Reply to: Causal claims, causal assumptions and protected area impact

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REPLYING TO: J. Geldmann et al. *Nature* https://doi.org/10.1038/s41586-024-08512-8 (2025).

In the accompanying Comment, Geldmann et al.[1] incorrectly claim that protected area (PA) efficacy cannot be established without biodiversity data that predates establishment of the PA. Spatial correlates of diversity are known as a result of centuries of ecological research; our analyses controlled for these factors in a variety of ways in order to isolate the impacts of protection per se on bird and mammal biodiversity. The proposition of Geldmann et al. that our results are biased because PAs were established in areas with high natural biodiversity ignores these analytical controls, is naive to the realities of on-the-ground conservation, and has been disproved by recent research. Although we look forward to future work that improves on our predictions, our study provides robust estimates of the biodiversity impacts of PAs across hyperdiverse Southeast Asia[2]—information that is critically needed to support large-scale conservation objectives.

Geldmann et al.[1] correctly state that the strongest causal inference is derived when treatments (PA status, in this case) are assigned randomly and prior to the onset of a study. In conservation, however, this is frequently unfeasible, such as for PAs that were established before the invention of robust biodiversity sampling methods (for example, before the camera trapping used in our study). We overcame this issue by assigning treatments as if they were random relative to pre-existing biodiversity across the landscape by controlling for confounding factors that would have driven spatial variation in pre-establishment diversity. Geldmann et al.[1] are of the opinion that controlling for these factors is not sufficient because some were measured after rather than before PA establishment. This claim is not relevant for many of the fundamental determinants of diversity, including latitude, longitude, elevation and general climatic conditions, which have not changed over the relevant timescales.

For the few temporally dynamic variables, the key consideration is whether changes over time would bias the results in ways that would reduce the effect sizes reported. Namely, forest structure and accessibility are temporally dynamic, but there is no evidence or intuition that these have changed in consistently biasing ways that would affect our inference. Geldmann et al.[1] conflate this absence of evidence with evidence of absence. Accessibility, in particular, has changed in predictable ways across the globe; areas that were accessible in the past are now even more so, and historically remote areas are now more accessible than they were[3]. In short, accessibility values have increased everywhere, but relative differences in accessibility across space have changed much less—this renders pre-establishment accessibility values highly correlated with post-establishment values, negating the critique of Geldmann et al.

The assertion by Geldmann et al. that diversity must be measured before the PA is established[1] ignores centuries of ecological research. Ecologists have been studying the spatial distribution of diversity since the inception of the field. The naturally driven spatial variation in tropical forest biodiversity is well known to be strongly linked to elevation, topography and climate[4–6]. In the directed acyclic graphs for our structural causal modelling (Extended Data Fig. 2 in ref. 2), elevation, topographic position index (TPI) and bioclimate were all included as influencers of forest structure, which was included in our linear mixed-effects models. Although forest structure values have changed over time, the influences of elevation, topography and climate have not.

As a follow-up analysis in response to the critique by Geldmann et al., we re-ran our mixed-effects models to explicitly include other known and temporally static correlates of diversity—elevation and TPI—as covariates. The prediction of Geldmann et al. would be that this would reduce the PA coefficients and render them non-significant. Instead, the PA coefficients increased in the bird functional richness model, changed only slightly in the species richness and phylogenetic diversity models, and remained highly significant in all cases (Table 1). Climate, another major correlate of diversity, covaries strongly with other variables in our models. Across bird sampling locations, the first principle component of the 35 bioclimatic variables from WorldClim[7] is highly correlated with latitude ($r = 0.89$), which is included in our models, and the second principle component is correlated with elevation ($r = -0.80$), which we tested in the follow-up analysis above. Climate changes are experienced

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Table 1 | Changes to bird 'protected area' model coefficients when adding elevation and TPI to the linear mixed-effects models

	β (standard error; P value)	
	Analysis without elevation and TPI	Analysis with elevation and TPI
Species richness	24.72 (4.95; <0.001)	25.54 (4.99; <0.001)
Functional richness	25.78 (6.52; <0.001)	29.08 (6.29; <0.001)
Phylogenetic diversity	0.38 (0.07; <0.001)	0.38 (0.07; <0.001)

at larger spatiotemporal scales than our paired inside-versus-outside treatment points[8,9]; therefore, as with accessibility, by accounting for differences seen today we are also accounting for differences that were likely to be present several decades ago when PAs were established. Overall, these analyses highlight that analysis of temporally static covariates generates similarly strong results to those in our original Article[2], again negating the critique.

To summarize, we thoroughly accounted for proxies for (that is, correlates of) pre-establishment biodiversity in our original Article[2] and in the follow-up analyses above. There are still additional factors (as is always the case in science) that could have affected pre-establishment diversity and were not included in our models. However, for the omission of these factors to bias our results along the lines that Geldmann et al. suggest[1], they would somehow have to be: correlated with the eventual locations of PAs, but uncorrelated with latitude, longitude, elevation, topography, climate, human accessibility, human development, forest height, forest cover, forest vertical complexity and tree leaf density (that is, the covariates that we tested or are highly correlated with the ones that we tested). It is difficult to imagine what factors could realistically meet these criteria. Geldmann et al. apparently could not imagine any either, as their simulation analysis used non-specific 'unobserved confounding variables' rather than any real biophysical metrics[1]. Their simulation is therefore abstract, implausible and not relevant to our empirical analyses.

Geldmann et al. propose a rival hypothesis that "diversity was higher in sites selected for protection than those that were not selected"[1]. Although modern systematic conservation prioritization strategies are intended to do exactly this, such methods were not in use decades ago when the majority of Southeast Asia's PAs were established. PA establishment has been based much more on sociopolitical and economic considerations—such as targeting areas unsuitable for logging or agriculture—than ecological concerns[3]. As a result, current PA coverage is an exceedingly poor reflection of historic underlying diversity[10,11]. Indeed, an analysis of global PAs found that "both old and new protected areas did not target places with high concentrations of threatened vertebrate species. Instead, they appeared to be established in locations that minimize conflict with agriculturally suitable lands"[12]. Finally, tropical vertebrate diversity has been very difficult to quantify until recently, and so could not have been included in conservation prioritization analyses even if such analyses had occurred. If managers had wanted to establish PAs in high-diversity areas, they would have had to use proxies such as elevation, topography, bioclimate and accessibility—the very factors that we controlled for.

We acknowledged in our original Article that establishing causality between PAs and spillover was problematic[2], but our stated justification for this analysis was to compare whether the data were consistent with patterns of spillover rather than to directly infer causality. Therefore, the claim in our abstract—"Rather than PAs generating leakage that deteriorated ecological conditions elsewhere, our results are consistent with PAs inducing spillover that benefits biodiversity in surrounding areas"—is valid.

Geldmann et al. bring up "the same problems of controlling for confounding bias"[1] that we refute above. They also suggest that there are difficulties in measuring spillover within the spatially complex constellation of PAs in the region, which we agree with and had discussed in our Article[2]. Indeed, we hope that our results spur further research on the patterns and mechanisms of spillover, which could result from animal demography and investment in outreach or enforcement targeted at large reserves, with the influences of these management strategies (for example, reduced hunting, alternative employment in the PA or associated ecotourism) permeating into surrounding areas. Finally, Geldmann et al. appear to have misunderstood another test that we performed—we did not actually assess "whether average diversity in unprotected sites within 2 km of a PA is larger than average diversity in unprotected sites farther away"[1], but rather tested the effects of 'distance to PA' as a continuous variable. We found a general lack of relationship between this variable and diversity but, as we stated in our paper, "Straight-line distance does not account for how topography, forest quality, human infrastructure, or hunting might affect animal movement out of protected areas and across the landscape, and so is only a very crude metric of PA proximity".

Causal inference is always stronger if multiple lines of evidence can be brought to bear for any particular question. We do not claim that our Article[2] singlehandedly justifies the entire United Nations 30 × 30 enterprise[13]. However it does provide an important contribution to a broader literature that strongly supports the case that PAs enhance biodiversity conservation. The expansion and effective management of PAs is critical, given that the current global protected estate is not sufficiently large[14], ecologically representative[11] or well-connected[15,16] to achieve the desired mitigation of the extinction crisis. Geldmann et al. apparently agree, despite the fact that biodiversity (and thus the most urgent need for new PAs) is concentrated in the Global South, whereas the pre-establishment diversity data that they consider so indispensable are essentially restricted to a tiny set of non-threatened species at a handful of sites in wealthy nations[17].

Therefore, and contrary to the claims of Geldmann et al., our results do in fact provide robust estimates of the biodiversity impacts of PAs across hyperdiverse Southeast Asia. All scientific estimates are imperfect, and we look forward to new research that improves on our predictions and updates the state of knowledge in the field. For now, massive global changes and the urgency of implementing the 30 × 30 commitment require policymakers to use the best available information at any given time. Our study provides a timely update to the state of the science for tropical PAs and biodiversity.

Methods

We compared mixed-effects models based on propensity score-matched data, as described in our original Article[2], with and without elevation and topographic position index as additional covariates.

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/s41586-024-08513-7.

Reporting summary

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

Data availability

Data are available at https://doi.org/10.6084/m9.figshare.22527298.v1 (ref. 18).

Matters arising

Code availability

Analysis code is available at https://doi.org/10.5281/zenodo.13742402 (ref. 19).

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