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Aligning renewable energy expansion with climate-driven range shifts

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Fossil fuel dependence can be reduced, in part, by renewable energy expansion. Increasingly, renewable energy siting seeks to avoid significant impacts on biodiversity but rarely considers how species ranges will shift under climate change. Here we undertake a systematic literature review on the topic and overlay future renewable energy siting maps with the ranges of two threatened species under future climate scenarios to highlight this potential conflict.

The world is at a critical threshold for stopping the worst of both climate change and biodiversity loss. Reinforced national policies and international climate goals are propelling substantial renewable energy (RE) development. Globally, 290 gigawatts (GW) of capacity were developed in 2021, with solar energy composing half of the expansion, followed by wind and hydropower. To stay on track for net zero emissions by 2050, solar and wind energy must grow an additional 1,120 GW of capacity annually by 2030[1].

At the same time, extinction rates are without precedent across human history. Global populations of mammals, birds, amphibians, reptiles and fish have declined by two-thirds in the last 50 years. Higher-level taxonomic losses (for example, of insects) may be the first in Earth's history, even across the 'Big Five' mass extinctions[2]. To date, habitat alteration and loss are the greatest drivers of species decline[3], with climate change expected to exacerbate these trends. In response to climate change, many species are expected to shift from formerly suitable areas into newly favourable areas, if habitat in these places still exists[4]. As a result of this confluence of global changes, a deeper understanding of how RE expansion will affect biodiversity is urgently needed.

Despite being necessary to abate anthropogenic climate change, RE can endanger biodiversity at local and regional scales. To date, the development of RE has emphasized large, centralized industrial power plants embodying increasingly greater annual land transformation (2,000 ha TWh^{-1} y^{-1} for ground-mounted photovoltaic solar energy and 12,000 ha TWh^{-1} y^{-1} for wind energy with spacing) that outpaces transformation rates by coal (1,000 ha TWh^{-1} y^{-1}) and natural gas (1,900 ha TWh^{-1} y^{-1})[5]. Land transformation can drive habitat loss in places that may serve as climate change refugia under future climate conditions[6], while physical barriers and disturbances surrounding RE power plants can hinder the ability of species to migrate (for example, by tracking isotherms). Alternatively, RE installations could also serve as opportunities for conservation, such as conferring opportunities for ecosystem restoration and assisted migration[7].

Although causing fewer negative impacts than fossil fuels, the accelerating RE build-out offers an opportunity to use the latest ecological modelling to minimize habitat impacts[8]. Impacts on biodiversity can occur throughout the life cycle of an RE facility, from construction (for example, habitat loss, vegetation removal and soil blading[9]) to operation (collisions and barotrauma) to decommissioning[9,10]. Large, ground-mounted solar energy (>1 MW) and wind energy facilities have an operational lifespan of 25–40 years and can embody expansive physical footprints[11], with environmental impacts probably to continue for decades and centuries beyond the lifespan of the original facility. Conflicts between RE siting and large terrestrial mammals, non-vertebrates, migratory species and plants have been largely ignored, with a few exceptions[12,13]. The migration of species necessitates a pathway through time and space, extending beyond the mere prevention of development in future habitats[14]. For example, ref. 15 found that solar energy development in the United States will impact land important for animal movement between protected areas (17% of total development) and land most valuable for climate-change-induced migration for a broad cohort of species (33%). Others[14] found that 11 out of 23 (48%) priority California bird species, including resident and migratory species, are potentially vulnerable to population-level effects from mortality caused by RE. Ultimately, potential conflicts between RE expansion and shifts in the ranges of biodiversity under climate change must be evaluated for all biodiversity and at the species-scale[15–17], which is feasible through advances in species distribution modelling (SDM).

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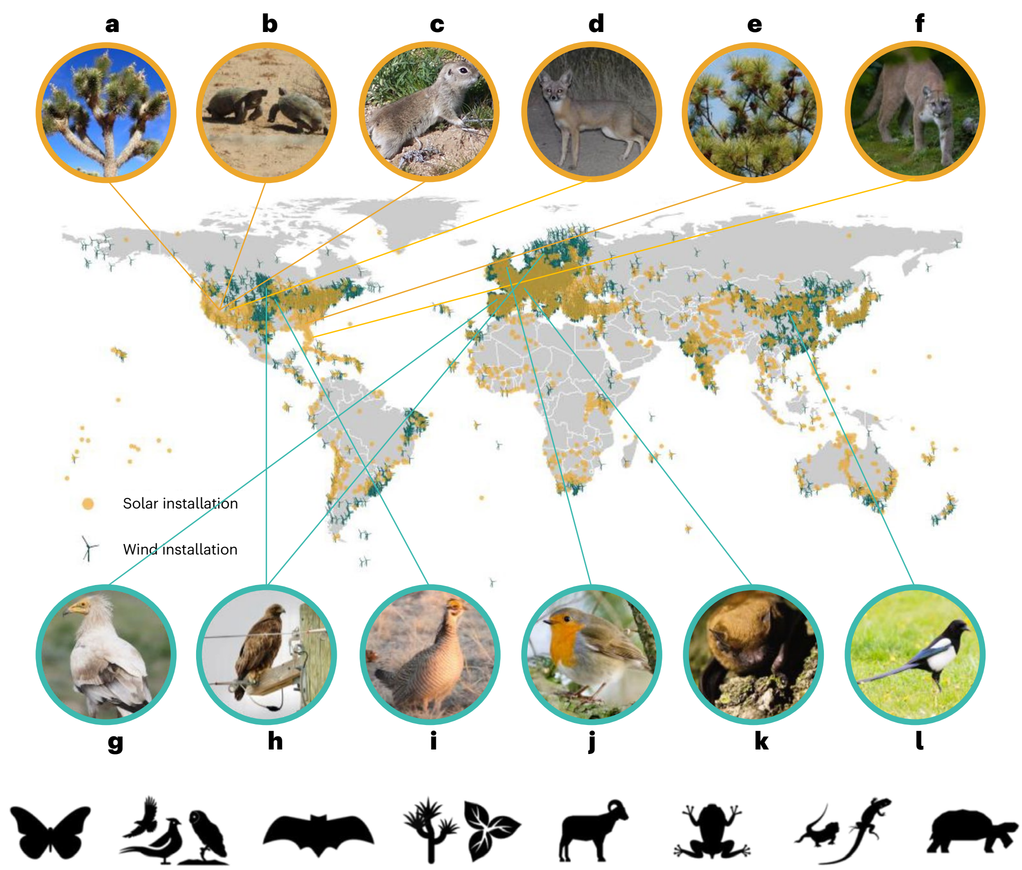

	Scientific names	Common names	Conservation status	Region	Energy	Citation
a	*Yucca brevifolia*	Joshua tree	LC	United States (CA)	Solar	Ref. [27]
b	*Gopherus agassizii*	Mojave desert tortoise	CR	United States (CA)	Solar	Refs. [28,29]
c	*Xerospermophilus mohavensis*	Mojave ground squirrel	NT	United States (CA)	Solar	Ref. [30]
d	*Vulpes macrotis mutica*	San Joaquin kit fox	EN	United States (CA)	Solar	Ref. [31]
e	*Pinus palustris*	Longleaf pine	EN	United States (southeast)	Solar	Ref. [32]
f	*Puma concolor*	Florida panther	EN	United States (FL)	Solar	Ref. [33]
g	*Neophron percnopterus*	Egyptian vulture	EN	Europe (Spain)	Wind	Ref. [34]
h	*Aquila chrysaetos*	Golden eagle	LC	Global	Wind	Ref. [35]
i	*Tympanuchus pallidicinctus*	Lesser prairie-chicken	VU	United States (Great Plains)	Wind	Refs. [36,37]
j	*Erithacus rubecula*	Robin redbreast	LC	Europe	Wind	Refs. [30,38]
k	*Nyctalus noctula*	Noctule bat	LC	Europe (Germany)	Wind	Refs. [30,38]
l	*Pica pica*	Magpie	LC	Asia (China)	Wind	Refs. [38,39]

Fig. 1 | Examples of species with documented impacts from RE expansion. **a**–**l**, Map showing the species of concern known to be affected by solar and wind installations (2020; refs. 26,27): *Y. brevifolia* (**a**), *Gopherus agassizii* (**b**), *Xerospermophilusmohavensis* (**c**), *V. macrotis mutica* (**d**), *Pinus palustris* (**e**), *Puma concolor* (**f**), *Neophron percnopterus* (**g**), *Aquila chrysaetos* (**h**), *Tympanuchus pallidicinctus* (**i**), *Erithacus rubecula* (**j**), *Nyctalus noctula* (**k**), *Pica pica* (**l**). USFWS, United States Fish and Wildlife Service; IUCN, International Union for Conservation of Nature; EN, Endangered; EP, Endangered/threatened but precluded; LC, Least concern; NT, Near threatened; R, rare; VU, Vulnerable. Icon credits (**a**–**l**): iNaturalist (https://www.inaturalist.org/ under a Creative Commons licence CC BY 4.0). (Acknowledgements section contains creator credits; Supplementary Text 2 gives the list of references in full)[28–40].

Anticipating which species are most likely to be affected now and in the future is key to a climate-resilient siting strategy that balances RE development with impacts on biodiversity (Fig. 1). We performed a systematic literature review in Web of Science (Clarivate Analytics) to assess how the impacts of climate change on species range shifts have been considered in the academic literature focused on RE siting (Extended Data Fig. 1). We focused on peer-reviewed journal articles that report biodiversity-related criteria for RE siting to capture siting and mapping activities with the potential to reduce risks of development to biodiversity directly. Although documentation alone does not reduce such risks, it is often a precursor to ameliorating impacts. Most of the empirical studies (93% of RE and biodiversity-related articles) documented the role of biodiversity as criteria for RE siting, emphasizing the use of contemporaneous species' ranges and/or conservation areas. We found that studies on the impacts of RE expansion on biodiversity emphasized RE-related content relative to biodiversity (based on the frequency of keywords) but documented biodiversity spans a diverse range of taxonomic

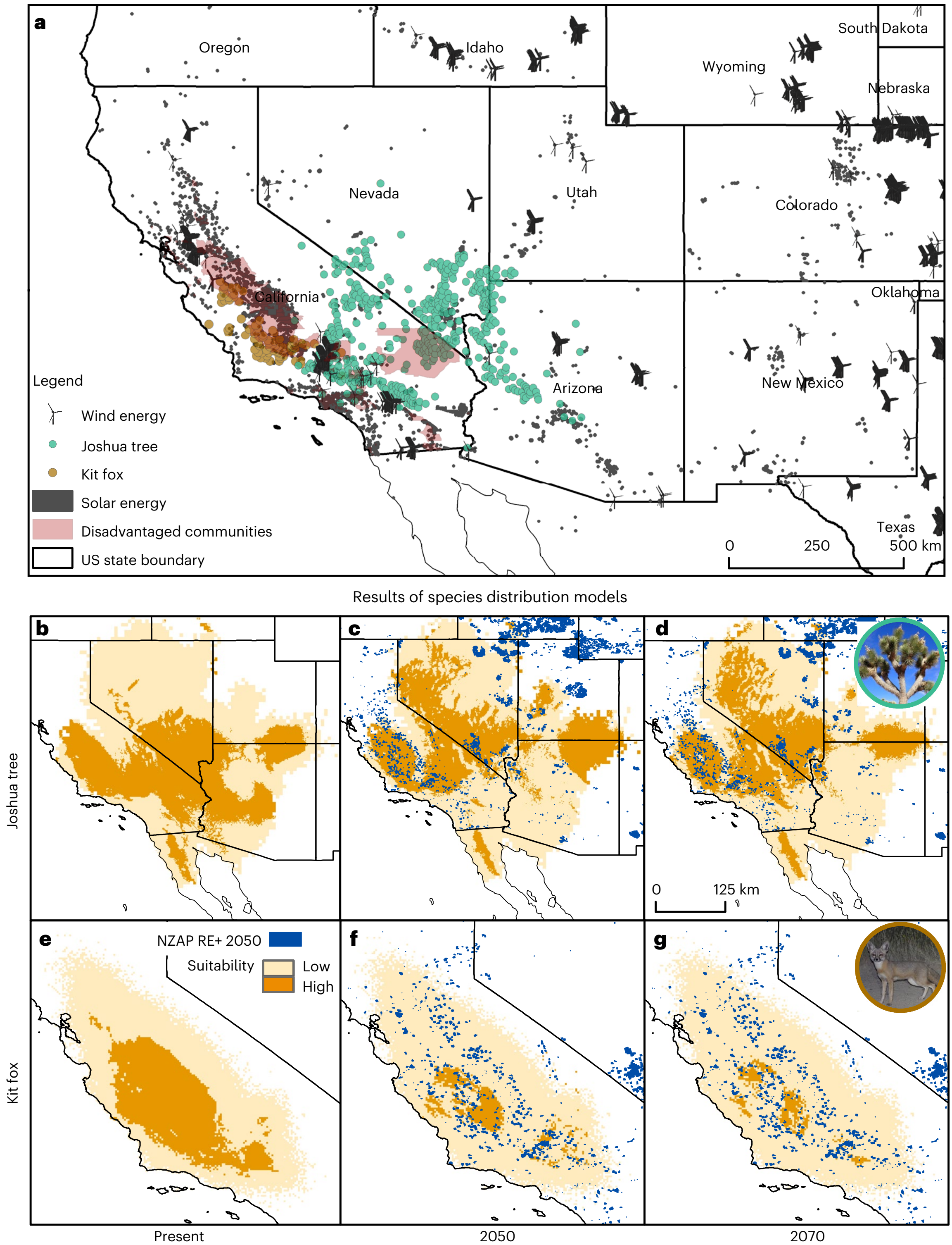

Fig. 2 | Present and future species distribution models of Joshua tree and kit fox highlighting the areas of overlap with RE. We predicted the present and potential future suitable habitat for two vulnerable species inhabiting deserts of the southwestern United States intersected with potential RE development. **a**, Overlay of current occurrences of Joshua tree and the endangered San Joaquin kit fox, RE development (wind and solar energy power plants), and disadvantaged communities. **b**–**d**, Results of SDM for Joshua tree with current (**b**) and future (2050, **c**; 2070, **d**) climate change under moderate emission scenarios. **e**–**g**, Results of SDM for San Joaquin kit fox with current (**e**) and future (2050, **f**; 2070, **g**) climate change. NZAP RE+ 2050 maps for RE potential in the United States intersecting with the species climate-driven range shifts (2050). Image credits (**d** and **g**): iNaturalist (under a Creative Commons licence CC BY 4.0). See Acknowledgements section for the creator credits.

groups, including some of the world's most threatened species (Fig. 1 and Extended Data Fig. 2). Nevertheless, only 18.4% of these RE-related articles documented the role of climate change impacts on biodiversity[9,18,19]. Furthermore, only 1.9% of these (18.4%) RE-related articles documented the potential for conflicts between RE expansion and climate-driven range shifts[19,20] (Extended Data Fig. 1). This dearth of literature stands in contrast to the rapidity with which RE is developing; a way forward is needed.

To illustrate how species range shifts can be incorporated into RE siting, we focused on two climate-vulnerable species of the southwestern United States: the Joshua tree (*Yucca brevifolia*; a candidate species for listing as threatened under the California Endangered Species Act) and the San Joaquin kit fox (*Vulpes macrotis mutica*; listed as federally endangered under the US Endangered Species Act). On the basis of projections from SDMs, under a moderate greenhouse gas emissions scenario (representative concentration pathway (RCP) 4.5), favourable climate for the Joshua tree will decrease in the south of the species range and increase in the north, with an overall decline in suitable area (with reference to currently suitable area) of 25% and 31% by 2050 and 2070, respectively (Fig. 2). In addition to climate stress, the current core of the species range, along southern California and Nevada, is also expected to be affected by RE development, projected to be favourable under Net-Zero America Project (NZAP) RE build-out E+ RE+ Scenario 5 (that is, 100% aggressive renewable development by 2050). Thus, southern Joshua tree populations are likely to be threatened by both climate and RE development. Likewise, the kit fox is expected to lose up to 81% of its suitable habitat in California under future (2070) climate change. However, kit foxes have been found to use solar facilities for habitat, meaning that careful attention to the species' ecological requirements could reduce the negative impacts of development. Existing California-based solar energy sites overlap with 0.05% and 0.2% of Joshua tree and kit fox predictive suitable habitat, respectively (Fig. 2). The overlap may increase up to 1.7% and 3.9% in the future under NZAP E+ RE+ scenarios for Joshua tree and kit fox, respectively.

Aligning RE expansion with climate-driven range shifts begins with the development of decision pathways that inform future RE expansion using simple to complex spatial analyses. Combining connectivity and SDMs to define conservation priorities for many species will help identify priority areas in the process of aligning RE expansion with climate-driven range shifts[21]. For example, a simple spatial 'overlay' could include spatially explicit RE expansion maps with species' distribution data and their future projections. A typical multicriteria analysis integrates technical, economic and sometimes socio-ecological constraints for mapping future RE infrastructure. Projected ranges can be included as another layer to account for shifting patterns of biodiversity. The proportion of future species range loss and other criteria can be weighted to create tiers of priority zones based on preferences, regulations, policies and values[22]. Analyses can be used to develop maps that include intermediate data (for example, species' current and future ranges, solar and wind future development scenarios, including climate-driven range shifts and case studies) that can be shared with stakeholders—in accordance with best practices supporting environmental justice and transparent decisions[23]—for feedback and then finalized as synthesized endproducts to inform decision outcomes. Ultimately, possible decision outcomes after including climate-driven range shifts could be avoidance, planned assisted migration, compensatory mitigation, ecological restoration and wildlife-friendly mitigation strategies.

Given their interconnectedness, climate change and biodiversity loss are referred to as the 'twin crises' facing the global financial system, posing an existential threat to nature, people, prosperity and security[24]. RE expansion is considered to be one key strategy for mitigating anthropogenic climate change by reducing fossil fuel dependence. The escalating pace of global change underscores the urgency of adopting a comprehensive approach to mitigate potential conflicts between large, land-intensive development and biodiversity. Climate change is a growing threat to many species and the expansion of RE will indirectly contribute to mitigating this threat in the future[25]. Thus, the time is right for a future-facing RE siting strategy that accounts for potential conflicts and opportunities between RE and long-view conservation.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-01941-3.

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Methods

Systematic literature review

We conducted a systematic literature review to develop a corpus of articles on RE and biodiversity. Next, we assessed the balance of subject matter (biodiversity, RE siting and methodological approaches) within each article by quantifying the frequency of keywords. Last, we analysed each article to determine the state of the knowledge on the consideration of climate-driven range shifts of species in the context of RE expansion.

Initial corpus development. To evaluate the extent to which considerations of biodiversity and climate-induced range shifts are integrated into the planning of RE installations, we conducted a systematic literature review following the PRISMA (preferred reporting items for systematic reviews and meta-analyses) guidelines[41] (Supplementary Fig. 1). Our review encompassed various publication types, including peer-reviewed journal articles, conference proceedings, book chapters and technical reports; collectively referred to as 'articles'. Articles were retrieved from Web of Science, a multidatabase platform (Clarivate), by entering a set of search strings into the platform from 4 November to 20 December 2022. We structured the search strings as follows: ("renewable" OR "solar" OR "wind") AND ("siting" OR "plan*" OR "site*") AND ("wildlife" OR "species" OR "biodiversity"). No temporal constraints were imposed in the search to ensure that articles were not precluded from retrieval on the basis of publication date. To avoid retrieving articles related to power plants sensu stricto, the search excluded terms containing the word "plant*". We acknowledge that this approach may not have comprehensively captured all articles documenting plants (kingdom Plantae) and their ecological ranges within the same context; however, the augmentation of the search strings with ("wildlife" OR "species" OR "biodiversity" OR "vegetation") and ("wildlife" OR "species" OR "biodiversity" OR "plant") led to a return of 29,598 and 77,244 articles, respectively. Consequently, our analytical focus emphasizes the consideration of wildlife and their ecological ranges within the context of RE planning studies. Upon execution of the search, we identified a total of 157 articles published between 1997 and 2022, which were integrated into a preliminary corpus.

Text analysis of the initial corpus. Next, we sought to understand the nature and balance of the content of the article through an analysis of the frequency of 18 keywords, which were categorized into three thematic groups: biodiversity, methods (methods commonly used to understand species' range shifts and siting-related RE opportunities and impacts) and renewable energy siting. Specifically, we used the pdftools R package[42,43] to quantify the frequency, mean and 95% confidence intervals of each keyword and the averaged frequency of keywords for each category. The frequency analysis included all text across the entire article (for example, from abstract to author contributions). These results provide insight into the frequency of specific keywords within the corpus, shedding light on the prevalence of various terms related to RE and biodiversity considerations in the literature (Extended Data Fig. 2). The six key terms per category were: (1) biodiversity—biodiversity, protected area, endangered species and wildlife, and climate change; (2) methods—multiple criteria decision analysis, criteria, analytic hierarchy process, overlay analysis, suitability prediction and maxent; and (3) renewable energy siting—energy, solar, wind, site, plan and planning.

Final corpus. The inclusion criteria for articles were based on the keyword sets. Specifically, if any keyword was identified once in an article, that article was included in the final corpus. We calculated the percentage of articles in the final corpus (that documented one or more keywords) that were identified in the initial corpus as an index for an approximate level of the robustness of our initial search in Web of Science. We established a three-tiered, non-exclusive classification system of increasing depth to improve upon the granularity of our analysis. The tiers are: (1) incorporated biodiversity in analysis, (2) assessed the impact of climate change on biodiversity and (3) examined climate-driven range shifts (Extended Data Fig. 1). The first tier encompasses all articles that took biodiversity into consideration. The second tier encompasses articles that explored the impact of climate change on biodiversity and the third tier includes articles that specifically addressed climate-driven range shifts.

Research questions. Articles that met the criteria (focused on RE, specifically solar and wind siting or their impacts on biodiversity) (94%) were analysed following methods by ref. 44 across a set of questions. These questions included:

- Where is/are the RE expansion impact(s) on biodiversity (or species, wildlife, hereafter biodiversity) documented?
- What energy type does the RE expansion include (solar, wind or both)?
- What type of methodology did the authors apply: (1) quantitative, (2) qualitative, (3) mixed methods (including the quantitative and qualitative) and (4) other non-analytical?
- For quantitative, qualitative or mixed-method analyses, did the authors include biodiversity as a criterion?
- Do the authors include biodiversity in their analysis?
- Does the article report the impact of climate change on biodiversity? If authors reported the impact of climate change on biodiversity, do they discuss climate-change-induced species range shifts?

Species distribution modelling

Data collection. Point occurrence data for the locations of species were obtained from the Global Biodiversity Information Facility (https://doi.org/10.15468/dl.eeccxs,10.15468/dl.4kzz82)[45]. Contemporary and future climate data were downloaded from WorldClim v.2.1 at 2.5 arcmin resolution[46]. To account for uncertainty, we examined output from several global circulation models and emission scenarios centred on the 2050s and 2070s. The current global inventory for solar energy and wind farms was obtained from refs. 26,27. Future spatial datasets for future RE potential pathways and infrastructure were obtained from Net-Zero America scenarios (https://netzeroamerica.princeton.edu; ref. 47). Net-Zero America reports five RE scenarios: high electrification (E+), less-high electrification (E−), high biomass (E− B+), renewable constrained (E+ RE−) and 100% renewable (E+ RE+). We obtained high electrification (E+) and 100% renewable (E+ RE+) for this analysis.

Processing. Downloaded species presence data were cleaned by carefully checking each point and removing the duplicates, oceanic points and outliers. Cleaned data were spatially rarefied ~10 km by using the 'spThin' R package to reduce spatial autocorrelation[48]. The data were then divided at random into training and testing sets for model calibration and evaluation. The modelling area was restricted to the species' accessible area[49] by using the Grinnell R package (https://github.com/fmachados/grinnell)[50], which enabled us to distinguish between environments that species can disperse to but are uninhabitable and environments that may be inhabitable but are inaccessible. Current and future climatic variables were clipped to the accessible area. For each taxon, we selected relevant predictors from among the BIOCLIM variables (except for BIOCLIM 8, 9, 18 and 19, as they yield odd spatial artifacts[51,52]). To reduce the correlation between the variables for model calibration, the correlation coefficient and principal components of the layers were calculated across present-day and future climates simultaneously[53]. Principal components together comprising 99% of the overall variation were be used for model calibration. For each species, a MaxEnt v.3.4.4 niche model was calibrated using the kuenm R package[54]. The analysis relied on presence-only data and used the MaxEnt model, which compares presence data with background locations where presence/absence is not observed. The inclusion of absences is important as it enables the prediction of the probability of presence, allowing for more accurate modelling. MaxEnt generates background observations (pseudo-absences) by selecting random points from the study area that are not known to be presence locations of the species of interest and predicts the fundamental niche of the species[55].

We use the kuenm R package, which enables detailed model calibration and selection, final model creation and evaluation and extrapolation risk analysis. Next, kuenm identifies and selects the best parameters for modelling using the following criteria: statistical significance, predictive power and model complexity. We also recognize the importance of providing measures of model performance for the SDM and incorporate these assessments to enhance the transparency and rigour of our analysis, including mean area under the curve ratio (>1) and omission error (<0.05) as evaluation metrics[54].

The accuracy of these models was assessed by using the partial receiver-operating characteristic score with a threshold of $E = 10$ (ref. 56). Current and future potential distribution maps were then developed for all species. The potential range shift was identified by overlaying present-day and potential future distribution maps using tools in the kuenm package[54]. Results of the SDM illustrate that current and future RE scenarios in the southwestern United States overlap with potentially suitable areas for both species *Y. brevifolia* and the endangered *V. macrotis mutica*.

We conduct a basic overlay analysis using these species and energy models to illustrate the conflicts between RE development and the suitability of habitats for current and future species populations. Nevertheless, when dealing with several species, conducting a connectivity analysis can assist in identifying priority areas that warrant further investigation[21] (Extended Data Fig. 3 and Supplementary Text 1 giving details of alignment workflow).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Datasets are available in the DRYAD repository, accessible at https://doi.org/10.5061/dryad.bnzs7h4j0 (ref. 57). Private access link to download the data files: https://datadryad.org/stash/share/G6ZVrB6TIqhDxNj1_N7IWob-2Opt269EwgnsQKgMMmg.

Code availability

Code for dispersal simulations and species distribution model analysis used in this study are adopted from https://github.com/fmachados/grinnell (ref. 50) and https://github.com/marlonecobos/kuenm (ref. 54).

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Author contributions

All authors conceived the idea for this manuscript. U.A. collected the data and conducted the analysis. U.A. and R.R.H. developed the figures and manuscript text draft. R.R.H., T.L.M. and A.B.S. edited the manuscript text and figures.

Competing interests

The authors declare no competing interests.

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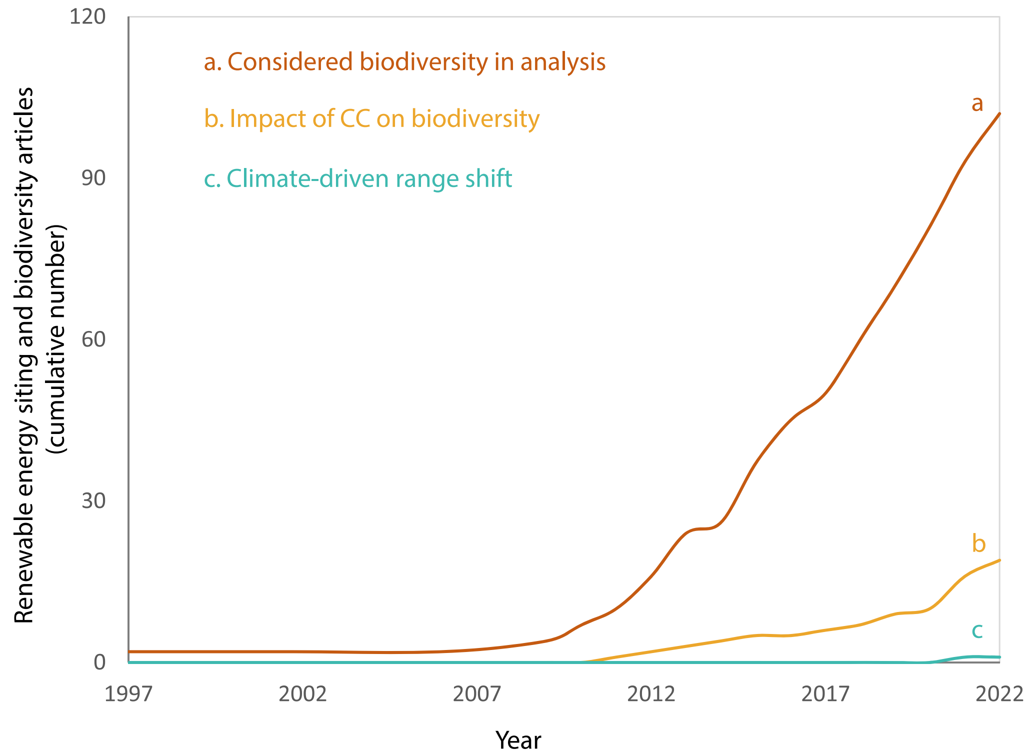
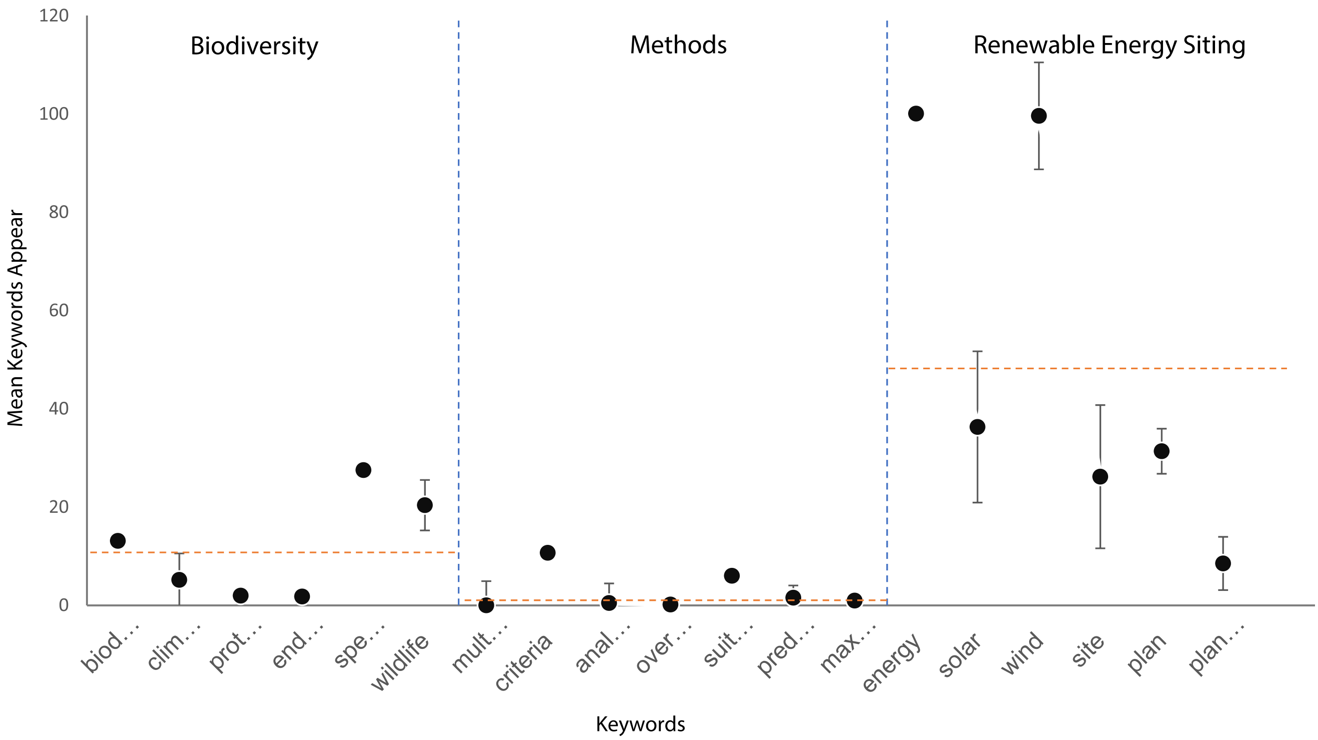
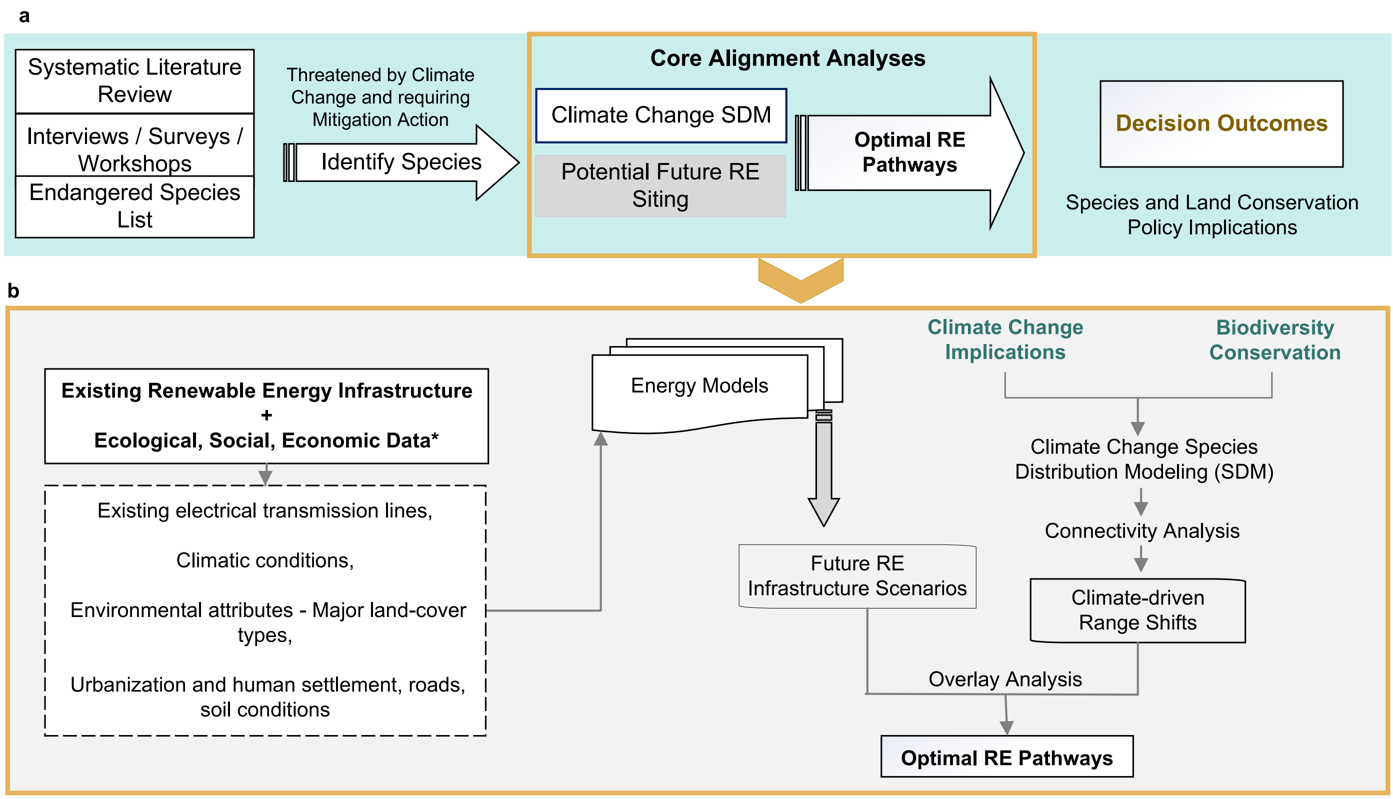


Extended Data Fig. 1 | Analysis of renewable energy siting and biodiversity-related academic articles. Cumulative number (n = 157) of renewable energy siting- and biodiversity-related academic articles published over time, categorized by tier (a, b, c) and meeting criteria for inclusion in the systematic literature review. Articles that met criteria were allocated to a three-tiered, non-exclusive classification of increasing depth if it documented the: (a) concept of biodiversity, for example, the inclusion of wildlife and other taxa, protected areas for conservation and similar overlapping topics (n = 146, 93%), (b) role of climate change on biodiversity and/or the taxonomic group(s) and/or the species of interest (n = 12, 18.4%) and (c) role of climate change as a driver of range shifts for biodiversity and/or the taxonomic group(s) and/or the species of interest (n = 2, 1.9%).



Extended Data Fig. 2 | Frequency of specific keywords within the corpus. The x-axis represents the key terms used in the search, including the six key terms per category were: (1) Biodiversity - "biodiversity," "climate change," "protected area," "endangered," "species," and "wildlife,"; (2) Methods - "multiple criteria decision analysis," "criteria," "analytic hierarchy process," "overlay analysis", "suitability prediction," and "maxent;" (3) Renewable Energy Siting - "energy," "solar," "wind," "site," "plan," and "planning." The y-axis shows the mean number of appearances of these keywords in all the articles (error bars represent 95% confidence intervals).

 https://doi.org/10.1038/s41558-024-01941-3



Extended Data Fig. 3 | Alignment of renewable energy expansion with climate-driven range shifts workflow. An example workflow showing major action steps (a) to align renewable energy expansion with climate-driven range shifts. First, research activities (for example, systematic literature review, interviews) are conducted to inform and identify an appropriate list of species that are threatened by climate change and require mitigation action. Diverse research activities (for example, systematic literature review, interviews) that capture the full knowledge system of actors and entities for a specific context and/or geography (for example, wind development in Texas) will reduce the chances of omitting a species of interest. Next, individual or batch species distribution modelling (SDM) is performed for each species and overlaid with spatially explicit models of renewable energy (RE) scenarios. Subsequent analyses are conducted to identify "Optimal RE Siting Pathways" (that is, spatial datasets) and ultimately, a set of decision outcomes that minimize conflicts with species impacted by climate change ("Decision Outcomes"). We provide a more detailed example of "Core Alignment Analyses" in (b).

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Secondary data was used
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Reporting on sex and gender	N/A
Reporting on race, ethnicity, or other socially relevant groupings	N/A
Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

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Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

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Life sciences study design

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Sample size	N/A
Data exclusions	N/A
Replication	N/A
Randomization	N/A
Blinding	N/A

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We performed a systematic literature review of studies on renewable energy siting and biodiversity.
Research sample	Studies published in the literature.
Sampling strategy	We collected all studies that met our criteria and that were available in Web of Science.
Data collection	We followed PRISMA protocol for a standardized literature review.
Timing	4 November 2022 - 20 December 2022
Data exclusions	Exclusions: used search strings to exclude non-relevant studies
Non-participation	N/A
Randomization	N/A

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We performed a species distribution modeling analysis under climate change senarios for Joshua tree and kit fox.
Research sample	Native range of Joshua tree and kit fox in USA
Sampling strategy	All occurrence points for both species in USA
Data collection	Secondary source (From Global Biodiversity Infromation Facility (GBIF))
Timing and spatial scale	Downloaded on December 20, 2022 from GBIF; USA
Data exclusions	Duplicate samples and samples having uncertainity less than 5km
Reproducibility	Yes, code and data is availble online
Randomization	Yes
Blinding	N/A

Did the study involve field work? ☐ Yes ☑ No

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☐	☐	Plants

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n/a	Involved in the study	
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☐	☐	Flow cytometry
☐	☐	MRI-based neuroimaging

Antibodies

Antibodies used	
Validation	

Eukaryotic cell lines

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Authentication	
Mycoplasma contamination	
Commonly misidentified lines (See ICLAC register)	

Palaeontology and Archaeology

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Specimen deposition	
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Wild animals	
Reporting on sex	
Field-collected samples	
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Study protocol	
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Policy information about dual use research of concern

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Could the accidental, deliberate or reckless misuse of agents or technologies generated in the work, or the application of information presented in the manuscript, pose a threat to:

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X	☐	Any other significant area

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Does the work involve any of these experiments of concern:

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X	☐	Demonstrate how to render a vaccine ineffective
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X	☐	Enhance the virulence of a pathogen or render a nonpathogen virulent
X	☐	Increase transmissibility of a pathogen
X	☐	Alter the host range of a pathogen
X	☐	Enable evasion of diagnostic/detection modalities
X	☐	Enable the weaponization of a biological agent or toxin
X	☐	Any other potentially harmful combination of experiments and agents

Plants

Seed stocks: N/A

Novel plant genotypes:

Authentication:

ChIP-seq

Data deposition

☐ Confirm that both raw and final processed data have been deposited in a public database such as GEO.

☐ Confirm that you have deposited or provided access to graph files (e.g. BED files) for the called peaks.

Data access links
May remain private before publication.
N/A

Files in database submission:

Genome browser session
(e.g. UCSC)

Methodology

Replicates:

Sequencing depth:

Antibodies:

Peak calling parameters:

Data quality:

Software

Flow Cytometry

Plots

Confirm that:

- [ ] The axis labels state the marker and fluorochrome used (e.g. CD4-FITC).
- [ ] The axis scales are clearly visible. Include numbers along axes only for bottom left plot of group (a 'group' is an analysis of identical markers).
- [ ] All plots are contour plots with outliers or pseudocolor plots.
- [ ] A numerical value for number of cells or percentage (with statistics) is provided.

Methodology

N/A

Sample preparation

Instrument

Software

Cell population abundance

Gating strategy

- [ ] Tick this box to confirm that a figure exemplifying the gating strategy is provided in the Supplementary Information.

Magnetic resonance imaging

Experimental design

Design type: N/A

Design specifications

Behavioral performance measures

Imaging type(s)

Field strength

Sequence & imaging parameters

Area of acquisition

Diffusion MRI ☐ Used ☐ Not used

Preprocessing

Preprocessing software

Normalization

Normalization template

Noise and artifact removal

Volume censoring

Statistical modeling & inference

Model type and settings

Effect(s) tested

Specify type of analysis: ☐ Whole brain ☐ ROI-based ☐ Both

Statistic type for inference

(See Eklund et al. 2016)

Correction

Models & analysis

n/a	Involved in the study
☐	☐ Functional and/or effective connectivity
☐	☐ Graph analysis
☐	☑ Multivariate modeling or predictive analysis

Functional and/or effective connectivity

Graph analysis

Multivariate modeling and predictive analysis: We conducted species distribution models and published methods, including code, along with resulting geospatial datasets.