nature communications

Article

https://doi.org/10.1038/s41467-025-59196-1

The importance of distinguishing between natural and managed tree cover gains in the moist tropics

Received: 3 April 2024

Accepted: 11 April 2025

Published online: 02 July 2025

Check for updates

Xueyuan Gao[1,2,3], Peter B. Reich[4,5,6], Jeffrey R. Vincent[7], Matthew E. Fagan[8], Robin L. Chazdon[9], Steffen Fritz[10], Dmitry Schepaschenko[10,11], Matthew D. Potts[12,13], Matthew C. Hansen[3], Martin Jung[11], Pedro H. S. Brancalion[14,15], María Uriarte[16], Trevor F. Keenan[12,17,18], Thomas W. Crowther[19], Ralph O. Dubayah[3], Myroslava Lesiv[10], Shunlin Liang[20] & Dongdong Wang[3,21]

Naturally regenerated forests and managed tree systems provide different levels of carbon, biodiversity, and livelihood benefits. Here, we show that tree cover gains in the moist tropics during 1982–2015 were 56% ± 3% naturally regenerated forests and 27% ± 2.6% managed tree systems, with these differences in forest type, not only natural conditions (climate, soil, and topography), driving observed carbon recovery rates. The remaining 17% ± 3% likely represents small, unmanaged tree patches within non-forest cover types. Achieving global forest restoration goals requires robust monitoring, reporting, and verification of forest types established by restoration initiatives.

Nature-based climate solutions[1], such as forest conservation[2], restoration[3,4], and sustainable management[5], offer a promising approach to mitigate the effects of global climate change, conserve biodiversity, and enhance rural livelihoods[6]. By sequestering carbon in terrestrial ecosystems, forest landscape restoration can yield substantial co-benefits for biodiversity and ecosystem services and is often a no-regret investment[7]. Land use projects, which are mostly forestry projects, issued approximately half of all credits from 2000 to 2021 on the voluntary carbon market[8] and have featured prominently in many Nationally Determined Contributions to the Paris Agreement[1]. Landscapes undergoing tree cover restoration are often a heterogeneous mosaic of various restoration approaches, including natural forest regrowth, planted forests for conservation purposes, commercial plantations, and agroforestry[6]. The relative impacts of these different land use strategies can be highly variable for biodiversity, climate, and human wellbeing[6]. Different restoration strategies are being used depending on site conditions, local opportunities, and needs, often necessitating trade-offs among conservation and production goals[9]. As

[1]Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ, USA. [2]High Meadows Environmental Institute, Princeton University, Princeton, NJ, USA. [3]Department of Geographical Sciences, University of Maryland, College Park, MD, USA. [4]Institute for Global Change Biology, University of Michigan, Ann Arbor, MI, USA. [5]Department of Forest Resources, University of Minnesota, St. Paul, MN, USA. [6]Hawkesbury Institute for the Environment, Western Sydney University, Penrith, NSW, Australia. [7]Nicholas School of the Environment, Duke University, Durham, NC, USA. [8]Department of Geography and Environmental Systems, University of Maryland Baltimore County, Baltimore, MD, USA. [9]Forest Research Institute, University of the Sunshine Coast, Sippy Downs, QLD, Australia. [10]Advancing Systems Analysis Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. [11]Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. [12]Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA, USA. [13]Carbon Direct Inc, New York, NY, USA. [14]Department of Forest Sciences, University of São Paulo, Piracicaba, Brazil. [15]Re.green, Rio de Janeiro, Brazil. [16]Department of Ecology, Evolution and Environmental Biology, Columbia University, New York, NY, USA. [17]Climate and Ecosystem Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA. [18]Earthshot Labs, Sebastapol, CA, USA. [19]Institute of Integrative Biology, ETH Zurich (Swiss Federal Institute of Technology), Zurich, Switzerland. [20]Jockey Club Laboratory of Quantitative Remote Sensing, Department of Geography, University of Hong Kong, Hong Kong, China. [21]Institute of Remote Sensing and GIS, School of Earth and Space Sciences, Peking University, Beijing, China. e-mail: xg6497@princeton.edu

tree plantations comprise nearly half of the restoration area pledged by over 60 nations to the Bonn Challenge[10] and have different environmental outcomes compared to naturally regenerated forests[9], it is critical to distinguish forest types when monitoring forest landscape restoration, assessing their socio-ecological determinants and outcomes, and evaluating their climate mitigation potential[11–14].

Here we use an annually resolved 30-m resolution tropical moist tree cover change dataset[15] developed by the European Commission's Joint Research Centre (JRC) and a 100-m global forest management type dataset[16] available for 2015 to distinguish tree cover gain types on former agricultural lands (croplands and pasturelands) in the global moist tropics. We intersect the 30-m tropical tree cover gain dataset with the 100-m global forest management layer to attribute tropical tree cover gains on former agricultural lands during 1982–2015 to the expansion of natural forest regrowth and three managed tree systems: timber plantations, oil palm plantations, and agroforestry (Fig. 1).

Results

Tropical moist forest restoration patterns

Examining tree cover gains on former agricultural lands across the entire tropical moist forest region, we estimate around 27% ± 2.6% of the tree cover gain in this region to be managed tree systems, whereas 56% ± 3% is due to natural forest regrowth (Table 1). The 27% estimate for managed tree systems is conservative relative to the range estimated by Fagan et al. [17], 34% to 68%, as we did not consider tree cover expansion in tropical dry forests or tropical grasslands, savannas, and shrublands[17]. The remaining 17% ± 3% of tree cover gain on former agricultural lands in the JRC's 30-m resolution dataset occurs in locations classified as non-forest land cover types by the 100-m forest management type dataset (Table 1), including cropland, pastureland, grassland, shrublands, and water bodies. This area likely represents small patches of unmanaged trees within these predominantly non-forest land covers.

Focusing on three major subareas of the entire tropical moist forest region—the Amazon, Borneo, and Central Africa— natural forest regrowth accounts for 62% ± 3.3% of tree cover gains on former agricultural lands (Table 1). Timber plantations, oil palm plantations, and agroforestry account for 0.2% ± 0.1%, 2% ± 0.9%, and 17% ± 1.9% of the gains, respectively, indicating that managed tree systems are a substantial part of moist tropical tree cover gains even in regions dominated by natural tree cover. Borneo's gain has a much larger percentage of managed tree systems (51% ± 8.1%) than did the Amazon's (16% ± 1.9%) or Central Africa's (14% ± 1.6%). In Amazon and Central Africa, oil palm plantations represent tinier fractions (60-fold and 400-fold smaller, respectively) of tree cover gain than in Borneo, where they are one-third as widespread as recovering natural forest.

Drivers of tropical carbon recovery rates

A previous study, Heinrich et al. [18] used the same moist tropical tree cover gain dataset from JRC and an observation-based biomass product to assess rates and drivers of aboveground carbon accumulation in tropical recovering forests. They found that regeneration rates in Borneo were around 45% and 58% higher than in Central Africa and the Amazon, respectively, in the first 20 years of recovery. This difference was attributed solely to climatic and topographical factors. However, the large percentage of managed tree systems in Borneo can have

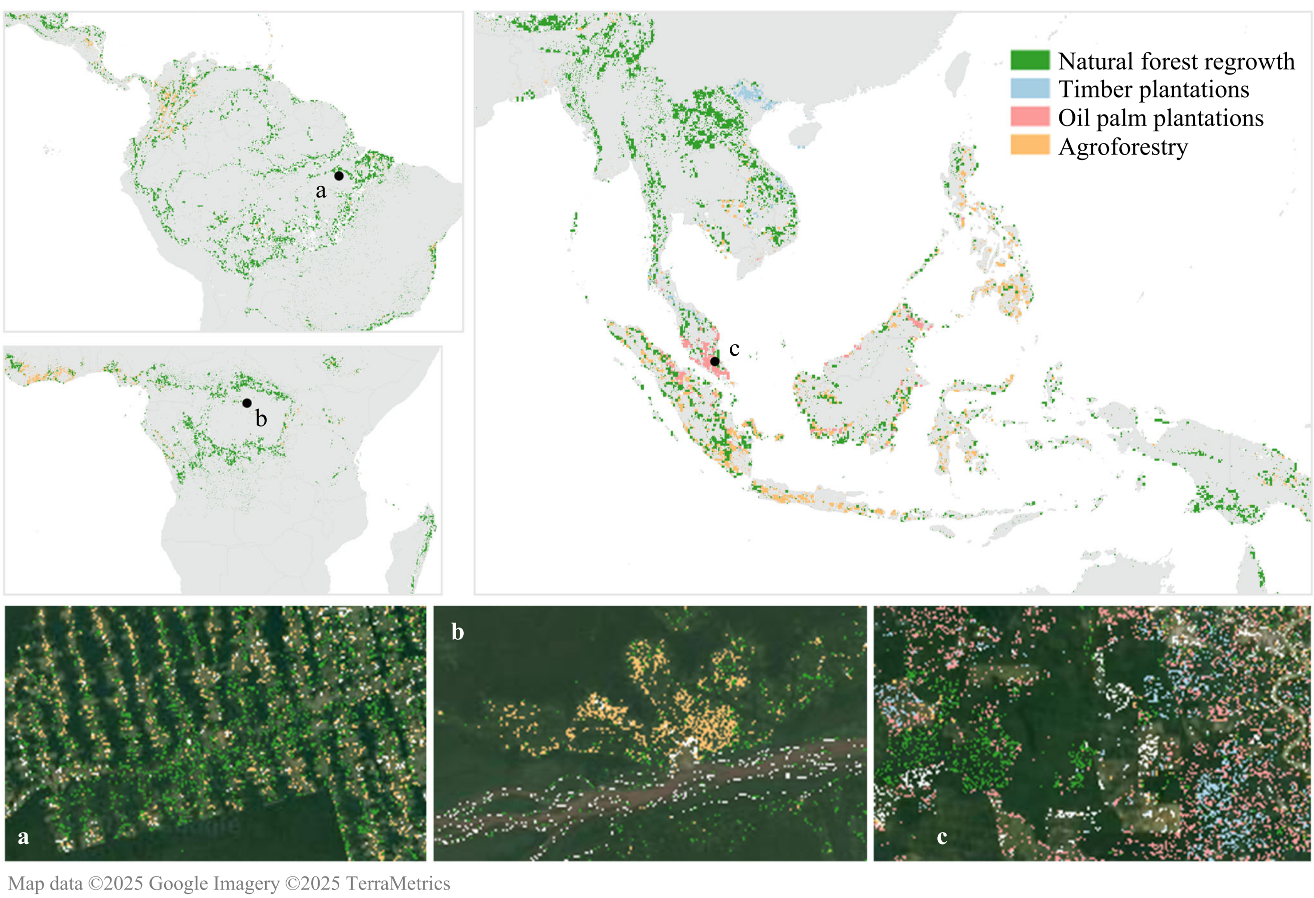

Fig. 1 | Moist tropical tree cover restoration areas and types on former agricultural land in 2015. The continental maps were aggregated from 100 m to 10,000 m resolution for visualization. Three sites **a**–**c** were selected to show the heterogeneity of the landscape in the original 100-m resolution where white color areas represent other land cover types (Table 1). The map in the original 100-m resolution can be viewed and downloaded via Google Earth Engine[36] (https://code.earthengine.google.com/a8ab0a204422bdaf13bd1eff4bc0a5ea). The basemap in the three sites is from Google Maps.

https://doi.org/10.1038/s41467-025-59196-1

Table 1 | Restoration types in moist tropical tree cover gains that occurred on former agricultural land during 1982–2015

Regions Restoration types classified as recovered forest		Amazon		Central Africa		Borneo		Amazon+ Central Africa+ Borneo		Entire moist tropical region	
		Area proportion	Area (Mha)	Area proportion	Area (Mha)	Area proportion	Area (Mha)	Area proportion	Area (Mha)	Area proportion	Area (Mha)
Natural forest regrowth		62% ± 3.3%	8.5 ± 0.5	77% ± 4.1%	4.7 ± 0.2	35% ± 1.8%	0.6 ± 0.03	62% ± 3.3%	13.8 ± 0.7	56% ± 3%	20 ± 1
Managed tree systems	Timber plantations	0.2% ± 0.1%	0.02 ± 0.01	0.03% ± 0.01%	0.002 ± 0.001	1% ± 0.3%	0.02 ± 0.01	0.2% ± 0.1%	0.03 ± 0.01	2% ± 1%	0.9 ± 0.4
	Oil palm plantations	0.5% ± 0.2%	0.05 ± 0.02	0.07% ± 0.03%	0.005 ± 0.002	16% ± 6.6%	0.5 ± 0.2	2% ± 0.9%	0.5 ± 0.2	4% ± 1.6%	1.4 ± 0.6
	Agroforestry	15% ± 1.7%	2.1 ± 0.2	13% ± 1.5%	0.9 ± 0.1	34% ± 3.9%	0.6 ± 0.1	17% ± 1.9%	3.5 ± 0.4	21% ± 2.4%	7.6 ± 0.9
Other land cover		22% ± 3.9%	3.0 ± 0.5	10% ± 1.7%	0.7 ± 0.1	14% ± 2.5%	0.3 ± 0.05	18% ± 3.2%	3.9 ± 0.7	17% ± 3%	6 ± 1

Agroforestry is defined as in the global forest management type layer and includes: (1) fruit trees; (2) tree shelter belts and small forest patches; (3) sparse trees in cropland and pasture; (4) shifting cultivation; and (5) trees in urban/built-up areas. It may contain smallholder oil palm plantations due to known limitations in the forest management map. "Other land cover" represents non-forest land types (e.g., cropland, pastureland, grassland, shrublands, water bodies, etc.). The area estimates have been adjusted based on the error matrix presented in Table 3 and the uncertainty estimation is based on 95% confidence interval (see "Methods").

either positive or negative effects on landscape carbon accumulation rates, hinging on the species that were planted and their growth rates[6]. Moreover, some areas of natural forest regrowth in Borneo have undergone assisted restoration practices like climber cutting and enrichment planting[19], which significantly accelerate aboveground carbon recovery compared to unassisted natural regeneration[19].

We applied the Global Forest Model (G4M)[20] to investigate to what extent regional variations in forest carbon accumulation rates can be attributed to natural conditions (climate, soil, and topography) or if management regimes need to be taken into account as well. The G4M simulations showed that, if we exclude managed tree systems, regional differences in secondary/degraded forest growth rates are substantially lower than found by Heinrich et al., with natural regrowth rates in Borneo only 10% higher than in Central Africa (compared to 45% in Heinrich et al.) and only 13% higher than in the Amazon (compared to 58% in Heinrich et al.). These results suggest that differences in restoration types and management practices might be strong drivers of remotely sensed geographic differences in tropical carbon recovery rates[21]. We posit that landscape restoration types and forest management practices are at least as important drivers of regional differences in regrowth rates as continent-scale differences in climate and topography. Furthermore, ignoring differences between the drivers of the expansion of plantations and agroforestry versus natural forest regrowth may compromise the identification of priority areas for promoting the expansion of natural forests to conserve biodiversity and mitigate climate change[22,23].

Discussion

"Agroforestry"—the largest contributor to managed tree cover gain on former agricultural lands—encompasses a heterogeneous range of managed tree systems (Table 1). Our use of the term follows the definition in the global forest management layer and includes: (1) fruit trees; (2) tree shelter belts and small forest patches; (3) sparse trees in cropland and pasture; (4) shifting cultivation; and (5) trees in urban/built-up areas. These different agroforestry systems differ in carbon accumulation rates and co-benefits for people and biodiversity[24–26]. Additionally, a typical biomass pixel (e.g., 100 m) in a remotely sensed representation of an agroforestry landscape could contain a significant signal from herbaceous crops and pastures. As a result, the remotely sensed carbon accumulation rates in agroforestry landscapes may differ substantially from the rates in natural secondary forests[27].

A higher proportion of agroforests in a study area may additionally have important implications for long-term carbon permanence. Establishing or enhancing tree cover on open farmland may increase net carbon storage[24]. However, thinning or clearing of forest to establish an agroforestry system could cause carbon losses[24], especially when agroforestry includes slash-and-burn practices that are among the factors explaining the reduced longevity of naturally regenerating tropical forests[22,28]. High uncertainty remains regarding which agroforestry actions provide mitigation and how to reliably track progress of agroforestry toward being a natural climate solution[24].

The 17% ± 3% of post-agricultural land area classified as tree cover gain in the JRC forest cover change dataset but not as natural forest regrowth or a managed tree system according to the global forest management dataset could include land where unmanaged forest regrowth has partially occurred but is hindered by factors such as invasive grasses, vines, shrubs, or ferns. Such land is unlikely to have accumulated much carbon, and management interventions would be required to accelerate forest recovery and carbon accumulation. The accurate delineation and management classification of such land is key, because its unintended and invisible inclusion in remote sensing analyzes of recovering forest underestimates the carbon sink potential of lands actually returned to forests of one kind or another.

The 100-m 2015 global forest management layer is currently the only available global product characterizing forest management types in a moderate-resolution manner[16,29]. We urge the remote sensing community to map not only where forests and other tree systems are being restored but also what types of tree systems are being restored[11]. This mapping effort should encompass not only the moist tropics, which we have focused on due to data availability, but also the dry tropics, subtropics, and temperate and boreal zones, which collectively account for even more of the world's forest biome area and are home to much more of the planet's human population[30].

The needs and priorities of local communities and national aspirations dictate the appropriate land management and restoration measures to be taken. Tree plantations and agroforestry may be locally appropriate choices, particularly when biophysical or socio-economic conditions do not support natural regeneration[31]. These market-driven tree systems can be especially valuable when payments for ecosystem services offered by governments or other organizations are either nonexistent, which is currently the case across most of the moist tropics, or not high enough to offset the costs (opportunity, implementation, maintenance) of natural forest regeneration[32].

Land management planners, investors, and implementers need rigorous monitoring, reporting, and verification systems to account for the environmental, ecological, and socioeconomic trade-offs of different forest restoration approaches[9]. Recent concerns about the over-crediting issues in Reducing Emissions from Deforestation and Forest Degradation (REDD+) projects have created a lack of confidence in nature-based carbon credits[2,33]. Although less criticism regarding project monitoring has been directed at forest restoration activities, termed Afforestation, Reforestation, and Revegetation (ARR) in the carbon market, the dialog surrounding REDD+ and the shift it has brought to the sector should serve as a cautionary tale, highlighting the need for careful progress to successfully scale up ARR activities. Moreover, ARR projects present their own set of unique challenges, particularly around the monitoring of diverse types of tree cover restoration and their subtle annual changes in carbon stocks. Distinguishing and disaggregating forms of tree cover that represent different tree management systems, not simply capturing the area of tree cover gain, would enable these systems to enhance the integrity of ARR credits in the carbon market[34]. This information may be critical for improving confidence in forest-featured Nationally Determined Contributions in the United Nations Framework Convention on Climate Change's Global Stocktake, and enhancing compatibility with the biodiversity targets of the Kunming-Montreal Global Biodiversity Framework.

Methods

Primary datasets

The global forest management layer was created at a 100-m resolution for the year 2015 with good overall accuracy (>82%) using time series from PROBA-V satellite imagery combined with unique reference samples[16]. It characterizes forest management classes such as intact forests, managed forests with natural regeneration, planted forests, plantation forest (rotation up to 15 years), oil palm plantations, and agroforestry.

The European Commission JRC tropical moist forest cover change dataset was created at a 30-m resolution over the period 1982–2022 using 41 years of Landsat time series[15]. It characterizes undisturbed tropical moist forest, degraded tropical moist forest, deforested land, forest regrowth, and permanent and seasonal water in its Annual Change Collection. It separately identifies agricultural lands (croplands and pasturelands) as a land cover type on which observed tree cover gain occurs.

We intersected the 30-m tropical tree cover gains (i.e., the "forest regrowth" category in the JRC Annual Change Collection) with the 100-m global forest management layer to attribute tropical tree cover gains on former agricultural lands during 1982–2015 to the expansion of natural forest regrowth and three managed tree systems. A map of tree cover gain types on former agricultural lands in the global tropics was finally generated in a 100-m resolution, and the area (in million hectares, Mha) of each tree cover gain type was extracted. The map reflects annual changes throughout the period, not just the difference between 1982 and 2015, and it is net of reversals out of tree cover. For example, a tree cover gain of X million hectares that occurred during Year t to Year $t+1$ but experienced a subsequent cumulative loss of Y million hectares ($Y<X$) during Year $t+1$ to 2015 is measured as a net gain of $X-Y$ million hectares.

Accuracy assessment

We conducted an independent accuracy assessment of the 100-m tropic tree cover gain type map by using the methodology set out in Olofsson et al. [35]. It allows the 95% confidence intervals to be estimated and the area estimates to be adjusted based on the error matrix. Using the mapped classes as strata (natural forest regrowth, timber plantations, oil palm plantations, agroforestry, and other land cover), we applied a random stratified sampling design to create 460 sample pixels in total, with a targeted overall accuracy of 75%. The sample size allocated to each class was determined by the targeted user's accuracy for that class. To create the reference classification for labeling each sample pixel, we used a combination of Landsat data from the USGS open archive, together with historical images in Google Earth. The error matric of sample counts and proportional area is presented in Tables 2 and 3. We also combined timber plantations, oil palm plantations, and agroforestry as "managed tree systems" and created an error matrix (Table 4), which shows a robust accuracy of the map of managed tree cover gains.

Tropical carbon recovery rate simulations

The G4M[20] (https://iiasa.ac.at/g4m) is a biophysical forestry model developed at International Institute for Applied Systems Analysis, which is used in many projects to inform European Commission on carbon sequestration, carbon stock, and harvest potential on different climate and management scenarios. The G4M estimates forest productivity based on dynamic site characteristics such as monthly temperature, precipitation, radiation, and CO_2 concentration, semi-

Table 2 | Description of sample data as an error matrix of sample counts

Mapped classes	Reference					
	Natural forest regrowth	Timber plantations	Oil palm plantations	Agroforestry	Other land cover	Total
Natural forest regrowth	159	1	3	2	13	178
Timber plantations	1	32	13	8	2	56
Oil palm plantations	3	0	28	16	7	54
Agroforestry	4	2	5	74	11	96
Other land cover	3	0	1	14	58	76
Total	170	35	50	114	91	460

Table 3 | The error matrix in Table 2 populated by estimated proportions of area

Mapped classes	Reference					User's	CI	Producer's	CI
	Natural forest regrowth	Timber plantations	Oil palm plantations	Agroforestry	Other land cover				
Natural forest regrowth	54.5%	0.3%	1.0%	0.7%	4.5%	89.3%	4.5%	97.2%	2.4%
Timber plantations	0.1%	1.7%	0.7%	0.4%	0.1%	57.1%	13.1%	67.4%	12.4%
Oil palm plantations	0.1%	0%	0.9%	0.5%	0.2%	51.9%	13.5%	22.8%	11.3%
Agroforestry	0.9%	0.5%	1.2%	17%	2.5%	77.1%	8.5%	81.5%	7.8%
Other land cover	0.5%	0%	0.2%	2.3%	9.4%	76.3%	9.6%	56.1%	11.2%
Overall accuracy						83.4%	3.6%		

CI is 95% confidence interval.

Table 4 | The error matrix after consolidating timber plantations, oil palm plantations, and agroforestry as "managed tree systems"

	Reference			User's	CI	Producer's	CI
Mapped classes	Natural forest regrowth	Managed tree systems	Other land cover				
Natural forest regrowth	54.5%	2.1%	4.5%	89.3%	4.5%	97.3%	2.4%
Managed tree systems	1.0%	23.1%	2.6%	86.4%	4.7%	83.8%	5.0%
Other land cover	0.5%	2.4%	9.4%	76.3%	9.6%	57.0%	11.2%
Overall accuracy				87.0%	3.3%		

CI is 95% confidence interval.

dynamic factors including water holding capacity and soil depth, as well as nitrogen, phosphorus, salinity, and pH values, and static attributes like air pressure. The model is calibrated using net primary production and biomass observations.

Data availability
All input datasets are available from the references cited. The moist tropical tree cover restoration areas and types map (Fig. 1) can be regenerated by running the Google Earth Engine codes provided herein.

Code availability
Google Earth Engine was used to perform all the analysis and codes are available in a public repository (https://code.earthengine.google.com/a8ab0a204422bdaf13bd1eff4bc0a5ea). Global Forest Model: https://github.com/GeorgKindermann/g4m.

References

1. Griscom, B. W. et al. Natural climate solutions. *Proc. Natl. Acad. Sci. USA* **114**, 11645–11650 (2017).
2. West, T. A. P. et al. Action needed to make carbon offsets from forest conservation work for climate change mitigation. *Science* **381**, 873–877 (2023).
3. Cook-Patton, S. C. et al. Mapping carbon accumulation potential from global natural forest regrowth. *Nature* **585**, 545–550 (2020).
4. Mo, L. et al. Integrated global assessment of the natural forest carbon potential. *Nature* 1–10 https://doi.org/10.1038/s41586-023-06723-z (2023).
5. Gao, X. et al. Exploration of a novel geoengineering solution: lighting up tropical forests at night. *Earth Syst. Dyn.* **13**, 219–230 (2022).
6. Vincent, J. R., Curran, S. R. & Ashton, M. S. Forest restoration in low- and middle-income countries. *Annu. Rev. Environ. Resour.* **46**, 289–317 (2021).
7. Poorter, L. et al. Multidimensional tropical forest recovery. *Science* **374**, 1370–1376 (2021).
8. DeFries, R. et al. Land management can contribute to net zero. *Science* **376**, 1163–1165 (2022).
9. Hua, F. et al. The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. *Science* **376**, 839–844 (2022).
10. Lewis, S. L., Wheeler, C. E., Mitchard, E. T. A. & Koch, A. Restoring natural forests is the best way to remove atmospheric carbon. *Nature* **568**, 25–28 (2019).
11. Jung, M. et al. The importance of capturing management in forest restoration targets. *Nat. Sustain.* 1–5 https://doi.org/10.1038/s41893-023-01192-8 (2023).
12. Wilson, S., Schelhas, J., Grau, R., Nanni, A. & Sloan, S. Forest ecosystem-service transitions: the ecological dimensions of the forest transition. *Ecol. Soc.* **22**, 38 (2017).
13. Xu, H. et al. Global forest plantations mapping and biomass carbon estimation. *J. Geophys. Res. Biogeosci.* **129**, e2023JG007441 (2024).
14. Williams, B. A. et al. Global potential for natural regeneration in deforested tropical regions. *Nature* 1–7 https://doi.org/10.1038/s41586-024-08106-4 (2024).
15. Vancutsem, C. et al. Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. *Sci. Adv.* **7**, eabe1603 (2021).
16. Lesiv, M. et al. Global forest management data for 2015 at a 100 m resolution. *Sci. Data* **9**, 199 (2022).
17. Fagan, M. E. et al. The expansion of tree plantations across tropical biomes. *Nat. Sustain.* **5**, 681–688 (2022).
18. Heinrich, V. H. A. et al. The carbon sink of secondary and degraded humid tropical forests. *Nature* **615**, 436–442 (2023).
19. Philipson, C. D. et al. Active restoration accelerates the carbon recovery of human-modified tropical forests. *Science* **369**, 838–841 (2020).
20. Kindermann, G. E. et al. Potential stocks and increments of woody biomass in the European Union under different management and climate scenarios. *Carbon Balanc. Manag.* **8**, 2 (2013).
21. Chazdon, R. & Brancalion, P. Restoring forests as a means to many ends. *Science* **365**, 24–25 (2019).

22. Brancalion, P. H. S. et al. A call to develop carbon credits for second-growth forests. *Nat. Ecol. Evol.* 1–2 https://doi.org/10.1038/s41559-023-02288-2 (2024).
23. Jung, M. et al. The global exposure of species ranges and protected areas to forest management. *Diver. Distrib.* **28**, 1487–1496 (2022).
24. Terasaki Hart, D. E. et al. Priority science can accelerate agroforestry as a natural climate solution. *Nat. Clim. Chang.* 1–12 https://doi.org/10.1038/s41558-023-01810-5 (2023).
25. Ma, Z., Chen, H. Y. H., Bork, E. W., Carlyle, C. N. & Chang, S. X. Carbon accumulation in agroforestry systems is affected by tree species diversity, age and regional climate: a global meta-analysis. *Glob. Ecol. Biogeogr.* **29**, 1817–1828 (2020).
26. Gao, X., Liang, S. & He, B. Detected global agricultural greening from satellite data. *Agric. For. Meteorol.* **276–277**, 107652 (2019).
27. Cardozo, E. G. et al. Agroforestry systems recover tree carbon stock faster than natural succession in Eastern Amazon, Brazil. *Agrofor. Syst.* **96**, 941–956 (2022).
28. Parker, D. et al. Land in limbo: Nearly one third of Indonesia's cleared old-growth forests left idle. *Proc. Natl. Acad. Sci. USA* **121**, e2318029121 (2024).
29. Xu, H. et al. Changes in the fine composition of global forests from 2001 to 2020. *J. Remote Sens.* **4**, 0119 (2024).
30. Dinerstein, E. et al. An ecoregion-based approach to protecting half the terrestrial realm. *BioScience* **67**, 534–545 (2017).
31. Busch, J. et al. Cost-effectiveness of natural forest regeneration and plantations for climate mitigation. *Nat. Clim. Chang.* 1–7 https://doi.org/10.1038/s41558-024-02068-1 (2024).
32. Guariguata, M. R., Chazdon, R. L., Brancalion, P. H. S. & David, L. Forests: when natural regeneration is unrealistic. *Nature* **570**, 164–164 (2019).
33. Pande, R. Fixing forest carbon credits. *Science* **383**, eadn4923 (2024).
34. Balmford, A. et al. Credit credibility threatens forests. *Science* **380**, 466–467 (2023).
35. Olofsson, P. et al. Good practices for estimating area and assessing accuracy of land change. *Remote Sens. Environ.* **148**, 42–57 (2014).
36. Gorelick, N. et al. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* **202**, 18–27 (2017).

Acknowledgements
We sincerely acknowledge Karen Holl and Chris Justice for their constructive comments and suggestions in the development of this paper. We also acknowledge Haijun Li for his valuable assistance in the accuracy validation of this work. P.B.R. was supported by the National Science Foundation: Biological Integration Institutes NSF-DBI-2021898. S.F., D.S., and M.L. acknowledge funding from the German International Climate Initiative (IKI) for the Transparent Monitoring Project. T.F.K. acknowledges support from a NASA Carbon Cycle Science Award 80NSSC21K1705 and a NASA GEDI award # 80NSSC24K0600.

Author contributions
X.G. conceived the idea, performed the analysis, and wrote the manuscript, with significant editing contributions from P.B.R., J.R.V., and M.E.F. D.S. ran the G4M and performed the model analysis. X.G., P.B.R., J.R.V., M.E.F., R.L.C., S.F., D.S., M.D.P., M.C.H., M.J., P.H.S.B., M.U., T.F.K., T.W.C., R.O.D., M.L., S.L., and D.W. edited, reviewed, and approved the manuscript.

Competing interests
M.D.P. is the Chief Science Officer for Carbon Direct Inc., a company combining science, technology, and capital to deliver quality CO_2 management at scale. M.D.P. is a shareholder in the company and thus stands to benefit financially from forest management targeted at climate change mitigation. P.H.S.B. is partner at Re.green, a forest restoration company. T.F.K. is the Chief Scientist for Earthshot Labs, a science and technology company focused on enabling global forest regeneration and conservation. T.F.K. is a shareholder in the company and thus stands to benefit financially from forest management targeted at climate change mitigation. The remaining authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41467-025-59196-1.

Correspondence and requests for materials should be addressed to Xueyuan Gao.

Peer review information *Nature Communications* thanks the anonymous reviewer(s) for their contribution to the peer review of this work. A peer review file is available.