management-gap

We found that only one third (32 %) of the 155,262 combinations of pressure × species/habitat × bioregion/season had measures reported. On average species and habitats had at least one pressure addressed by adequate measures in 54 % of the country × bioregion/season combinations where they occur, but only in 9 % of them there were management actions reported for all pressures impacting the species/habitat. More than one fourth of all species and habitats (29 %) did not have any measure reported for any of the country × bioregion/season where they occur. Management-gaps were large for all taxa, but especially for birds, amphibians and reptiles for which <5 % of countries × bioregion/season where they are reported under pressure had all pressures addressed (full-gap; Fig. 1, Supplementary Table 1). On the other hand, habitats and fish had at least one pressure addressed in >75 % of all countries × bioregion where they occur (partial-gap; Fig. 1). This management-gap was also spatially heterogeneous, with some country

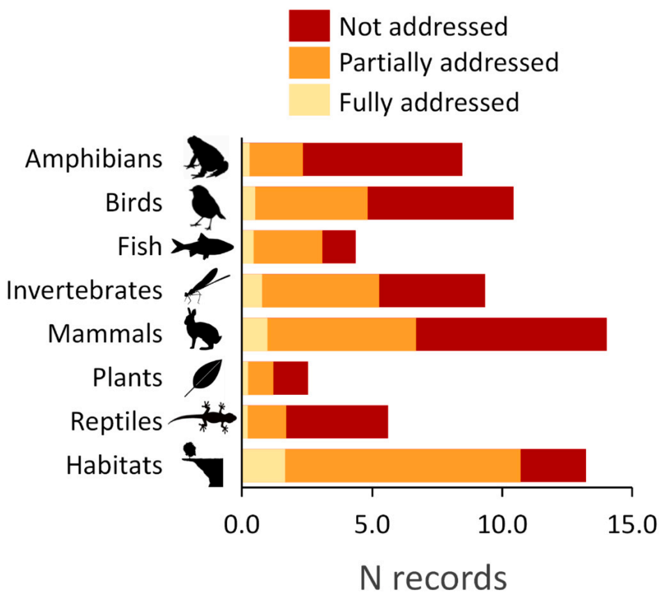


Fig. 1. Summary of management-gaps identified from the last State of the Nature report (EC, 2020a, b). Bars show the average number of records where species/habitats were impacted by at least one pressure (red bars), where pressures were partially addressed (at least one pressure not addressed; orange bars), and where pressures were fully addressed (yellow bars). Records for species and habitats in the Habitats Directive represent the combination of unique bioregions × country, while for species in the Birds Directive represent the unique combination of country × season (breeding, wintering, and pass), due to differences in data availability from the Art. 17 and 12 of these Directives respectively. Images sourced from: es.silhouette-ac.com and phylopic.org. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

× bioregions/season better covered (e.g., the Baltic region of Estonia or the marine portion of the Macaronesian region of Portugal with 52 % and 40 % of species with all pressures addressed, respectively) than others (e.g., marine regions in Denmark, Germany, Finland and Sweden with none of their species free from pressures). When translated into Natura 2000 sites, only 596 sites had actions reported for all pressures, so 98 % of sites had at least one pressure with no management action reported. On average sites had 8.6 (±4.1 SD) pressures with no management action reported, but it was also spatially heterogeneous, ranging from 3.7 in Romania to 13.2 in Cyprus (Fig. 2). Each species had on average 3.2 (±1.7 SD) pressures with no management action reported across all Natura 2000 sites where they occur.

3.2. *Spatial prioritisation of management*

The MIP model was able to find solutions with quality-gaps <0.5 % within the time limit for all target levels (Table 1). These solutions showed that to reduce the current management-gap by 5 % for all species we would need to address 2.1 % of all pressures × Natura 2000 sites, while if we aimed at reducing the management-gap by 30 % we would need to address 16.4 % of all pressures × Natura 2000 sites (Table 1). The number of pressures that would need to be addressed per Natura 2000 site, where at least one pressure was selected, ranged on average between 5.3 (±3.8 SD) for target 5 and 7.9 (±4.0 SD) for target 30. The distribution of effort to address the management-gap was spatially heterogeneous. Although the average proportion of Natura 2000 sites per country where at least one pressure was selected ranged from 4.7 to 21.0 for target 5 and 30, respectively (Fig. 3), these numbers showed a large spatial heterogeneity across the Member States (Supplementary Table 2). For example, while 24 Natura 2000 sites in Denmark (6.9 %) had at least one pressure selected under target 30, Cyprus had 41 Natura 2000 sites (66.1 %) with at least one pressure selected. The spatial heterogeneity across countries was true not only when looking at the number of Natura 2000 sites with at least one pressure selected, but also regarding the number of pressures selected in those Natura 2000 sites (Fig. 3). For example, the number of pressures selected by Natura 2000 site was 2.9 in Romania ($N = 81$ sites) to 11.6 pressures in Slovenia ($N = 52$ sites; Supplementary Table 2).

The average reduction in pressure incidence across species and habitats ranged between 28 and 53 % for target 5 and 30 respectively (Fig. 4). This means that on average there would be 53 % less pressures across all Natura 2000 sites were species and habitats occurred on average for that given target. If pressures selected were adequately treated species and habitats would be pressure-free in 10–34 % of all sites where they currently co-occur with at least one pressure, on average (Fig. 4). The solutions that we obtained from the optimisation model resulted always in a larger benefit than when distributing the same effort (number of pressures × Natura 2000 site) randomly. The reduction in pressure across species and habitats was more than twice for our solutions (2.9–2.0 for targets 5 and 30 respectively) compared to random allocation of the same effort (Supplementary Table 3).

4. Discussion

Effective biodiversity conservation requires adequate management of pressures (Game et al., 2013) and mechanisms to translate available information into action are urgently needed (Buxton et al., 2021). Here, we have demonstrated how to prioritise management effort to fill the management-gaps of pressures reported as not adequately addressed in the last EU State of the Nature report (EC, 2020b). These results could help guide future management effort and overcome the continuous decline of biodiversity in the EU. We have applied a novel spatial prioritisation approach, based on the principles of systematic planning and Integer Lineal Programming (Salgado-Rojas et al., 2020), that allows optimising the allocation of management effort needed to reduce pressure incidence across species and habitats in the Natura 2000 network. Our results show that adequate planning can help achieve ambitious management targets, like reducing pressure incidence by 30 % on all species and habitats by implementing actions for a small proportion of all pressure incidences in a reduced number of all Natura 2000 sites. Prioritisation exercises such as the one we demonstrate here could be valuable for designing management plans that maximise the benefit across all species and habitats under limited resources.

Despite the large management effort implemented over the 2013–2018 period, with >50,000 individual measures (EC, 2020b), these only cover a small fraction of all measures that would have been needed to address all reported pressures. We uncover a large management-gap, with two thirds of all incidences of pressures on individual species and habitats, according to the information provided by the Member States. The management-gap was heterogeneously distributed across taxonomic groups, being especially important for amphibians and reptiles, and space more relevant in countries such as Denmark, Germany, Finland and Sweden. Addressing this management-gap must be a priority to stop the decline of biodiversity in the EU. In this sense, all pressures are important and, ideally, they should all be adequately identified and addressed to halt biodiversity loss. However, even under the renovated commitments for a better funded conservation policy in the EU (EC, 2020a), resources will likely continue to be insufficient to cover all pressures wherever they impact biodiversity (Mammola et al., 2020). Prioritisation of conservation efforts seems, therefore, unavoidable to overcome our limited management capacity.

We found that the distribution of management effort to achieve the targets we aimed was spatially heterogeneous, with more than one fourth of all pressures selected allocated in two countries (Germany −16.7 % and Sweden −12.3 %, for target 30), mirroring the spatial heterogeneity in the management-gap. The approach that we used here goes beyond traditional analyses of best management strategies to

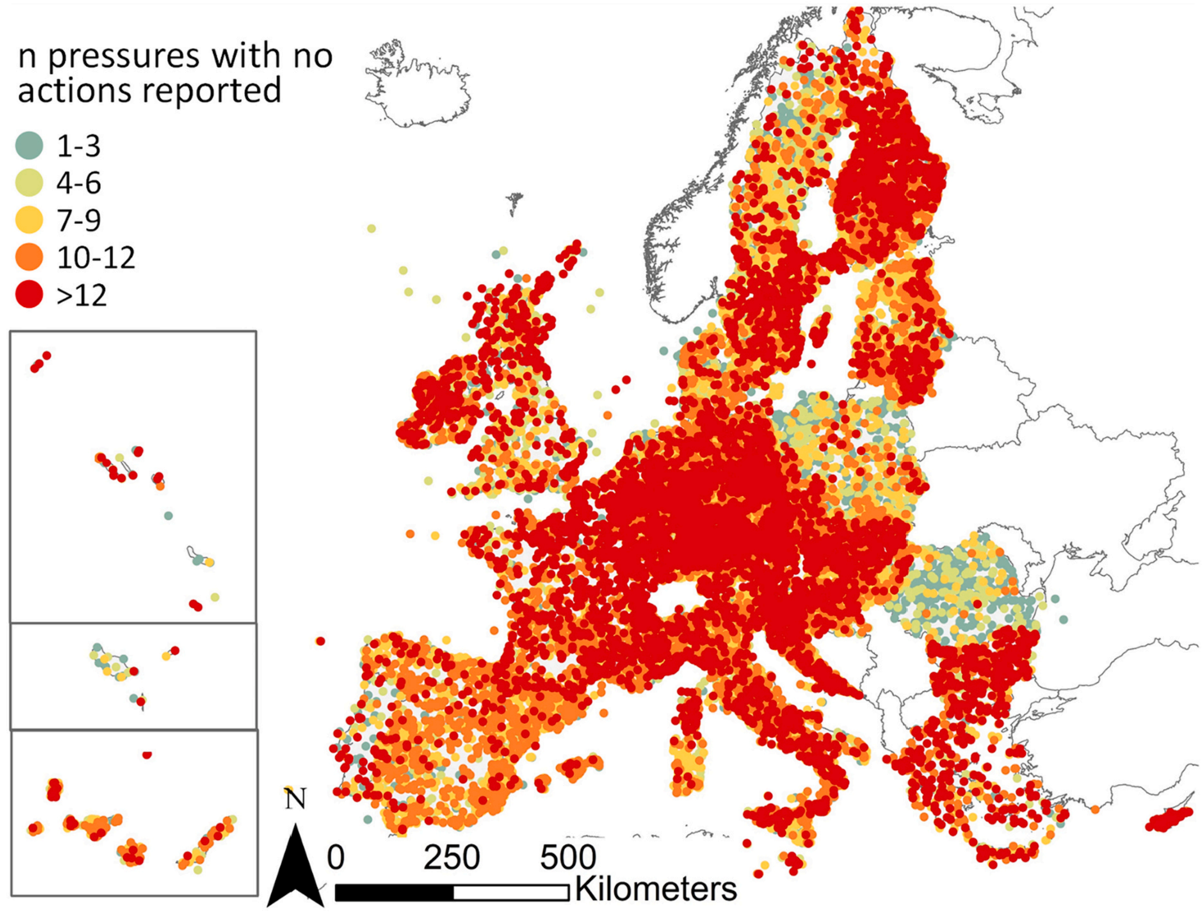
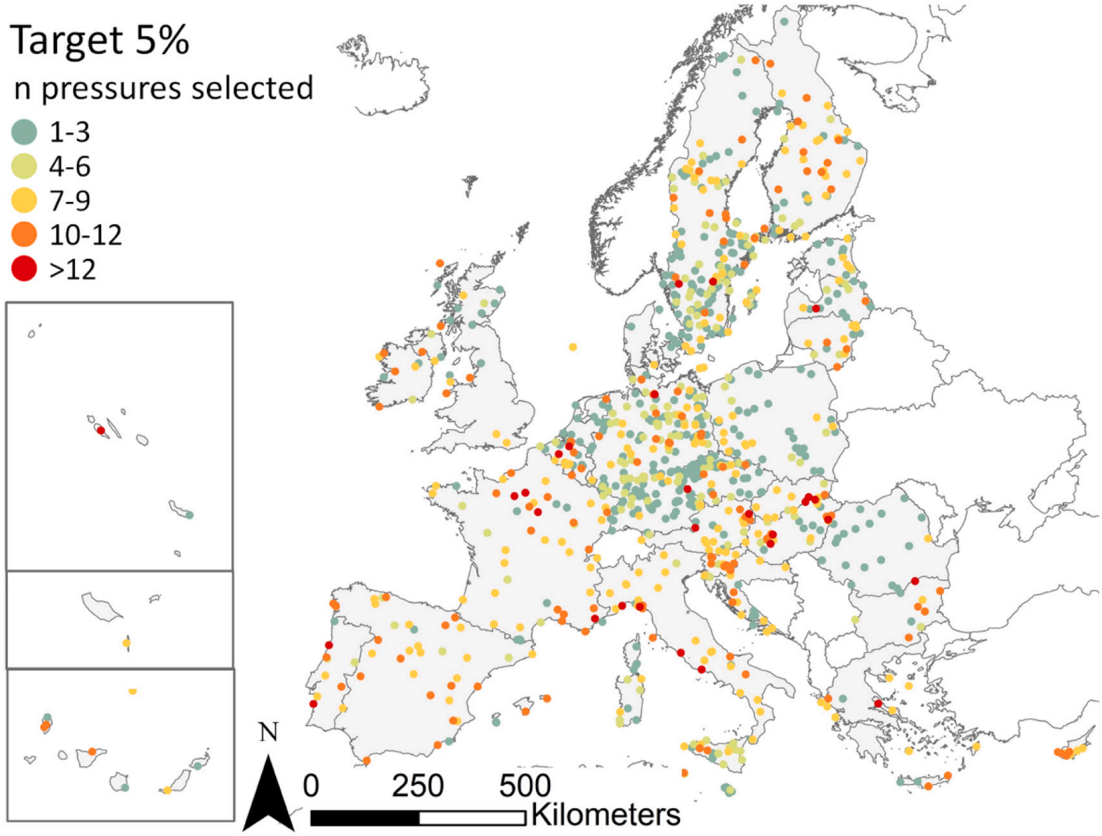


Fig. 2. Number of pressures not addressed for at least one species per Natura 2000 site, represented by their centroids for displaying purposes.

address multiple pressures for a single species at a time (Joseph et al., 2009), or multiple species but non spatial (so no indication on where the pressures need to be addressed; Chadés et al., 2015; Mantyka-Pringle et al., 2016; Moore et al., 2021). Our approach, based on integer lineal programming, also overcomes traditional limitations of heuristic-based optimisation algorithms, in terms of complexity of the problem that can be addressed (number of species, sites and pressures simultaneously), computational times and lack of information on quality of solutions (Beyer et al., 2016; Hanson et al., 2019; Salgado-Rojas et al., 2020). Despite the large dimension of the optimisation problem that we addressed here, the optimisation model was always able to find solutions close to optimum, with quality-gaps <0.5 %. The prioritisation analysis proved to be very efficient at identifying the most cost-effective set of pressures to be targeted to reduce the impact of these pressures across all species. For example, the incidence of pressures on species could be halved on average across all species and habitats by targeting with adequate management just 16.4 % of all pressures reported. Moreover, this level of management intensity would also secure that on average species and habitats would be pressure-free in one third of all Natura 2000 sites where they are currently impacted by at least one pressure with no management action reported. Therefore, spatial prioritisation of management effort can support ambitious targets even when limited resources are available. The spatial pattern of solutions that we show could, however, be influenced by inadequate reporting on some taxa by some of the Member States (e.g., no information on bird species was found for Romania). Being a spatially explicit task, these prioritisation exercises are founded on spatial data on the distribution of pressures and the species/habitats they impact to. It is, therefore, important to invest in the development of monitoring programs (Navarro et al., 2017) to identify where impacts to species occur in space, key to inform the distribution of management effort (Tulloch et al., 2015; Bowler et al., 2020).

The current monitoring and reporting approach established in the Nature Directives (articles 12 and 17 of the Birds and Habitats Directives, respectively) is a valuable tool to know what pressures impact biodiversity and where, that can help identify management priorities. However, this information is currently recorded at a low spatial resolution (country or bioregion), which might undermine its potential value for decision-making. Management of pressures occurs at smaller scales, normally within individual Natura 2000 sites, so the information provided by these periodic reports lack sufficient detail as to be useful to estimate potential management costs or inform decisions on what to do and where. To overcome the mismatch between the resolution at which pressure information was available and the resolution at which these pressures are addressed, we assumed that pressures occurred in all Natura 2000 sites in the country × bioregion where they were reported for a given species and where the species was also reported in the Standard Data Forms. For example, *Anaecypris hispanica* was reported as impacted by invasive species, agriculture, transport infrastructure, natural abiotic and biotic processes and climate change, in the Mediterranean bioregion of Spain. However, there were management actions reported only for two of these pressures (invasive species and natural abiotic and biotic processes), leaving the other three without management coverage. According to the Standard Data Forms of the Natura 2000 network, *A. hispanica* is a species of management concern in 40 Natura 2000 sites in this bioregion in Spain, which is where we assumed the unaddressed pressures needed management actions for this species. This is, therefore, a small subset of all Natura 2000 sites in the bioregion, as all those other sites where *A. hispanica* was not listed as a species of management concern were excluded from the list of management-gaps.



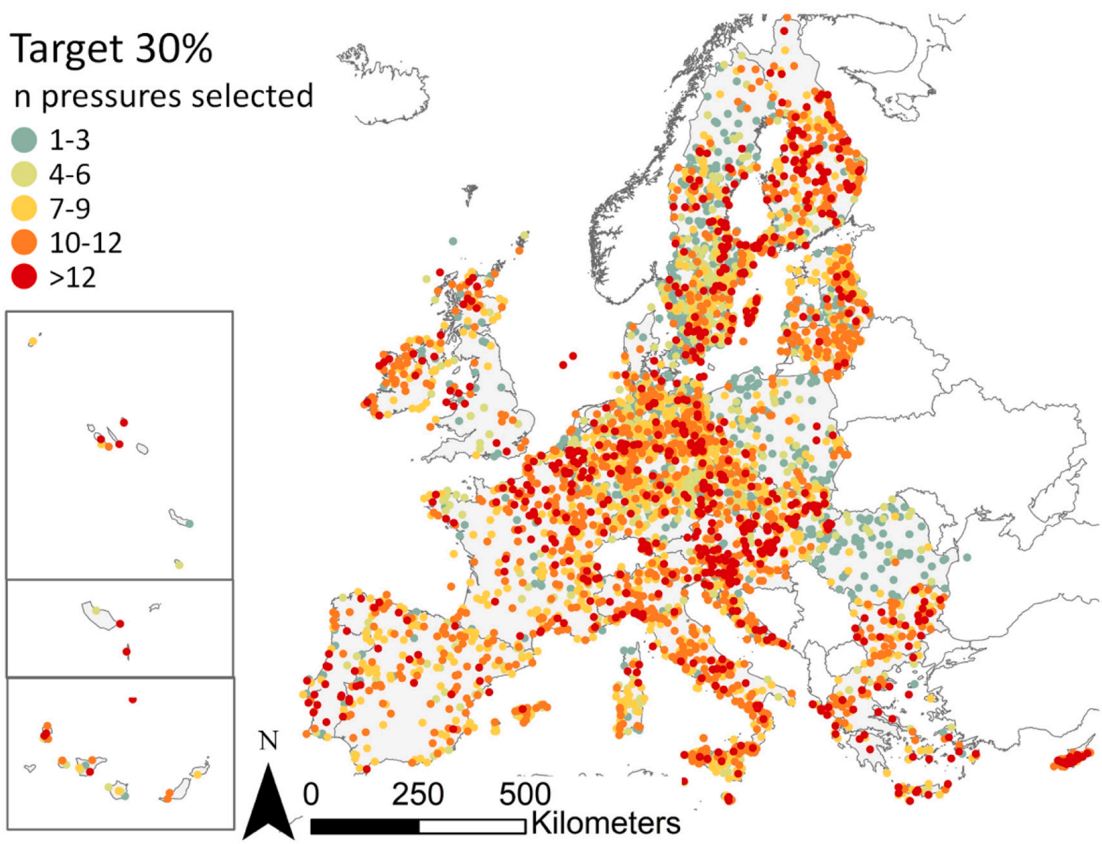


Fig. 3. Number of pressures selected per Natura 2000 site included in the solution, for target 5 and 30 %. Only Natura 2000 sites with at least one pressure selected are shown. Pressures selecetd in each Natura 2000 site would represent the full management-gap or a subset of it.

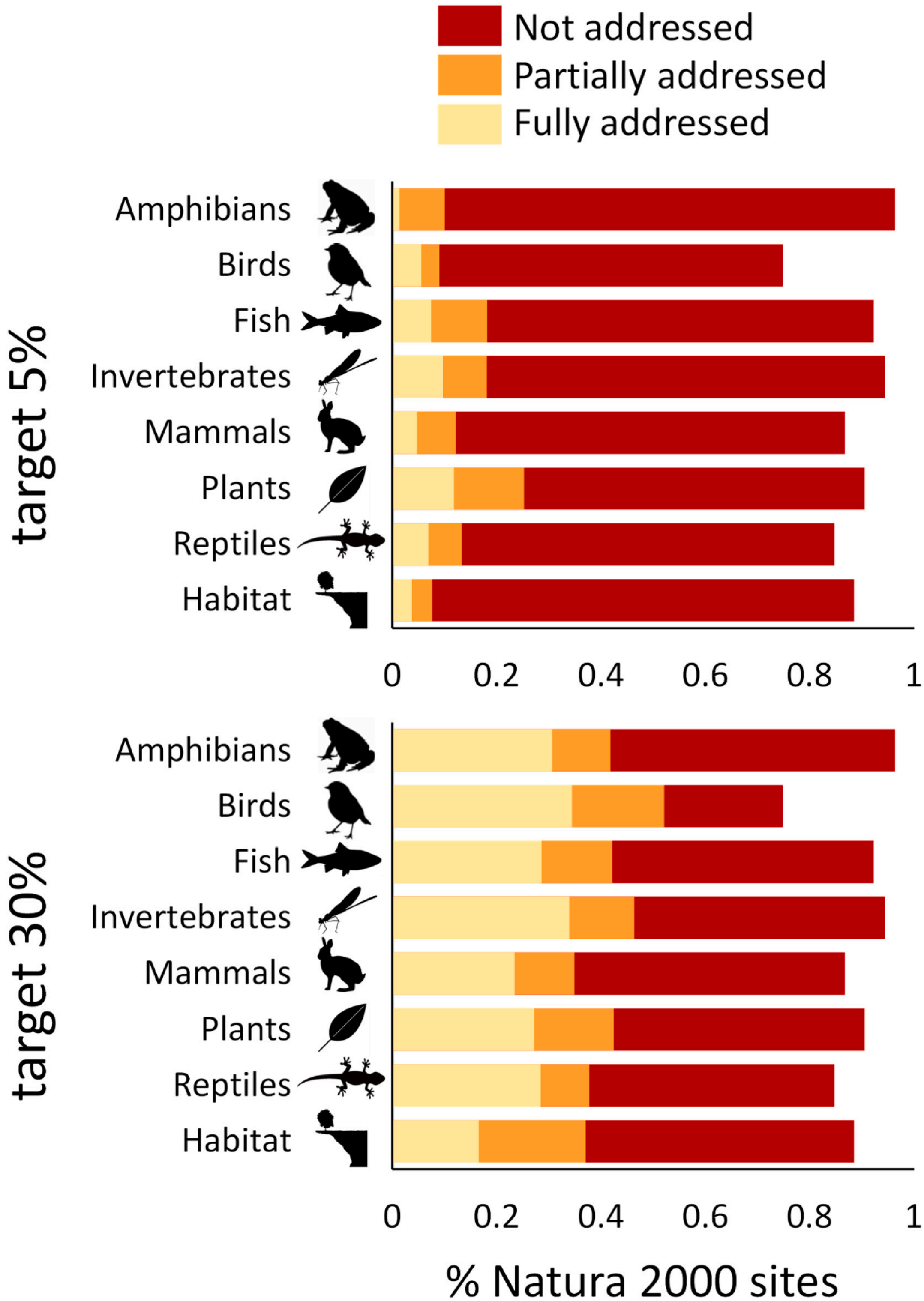


Fig. 4. Average proportion of Natura 2000 sites where species/habitats were impacted by at least one pressure (red bars), proportion of sites where pressures were partially addressed (at least one pressure not addressed; orange bars), and proportion of sites where pressures were fully addressed (yellow bars) for two different targets. Images sourced from: es.silhouette-ac.com and phylopic.org. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This was a conservative approach to ensure that all pressures reported were accounted for in the analyses, and although we only considered Natura 2000 sites where each species was reported as of management concern, we could have overestimated the number of Natura 2000 sites where each pressure was impacting each species/habitat. We acknowledge that developing a fine spatial resolution database on pressures is costly and goes beyond the objectives of the Nature Directiveś reporting system. However, further efforts beyond this reporting schedule might be needed to improve our capacity to better estimate budget needs and make informed decisions in the future. Given

Table 1
Summary of quality-gaps, number of Natura 2000 sites where at least one pressure was selected, number of pressures selected across all Natura 200 sites and number of unique combination of species/habitats × pressure × Natura 2000 sites that would benefit. Between parentheses it is shown the proportion of the total combinations of pressure × Natura 2000 or species/habitats × pressure available that were selected.

Target	Quality-gap (%)	Natura 2000 sites	N pressures × Natura 2000 sites	N pressures × species/habitats
5	0.43	952 (3.4)	5,008 (2.1)	81,928 (6.7)
10	0.30	1661 (6.0)	10,714 (4.6)	152,350 (12.4)
15	0.21	2409 (8.6)	17,014 (7.2)	219,355 (17.9)
20	0.12	3204 (11.5)	23,756 (10.1)	285,715 (23.3)
25	0.10	4024 (14.4)	30,976 (13.2)	350,193 (28.5)
30	0.10	4899 (17.6)	38,655 (16.4)	414,499 (33.8)

the limited resources available, these future efforts should strike the balance between gathering more precise data and implementing management actions (Chadès et al., 2008; Buxton et al., 2021).

Prioritisation analyses, like we demonstrate here, could be valuable resources to operationalise the implementation of management planning tools rooted in EU policy, such as the Prioritised Action Frameworks (PAFs). These PAFs are instruments included in the Habitats Directive that aim to identify Natura 2000 conservation priorities at national or regional scales and the different funding sources to cover them (Kettunen et al., 2009). Although originally depicted in the Habitats Directive, PAFs also apply to the Special Protection Areas (SPAs) designated under the Birds Directive, covering thus the full extent of the Natura 2000 network. The spatial priorities identified in this study could inform on what pressures to address and where — Natura 2000 site — to develop PAFs at any scale. For example, out of the 40 Natura 2000 sites where *A. hispanica* co-occurred with some unaddressed pressures in Spain, only 21 were selected in our solutions to achieve the recovery target in Spain. This information could be used to identify where to focus management efforts for this species. The advantage of our approach is that the sites and pressures to be addressed have been selected not only looking at *A. hispanica*, but all the remaining species jointly, so the species that co-benefit is maximised. We have demonstrated its potential by using the full dataset from the last State of the Natura report, but the same approach could be repeated at smaller scale, or finer resolution, to fit National or regional needs such as the development of PAFs.

Future applications of our approach could benefit from addressing interactions between pressures. In some cases, the co-occurrence of multiple pressure translates into synergistic impacts on some species and habitats, higher than the sum of their individual impacts. In our case, the impacts of different pressures were treated as independent and additive, while the benefit of addressing their interaction in the design of management plans has demonstrated (e.g., Auerbach et al., 2015). Moreover, our analyses focused only on species and habitats included in the annexes of the Nature Directives, for which information was available in the State of the Nature report (EC, 2020b). However, these lists only represent a portion of all species and habitats in need of conservation management, as many threatened species are not included in these annexes (Maiorano et al., 2015; Sánchez-Fernández et al., 2017; Hermoso et al., 2019). Therefore, further effort is needed to cover the knowledge gap on pressures impacting those other threatened species and habitats if the ultimate objective of the EU biodiversity policy of halting biodiversity loss is to be achieved.

5. Conclusions

The large management-gap reported in the last State of the Nature (EC, 2020b) could be behind the limited advance towards halting biodiversity loss in the EU. Addressing this gap could be seen as a daunting task under the limited resources available. However, spatial prioritisation of management effort, planned jointly for all species and habitats, can help maximise the return on investment (e.g., number of species benefited for a given effort) and guide the development of well informed and transparent recovery plans. In this way, the approach we present here could help operationalise some management tools like PAFs in the EU, or any other action planning framework elsewhere. The pressures and Natura 2000 sites identified in these types of spatial optimisation exercises could guide the identification of management priorities within these action planning frameworks, and maximise the species benefited under limited resources. Ultimately, adequately planned management efforts should help bend the curve of biodiversity loss.

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CRediT authorship contribution statement

Virgilio Hermoso: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. **José Salgado-Rojas:** Conceptualization, Methodology, Writing – review & editing. **Mónica Lanzas:** Writing – review & editing. **Eduardo Álvarez-Miranda:** Writing – review & editing.

Declaration of competing interest

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

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