
Article:
Sze, J.S. orcid.org/0000-0001-8183-766X, Childs, D.Z. orcid.org/0000-0002-0675-4933, Carrasco, L.R. et al. (1 more author) (2022) Indigenous lands in protected areas have high forest integrity across the tropics. Current Biology, 32 (22). pp. 4949-4956. ISSN: 0960-9822

https://doi.org/10.1016/j.cub.2022.09.040

Report

Current Biology

Indigenous lands in protected areas have high forest integrity across the tropics

Highlights

- PIAs have the most protective effect on tropical forest integrity
- PAs are also effective, but not ILs in Asia and Americas
- Land-use intensity is the lowest in PIAs
- Legal protection might be important for conserving forest integrity in the tropics

Authors

Jocelyne S. Sze, Dylan Z. Childs, L. Roman Carrasco, David P. Edwards

Correspondence

jssze1@sheffield.ac.uk (J.S.S.), david.edwards@sheffield.ac.uk (D.P.E.)

In brief

Tropical forest integrity is important for conservation. Sze et al. show that across the tropics, the overlap of protected areas and Indigenous lands has the highest effect in maintaining forest integrity and experienced the lowest increase in intensive land uses.

Sze et al., 2022, Current Biology *32*, 4949–4956
November 21, 2022
https://doi.org/10.1016/j.cub.2022.09.040

CellPress

Current Biology

CellPress
OPEN ACCESS

Report

Indigenous lands in protected areas have high forest integrity across the tropics

Jocelyne S. Sze,[1,3,4,*] Dylan Z. Childs,[1] L. Roman Carrasco,[2] and David P. Edwards[1,*]
[1]School of Biosciences, The University of Sheffield, Sheffield S10 2TN, UK
[2]Department of Biological Sciences, National University of Singapore, Singapore 119077, Singapore
[3]Twitter: @jocelynesze
[4]Lead contact
*Correspondence: jssze1@sheffield.ac.uk (J.S. S.), david.edwards@sheffield.ac.uk (D.P. E.)
https://doi.org/10.1016/j.cub.2022.09.040

SUMMARY

Intact tropical forests have a high conservation value.[1] Although perceived as wild,[2] they have been under long-term human influence.[3] As global area-based conservation targets increase, the ecological contributions of Indigenous peoples through their governance institutions and practices[4] are gaining mainstream interest. Indigenous lands—covering a quarter of Earth's surface[5] and overlapping with a third of intact forests[6]—often have reduced deforestation, degradation, and carbon emissions, compared with non-protected areas and protected areas.[7,8] A key question with implications for the design of more equitable and effective conservation policies is to understand the impacts of Indigenous lands on forest integrity and long-term use, as critical measures of ecosystem health included within the post-2020 Global Biodiversity Framework.[9] Using the forest landscape integrity index[10] and Anthromes[11] datasets, we find that high-integrity forests tend to be located within the overlap of protected areas and Indigenous lands (protected-Indigenous areas). After accounting for location biases through statistical matching and regression, protected-Indigenous areas had the highest protective effect on forest integrity and the lowest land-use intensity relative to Indigenous lands, protected areas, and non-protected controls pan-tropically. The protective effect of Indigenous lands on forest integrity was lower in Indigenous lands than in protected areas and non-protected areas in the Americas and Asia. The combined positive effects of state legislation and Indigenous presence in protected-Indigenous areas may contribute to maintaining tropical forest integrity. Understanding management and governance in protected-Indigenous areas can help states to appropriately support community-governed lands.

RESULTS AND DISCUSSION

Tropical indigenous lands, forest integrity, and anthromes

Intact, high-integrity forests are important for conservation and planetary functioning,[1] with forest integrity indicated as a key measure of ecosystem health in the post-2020 Global Biodiversity Framework.[9] Intact forests have been defined as seamless mosaics covering a minimum area of 500 km^2 with no remotely detected signs of human activity[12] and bearing similarities to high-integrity forests, which conceptually refer to areas with minimal anthropogenic modifications to its structure, composition, and function.[10] To understand how Indigenous presence and long-term use affects forest integrity across the tropics, we used the Indigenous peoples' land dataset[5] and World Database of Protected Areas[13] to identify 3.4 Mkm^2 of Indigenous lands (ILs), 2 Mkm^2 of protected areas (PAs), 1.7 Mkm^2 of protected-Indigenous areas (PIAs), and 11 Mkm^2 of non-protected areas (non-PAs) (Figure S1).

More than half (56.4%) of tropical forested areas were in the Americas, with 26.8% in Asia and 16.7% in Africa (Figure 1A). The Americas had the highest coverage of PAs and the greatest overlap of PAs and ILs, whereas Asia had the highest coverage of ILs but lowest coverage of PAs, and Africa had the lowest coverage of PIAs (Table S1A).

Using the forest landscape integrity index (FLII) product, which uses satellite-detected disturbances such as road-building, canopy loss, and connectivity loss to model a scaled metric for forest integrity,[10] we find that high-integrity tropical forests (where FLII score exceeds 9.6) mirror the distribution of intact forest landscapes (IFLs)[12] with 76.3% overlapping (Figure S2; Table S1B). These high-integrity tropical forests were concentrated in the Amazon and Guiana Shield, Congo, Bornean Highlands, and New Guinea. Lower-integrity tropical forests were prevalent in Central America, the Brazilian Atlantic and Caatinga, West Africa, Indochina, and the lowlands of insular Southeast Asia (Figure 1B).

To understand long-term land-use intensity within our study areas, we used the most recent Anthromes data to provide a consistent overview of land use and intensity over time, characterizing landscapes shaped by human interactions with ecosystems.[11] The Anthromes data classify dense settlements, villages, croplands, and rangelands as intensive land

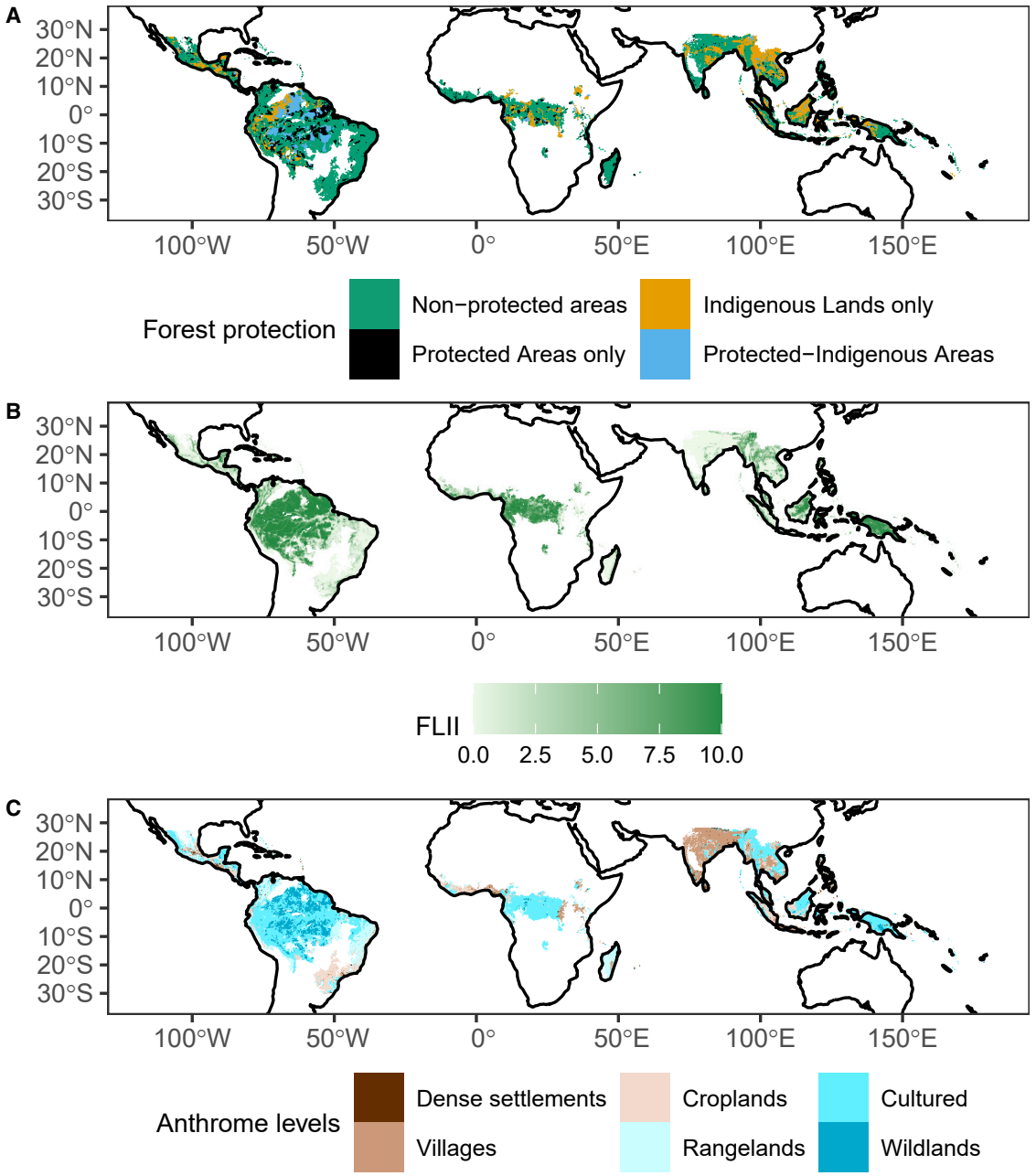

Figure 1. Map of study area across the tropics

(A) Protection types, intentionally coarsened to 30 km grids with dominant protection type represented to obscure Indigenous land boundaries to prevent inadvertent harm.

(B) Forest landscape integrity index (FLII) scores, with 10 representing the highest forest integrity score.

(C) Anthrome levels in 2010.

See also Figure S2 and Table S1.

uses; cultured landscapes as low-intensity inhabited areas (with less than 20% intensive land use); and wildlands as having a complete absence of permanent human populations and intensive land uses. Most of our study area was covered by low land-use intensity cultured landscapes, such as inhabited drylands and woodlands, in 2010 (Figure 1C), although villages featured prominently in the Indian subcontinent. Only 17.2% of the total study region was considered as wildlands, most of which were in the Amazon. Of the high-integrity forests, only 32.3% were considered as wildlands in 2010 (Figure S2); in Africa and Asia, most high-integrity forests fell under cultured landscapes, reinforcing the fact that many areas of conservation importance are not truly wild and human-free but are home to human communities.[2]

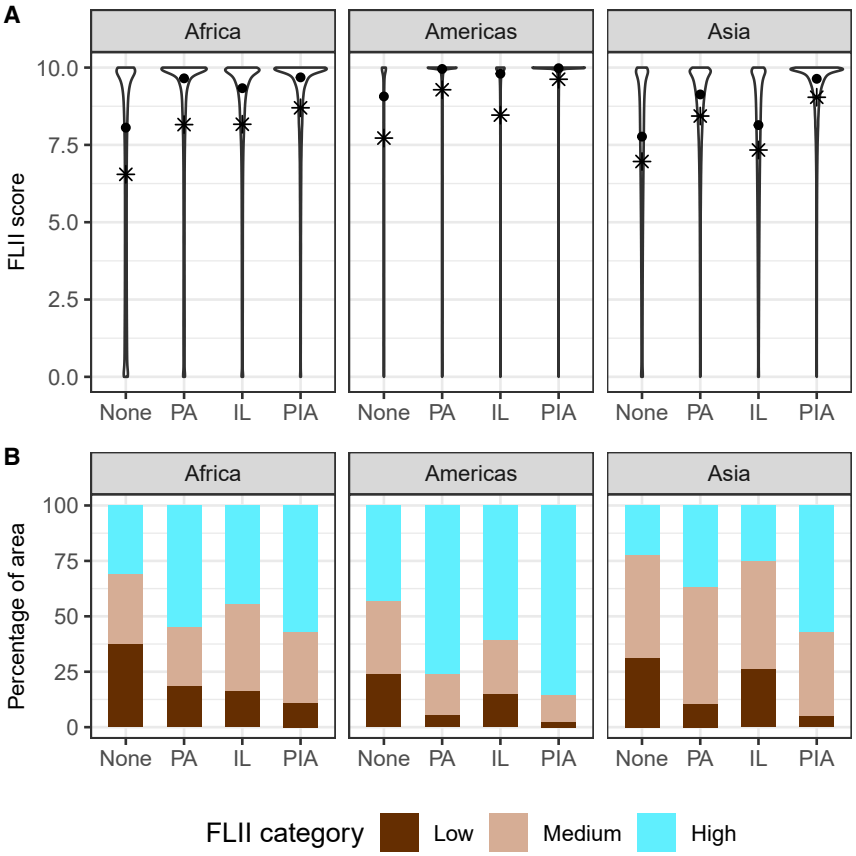

Figure 2. Distribution of FLII in non-protected areas, protected areas only (PAs), Indigenous lands only (ILs), and protected-Indigenous areas (PIAs) across tropical regions

(A) Violin plots of FLII values for each protection type, with mean value represented by the asterisk symbol and median value represented by the filled circle.

(B) Percentage of forest protection type within FLII categories, where FLII values 0–6 = low, 6–9.6 = medium, and 9.6–10 = high.

See also Table S2.

While the Americas have a high coverage of wildlands, due in part to depopulation following European arrival in 1492, the richness of these forests has also been shaped by pre-colonial forest use.[3,14] For example, the hyper-diverse Ecuadorian Andean cloud forests were once open fields cultivated by the Indigenous Quijos population.[15] Indigenous communities can enhance forest integrity through management practices that benefit biodiversity,[16] such as the planting of useful fruit and timber trees and abandonment of plots, which result in complex forest structures.[17] They may also enforce their land rights to keep out infrastructure, (illegal) selective logging, agribusiness expansion, and extractive industries.[18,19] On the other hand, they might reduce forest integrity through inadequately regulated timber use or the hunting of large-bodied, seed-dispersing vertebrates,[20] or they may be constrained by national infrastructural and economic development plans,[21] exemplified by increasing environmental conflicts.[22]

Most forest integrity measures, including the FLII, rely on remote sensing that only captures human influences directly detectable by satellites, like land-cover changes. This makes them biased toward monitoring for industrial-scale impacts that include mega infrastructure, motorized transport networks, and monoculture plantations, while missing other aspects of forest health such as faunal diversity[23] and forest composition. Nonetheless, the FLII captures other anthropogenic impacts such as hunting and edge effects by modeling inferred pressures and provides a measure of the degree to which forest structure has been altered.

Comparing FLII scores by protection types within each tropical region (Figure 2A), we found that on average, non-PAs had the lowest forest integrity (7.21 ± 3.04 [mean ± SD]), followed by ILs (7.82 ± 2.61) and PAs (9.04 ± 1.96), while PIAs had the highest forest integrity (9.48 ± 1.31; Table S2). In the Americas, only non-PAs had <50% of their area covered by high-integrity forests (Figure 2B). High-integrity forests covered >50% of PAs and PIAs and 44.4% of ILs in Africa, whereas in Asia they covered >50% of PIAs, 36.6% of PAs, and only 24.8% of ILs. PIAs thus support a large area of high-integrity tropical forests, although this may be due to biases in locations far from deforestation and forest-use pressures[24] that could confound their protective effect.

Effect of protection type on forest integrity

To account for potential confounders in location biases, we used propensity score matching to identify comparable areas of protection types (STAR Methods). These matched areas covered 444,985 km^2 of ILs, 490,353 km^2 of PAs, 356,745 km^2 of PIAs, and 1,355,865 km^2 of non-PAs. To predict the effect of protection types on forest integrity within matched areas (STAR Methods), we ran generalized additive mixed models (GAMMs). We found mixed results across different tropical regions (Figure 3; Table S1C). In Africa, PAs, ILs, and PIAs all had a greater protective effect on forest integrity than non-PAs by 3%–5.2%, with PIAs having the highest protective effect. In the Americas and Asia, PAs and PIAs had a greater protective effect than non-PAs by 1%–3%, whereas ILs had a lower protective effect than non-PAs by 0.1%–3.5%. Repeating our analysis with only multi-use PAs (IUCN categories V and VI) has shown similar results (Figure S3).

Forest integrity in ILs in the Americas and Asia scored lower than non-PAs, whereas areas that intersect with PAs (i.e., PIAs) scored higher, suggesting that state legislation impacts on forest integrity in these tropical regions. While this may appear to contradict previous work on reduced deforestation and degradation in ILs,[8] FLII incorporates inferred deforestation pressures and lost forest connectivity that reflect larger-scale development pressures.

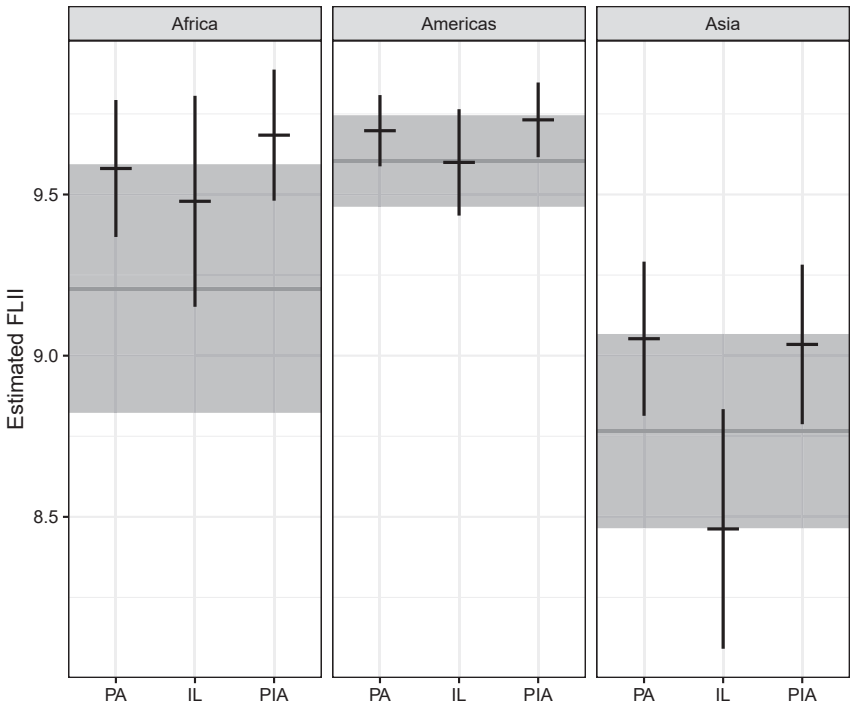

Figure 3. Estimated FLII scores of protection types based on regional GAMMs

Black horizontal lines represent the estimated FLII score, and vertical lines represent their standard errors. Gray horizontal lines represent the estimated FLII score for non-protected areas, and gray shaded areas represent its standard error.

See also Figure S3 and Table S1.

Most ILs, especially in Asia, have not been legally recognized,[25] which may partially contribute to their having lower forest integrity than non-PAs. This is compounded by the fact that the majority of mineral, oil, and gas deposits are located within ILs worldwide, attracting exploitation by extractive industries and governments for revenue generation.[26] Indeed, governments in countries ranging from Brazil to the Philippines have used the COVID-19 pandemic to pass laws enabling forest exploitation at the expense of Indigenous and local communities.[27–29]

High economic growth rates in Latin America and Asia have stimulated the expansion of extractive industries in these tropical regions.[30] The fact that PAs and PIAs retained high forest integrity even after accounting for location biases suggests that legal protection hinders forest fragmentation and large-scale developments, corroborating findings that forest PAs mitigate anthropogenic pressures.[31] Across the Amazon, Indigenous territories with legal tenure have reduced deforestation,[32–34] and Indigenous peoples mobilized to protect their lands from extractive industries, such as the Munduruku peoples of the Brazilian Amazon resisting hydropower development.[35] However, without state legislation and support, the expansion of extractive industries, infrastructural development, and their associated consequences (which may or may not be desired by Indigenous communities) have impacted tropical forest integrity in ILs and non-PAs.

Our findings are mediated by the limitation that the datasets we used for ILs and PAs do not indicate the nature of management and/or governance relationship within these areas, nor do they provide information on tenure status, which are critical to producing socially equitable and positive conservation outcomes.[36] The data on ILs may also be incomplete, omitting areas where Indigenous peoples are present and influencing the landscape while including areas where they are no longer present or have influence. In addition, our study only considered ILs, which overlooks areas inhabited by local communities who may also have similar positive long-term relationships with their lands.[37]

Anthromes changes from 1950 to 2010

To further understand how land-use intensity is associated with protection types and has changed across the tropics, we examined land-use intensity using the Anthromes dataset within our matched areas (STAR Methods). From 1950 to 2010, there has been an increase in land-use intensity across all tropical regions in all protection types (Figure 4; Table S3).

Dense settlements and villages increased 6-fold on average, with the largest increase in Africa, followed by the Americas and Asia. Similarly, the largest increase in croplands was in Africa, followed by the Americas and Asia. Most of this expansion toward more intensive land uses came at the expense of cultured landscapes, and wildlands remained consistent in coverage, reflecting globalized and industrial intensification of land use.[38]

The Americas held the highest coverage of wildlands at 33.7%, whereas in Africa and Asia wildlands covered only about 3.1% of the study area. By 2010, intensive land uses (dense settlements, villages, croplands, and rangelands) covered between 0.9% and 32.5% of the different protection types. On average, 22% of non-PAs were intensively used, compared with only 5.8% of PIAs.

Although the Anthromes dataset could overstate the extent to which the earth has been transformed by human action,[39] human influence on landscapes does not necessarily imply degradation, and other maps converge on similar estimates of human influence.[40] Our regional-scale spatial analysis found that land-use intensity has increased over time, with PIAs experiencing the lowest increase; however, local-scale case studies would improve our understanding of its implications and socio-environmental impacts.

Priority of industry-free over human-free

There is increasing clarity on the impact of capitalist-driven extractive industries on areas of conservation concern, including IFLs.[41] The expansion of industrial agriculture into tropical forests has displaced local peoples to more ecologically marginal areas, causing further degradation and deforestation in frontiers.[42] Additionally, mega-infrastructure and economic growth

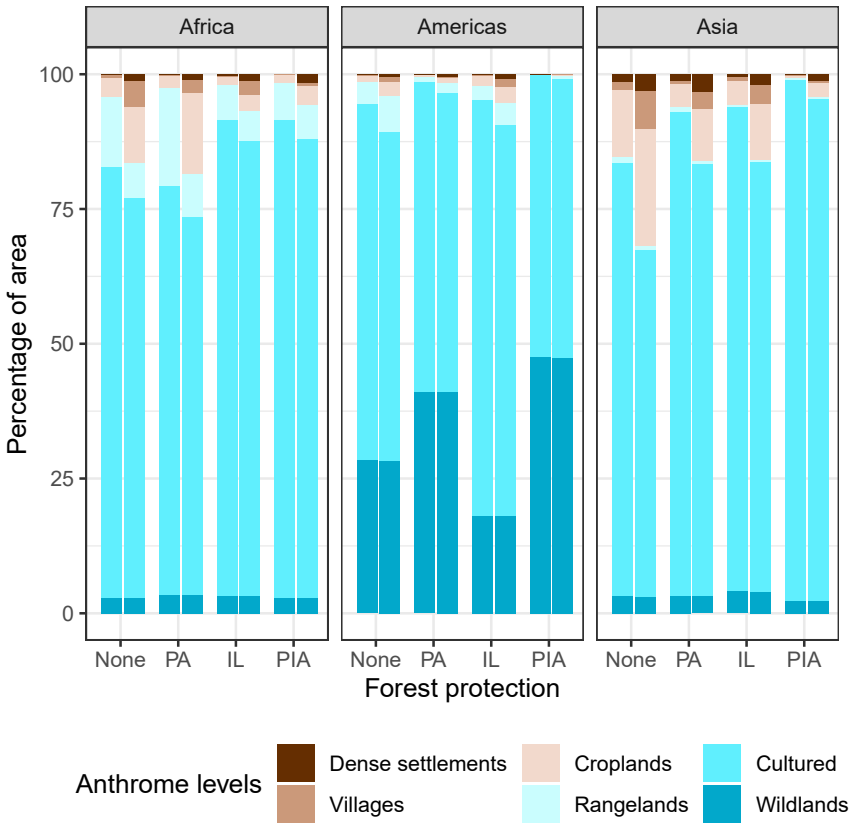

Figure 4. Percentage coverage of Anthrome levels within matched areas

1950 data are represented in the left column and 2010 data in the right column for each protection type.

See also Table S3.

threaten ecosystem integrity and the achievement of conservation targets.[43,44]

Although we found that PAs can still mitigate large-scale infrastructural development, established PAs across the tropics are being downgraded, downsized, and degazetted to allow for industrial-scale resource extraction.[45,46] They can also suffer because of inadequate funding and encroachment for hunting, logging, or clearance.[47] Countries worldwide have begun implementing post-COVID economic stimulus plans and policies authorizing industrial and extractive activities within PAs.[48] These are likely to impact the ability of PAs to continue meeting their conservation objectives.

Conservation policies have moved beyond only area-based targets to encompass metrics including ecosystem integrity and management effectiveness.[9] However, the different forms of human-nature relationships and governance arrangements between Indigenous peoples and local communities and state authorities are also important for achieving positive and equitable social and environmental outcomes. Future research could focus on how aspects of livelihoods, biocultural and relational values,[49] knowledge systems,[50] and power dynamics[51] within PAs, ILs, and in particular PIAs impact forest integrity and connectivity. This would further our understanding of the contexts in which different conservation policies would be suitable.

Recognizing indigenous lands in protected areas

Our study found the overlap between ILs and PAs to have high forest integrity and minimal intensive and extensive human land use across the tropics. These spaces often have complex governance relationships, particularly around the recognition and respect of Indigenous peoples' rights.[52] In Indonesia, for example, the creation of Betung Kerihun National Park imposed restrictions on the Dayaks contrary to their customary law, creating distrust and resentment,[53] whereas the Kayan Mentarang National Park is now co-managed by Indigenous authorities, with their customary lands legally recognized.[54] Yet even where conservation areas are, or appear to be, proposed and managed by Indigenous communities, the relationship often remains tenuous due to histories of coloniality,[19,55] and participation can remain representational.[56]

The Global Biodiversity Framework will likely increase the global land area under some form of protection; safeguards are needed to ensure that communities who have not contributed to damaging ecosystems, or who may be actively contributing to protecting ecosystem integrity, are not harmed in the process of securing conservation outcomes.[57,58] Even though our results point to the value of legal protection, the nature and form of legal protection of areas and how they articulate and interact with the Indigenous peoples and local communities already living there will need to be carefully negotiated. Legal recognition for Indigenous peoples and their territories can achieve better socio-ecological outcomes when the process of acquiring legal recognition, the form and extent of legal rights, and the implementation of those rights are navigated sensitively according to their specific contexts.[59]

Pursuing global targets without due attention to power imbalances among local governance actors often results in social inequity and failed environmental objectives.[51] Equitable ways forward include promoting alternative models to strict PAs in conservation priority areas, such as "territories of life" where communities retain their land ownership and tenure rights and actively govern their lands for conservation and community well-being.[18] Conservation could also move toward providing funding support through mechanisms such as a conservation basic income, buffering the economic pressures of industrial extractivism,[60] and co-establishing conservation plans with communities, such as in Pastaza, Ecuador.[61]

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2022.09.040.

ACKNOWLEDGMENTS

We thank Z. Molnar and S. Garnett for constructive comments, and Garnett et al. for making their data available for use. We acknowledge Indigenous peoples and traditional custodians worldwide and recognize their collective wisdom. Funding was provided to D.P.E. from the Natural Environment Research Council (grant number NE/R017441/1).

AUTHOR CONTRIBUTIONS

Conceptualization, J.S.S., D.Z.C., L.R.C., and D.P.E.; data curation and formal analysis, J.S.S.; writing – initial draft, J.S.S.; writing – review & editing, J.S.S., D.Z.C., L.R.C., and D.P.E.; visualization, J.S.S.; supervision, D.Z.C., L.R.C., and D.P.E.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: May 30, 2022
Revised: August 4, 2022
Accepted: September 21, 2022
Published: October 26, 2022

REFERENCES

1. Watson, J.E.M., Evans, T., Venter, O., Williams, B., Tulloch, A., Stewart, C., Thompson, I., Ray, J.C., Murray, K., Salazar, A., et al. (2018). The exceptional value of intact forest ecosystems. Nat. Ecol. Evol. *2*, 599–610. https://doi.org/10.1038/s41559-018-0490-x.
2. Fletcher, M.-S., Hamilton, R., Dressler, W., and Palmer, L. (2021). Indigenous knowledge and the shackles of wilderness. Proc. Natl. Acad. Sci. USA *118*. e2022218118. https://doi.org/10.1073/pnas.2022218118.
3. Roberts, P., Hunt, C., Arroyo-Kalin, M., Evans, D., and Boivin, N. (2017). The deep human prehistory of global tropical forests and its relevance for modern conservation. Nat. Plants *3*, 17093. https://doi.org/10.1038/nplants.2017.93.
4. Dawson, N.M., Coolsaet, B., Sterling, E.J., Loveridge, R., Gross-Camp, N.D., Wongbusarakum, S., Sangha, K.K., Scherl, L.M., Phan, H.P., Zafra-Calvo, N., et al. (2021). The role of Indigenous peoples and local communities in effective and equitable conservation. Ecol. Soc. *26*, 19. https://doi.org/10.5751/ES-12625-260319.
5. Garnett, S.T., Burgess, N.D., Fa, J.E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C.J., Watson, J.E.M., Zander, K.K., Austin, B., Brondizio, E.S., et al. (2018). A spatial overview of the global importance of Indigenous lands for conservation. Nat. Sustain. *1*, 369–374. https://doi.org/10.1038/s41893-018-0100-6.
6. Fa, J.E., Watson, J.E., Leiper, I., Potapov, P., Evans, T.D., Burgess, N.D., Molnár, Z., Fernández-Llamazares, Á., Duncan, T., Wang, S., et al. (2020). Importance of Indigenous Peoples' lands for the conservation of Intact Forest Landscapes. Front. Ecol. Environ. *18*, 135–140. https://doi.org/10.1002/fee.2148.
7. Walker, W.S., Gorelik, S.R., Baccini, A., Aragon-Osejo, J.L., Josse, C., Meyer, C., Macedo, M.N., Augusto, C., Rios, S., Katan, T., et al. (2020). The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas. Proc. Natl. Acad. Sci. USA *117*, 3015–3025. https://doi.org/10.1073/pnas.1913321117.
8. Sze, J.S., Carrasco, L.R., Childs, D., and Edwards, D.P. (2022). Reduced deforestation and degradation in Indigenous Lands pan-tropically. Nat. Sustain. *5*, 123–130. https://doi.org/10.1038/s41893-021-00815-2.
9. Convention on Biological Diversity (2020). Zero draft of the post-2020 global biodiversity framework. CBD/WG2020/2/3.
10. Grantham, H.S., Duncan, A., Evans, T.D., Jones, K.R., Beyer, H.L., Schuster, R., Walston, J., Ray, J.C., Robinson, J.G., Callow, M., et al. (2020). Anthropogenic modification of forests means only 40% of remaining forests have high ecosystem integrity. Nat. Commun. *11*, 5978. https://doi.org/10.1038/s41467-020-19493-3.
11. Ellis, E.C., Gauthier, N., Klein Goldewijk, K., Bliege Bird, R., Boivin, N., Díaz, S., Fuller, D.Q., Gill, J.L., Kaplan, J.O., Kingston, N., et al. (2021). People have shaped most of terrestrial nature for at least 12,000 years. Proc. Natl. Acad. Sci. USA *118*. e2023483118. https://doi.org/10.1073/pnas.2023483118.
12. Potapov, P., Hansen, M.C., Laestadius, L., Turubanova, S., Yaroshenko, A., Thies, C., Smith, W., Zhuravleva, I., Komarova, A., Minnemeyer, S., et al. (2017). The last frontiers of wilderness: tracking loss of intact forest landscapes from 2000 to 2013. Sci. Adv. *3*, e1600821. https://doi.org/10.1126/sciadv.1600821.
13. UNEP-WCMC, and IUCN (2020). Protected Planet: The World Database on Protected Areas (WDPA) (UNEP-WCMC and IUCN).
14. Levis, C., Costa, F.R.C., Bongers, F., Peña-Claros, M., Clement, C.R., Junqueira, A.B., Neves, E.G., Tamanaha, E.K., Figueiredo, F.O.G., Salomão, R.P., et al. (2017). Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. Science *355*, 925–931. https://doi.org/10.1126/science.aal0157.
15. Loughlin, N.J.D., Gosling, W.D., Mothes, P., and Montoya, E. (2018). Ecological consequences of post-Columbian indigenous depopulation in the Andean–Amazonian corridor. Nat. Ecol. Evol. *2*, 1233–1236. https://doi.org/10.1038/s41559-018-0602-7.
16. Heckenberger, M.J., Russell, J.C., Toney, J.R., and Schmidt, M.J. (2007). The legacy of cultural landscapes in the Brazilian Amazon: implications for biodiversity. Philos. Trans. R. Soc. Lond. B Biol. Sci. *362*, 197–208. https://doi.org/10.1098/rstb.2006.1979.
17. Michon, G., de Foresta, H., Levang, P., and Verdeaux, F. (2007). Domestic forests: a new paradigm for integrating local communities' forestry into tropical forest science. Ecol. Soc. *12*, 1.
18. ICCA Consortium (2021). Territories of Life: 2021 Report (ICCA Consortium).
19. Youdelis, M., Townsend, J., Bhattacharyya, J., Moola, F., and Fobister, J.B. (2021). Decolonial conservation: establishing Indigenous Protected Areas for future generations in the face of extractive capitalism. J. Polit. Ecol. *28*, 4716. https://doi.org/10.2458/jpe.4716.
20. Gardner, C.J., Bicknell, J.E., Baldwin-Cantello, W., Struebig, M.J., and Davies, Z.G. (2019). Quantifying the impacts of defaunation on natural forest regeneration in a global meta-analysis. Nat. Commun. *10*, 4590. https://doi.org/10.1038/s41467-019-12539-1.
21. Bebbington, A.J., Humphreys Bebbington, D., Sauls, L.A., Rogan, J., Agrawal, S., Gamboa, C., Imhof, A., Johnson, K., Rosa, H., Royo, A., et al. (2018). Resource extraction and infrastructure threaten forest cover

and community rights. Proc. Natl. Acad. Sci. USA *115*, 13164–13173. https://doi.org/10.1073/pnas.1812505115.

22. Scheidel, A., Del Bene, D., Liu, J., Navas, G., Mingorría, S., Demaria, F., Avila, S., Roy, B., Ertör, I., Temper, L., et al. (2020). Environmental conflicts and defenders: a global overview. Glob. Environ. Change *63*, 102104. https://doi.org/10.1016/j.gloenvcha.2020.102104.
23. Plumptre, A.J., Baisero, D., Belote, R.T., Vázquez-Domínguez, E., Faurby, S., Jędrzejewski, W., Kiara, H., Kühl, H., Benítez-López, A., Luna-Aranguré, C., et al. (2021). Where might we find ecologically intact communities? Front. For. Glob. Change *4*, 626635. https://doi.org/10.3389/ffgc.2021.626635.
24. Joppa, L.N., and Pfaff, A. (2009). High and far: biases in the location of protected areas. PLoS One *4*, e8273. https://doi.org/10.1371/journal.pone.0008273.
25. Rights and Resources Initiative (2020). Estimate of the area of land and territories of Indigenous Peoples, local communities, and Afro-descendants where their rights have not been recognized (Rights and Resources Initiative).
26. Anongos, A., and Whitmore, A.; Tebtebba (2012). Pitfalls & Pipelines: Indigenous Peoples and Extractive Industries (Tebtebba Foundation).
27. Asia Indigenous Peoples Pact, Coalition for Tenure Justice in Indonesia, and Rights and Resources Initiative (2020). Under the Cover of COVID: New Laws in Asia Favor Business at the Cost of Indigenous Peoples' and Local Communities' Land and Territorial Rights (Rights and Resources Initiative).
28. Dressler, W. (2021). Quarantining activism: COVID-19, frontline defenders and intensifying extractivism in the Philippines. J. Polit. Ecol. *28*, 2955. https://doi.org/10.2458/jpe.2955.
29. Resende, F.M., Meyer, L., Vieira, R.R.S., Bizri, H.R.E., Pacheco, A.A., Fernandes, G.W., and Loyola, R. (2021). COVID-19 Pandemic and Harmful Policies Push Brazil into an Environmental Crisis (Open Science Framework). https://doi.org/10.31219/osf.io/w4jpn.
30. European Parliament and Directorate General for External Policies of the Union (2014). Indigenous Peoples, Extractive Industries and Human Rights (Publications Office).
31. Geldmann, J., Manica, A., Burgess, N.D., Coad, L., and Balmford, A. (2019). A global-level assessment of the effectiveness of protected areas at resisting anthropogenic pressures. Proc. Natl. Acad. Sci. USA *116*, 23209–23215. https://doi.org/10.1073/pnas.1908221116.
32. Nepstad, D., Schwartzman, S., Bamberger, B., Santilli, M., Ray, D., Schlesinger, P., Lefebvre, P., Alencar, A., Prinz, E., Fiske, G., et al. (2006). Inhibition of Amazon deforestation and fire by parks and indigenous lands: inhibition of Amazon deforestation and fire. Conserv. Biol. *20*, 65–73. https://doi.org/10.1111/j.1523-1739.2006.00351.x.
33. Vergara-Asenjo, G., and Potvin, C. (2014). Forest protection and tenure status: the key role of indigenous peoples and protected areas in Panama. Glob. Environ. Change *28*, 205–215. https://doi.org/10.1016/j.gloenvcha.2014.07.002.
34. Nolte, C., Agrawal, A., Silvius, K.M., and Soares-Filho, B.S. (2013). Governance regime and location influence avoided deforestation success of protected areas in the Brazilian Amazon. Proc. Natl. Acad. Sci. USA *110*, 4956–4961. https://doi.org/10.1073/pnas.1214786110.
35. Walker, R., and Simmons, C. (2018). Endangered Amazon: an indigenous tribe fights back Against hydropower development in the Tapajós valley. Environ. Sci. Policy Sustain. Dev. *60*, 4–15. https://doi.org/10.1080/00139157.2018.1418994.
36. Armitage, D., Mbatha, P., Muhl, E., Rice, W., and Sowman, M. (2020). Governance principles for community-centered conservation in the post-2020 global biodiversity framework. Conserv. Sci. Pract. *2*, e160. https://doi.org/10.1111/csp2.160.
37. WWF, UNEP-WCMC, SGP/ICCA-GSI, LM, TNC, CI, WCS, EP, ILC-S, CM (2021). The state of Indigenous Peoples' and Local Communities' lands and territories: a technical review of the state of Indigenous Peoples' and Local Communities' lands, their contributions to global biodiversity conservation and ecosystem services, the pressures they face, and recommendations for actions.
38. Kastner, T., Matej, S., Forrest, M., Gingrich, S., Haberl, H., Hickler, T., Krausmann, F., Lasslop, G., Niedertscheider, M., Plutzar, C., et al. (2022). Land use intensification increasingly drives the spatiotemporal patterns of the global human appropriation of net primary production in the last century. Glob. Change Biol. *28*, 307–322. https://doi.org/10.1111/gcb.15932.
39. Sayre, N.F., Davis, D.K., Bestelmeyer, B., and Williamson, J.C. (2017). Rangelands: where anthromes meet their limits. Land *6*, 31. https://doi.org/10.3390/land6020031.
40. Riggio, J., Baillie, J.E.M., Brumby, S., Ellis, E., Kennedy, C.M., Oakleaf, J.R., Tait, A., Tepe, T., Theobald, D.M., Venter, O., et al. (2020). Global human influence maps reveal clear opportunities in conserving Earth's remaining intact terrestrial ecosystems. Glob. Change Biol. *26*, 4344–4356. https://doi.org/10.1111/gcb.15109.
41. Grantham, H.S., Tibaldeschi, P., Izquierdo, P., Mo, K., Patterson, D.J., Rainey, H., Watson, J.E.M., and Jones, K.R. (2021). The emerging threat of extractives sector to intact forest landscapes. Front. For. Glob. Change *4*, 692338. https://doi.org/10.3389/ffgc.2021.692338.
42. Levers, C., Romero-Muñoz, A., Baumann, M., De Marzo, T., Fernández, P.D., Gasparri, N.I., Gavier-Pizarro, G.I., Waroux, Y.L.P. de, Piquer-Rodríguez, M., Semper-Pascual, A., et al. (2021). Agricultural expansion and the ecological marginalization of forest-dependent people. Proc. Natl. Acad. Sci. USA *118*. e2100436118. https://doi.org/10.1073/pnas.2100436118.
43. Johnson, C.J., Venter, O., Ray, J.C., and Watson, J.E.M. (2020). Growth-inducing infrastructure represents transformative yet ignored keystone environmental decisions. Conserv. Lett. *13*, e12696. https://doi.org/10.1111/conl.12696.
44. Moranta, J., Torres, C., Murray, I., Hidalgo, M., Hinz, H., and Gouraguine, A. (2022). Transcending capitalism growth strategies for biodiversity conservation. Conserv. Biol. *36*, e13821. https://doi.org/10.1111/cobi.13821.
45. Mascia, M.B., Pailler, S., Krithivasan, R., Roshchanka, V., Burns, D., Mlotha, M.J., Murray, D.R., and Peng, N. (2014). Protected area downgrading, downsizing, and degazettement (PADDD) in Africa, Asia, and Latin America and the Caribbean, 1900–2010. Biol. Conserv. *169*, 355–361. https://doi.org/10.1016/j.biocon.2013.11.021.
46. Golden Kroner, R.E., Qin, S., Cook, C.N., Krithivasan, R., Pack, S.M., Bonilla, O.D., Cort-Kansinally, K.A., Coutinho, B., Feng, M., Martínez Garcia, M.I., et al. (2019). The uncertain future of protected lands and waters. Science *364*, 881–886. https://doi.org/10.1126/science.aau5525.
47. Coad, L., Watson, J.E., Geldmann, J., Burgess, N.D., Leverington, F., Hockings, M., Knights, K., and Di Marco, M. (2019). Widespread shortfalls in protected area resourcing undermine efforts to conserve biodiversity. Front. Ecol. Environ. *17*, 259–264. https://doi.org/10.1002/fee.2042.
48. Golden Kroner, R., Barbier, E.B., Chassot, O., Chaudhary, S., Cordova, L., Jr., Cruz-Trinidad, A., Cumming, T., Howard, J., Karibuhoye Said, C., Kun, Z., et al. (2021). COVID-era policies and economic recovery plans: are governments building back better for protected and conserved areas? PARKS *27*, 135–148. https://doi.org/10.2305/IUCN.CH.2021.PARKS-27-SIRGK.en.
49. Merçon, J., Vetter, S., Tengö, M., Cocks, M., Balvanera, P., Rosell, J.A., and Ayala-Orozco, B. (2019). From local landscapes to international policy: contributions of the biocultural paradigm to global sustainability. Glob. Sustain. *2*, e7. https://doi.org/10.1017/sus.2019.4.
50. Ens, E., Reyes-García, V., Asselin, H., Hsu, M., Reimerson, E., Reihana, K., Sithole, B., Shen, X., Cavanagh, V., and Adams, M. (2021). Recognition of indigenous ecological knowledge systems in conservation and their role to narrow the knowledge-implementation gap. In Closing the Knowledge-Implementation Gap in Conservation Science Wildlife Research Monographs, C.C. Ferreira, and C.F.C. Klütsch, eds. (Springer International Publishing), pp. 109–139. https://doi.org/10.1007/978-3-030-81085-6_5.

51. McDermott, C.L., Montana, J., Bennett, A., Gueiros, C., Hamilton, R., Hirons, M., Maguire-Rajpaul, V.A., Parry, E., and Picot, L. (2022). Transforming land use governance: global targets without equity miss the mark. Env. Pol. Gov. Published online July 22, 2022. https://doi.org/10.1002/eet.2027.

52. Stevens, S., Broome, N.P., and Jaegar, T. (2016). Recognising and respecting ICCAs overlapped by protected areas. https://www.iccaconsortium.org/.

53. Sunkar, A., and Santosa, Y. (2018). Biodiversity conservation at Betung Kerihun National Park: the positive role of customary law in mitigating a local community trust deficit. IOP Conf. Ser. Earth Environ. Sci. *196*, 012024. https://doi.org/10.1088/1755-1315/196/1/012024.

54. Anau, N., Hakim, A., Lekson, A.S., and Setyowati, E. (2019). Local wisdom practices of Dayak indigenous people in the management of Tana' Ulen in the Kayan Mentarang national park of Malinau regency, north Kalimantan Province, Indonesia. Russ. J. Agric. Socio Econ. Sci. *91*, 156–167. https://doi.org/10.18551/rjoas.2019-07.16.

55. Rubis, J.M., and Theriault, N. (2020). Concealing protocols: conservation, Indigenous survivance, and the dilemmas of visibility. Soc. Cult. Geogr. *21*, 962–984. https://doi.org/10.1080/14649365.2019.1574882.

56. Paulson, N., Laudati, A., Doolittle, A., Welch-Devine, M., and Pena, P. (2012). Indigenous peoples' participation in global conservation: looking beyond headdresses and face paint. Environ. Values *21*, 255–276. https://doi.org/10.3197/096327112X13400390125894.

57. Haenssgen, M.J., Lechner, A.M., Rakotonarivo, S., Leepreecha, P., Sakboon, M., Chu, T.-W., Auclair, E., and Vlaev, I. (2022). Implementation of the COP26 declaration to halt forest loss must safeguard and include Indigenous people. Nat. Ecol. Evol. *6*, 235–236. https://doi.org/10.1038/s41559-021-01650-6.

58. Obura, D.O., Katerere, Y., Mayet, M., Kaelo, D., Msweli, S., Mather, K., Harris, J., Louis, M., Kramer, R., Teferi, T., et al. (2021). Integrate biodiversity targets from local to global levels. Science *373*, 746–748. https://doi.org/10.1126/science.abh2234.

59. Larson, A.M., and Springer, J. (2016). Recognition and Respect for Tenure Rights (IUCN, CEESP and CIFOR).

60. Fletcher, R., and Büscher, B. (2020). Conservation basic income: a non-market mechanism to support convivial conservation. Biol. Conserv. *244*, 108520. https://doi.org/10.1016/j.biocon.2020.108520.

61. Selibas, D. (2022). Ecuador's Pastaza Province, Indigenous groups collaborate on forest conservation (Mongabay). https://news.mongabay.com/2022/04/ecuadors-pastaza-province-indigenous-groups-collaborate-on-forest-conservation/.

62. Dinerstein, E., Olson, D., Joshi, A., Vynne, C., Burgess, N.D., Wikramanayake, E., Hahn, N., Palminteri, S., Hedao, P., Noss, R., et al. (2017). An ecoregion-based approach to protecting half the terrestrial. BioScience *67*, 534–545. https://doi.org/10.1093/biosci/bix014.

63. Global Forest Watch (2019). Spatial Database of Planted Trees. https://www.wri.org/research/spatial-database-planted-trees-sdpt-version-10.

64. Transparent World, and Global Forest Watch (2019). Tree Plantations. https://data.globalforestwatch.org/maps/tree-plantations.

65. Amatulli, G., Domisch, S., Tuanmu, M.-N., Parmentier, B., Ranipeta, A., Malczyk, J., and Jetz, W. (2018). A suite of global, cross-scale topographic variables for environmental and biodiversity modeling. Sci. Data *5*, 180040. https://doi.org/10.1038/sdata.2018.40.

66. Lloyd, C.T., Sorichetta, A., and Tatem, A.J. (2017). High resolution global gridded data for use in population studies. Sci. Data *4*, 170001. https://doi.org/10.1038/sdata.2017.1.

67. Nelson, A., Weiss, D.J., van Etten, J., Cattaneo, A., McMenomy, T.S., and Koo, J. (2019). A suite of global accessibility indicators. Sci. Data *6*, 266. https://doi.org/10.1038/s41597-019-0265-5.

68. Center for International Earth Science Information Network - CIESIN - Columbia University, and Information Technology Outreach Services - ITOS - University of Georgia (2013). Global Roads Open Access Data Set (gROADSv1). Version 1 (1980–2010).

69. Global Land Analysis & Discovery, Department of Geographical Sciences, University of Maryland (2013). Global 2010 Tree Cover (30m). https://glad.umd.edu/dataset/global-2010-tree-cover-30-m.

70. Global Administrative Areas (2018). GAD database of Global Administrative Areas, version 3.6.

71. R Core Team (2021). R: A Language and Environment for Statistical Computing (R Development Core Team).

72. QGIS (2020). QGIS Geographic Information System. https://www.qgis.org/.

73. Environmental Systems Research Institute (2019). ArcGIS desktop. https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview.

74. Hanson, J.O. (2020). wdpar: interface to the world database on protected areas (R Project).

75. Ho, D.E., Imai, K., King, G., and Stuart, E.A. (2018). MatchIt: nonparametric preprocessing for parametric causal inference. J. Stat. Soft. *42*, 1–28.

76. Brooks, T.M., Akçakaya, H.R., Burgess, N.D., Butchart, S.H.M., Hilton-Taylor, C., Hoffmann, M., Juffe-Bignoli, D., Kingston, N., MacSharry, B., Parr, M., et al. (2016). Analysing biodiversity and conservation knowledge products to support regional environmental assessments. Sci. Data *3*, 160007. https://doi.org/10.1038/sdata.2016.7.

77. Wood, S. (2019). mgcv: Mixed GAM computation vehicle with automatic smoothness estimation. R-package version 1.8–31. https://CRAN.R-project.org/package=mgcv.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
R version 4.1.1	The R Foundation	https://www.r-project.org
R Studio version 1.4.1717	RStudio	https://www.rstudio.com/products/rstudio/download/
QGIS version 3.4	Open Source Geospatial Foundation	https://www.qgis.org/en/site/forusers/download.html
ArcMap version 10.7.1	ESRI	http://desktop.arcgis.com/en/arcmap/
Custom code	Author's own	https://github.com/JocelyneSze/PhD-Ch3-ForestIntegrity
Other		
World Database of Protected Areas (Jan 2020)	UNEP-WCMC and IUCN[13]	https://www.protectedplanet.net/
Indigenous Peoples' Land	Garnett et al.[5]	Requested from author
Forest Landscape Integrity Index	Grantham et al.[10]	https://www.forestlandscapeintegrity.com/download-data
Anthromes (years 1950 and 2010)	Ellis et al.[11]	https://dataverse.harvard.edu/dataverse/anthromes_12k/
Intact Forest Landscapes	Potapov et al.[12]	https://www.intactforests.org/data.ifl.html
Ecoregions	Dinerstein et al.[62]	http://ecoregions2017.appspot.com/
Spatial Database of Planted Trees	Global Forest Watch[63]	https://data.globalforestwatch.org/documents/gfw::planted-forests/about
Tree Plantations dataset	Transparent World and Global Forest Watch[64]	https://data.globalforestwatch.org/datasets/gfw::tree-plantations/explore
Slope	Amatulli et al.[65]	http://www.earthenv.org/topography
Elevation	Amatulli et al.[65]	http://www.earthenv.org/topography
Population density	Lloyd et al.[66]	https://www.worldpop.org/geodata/listing?id=64
Travel time (travel time to nearest urban area with at least 5000 inhabitants in 2015)	Nelson et al.[67]	https://figshare.com/articles/travel_time_to_cities_and_ports_in_the_year_2015/7638134/3
Distance to roads, from SEDAC gRoads v1 with ArcMap Distance toolset to calculate distance from each raster cell to nearest road	Author's own; CIESIN and ITOS[68]	https://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1/data-download
Forest area in 2010, from Global Forest Watch tree cover in 2010 at 25% canopy cover threshold	Author's own; Global Land Analysis & Discovery, Department of Geographical Sciences, University of Maryland[69]	https://glad.umd.edu/dataset/global-2010-tree-cover-30-m
Country polygons (GADM version 3.6)	Global Administrative Areas[70]	https://gadm.org/download_world.html

RESOURCE AVAILABILITY

Lead contact

Further information and requests for information should be directed to and will be fulfilled by the lead contact, Jocelyne S. Sze (jssze1@sheffield.ac.uk).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- All datasets used can be downloaded from the original sources or requested from the respective authors as listed in the key resources table.
- All original code has been deposited in the GitHub repository listed in the key resources table and is publicly available as of the date of publication.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Study site information

We focused on tropical forest biomes (Tropical and Subtropical Moist Broadleaf Forests, Tropical and Subtropical Dry Broadleaf Forests, and Tropical and Subtropical Coniferous Forests biomes),[62] clipping all data layers to their extent and rasterizing layers to 1 km^2 resolution. Spatial data processing was done in R,[71] QGIS[72] and ArcMap[73] in Mollweide equal-area projection (ESRI 54009), before transformation to geographic coordinate system (EPSG 4326) and eventual conversion to a standard data frame. A spatial mask was applied to exclude planted areas from study (Spatial Database of Planted Trees[63] and Tree Plantations[64]), as well as the 1777 PAs established after our baseline year (i.e., 2010).

METHOD DETAILS

Forest protection type map

We identified three broad categories of protecting land within tropical moist forests: Indigenous Lands, Protected Areas (PAs), overlapping Protected-Indigenous Areas (PIAs), as well as non-protected areas as controls (Figure S1). Indigenous Peoples' Lands is a database of areas where Indigenous peoples have land tenure or *de facto* management.[5] Although areas mapped as Indigenous may not fully be under Indigenous control, and areas not mapped as Indigenous are not necessarily non-Indigenous, we take the data to represent land where Indigenous peoples have likely had influence. PAs, as listed within the World Database of Protected Areas,[13] are designated by the respective state and legislated to be protected for conservation purposes.

We downloaded protected areas using the R package wdpar.[74] We included terrestrial PAs of all categories designated to year 2010, which we took as the baseline year. Following the recommended protocol for cleaning data, we removed non-established sites, UNESCO man and biosphere sites, and point sites due to lack of area information, with additional manual editing in QGIS to remove self-intersections. PAs that had no establishment year (value of 0 in the STATUS_YEAR column) were assumed to have been established before the study period and were included. To obtain PA-only areas, we filtered out PAs that were governed by Indigenous people as listed in the attribute table and removed areas of the PIA spatial intersection, resulting in 3955 PAs.

We obtained spatial data on ILs from the authors and intersected PAs not listed as governed by Indigenous peoples. This spatial intersection was joined with PAs governed by Indigenous peoples (467 PAs) to create Protected-Indigenous Areas (PIAs). To obtain IL-only areas, we removed areas of the PIA spatial intersection from the Indigenous Peoples' Land data.

The remaining areas that fall outside PAs (to January 2020), ILs, or PIAs were considered non-protected (Table S1A). These vector data were then rasterised to 1 km^2 pixels, eliminating double-counting. All pixels that touched the borders of PAs, ILs, or PIAs, were also excluded from the study.

Anthrome levels

We selected Anthrome maps for the years 1950 and 2010 (our baseline year).[11] We include anthromes for 1950 as it represents a time period before extensive land-use changes (i.e., the Green Revolution), to examine how land-use intensity had changed in the decades prior to our study period, though we note that most PAs may not have been designated at that time. Discrete categories are defined based on population densities and intensive land-use cover at regional landscape scales ($\sim$100 km^2). In the broadest classification of anthromes, wildlands are characterized by complete absence of human populations and intensive land-uses, cultured anthromes with less than 20% intensive land-use, and intensive anthromes with more than 20% intensive land-use cover. We used the second-level classification: dense settlements (urban areas), villages (dense agricultural settlements), croplands (lands used mainly for annual crops), rangelands (lands used mainly for livestock grazing), cultured (inhabited lands with minor use for permanent agriculture and settlement), and wildlands (lands without human populations or substantial land-use). Dense settlements, villages, croplands, and rangelands are classified as intensive land-uses.

QUANTIFICATION AND STATISTICAL ANALYSIS

Identifying comparable areas with matching

All analyses were conducted in R.[71] As locations of PAs are biased towards remote, steep, and high-elevation areas,[24] which also affects the likelihood of forest disturbance, we used statistical matching to identify forest areas that would be more comparable. Following Sze et al.,[8] we included variables that affect forest disturbance and assignment of PAs: slope,[65] elevation,[65] population density,[66] travel time to nearest urban area,[67] distance to road,[68] baseline forest area,[69] and country[70] (Table S4).

We used the MatchIt package[75] to conduct propensity score matching for each protection type and unprotected area within each tropical region, following Brook et al.'s[76] convention of sorting overseas territories according to geography rather than governing territory. For each of the nine sets of matching, we drew five samples, with replacement, from the full dataset to keep it computationally tractable, resulting in $\sim$85,000 matched pixels for each set. Matching was done with the default logit method, 1:1 nearest neighbor match without replacement, and caliper size of 0.25 to ensure good matches. If no matches were available within the specified calipers, we opted to take the nearest available match. We included all numeric covariates (slope, elevation, population density, travel time, distance to roads, baseline forest area) with country as an exact match, and checked that balance was improved from the matching (Table S5). We then combined the data from across the five matched samples to create a map of matched protection types,

representing more comparable areas, covering 444,985 km^2 of ILs, 490,353 km^2 of PAs, 356,745 km^2 of PIAs, and 1,355,865 km^2 of non-protected areas.

Overlay of anthromes on matched areas

We overlaid the Anthrome layers on our matched areas and counted the number of pixels of each anthromes level within different protection types for the years 1950 and 2010 (Figure 3; Table S3).

Estimating forest integrity

We used the FLII as a measure of forest integrity,[10] which improves on the widely-used Intact Forest Landscapes (IFL)[12] by creating a scaled index that additionally incorporates inferred forest pressure by modelling based on proximity to observed pressures to account for edge effects and other human use of forests, such as hunting. We overlaid FLII over our study area to provide an overview of how forest integrity is distributed across the tropics (Figures 1B and 2; Table S2). We also included comparison with the IFL (Figure S2; Table S1B). Observed pressures are mapped from infrastructure (e.g., military, energy generation, and transport infrastructure), agricultural croplands, and recent deforestation, combined with models of inferred pressure and lost forest connectivity to create an index ranging from 0 to 10. This index reflects the degree of anthropogenic modification in 2019, with 10 representing forests with no detectable modification. Following Grantham et al.,[10] in addition to reporting mean and median FLII values, we also categorized FLII into three levels of low (0-6), medium (6-9.6), and high (9.6-10) integrity.

Imbalances remaining in the covariates after matching were accounted for with regression. Split by regions, we had 935930 pixels for Africa, 997714 for Americas, and 532786 for Asia. We fitted generalized additive mixed models for each region using the mgcv package,[77] including a parametric term for protection type and numeric covariates (slope, elevation, population density, travel time, distance to roads, baseline forest area) as cubic regression smoothing splines. Slope, elevation, travel time, and distance to roads were heavily right-skewed and were cube-root transformed, while population density was transformed by ^(1/5) for Africa and Asia and ^(1/6) for the Americas. We fitted country-level random slopes for 2010 forest area, an interaction term between protection type and country, and a random intercept for country. We used the bam function for large datasets, default fREML method, and quasi-binomial distribution (rescaling FLII to 0 to 1).

To estimate the effect of protection type on FLII, we took median values of numeric covariates and combinations of each country and protection type to create the prediction dataset. We then excluded country effects to isolate the effect of protection types when running the prediction. Additionally, since strict PAs (categories I to IV) often preclude human activities that may affect our results, we repeated our analysis, including only multi-use PAs (categories V and VI) within PA protection type, as a robustness check (Figure S3).