Assessing ecological exposure from utility-scale wind and solar expansion: a global integrity-conditioned framework for environmental management

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Online Resource 1

S1. Data Sources and Versions

Table S1. Data sources and versions used in the analysis.

Dataset	Version / Release	Spatial Resolution	Format Used	License / Access
Global Renewables Watch (Solar & Wind)	Q2 2024	Asset-level (polygons & points)	GeoPackage (.gpkg)	Open data (MIT-style distribution)
Global Human Modification (gHM)	Version 1 (2019)	~1 km raster	GeoTIFF (.tif)	NASA SEDAC open access
Human Footprint	LWP-3 (2009, 2018 release)	~1 km raster	GeoTIFF (.tif)	NASA SEDAC open access
World Database on Protected Areas (WDPA)	2024 release	Polygon (global)	Shapefile (.shp)	Free for research; redistribution restricted
GADM Administrative Boundaries	Version 4.1	Polygon (multi-level)	GeoPackage (.gpkg)	Academic use; redistribution restricted

All datasets are publicly accessible from the original providers. Derived indicators and processing scripts necessary to reproduce the analysis will be made available upon publication.

S2. Scale–Siting Decomposition Tables (Fig. 2)

Table S2. Panel A – gHM baseline integrity

Quadrant	n	% obs	ΔA (km²)	% ΔA	ΔA×I (km²)	% ΔA×I	ΔA×(1−I) (km²)	% ΔA×(1−I)
High-scale / High-integrity	29	24.4%	33.508	83.7%	26.776	93.4%	6.732	59.1%
High-scale / Low-integrity	27	22.7%	5.290	13.2%	1.324	4.62%	3.966	34.8%
Low-scale / High-integrity	31	26.1%	0.578	1.44%	0.391	1.36%	0.187	1.65%
Low-scale / Low-integrity	32	26.9%	0.669	1.67%	0.166	0.58%	0.503	4.41%
Total	119	100.0%	—	100.0%	—	100.0%	—	100.0%

Table S3. Panel B – Human Footprint baseline integrity

Quadrant	n	% obs	ΔA (km²)	% ΔA	ΔA×I (km²)	% ΔA×I	ΔA×(1−I) (km²)	% ΔA×(1−I)
High-scale / High-integrity	41	31.8%	35.784	82.5%	32.153	87.8%	3.630	53.7%
High-scale / Low-integrity	24	18.6%	6.314	14.6%	3.588	9.80%	2.726	40.3%
Low-scale / High-integrity	24	18.6%	0.518	1.20%	0.458	1.25%	0.061	0.90%
Low-scale / Low-integrity	40	31.0%	0.753	1.74%	0.406	1.11%	0.348	5.14%
Total	129	100.0%	—	100.0%	—	100.0%	—	100.0%

S3. Robustness Checks

Indicators are recomputed under alternative integrity layers (gHM vs Human Footprint) and nonlinear weighting exponents ($\gamma = 2, 3$) for RIEPI, and under alternative upper-tail thresholds ($q = 0.80, 0.95$) for RLHIPI. Table S4 summarizes ranking instability relative to the baseline specification.

Ranking instability is reported as $|\Delta rank| = |rank_{alt} - rank_{base}|$ together with Spearman rank correlations. Rankings use 2017–2024 totals (descending order; 1 = highest exposure) and the "min" tie rule. RLHIPI robustness is evaluated on the subset of countries with non-zero RLHIPI under at least one threshold to avoid tie-driven rank noise. Additional pre-specified tests that require reprocessing of footprint geometries (wind buffer radii) or alternative quantile definitions (deployment-conditioned and global quantiles) follow the same workflow and can be regenerated from the spatial pipeline.

Table S4. Ranking robustness summary (country-level).

Specification	N	Median |Δrank|	Mean |Δrank|	Max |Δrank|	Spearman ρ	% reclassified
Panel A: RIEPI robustness (baseline: gHM, γ = 1)						
HFP layer (γ=1)	40	2	2.0	11	0.97	82.5
γ=2 (gHM)	40	2	2.3	9	0.96	85.0
γ=3 (gHM)	40	2	4.0	20	0.86	75.0
HFP, γ=2	40	3	4.2	11	0.89	90.0
HFP, γ=3	40	4	6.0	19	0.75	92.5
Panel B: RLHIPI robustness (baseline: q = 0.90)						
q=0.80 (vs 0.90)	10	0	0	0	1.00	0.0
q=0.95 (vs 0.90)	10	1	1.1	2	0.72	100.0

RIEPI rankings remain highly correlated across moderate specification changes, while stronger non-linear weighting produces larger reordering. RLHIPI rankings are stable under modest threshold variation and shift primarily when the tail definition is tightened to the extreme tail (q = 0.95).

S4. Country hotspot summaries

Table S5 reports the countries with the highest cumulative integrity-conditioned exposure under the baseline gHM specification for 2017–2024. Fig. S1 maps the same cumulative country-level surface and pairs it with a top-country ranking. For plotting only, country boundaries follow the Natural Earth low-resolution layer; the table retains the full analytic country list used in the indicator calculations.

Table S5. Top country exposure hotspots by cumulative RIEPI (gHM baseline, 2017–2024).

Rank	Country	Cum. ΔA (km²)	Cum. RIEPI (km²-eq)	Footprint rank	Shift	Peak RLHIPI q0.90	Peak year
1	Mexico	8.35	3.75	2	+1	1.00	2018
2	Chile	22.94	2.20	1	-1	0.36	2022
3	Israel	1.13	0.88	5	+2	0.00	—
4	Japan	0.78	0.70	7	+3	0.00	—
5	Turkmenistan	0.81	0.53	6	+1	0.00	—
6	Jamaica	0.44	0.36	9	+3	0.00	—
7	Armenia	0.60	0.20	8	+1	0.00	—
8	Cyprus	0.24	0.19	15	+7	0.00	—
9	Kuwait	0.36	0.18	11	+2	0.00	—
10	Russia	0.32	0.18	12	+2	0.00	—

Positive shift values indicate that a country moves upward in the exposure ranking when footprint growth is conditioned on baseline integrity.

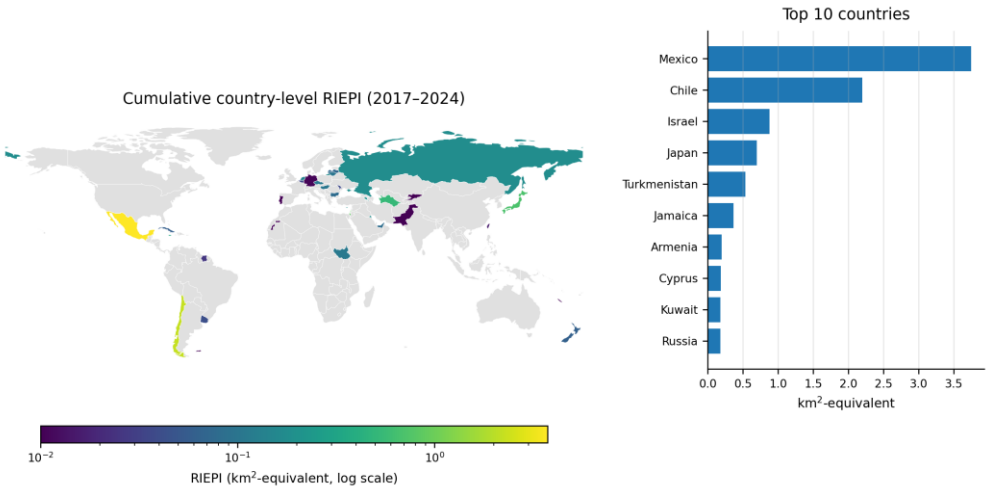

Fig. S1. Country hotspot map and top-country ranking for cumulative RIEPI (gHM baseline, 2017–2024). The map uses a logarithmic color scale to improve visibility outside the highest-exposure cases.

S5. Regional hotspot summaries

Table S6 reports the regional units with the highest cumulative RIEPI over 2017–2024. The regional ranking shows that aggregate country-level exposure is anchored in a small set of repeatedly observed subnational units rather than being evenly distributed across space.

Table S6. Top regional exposure hotspots by cumulative RIEPI (gHM baseline, 2017–2024).

Rank	Region	Country	Cum. ΔA (km²)	Cum. RIEPI (km²-eq)	Shift	Peak RLHIPI q0.90	Peak year
1	Aguascalientes	Mexico	8.35	3.75	+1	1.00	2018
2	Antofagasta	Chile	22.94	2.20	-1	0.36	2022
3	Golan	Israel	1.13	0.88	+2	0.00	—
4	Aichi	Japan	0.78	0.70	+4	0.00	—
5	Aşgabat	Turkmenistan	0.81	0.53	+1	0.00	—
6	Ahal	Turkmenistan	0.81	0.53	+1	0.00	—
7	Clarendon	Jamaica	0.44	0.36	+3	0.00	—
8	Aragatsotn	Armenia	0.60	0.20	+1	0.00	—
9	Famagusta	Cyprus	0.24	0.19	+7	0.00	—
10	Al Ahmadi	Kuwait	0.36	0.18	+2	0.00	—

Peak RLHIPI q0.90 reports the largest annual upper-tail exposure share observed for each region in the baseline tail specification.

S6. RLHIPI hotspot persistence across thresholds

Fig. S2 plots every country-year observation with positive RLHIPI under at least one threshold (q = 0.80, 0.90, or 0.95). The plot highlights whether country-year tail hotspots persist or disappear as the tail definition is tightened. RLHIPI should therefore be interpreted as a concentration diagnostic for exposure in the highest-integrity fraction of landscapes, not as a direct estimate of realized biodiversity outcomes.

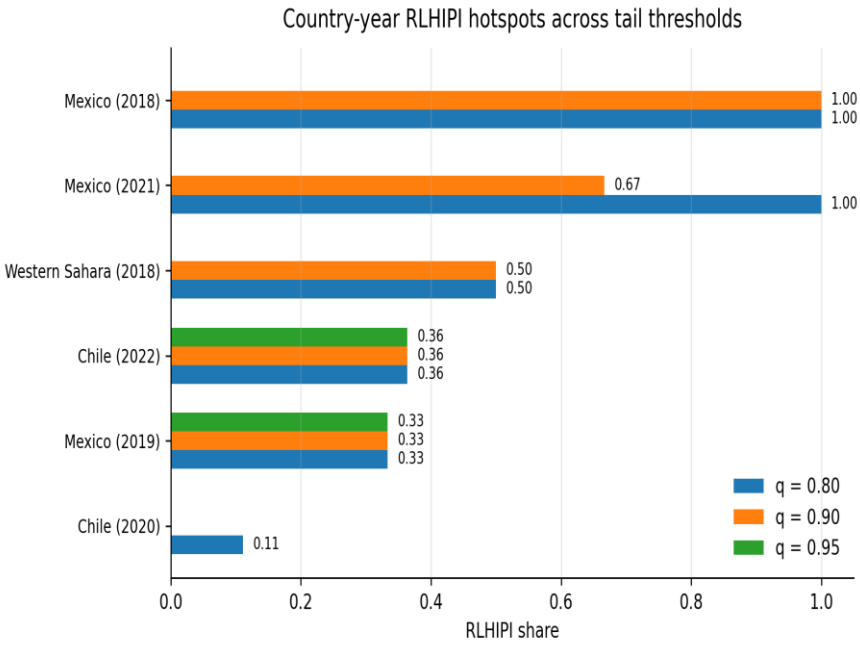

Fig. S2. Country-year RLHIPI hotspots across q = 0.80, 0.90, and 0.95. Only observations with positive RLHIPI under at least one threshold are shown.