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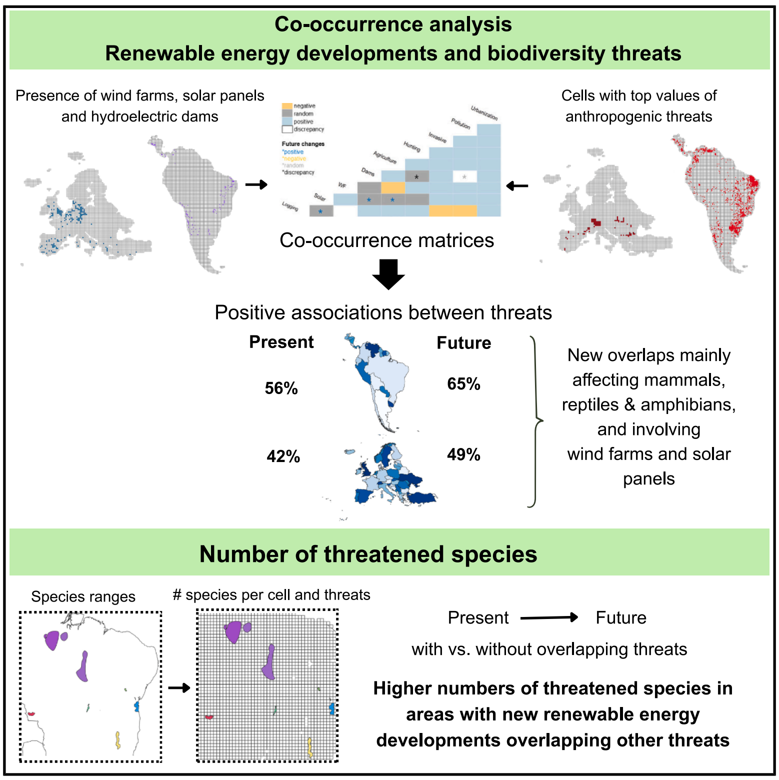
Assessing the associations between renewable energy generation and other human-induced threats to terrestrial biodiversity

Graphical abstract



Highlights

- Renewable energy developments often overlap with existing threats to wildlife
- South and Central America show more overlapping threats than Europe
- Renewable energy expansion creates new overlaps, mainly affecting amphibians, reptiles, and mammals
- Several areas with overlapping threats host significantly more threatened species

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In brief

Gorosábel et al. show that while renewable energy is vital for combating climate change, there is a spatial overlap with other human activities that already threaten wildlife, and this increases with the expansion of wind farms and solar panels. South and Central America presented more overlapping threats than Europe, and particular areas with overlapping threats host significantly more threatened species. The findings highlight the importance of strategic planning to expand renewable energy while protecting biodiversity.

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Article

Assessing the associations between renewable energy generation and other human-induced threats to terrestrial biodiversity

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SCIENCE FOR SOCIETY Renewable energy (RE) is essential for fighting climate change, but it can overlap with other human activities that already threaten biodiversity. We examined how wind farms, solar panels, and hydropower dams intersect with major threats to birds, mammals, reptiles, and amphibians in South and Central America and Europe under current conditions and future RE expansion. We also assessed the threatened species in areas with and without overlapping threats. Results show RE developments often occur in already impacted areas. South and Central America exhibit more overlaps than Europe, with more threats associated now and in the future. Future RE expansion will likely create new overlaps, usually involving solar and wind. Several areas where new RE overlap with other threats contain higher numbers of threatened species. These highlight the need for strategic RE planning to maximize climate benefits while minimizing impacts on biodiversity.

SUMMARY

Renewable energy (RE) is crucial in fighting climate change but can overlap with other human-induced threats to biodiversity. We assess associations between RE developments (wind farms, solar panels, and dams) and major anthropogenic threats to terrestrial biodiversity (birds, mammals, reptiles, and amphibians) in South and Central America and Europe, under present conditions and future RE expansion. We also evaluate the number of threatened species in areas with and without overlapping threats. Results show that RE is positively associated with other threats, with South and Central America exhibiting a higher prevalence of positive associations than Europe (present: 56% vs. 42%; future: 65% vs. 49%). Future patterns reveal new positive associations between threats, particularly for mammals, reptiles, and amphibians, with solar and wind developments most frequently involved. Additionally, higher numbers of threatened species occur in areas with new RE developments overlapping other threats. These findings help balance RE expansion and biodiversity conservation.

INTRODUCTION

Renewable energy (RE) production is crucially important in reducing our dependency on fossil fuels, and most countries are aiming for carbon neutrality by mid-century.[1] As a result, changes in the global energy sector have already begun and are predicted to continue over the next decades.[2] This is shown by the European Union's (EU) commitment to becoming the world's first climate-neutral continent by 2050.[3] In 2022, the EU achieved a 22% share of gross final energy consumption from RE with an investment of 154 billion USD.[4,5] Similarly, in South and Central American countries, a 79% average of RE in electricity generation was reported in 2022, with hydropower providing most of the electricity.[6] In terms of investment, Brazil had the highest in South America, with 7 billion USD invested in clean energies in 2022, and prospects for clean energy are showing major signs of improvement in solar and wind.[6] Even though there are clear benefits of RE, as with any other human activity, the related infrastructure associated with these developments also has the potential to negatively affect biodiversity.

Existing literature shows that the negative impacts of RE are primarily linked to direct mortality, land-use change, and the displacement of species and ecological processes.[7–11] Research on terrestrial vertebrates has focused mainly on bird and bat mortality at wind farms (hereafter "WFs"), but studies also document functional habitat loss in Europe[8,9,12,13] and spatial overlap between WFs and species distributions in Latin America.[14] Beyond wind energy, impacts have been reported across taxa and energy types, including altered amphibian communities near hydropower plants,[11] reduced reproductive calling in amphibians due to turbine vibration,[15] and both direct and indirect habitat loss from solar panels (hereafter "solar") affecting mammals, birds, reptiles, and large herbivores through avoidance and barrier effects.[16–19] RE developments also overlap with critical conservation areas globally,[20] and the RE production and distribution infrastructure will exacerbate mining pressures on biodiversity.[21]

The risks associated with RE developments need to be considered in conjunction with other human pressures that are already threatening wildlife, such as agriculture, urbanization, deforestation, invasive species, and pollution.[22–24] Currently, 12% of all bird species, 26% of all mammals, 21% of all reptiles, and 41% of all amphibians are threatened with extinction, often arising from compound effects of multiple activities and drivers.[25] Thus, the potential interaction between threats can vary and becomes more relevant in areas where threats co-occur spatially and temporally. This is due to the potential synergistic effect that could exacerbate their impacts on biodiversity,[26] resulting in combined effects greater than the sum of individual impacts and increasing pressure on species.[27] Recognizing and explicitly accounting for the co-occurrence of threats can help us identify areas where threats might interact and, thus, help us better understand their dynamics and impacts on ecosystems.[22,28,29] Furthermore, different parts of the world have different histories of human impact on nature, with afforestation and cropland abandonment in the Global North and deforestation and agricultural expansion in the South.[30] Despite its importance, we still have limited knowledge about the association between threats, and the co-occurrence between the location of RE and other human activities has not been evaluated.

Here, we aim to assess the associations between the location of onshore RE developments and other human-induced threats to terrestrial vertebrates (birds, mammals, reptiles, and amphibians) in the present and consider the future expansion of RE in South and Central America and Europe. We focus on these two regions because they represent contrasting socio-ecological contexts, biodiversity profiles, and stages of RE expansion, allowing assessment of both context-specific and generalizable patterns.[30,31] As RE, we considered WF, solar (including photovoltaic and thermal technologies), and dams for hydropower, and as human-induced threats, agriculture, deforestation, urbanization, hunting, invasive species, and pollution. We also assess the conservation importance of the areas where threats are overlapping, considering all threatened species. Since more threats together can increase the pressure on ecosystems, affecting not only the species known as impacted by RE based on the IUCN Red List of Threatened Species but also other species present in those areas.

Through a co-occurrence analysis of threats, this study identifies positive associations between RE and the highest likelihood of threat impacts in the present and considers the future expansion of RE. Although the co-occurrence of threats varies across regions and taxonomic groups, South and Central America exhibit more frequent overlap of threats than Europe. In the future, new positive associations between RE and other threats are projected to emerge, particularly for amphibians, reptiles, and mammals, with solar and wind energy developments most often involved. Moreover, areas where new RE developments overlap with existing threats support a significantly higher number of threatened species, suggesting that RE expansion may be taking place in areas of high conservation importance. In this study, the scale of our analysis (50 $\times$ 50 km) is limited by how the threat maps were constructed,[23] and our results are not intended to guide local conservation action. Instead, our study contributes to understanding how the current and future expansion of RE developments is co-occurring with already existing threats across two contrasting regions and multiple taxa. This could lead to better prioritizing and optimizing efforts for the positive benefits of RE while minimizing their negative effects on biodiversity.

RESULTS

RE developments

In South and Central America, we found more WFs (n = 875) than any other RE type (378 solar and 277 dams). However, solar is expected to expand the most, with 3,052 new developments (Tables S2 and S3), followed by WFs (n = 625) and hydroelectric dams (n = 104). Brazil was the country with the highest number of all types of RE in both scenarios (Table S3). In Europe, WFs were also the most abundant RE type in the present (n = 5,416) and predicted to remain the most abundant in the future (n = 2,968; Tables S4 and S5). Germany (present) and Greece (future) were leading in the number of WFs, the UK (present) and Spain (future) in solar, and Spain (present) and the UK (future) in dams (Table S5).

In terms of the area occupied by each RE type (considering the 50 $\times$ 50 km cells), South and Central America had a relatively small proportion of cells occupied in the present by at least one development of solar (1.6%), WF (1.9%), and hydroelectric dams (2.9%). Even though all these values are expected to increase in the future (solar: 5.7%, WF: 3.1%, and dams: 3.9%), solar presented the largest expansion with 318 new cells occupied by this type of RE. By contrast, Europe exhibited substantially higher levels of occupancy, with WF representing the most widespread RE type both at present (31.4%) and in the future (39.1%, with 261 new cells), followed by solar, which showed a pronounced increase from 10.1% to 20.6%, with 350 new cells occupied in the future. Hydroelectric dams also displayed more moderate changes (14.5% to 15.2%) with only 25 new cells in the future.

Present co-occurrences of threats

Patterns of threat co-occurrence showed that RE is co-occurring more than expected with other threats in both regions, but several differences were found, highlighting regional differences in the strength and distribution of associations among threats. Examining the current threat co-occurrence patterns in South and Central America, we found that 56% of the threat

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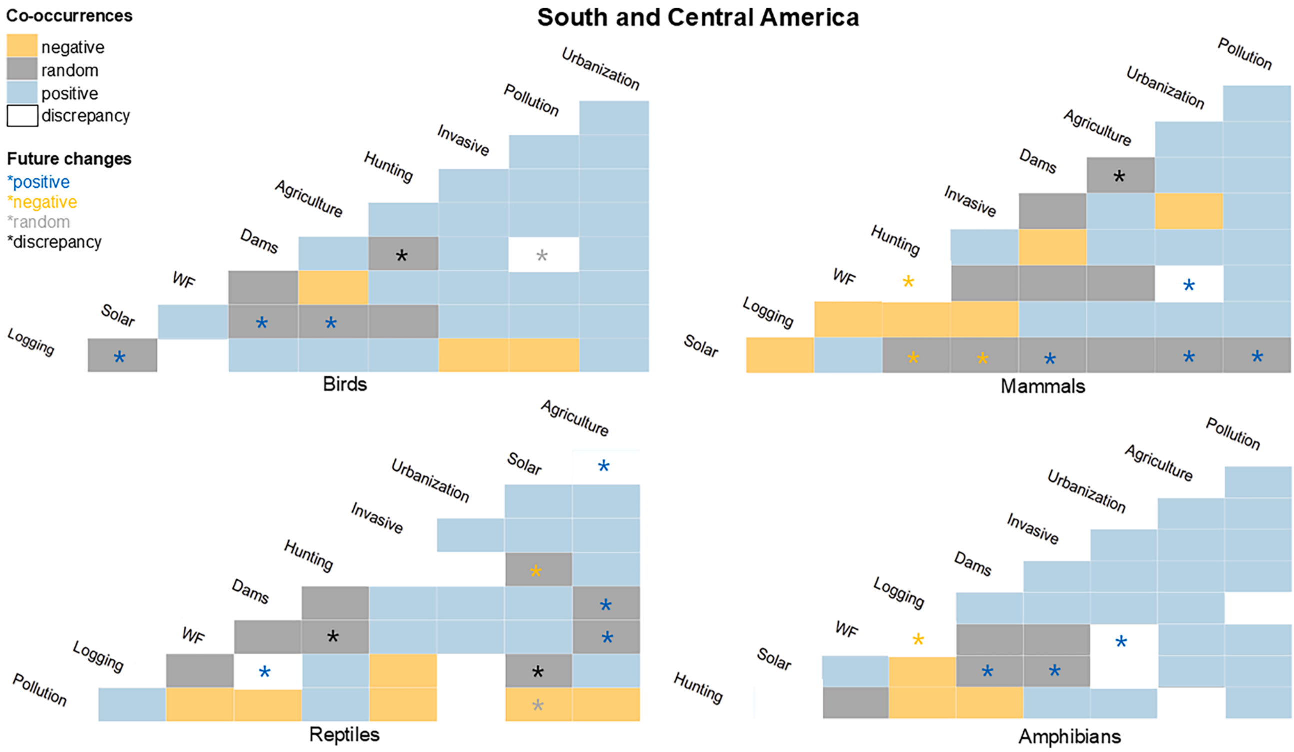

Figure 1. Heatmap indicating the associations determined by the probabilistic co-occurrence models for birds, mammals, reptiles, and amphibians in South and Central America

Colors indicate the type of co-occurrence association between threats (positive, negative, or random) and discrepancy between the confidence intervals and future changes in the associations are indicated with asterisks (*). More details in the supplemental information.

associations were positive, showing that threats are co-occurring more than randomly expected. Within taxa, birds displayed the greatest prevalence of positive associations among threat pairs, with 69% demonstrating positive co-occurrence, whereas reptiles exhibited the fewest (44%) (Figure 1; Table S8). Considering all threats that were positively associated with RE for all taxa combined, we identified more overlapping threats in Brazil, Colombia, Uruguay, and Chile, and the threats' associations with dams were the most frequent and widely distributed in the region (Figures 3, S13, and S14).

In Europe, 42% of the threat associations were positive, considering all taxa. Between individual taxa, mammals and amphibians showed the highest proportion of positive threat co-occurrences (50% each), while birds had the lowest (33%) (Figure 2; Table S9). Considering all the threats positively associated with RE for all taxa combined, we found more associations with dams in southern Europe. The highest number of associations with WFs was in Spain, France, and Germany and with solar in Spain and the UK (Figures 4, S15, and S16).

Future co-occurrences of threats

For future co-occurrences, we found an increase in threat overlaps in both regions. Particularly in South and Central America, the positive associations increased to 65% of threat associations. All taxa presented new positive associations between threats, signaling that the expansion of different RE types will overlap more frequently than randomly expected with other threats (Figure 1). Most of these new associations included solar (69%) (Figure 1).

Birds were still the taxon exhibiting the highest proportion of positive associations (78%) and reptiles the lowest (56%) (Figure 1). Considering all RE and taxa, the future expansion of positive associations was observed mostly in Brazil and Colombia, and solar showed the biggest expansion of all the RE types (Figure 3).

In Europe, the positive co-occurrences in the future increased to 49%, and the expansion of solar in Europe resulted in most of these new associations (80%) (Figure 2). The highest number of positive co-occurrences was observed for amphibians (67%), presenting 6 new positive associations between threats (Figure 2), while birds still had the lowest (36%) (Figure 2; Table S9). Moreover, amphibians were the taxon with the highest values of the likelihood of all threats except hunting (Table S7). Even though Europe presented fewer positive co-occurrences between threats than South and Central America, the greatest number of cells containing two threats involved RE, particularly WF and logging for mammals, solar and WF for reptiles, and WF and urbanization for amphibians (Table S9). Finally, considering all the threats positively associated with RE for all taxa combined, the associations with solar were the ones that appeared to expand the most, particularly in the Iberian Peninsula and Greece (Figure 4).

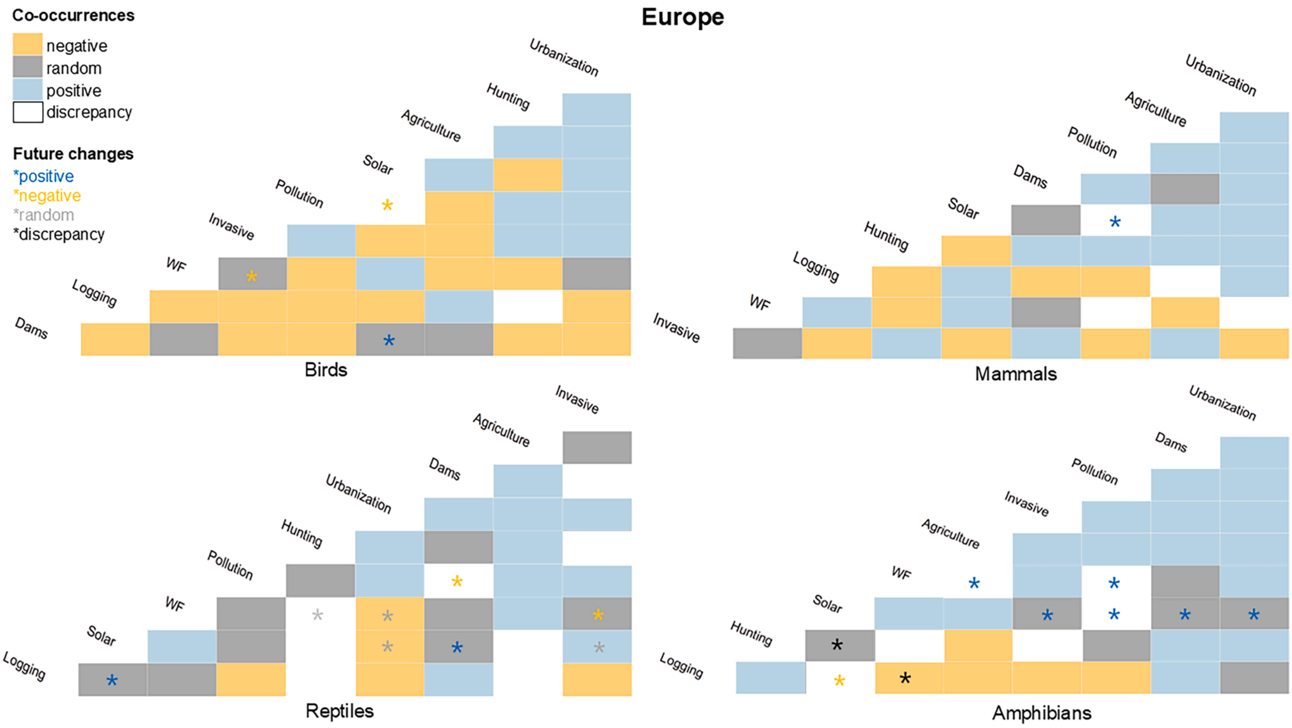

Figure 2. Heatmap indicating the associations determined by the probabilistic co-occurrence models for birds, mammals, reptiles, and amphibians in Europe

Colors indicate the type of co-occurrence association between threats (positive, negative, or random) and discrepancy between the confidence intervals and future changes in the associations are indicated with asterisks (*). More details in the supplemental information.

Link to threatened status

Considering all the areas with overlapping and positively co-occurring threats across taxa, the areas with a higher number of threatened species were located mainly in Ecuador, Colombia, Brazil, the Iberian Peninsula, Greece, and the coasts of the Adriatic Sea (Figures 5, S19, and S20).

When analyzing each taxon separately, the areas where the RE was found to positively co-occur with other human-induced threats constituted a small part of each region (effect sizes range from 0.14 to −0.05; Figures S9–S12). However, we found significant differences in the number of threatened species between cells with and without overlapping threats (Tables S11, S12, S13, and S14). Cells with overlapping threats showed a higher mean number of threatened species across multiple threat associations. In South and Central America, reptiles (71.43%) in the present and birds (95.24%) in the future exhibited the highest proportion of these associations. In Europe, birds consistently showed the highest proportions, both in the present (58.73%) and the future (60.32%). Additionally, temporal changes were detected. For some threat pairs, no significant differences in the number of threatened species were observed under present conditions. However, significant differences emerged in the future, with higher mean numbers of species in cells with overlapping threats. Most of these cases involved solar and WFs and were observed in South and Central American birds and in European mammals and reptiles (Table S11).

DISCUSSION

Using the location of RE developments and threat maps, we provide the first study that evaluates the co-occurrences between RE and other human-induced threats to terrestrial biodiversity across Europe and South and Central America. Our results showed that RE is co-occurring more than expected with other threats and that the planned expansion of RE, especially solar and WFs, is likely to take place in areas where species are already heavily affected by other human activities.

Dams showed the highest number of co-occurrences with other threats and were widely distributed across both regions. This likely reflects the fact that dams represent the oldest RE type, which is also widely distributed. Moreover, dams provide power at a cheaper rate while having the highest power-generating capacity.[32] Our findings revealed that dams were positively associated with almost all threats for amphibians, suggesting that, based on this pattern, amphibians appear to be the most vulnerable group to the potential interaction between threats and dams. This aligns with previous studies of the negative effects on amphibians, underscoring their vulnerability to the deterioration of water quality, habitat degradation, and changes in hydrological regimes.[11,33] The potential negative effects of dams on waterways and associated biodiversity indicate that careful consideration is needed when deciding where and whether to establish and maintain them. This also underscores the importance of prioritizing dam removal when structures are

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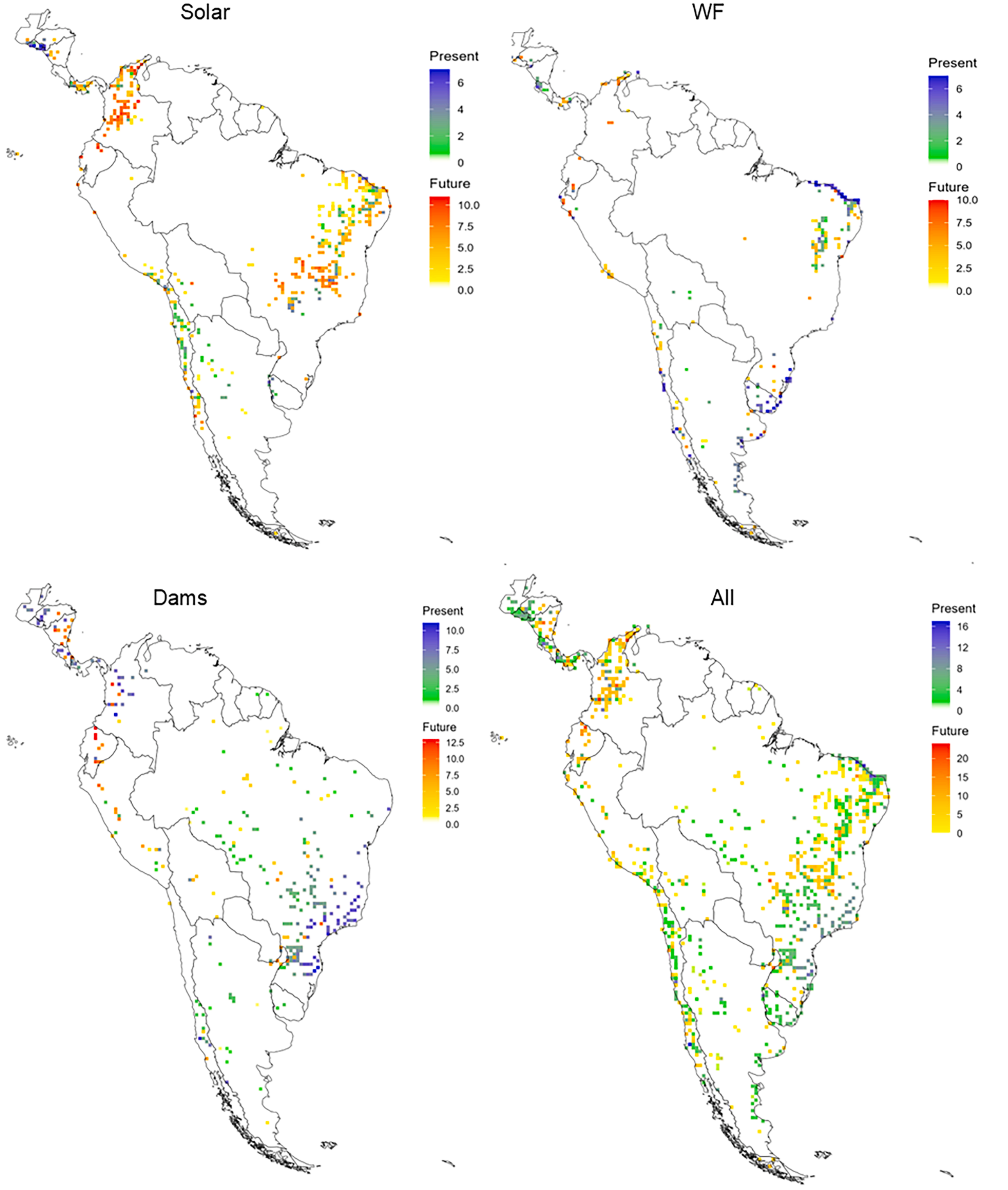

Figure 3. Maps of the sum of all the positive associations between RE (solar: solar panels; WF: wind farms; and dams) and other human-induced threats in each 50 × 50 km cell, and all combinations together (all threats) in South and Central America for all taxa combined

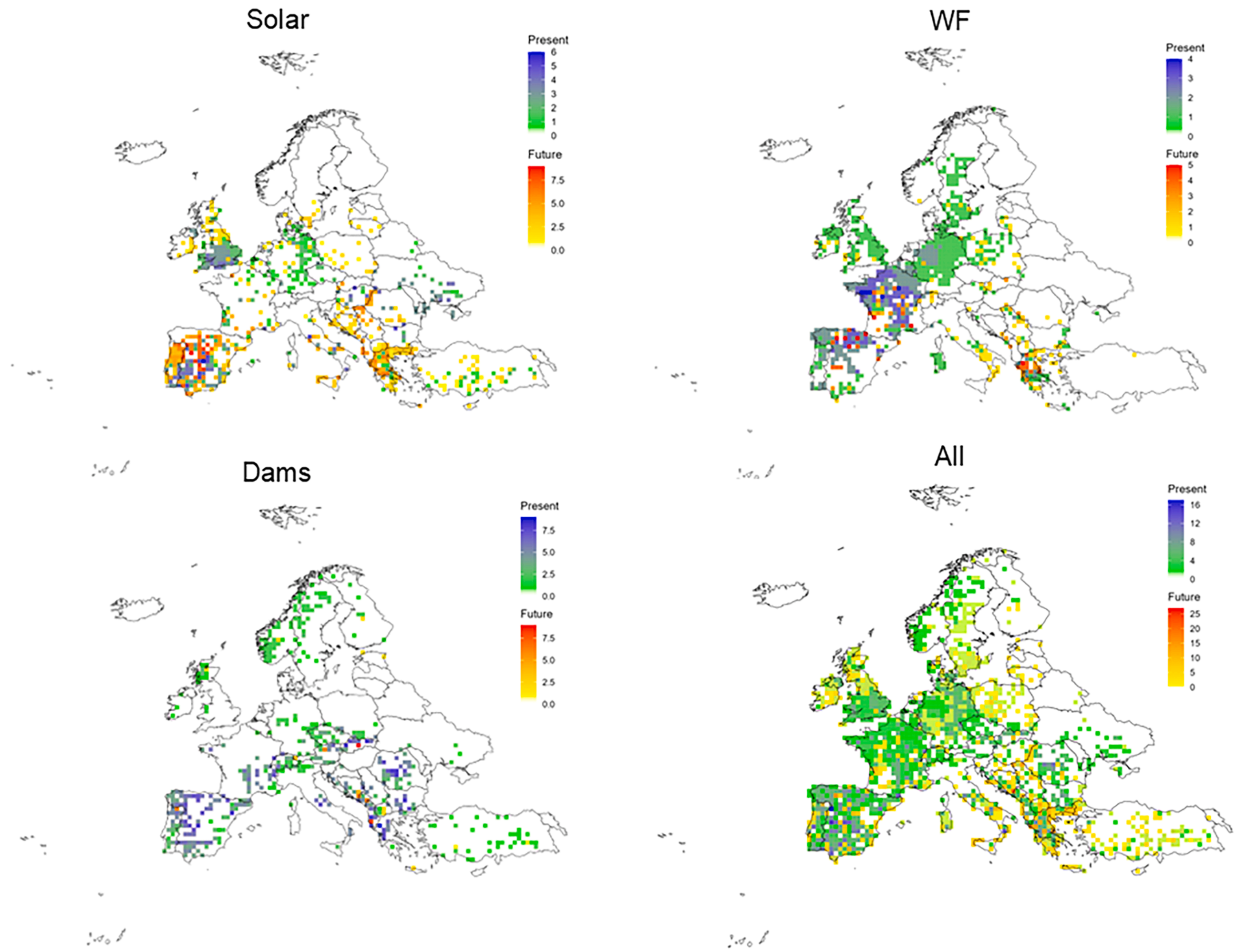

Figure 4. Maps of the sum of all the positive associations between RE (solar: solar panels; WF: wind farms; and dams) and other human-induced threats in each 50 × 50 km cell, and all combinations together (all threats) in Europe for all taxa combined

no longer in use or financially viable. Particularly in Europe, this consideration is reflected in the EU Biodiversity Strategy for 2030, which plans to remove dams and other river barriers to restore the river continuum,[34] which could change the association between threats in the future.

Solar and WFs co-occurred across all taxa in both regions, indicating that these RE types tend to be established in the same places. Both types are expected to expand in the future, but our analysis projected that newly emerging positive threat associations are predominantly linked to solar. Even though the studies assessing the impacts of solar are increasing, recent reviews showed a strong bias toward regions and habitats, highlighting an important gap in South and Central America and in forest and shrublands.[19,35] Moreover, new positive associations between these RE and activities related to land-use change (agriculture, logging, and urbanization) were found. All these activities required large amounts of space,[7,31,32] which is particularly concerning when the future areas with these overlaps have more threatened species than the areas without them. Although the impacts on taxa and regions can vary, this type of threat-overlap could be reduced by careful land-use planning, as suggested by Veach et al.[36] for other threats.

The positive associations between RE and invasive species and pollution could be explained by the disruption generated in the area. Existing literature showed that RE developments can help spread alien and invasive plants due to the reduction in the habitats' resilience to alien plant invasions due to WF, for which early detection and eradication can effectively control them.[37] Additionally, noise pollution generated by WF can also be detrimental for wildlife, suggesting that mitigation measures such as improved turbine design and strategic siting, as well as the explicit inclusion of noise impacts in Environmental Impact Assessments, may reduce these effects.[38]

CONSERVATION CHALLENGES

Our results show that many areas where new RE developments are expected to co-occur with other threats harbor a higher

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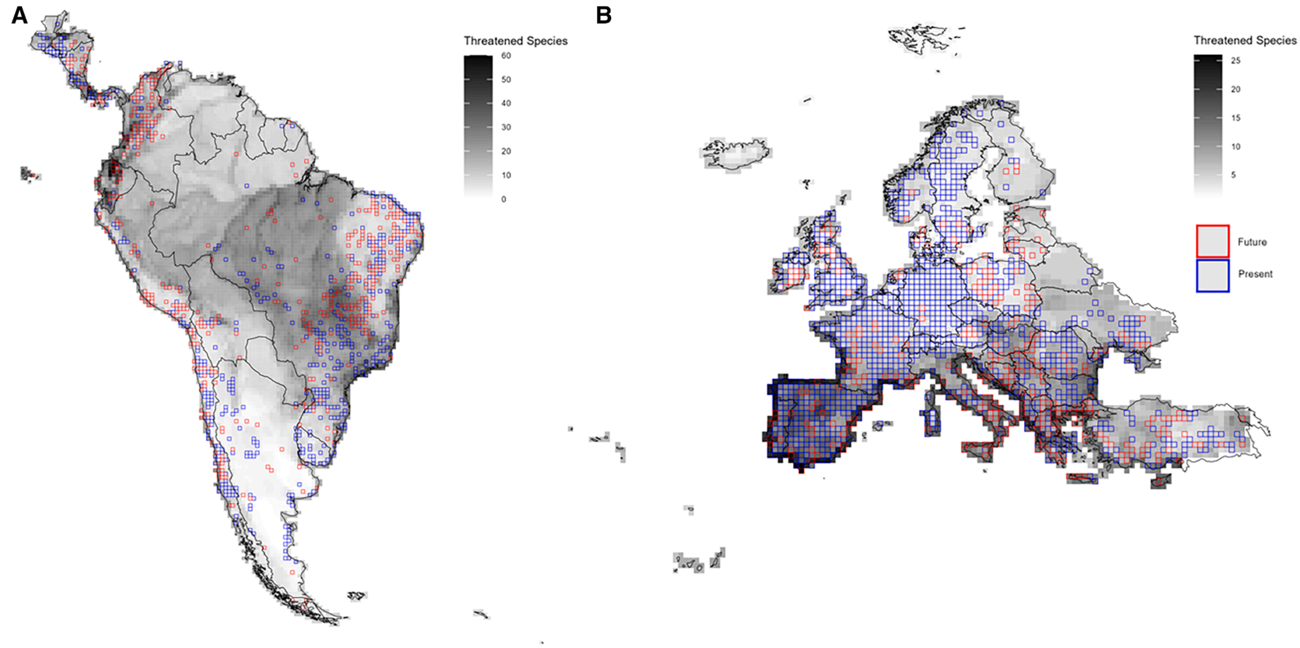

Figure 5. Number of threatened species listed in the IUCN Red List (IUCN, 2022) across each region and the cells (50 × 50 km) where RE and other human-induced threats had a positive co-occurrence for all taxa in the present (blue) and the future expansion of these associations (red)
(A) South and Central America.
(B) Europe.

number of threatened species. Thus, the expansion of RE might be occurring in important areas for biodiversity conservation. As mentioned, this study focused on globally threatened species, but non-threatened and nationally protected ones can also be affected by RE.[39,40] Importantly, the effects of RE on many species remain poorly understood, and this study could help draw attention to particular areas of interest and help assess the areas where more species could be affected, for example, through food webs.[41]

Our study focused primarily on the overlap between other human-induced threats and RE, but we are unable to definitively determine whether these interactions have an additive (equal), synergistic (greater), or antagonistic (less) effect compared with the sum of their individual impacts.[27] Our co-occurrence clustering showed no clear patterns across taxa or regions, but considering all threats, some of them were central for certain taxa (e.g., urbanization for birds, agriculture for mammals in South and Central America, and urbanization and dams for European amphibians, Figures S17 and S18). This suggests that a threat could affect species much more frequently in combination with other threats than randomly expected, as found by Spiller et al.[29] for freshwater species. However, the high variation across threats indicates that not all threats are positively associated with each other. Nonetheless, the presence of multiple threats concentrated within a cell is concerning, particularly given that we focused on regions with the highest likelihood of threat impacts for each taxon (Tables S6 and S7). This is particularly important for amphibians, which were the taxa with the highest values of the likelihood of almost all threats (Table S6 and S7) and had more new positive co-occurrences in the future. While the interactions between threats were not explored in this study, negative impacts such as wind turbine vibrations and agriculture were separately documented for amphibians.[15,42] A new positive association between WFs and agriculture has been projected for the European future, emphasizing the need for further research. Moreover, amphibians remain significantly understudied concerning the impacts of WFs and solar.[19,35]

Throughout this study, we focused on the potential negative effects arising from the co-occurrence of threats. However, in certain contexts, other research has documented positive effects of RE developments on biodiversity. For example, small-scale solar developments in agricultural landscapes have been shown to increase the abundance of some bird species,[43] or positive ecological effects of WF on vegetation were found in a desert.[44] Co-locating RE in intensively used areas, such as agrivoltaic systems that integrate solar with crop cultivation or animal husbandry, could also offer a potential solution by maximizing land-use efficiency and increasing food and energy production while minimizing ecological impacts.[45] Nevertheless, these potential benefits are highly context-dependent and must be evaluated locally. This underscores the need for more site-specific studies, particularly in the areas highlighted in this work where multiple threats are co-occurring.

Limitations of the study

There are challenges in this study that are important to consider. The first one is related to the threat maps, which were developed based on the species present in each area and did not consider that the species had already been extirpated.[23,46] This could partially explain the lower number of positive co-occurrences in Europe, which does not mean that species are less affected by human activities, but only that fewer species are still around to experience the impact. The scale used (50 × 50 km) also introduced some issues and could lead to overestimating the areas where positive threat associations and the species overlapping with them are found, since the RE developments are usually much smaller than 2,500 km^2 and not equally distributed within a cell. However, many species travel long distances every day,[47,48] increasing the probabilities of encountering RE. Related to the RE data, we considered the presence of at least one RE development, so we are not capturing the intensification of these areas, but it is something that must be studied in the future, especially for WFs, for which the number of wind turbines in each area could vary the effect on species.[49] This could also explain the lack of new positive co-occurrences between threats for European birds, for which the new threat could be the intensification of an area, as it was determined by previous studies.[40,50] Further studies should also focus on other taxa, as RE impacts have been reported, such as the impact of dams on fish[51] or solar panels on insects.[19]

Conclusion and final remarks

In this study, we found that many threats are co-occurring in both regions, which highlights the importance of assessing the impacts of multiple threats on species. This becomes even more critical when the initial conditions of an area pose high risks for endangered species. However, very few studies considered the potential interaction between RE and other human-induced threats (e.g., Sanz-Aguilar et al.[52]). Thus, our results can help promote more studies that can evaluate conservation actions targeting the threats involved in the highlighted areas. Our results revealed positive associations between RE and other human-induced threats across taxa and regions, in line with previous findings.[14] These patterns underscore the need for careful, forward-looking strategies to reduce potential cumulative impacts as RE expands. Avoiding undisturbed areas with higher concentrations of threatened species should be a primary consideration, as land-use change remains a major driver of habitat and biodiversity loss.[31] Co-locating RE projects with existing infrastructure or developing them on degraded lands would be optimal from a conservation perspective.[53] For instance, urban or degraded lands as part of restoration projects (providing a sustainable source of funding for the restoration activity) were proposed for the installation of solar to mitigate habitat loss in natural and semi-natural habitats.[19,54–56] In this sense, our results showed that in the future in South and Central America, WFs are positively associated with urbanization for all groups. However, wind turbines can also cause significant disturbance to people,[32,57] so more information is needed to understand this relationship. Nevertheless, when selecting sites for new RE developments, cumulative impact assessments and careful land-use planning are needed to evaluate the combined effects of all human activities on species, rather than focusing solely on a specific development.[53] Additionally, monitoring and mitigation measures during the development and operation stages are crucial to ensure that RE developments have the lowest impact possible. Moreover, adopting standardized monitoring measures across RE would make data comparable across sites and regions and help improve our understanding of RE impact.[19,49]

Identifying commonly co-occurring threats and the spatial patterns of these associations are crucial steps in understanding their interactions and conducting a more comprehensive assessment of all human impacts on biodiversity. By integrating RE developments with other human-induced threats, we can refine our prioritization and optimize strategies that address both the urgent need to transition away from fossil fuels and the equally critical goal of halting biodiversity loss.

METHODS

RE developments data

We used the online and open access worldwide databases of Global Energy Monitor (https://globalenergymonitor.org/) for the present and future locations of onshore WFs and solar, and for the future locations of hydropower dams. We used only medium and large developments (>10 MW), excluding small and residential installations, and independently validated the locations to identify and remove errors and verify the data accuracy of the global dataset using Google Earth imagery. For the present, we considered the developments that were already in the operation state. The future scenario considered the expansion of RE by adding the developments under construction, in the pre-construction stage, and announced to the present ones. The future includes developments that are planned until 2032 in South and Central America and 2038 in Europe. For the current locations of dams, we used the data of the Global Dam Watch (GDM) database (version 1.0) published by Lehner et al.,[58] which prioritizes larger dams. We selected the dams with electricity power production and excluded the ones with poor and unreliable quality data. We then restricted the analysis to South and Central America and Europe and informed the details for each region (Tables S1–S5). Further details regarding the methods can be found in the supplemental information.

Threat maps

We used an updated version of the threat maps of birds, mammals, and amphibians generated by Harfoot et al.[23] and for reptiles by Farooq et al.[46] that include the main threats identified by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)[59]: habitat loss and degradation (split into agriculture, logging, and urbanization), hunting and trapping, invasive species, and pollution. We excluded climate change since its effects will depend on global efforts and cannot be significantly influenced locally, as mentioned by previous authors.[36] The threat maps used were generated using the data from the assessed species in the IUCN Red List (2022–2) with a probabilistic framework, incorporating the spatial uncertainty of only knowing that a species is affected somewhere in its range. These maps have a resolution of 50 × 50 km, where each cell represents the probability of impact of a particular threat as the proportion of species occurring in the cell affected by that threat. We clipped the areas corresponding to our regions and excluded the cells with fewer than 10 species present for each taxon.[23,46]

Co-occurrences

We used a co-occurrence approach to describe clustering in threat and RE presence for both study regions. For each RE type, we selected the 50 × 50 km cells with the presence of at least one development and generated a binary map (1 = presence, 0 = absence) for the present and future separately. For the threat maps, we transformed each continuous map into binary maps, where one corresponded to the cells with the top 25% values of each threat, taxon, and region separately. We selected this threshold to detect the areas with the highest probabilities of impact of each threat, but to test our threshold, we created a confidence interval (top 27.5% and 23.5%; Tables S6 and S7).

For the co-occurrence analysis, we used the *cooccur* package in R studio (R4.2.1).[60] This approach implements a probabilistic network model to directly test co-occurrences among observed threats,[61] assuming that the probability of the occurrence of a threat that affects any taxon is equal to its observed occurrence among all sites. Based on this model, we estimated the deviance between the number of times two variables (each RE with each threat) co-occurred in a grid cell and the pattern expected by chance (variables being independently distributed). From this, the probability that the observed frequency of co-occurrence can be expressed as significantly higher (positive association), significantly lower (negative association), or not significantly different from a random association.[61] In the context of this study, a positive association means that an RE type and a threat tend to co-occur in the same cells more than randomly expected. To test the impact of our binary threat detection threshold, we run three matrices (25%, 27.5%, and 23.5% threat thresholds; Figures S1–S8) and only considered the results that were consistent across all three levels. To compare results between study regions and present and future scenarios, we calculated the standardized effect sizes (Figures S9–S12), as the differences between expected and observed frequency of co-occurrence divided by the number of cells in the dataset.[60,61] Finally, we summed all the positive co-occurrences between RE and other human-induced threats for all taxa in each cell, for the present and the future separately.

IUCN Red List data

As an exploratory analysis to evaluate the conservation relevance of each 50 × 50 km cell, we quantified the number of threatened species (vulnerable, endangered, and critically endangered) in the IUCN Red List (IUCN, 2023–2) present in each cell (Table S10; supplemental note). First, we selected the cells with overlapping threats with a positive co-occurrence in the present and the future across taxa and spatially assessed the areas where more threatened species were present. Second, we considered all possible combinations of threats involving RE in the present and future and classified each cell into two groups: cells with and without overlapping threats. We calculated the mean using a bootstrapping approach and its confidence intervals (Tables S13 and S14) and compared the number of threatened species between groups using a Mann-Whitney U test[62] for each threatened category, pair of threats, and region. We included all threatened species of each taxon, regardless of whether they were explicitly threatened by RE. While we recognize that species are not equally affected by RE, as shown by Thaxter et al.,[49] our rationale for including all threatened species was to broadly capture the areas where species may be more exposed to human pressures, thereby providing a more inclusive picture of potential conservation priorities.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Antonella Gorosábel (gorosabel@sund.ku.dk).

Materials availability

This study did not use materials or generate any new, unique reagents.

Data and code availability

All data used in this study are publicly available (see the methods section). The original code and final tables used have been deposited and are publicly available at Zenodo (https://doi.org/10.5281/zenodo.18587479) as of the date of publication. Data generated from this study are included in the main text or in the supplemental information.

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AUTHOR CONTRIBUTIONS

Conceptualization and study design: A.G. and J.G.; data acquisition: A.G., H.F., and M.M.; methodology and data analysis: A.G., L.L.I., and J.G.; interpretation of results: A.G., L.L.I., M.M., and J.G.; funding acquisition: A.G. and J.G.; writing – original draft: A.G.; writing – review and editing: all authors; supervision and coordination: J.G.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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