

Supplementary Information for

Canopy functional composition as an indicator of bird traits, taxonomy, and vulnerability in tropical Peruvian forests

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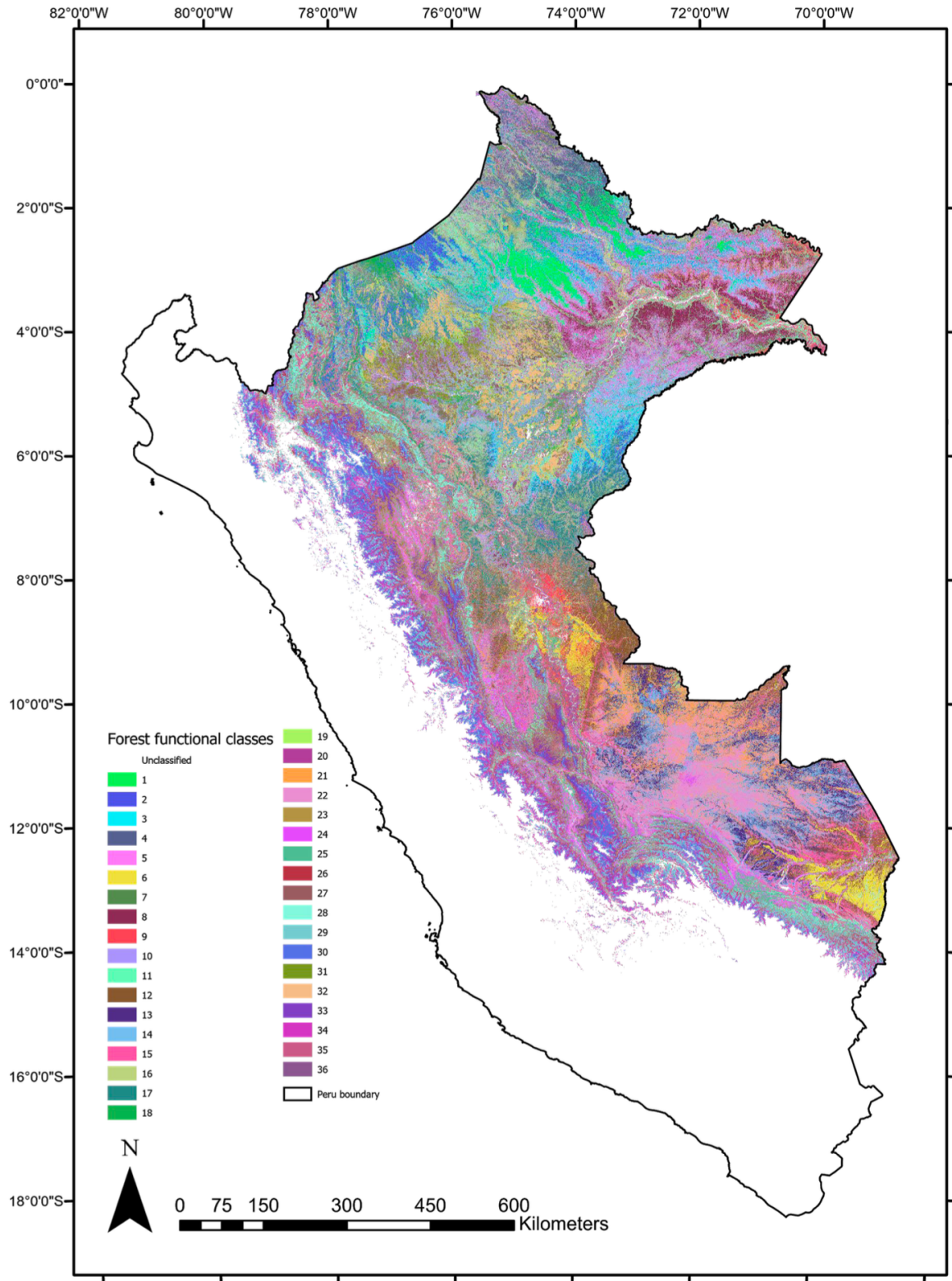
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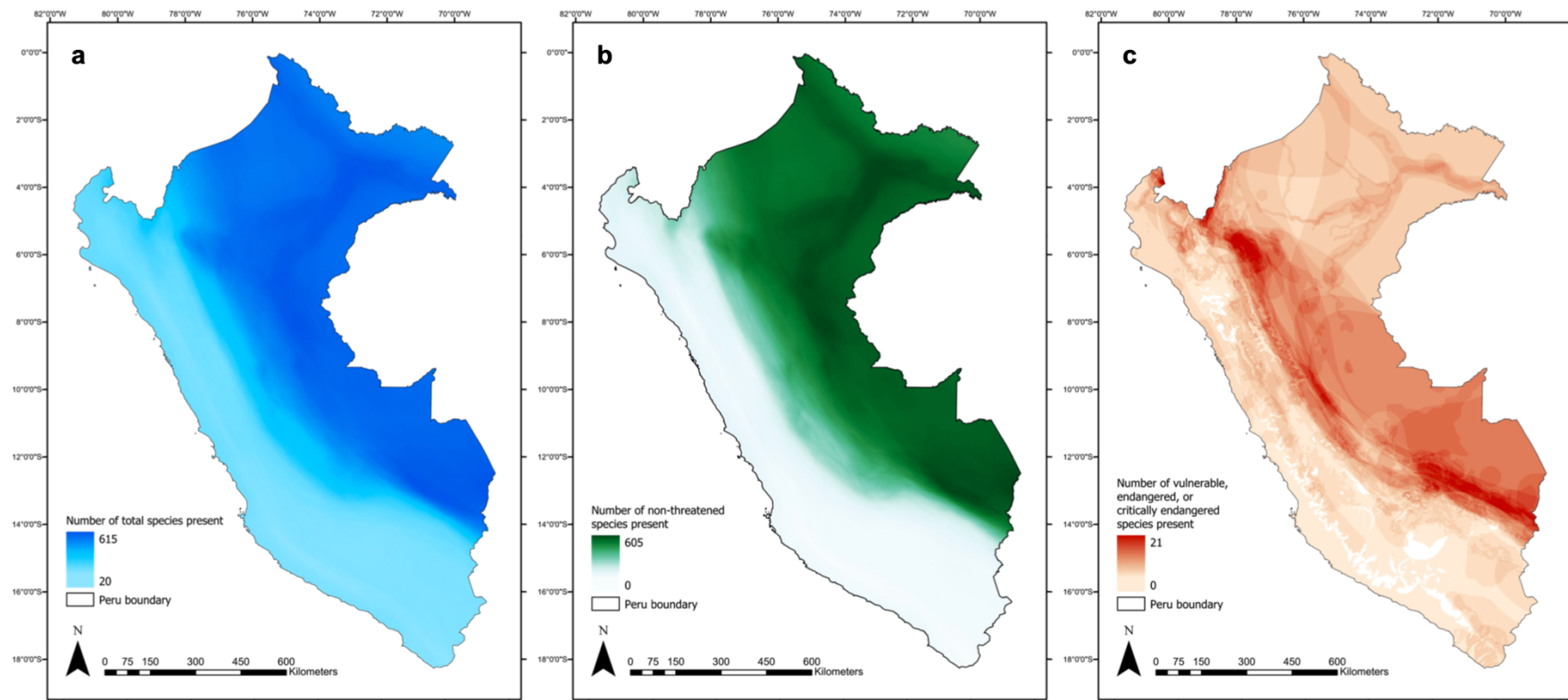
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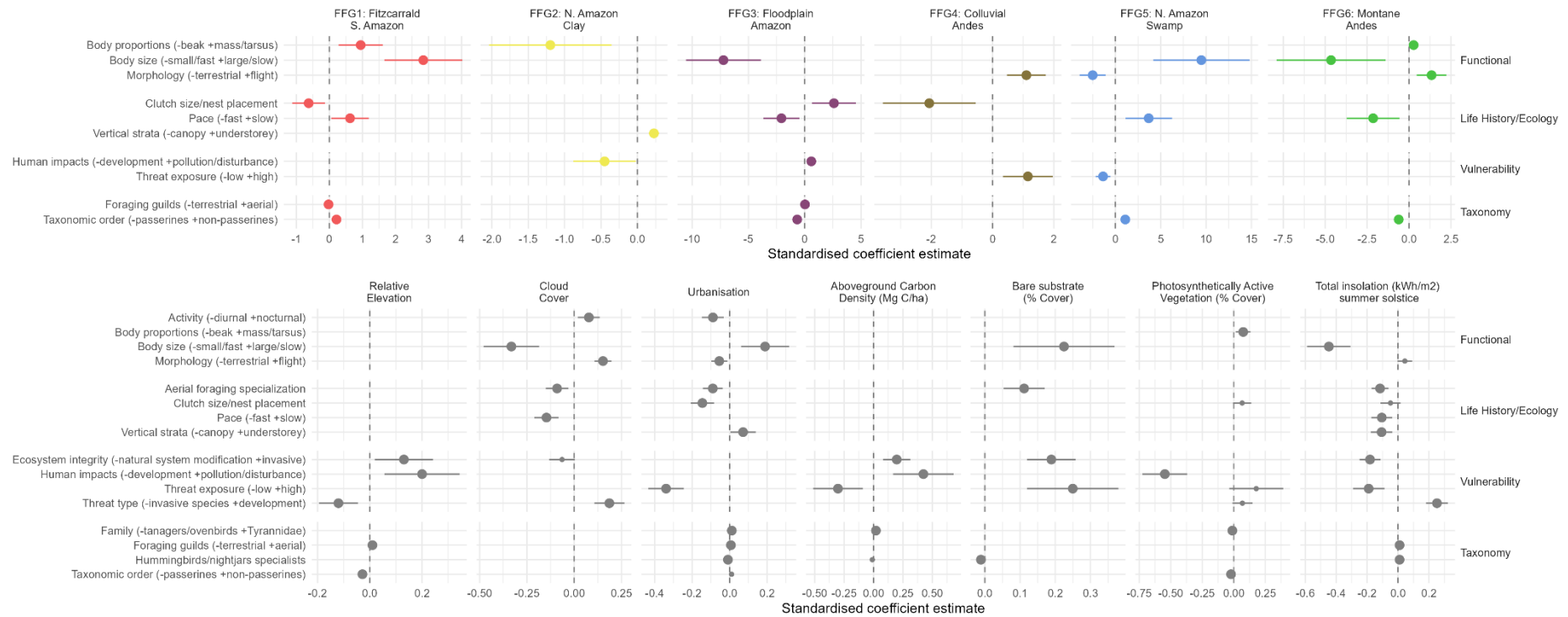
Supplementary Figure 1.

Forest canopy functional diversity of Peru, indicating the distribution of 36 forest functional classes (FFCs) shown by different colours. Map was created using QGIS v3.3.



Supplementary Figure 2.

Bird diversity maps of Peru. Maps indicate the distribution of (a) all bird species (pale blue represents low and dark blue represents high diversity), (b) non-threatened bird species (Least Concerned and Near Threatened; pale green represents low and dark green represents high diversity), and (c) threatened bird species (Vulnerable, Endangered, and Critically Endangered; pale red represents low and dark red represents high diversity). Maps were created using QGIS v3.3.



Supplementary Figure 3.

Coefficient estimates from top-ranked linear models linking forest functional group composition (shown by the same colour codes as in Fig. 2a) to bird functional and life history traits, vulnerability, and taxonomic structure. Each row shows a PCA axis (response), and estimates indicate the direction and uncertainty of association with each of six forest functional groups and the retained environmental predictors (including elevation, cloud cover, urbanisation, aboveground carbon density, bare substrate, photosynthetic vegetation, and solar insolation). Points represent mean estimates ($n = 1,303$ bird species) and lines indicate 95% confidence intervals (see Supplementary Data 13 for values). Larger points represent those predictors with strong evidence of a relationship (confidence intervals did not cross the zero-effect line). Only predictors that were retained in the most parsimonious model in each model selection set are plotted.

Supplementary Table 1.

List of variables used for evaluating the extinction risk of Peruvian bird species and the interactions between species data and environmental data. Displayed are the variable groups, name and description of the variables, and the source references.

Group	Variable	Description	Source
Functional	Body Mass	Mean body mass (in gram; log _e transformed).	1
	Culmen	Length from the tip of the beak to the base of the skull (mm).	1
	Beak Depth	Depth of the beak at the anterior edge of the nostrils (mm).	1
	Beak Width	Width of the beak at the anterior edge of the nostrils (mm).	1
	Kipp's Distance	Length from the tip of the first secondary feather to the tip of the longest primary (mm).	1
	Wing Length	Length from the carpal joint (bend of the wing) to the tip of the longest primary on the unflattened wing (mm).	1
	Tarsus Length	Length of the tarsus (mm) from the posterior notch between tibia and tarsus, to the end of the last scale of acrotarsium (at the bend of the foot).	1
	Tail Length	Distance between the tip of the longest rectrix and the point at which the two central rectrices protrude from the skin, typically measured using a ruler inserted between the two central rectrices (mm).	1
	Breeding System	Categorical variable: Cooperative, Non-cooperative.	2
	Territoriality	Categorical variable: None, Weak, Strong.	2
	Nocturnal	Main foraging activity at night (yes/no).	3
Life history	Generation Length	Mean generation length (in year).	3
	Nest Placement	Categorical variable: Cavity, Exposed Elevated, Exposed Ground.	2
	Clutch Size	Mean clutch size of the species (log _e).	2
	Diet	Assignment to the dominant among five diet categories: Plant Seed (plant and seeds), Fruit (fruits and nectar), Invertebrates, Vertebrate (vertebrates, fish, carrion), Omnivore.	4
	Understory Foraging Strategy	Prevalence of foraging in forest understory (below 2 m).	4
	Midhigh Foraging Strategy	Prevalence of foraging between forest understory and canopy (over 2 m).	4
	Canopy Foraging Strategy	Prevalence of foraging in forest canopy.	4
	Aerial Foraging Strategy	Prevalence of foraging well above the vegetation.	4

Vulnerability	IUCN Red List	RedList category of conservation status from 2016. Categorical variable: (LC) Least Concern, (NT) Near Threatened, (VU) Vulnerable, (EN) Endangered, (CR) Critically Endangered, (DD) Data Deficient.	3
	Population Trend	Global population trend of the species. Categorical variable: Decreasing, Increasing, Stable.	3
	Biological Resource Use	Threats from consumptive use of "wild" biological resources including both deliberate and unintentional harvesting effects; also persecution or control of specific species.	3
	Energy Production & Mining	Threats from production of non-biological resources.	3
	Human Intrusions & Disturbance	Threats from human activities that alter, destroy and disturb habitats and species associated with non-consumptive uses of biological resources.	3
	Invasive and Other Problematic Species, Genes & Diseases	Threats from non-native and native plants, animals, pathogens/microbes, or genetic materials that have or are predicted to have harmful effects on biodiversity following their introduction, spread and/or increase in abundance.	3
	Natural System Modifications	Threats from actions that convert or degrade habitat in service of "managing" natural or semi-natural systems, often to improve human welfare.	3
	Pollution	Threats from introduction of exotic and/or excess materials or energy from point and nonpoint sources.	3
	Residential & Commercial Development	Threats from human settlements or other non-agricultural land uses with a substantial footprint.	3
	Transportation & Service Corridors	Threats from long narrow transport corridors and the vehicles that use them including associated wildlife mortality.	3
Taxonomy	Order	Taxonomic order of birds.	3
	Family	Taxonomic family of birds.	3

Supplementary Table 2.

Modelling framework of the analysis. Summary of analytical steps, data transformations, and ecological interpretation.

Analytical step	Methodological approach	Ecological interpretation
Step 1. Defining bird syndromes (response variables)	Principal Component Analysis (PCA) applied to 32 morphological and ecological traits (Supplementary Table 1).	Grouping the birds. Instead of testing 32 separate traits (which are often redundant), we grouped them into “syndromes”. • <i>Example:</i> Birds that are large and long-lived and eat fruit are grouped into PC1 (see Fig. 1). • <i>Benefit:</i> This simplifies the bird community into a few key strategies (e.g., the slow-paced forest specialist vs. the fast-paced generalist).
Step 2. Defining forest function (key predictor)	Clustering of canopy traits. Remote sensing data (spectroscopy) clustered into 6 distinct Forest Functional Groups (FFGs) based on chemical and structural similarity.	The functional landscape. We mapped the forest not just by trees vs. no trees, but by how the forest functions. • <i>Example:</i> FFG5 (swamp forest) is chemically distinct from FFG3 (floodplain), even if they look similar from a satellite photo. • <i>Goal:</i> To test if these hidden chemical/functional differences drive bird functional traits.
Step 3. Establishing the baseline model	Model Selection (AICc). We tested all possible combinations of the seven environmental baseline predictors (elevation, cloud cover, aboveground carbon density, urbanisation, bare substrate, photosynthetic vegetation, and total solar insolation in December). We selected the most parsimonious model within $AICc < 2$.	• <i>Goal:</i> To identify the best-fit baseline model that uses environmental predictors that explain bird traits. I.e. what environmental factors predict the traits of bird species?

Step 4. Testing the model effects of the FFG predictors.	Model selection (AICc). We held the baseline model in for each bird trait response variable as determined in Step 3 and added the FFG predictors, fitting models with all combinations of these six predictors.	• <i>Goal:</i> To whether adding FFG predictors improved the model fits, over and above the environmental variables from Step 3. This is the key test, determining that vegetation functional groups predicts bird traits, over and above environmental factors such as elevation, cloud cover, urbanisation, etc.)
Step 5. Isolating the importance of canopy function	Variance Partitioning (ΔR^2). For each bird trait response variable, we calculated the total variance explained (R^2) by the best-fit model with the environmental variables (from Step 3). We then calculated the total variance explained (R^2) by the best-fit model that included the FFG variables (Step 4). We then calculated the percentage improvement between the two models.	The added value test. We asked: How much unique predictive power do the chemical canopy maps add? • By comparing the predictive power with and without the FFG data, we precisely measured their unique contribution.
Step 6. Interpretation	Beta coefficients & loadings. Examining the direction and strength of relationships between FFGs and bird PCs.	We looked at who lives where (see Table 1). • <i>Finding example:</i> Very large-bodied, slow-reproducing birds with terrestrial foraging habits (Functional PC1, Life History PC2) are strongly associated with chemically unique swamp forests (FFG5). • <i>Implication example:</i> If we lose swamp forests, we lose that specific bird life-history strategy and evolutionary lineage (non-passerines).

Supplementary References

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2. Tobias, J. A. & Pigot, A. L. Integrating behaviour and ecology into global biodiversity conservation strategies. *Philosophical Transactions of the Royal Society B: Biological Sciences* **374**, 20190012 (2019).
3. HBW and BirdLife International. Handbook of the Birds of the World and BirdLife International digital checklist of the birds of the world. Version 9. Available at: http://datazone.birdlife.org/userfiles/file/Species/Taxonomy/HBW-BirdLife_Checklist_v9_Oct24.zip. (2024).
4. Wilman, H. *et al.* EltonTraits 1.0: Species-level foraging attributes of the world's birds and mammals. *Ecology* **95**, 2027–2027 (2014).