

Episodic changes in global forest edges in the 21st century

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Seventy percent of global forests lie within 1 km of an edge, yet their temporal dynamics remain poorly characterized. By developing the high spatial-resolution (0.00025°) global forest edge maps for 2000–2020, we find a 24 million km (7%) decline in edge length. During 2015–2020, edge length falls while forest area slightly grows, driven by patch merging in temperate/boreal regions and tropical fragmentation. In contrast, countries such as Laos, Liberia, India, and China gain edges from new forest patches. These episodic changes closely track policy-driven land management, including logging bans, agricultural expansion, and reforestation. Given forest edges' critical roles in biodiversity and microclimate regulation, our results highlight contrasting biome patterns and the need for adaptive policies balancing conservation, carbon storage, and land use.

Nearly 70% of the world's forests lie within 1 km of an edge¹, underscoring the global prevalence of transitional zones where forests meet other ecosystems. These edges are fundamental morphological characteristics shaped by processes such as expansion, contraction, fragmentation, and merging². Forest edges play a crucial role in maintaining biodiversity and facilitating ecological processes³ because their structure, composition, and function differ substantially from interior forests^{4,5}. They often have more open canopies, support early-successional and disturbance-adapted species, and exhibit faster nutrient cycling. These differences strongly influence microclimates, such as light availability, wind exposure, temperature variability, and moisture levels, which in turn shape tree growth patterns and the abundance and diversity of associated wildlife communities^{6,7}. Accordingly, forest edge length has been considered as a key state variable, comparable to forest area and fragmentation but far less studied⁸, representing the measurable extent of forest-nonforest interface where energy, matter, and organisms cross boundaries.

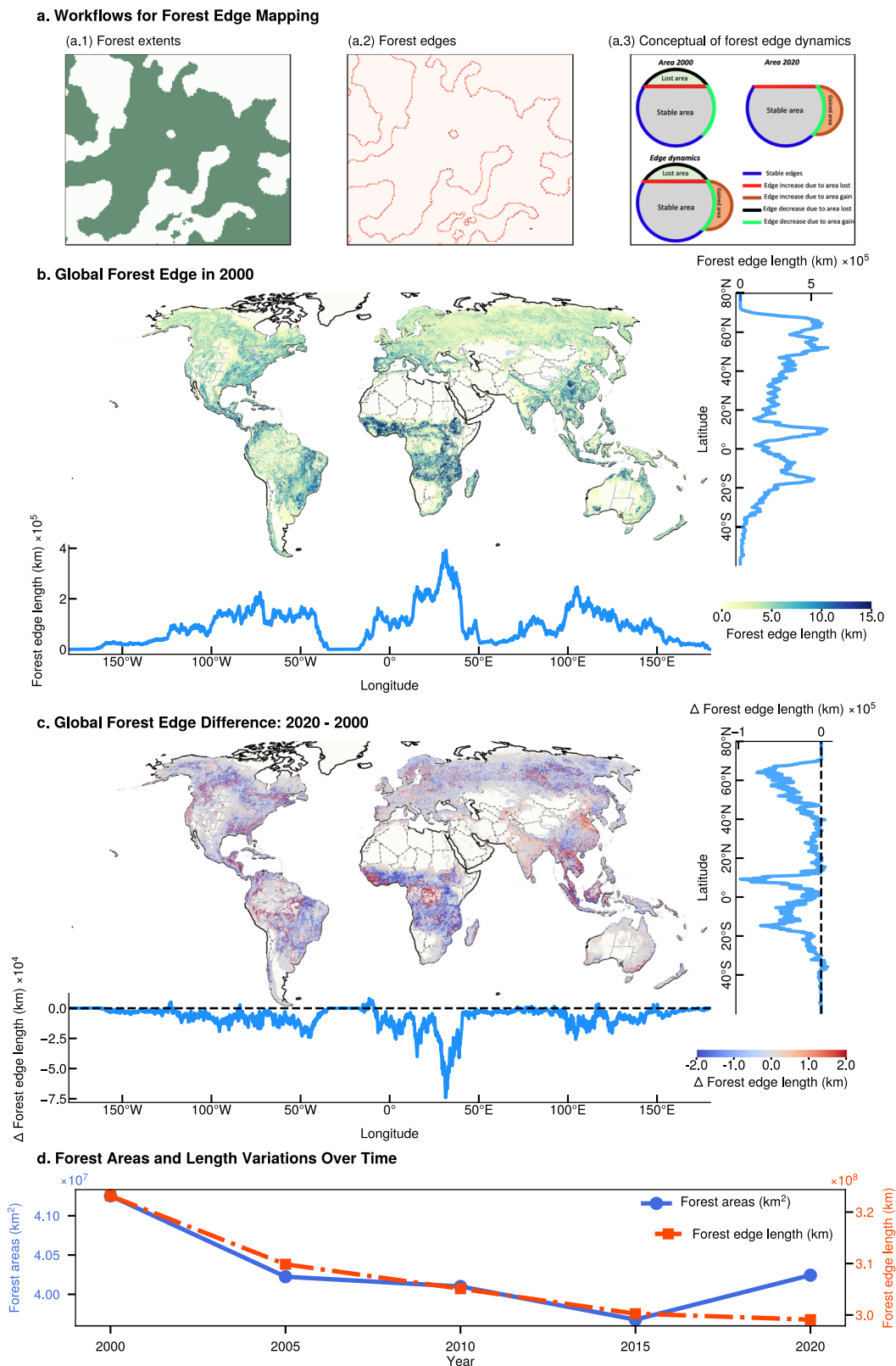
Forest landscape structure can be described using multiple complementary dimensions, including forest area and edge length, which quantify total extent and boundary exposure, while fragmentation represents a broader condition characterized by patterns of patch subdivision and connectivity. These dimensions can evolve

independently because different ecological and anthropogenic processes reshape forests in distinct ways. For example, fragmentation often increases edge length while reducing area by subdividing continuous forests^{5,9,10}, yet edge length may decline when small patches disappear through attrition or when boundaries are simplified. Connectivity indices alone can therefore misrepresent morphology. Relationships between edge and area are also process dependent: deforestation generally increases edge while reducing area¹⁰; patch merging often decreases edge but increases area¹¹; Expansion through afforestation or regeneration can increase both forest edge and area^{10,12,13}; and conversion to agriculture or urban land typically reduces both of them^{14,15}. These contrasting dynamics illustrate the complexity of forest dynamics and the possible diverse ecological consequences of edge effects¹⁶. They also highlight the need for global mapping of edge length, which remains scarce despite extensive work on fragmentation^{1,10,17–19}. Quantifying global forest edge dynamics is essential to complement area- and fragmentation-based targets with edge-sensitive objectives to preserve core habitat, biodiversity, and ecosystem function.

Recent advancements in satellite remote sensing now make such mapping feasible^{20–22}. Here we present the global, time-resolved maps of forest edge length at ~30 m resolution (0.00025°) every five years

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from 2000 to 2020, derived from Landsat-based forest extent data enhanced with spaceborne LiDAR. We classify forest patch dynamics into five categories that capture distinct processes of edge gain and loss (Fig. 1a and see “Methods”), summarize the forest edge and area dynamics by country, climate zone, and continent, and introduce a country-scale shape benchmark-- defined as the residual from a globally fitted power-law scaling between forest edge length and forest

area--that isolates morphological patterns from area change. By integrating this benchmark with our classification framework, we disentangle deforestation from fragmentation and provide a dynamic global assessment of forest edge patterns. Because governance and policy can reshape disturbance regimes more abruptly than ecological processes^{23–26}, incorporating forest morphology into conservation

Fig. 1 | Global forest edge and change. **a** Workflows for Forest Edge Mapping: Subpanels a.1 through a.3 offers a detailed view of the workflows from forest extents extraction, forest edge mapping based on the forest extents and forest edge dynamics classification according to changes in forest extent over time (see Methods). Forest extent in a.1 and a.2 was derived from the GLAD global land cover and land use change dataset²¹. **b** Global Forest Edge Length in 2000: This panel presents a world map and corresponding latitudinal and longitudinal histograms displaying the extent of forest edges in kilometers (km) across the globe in the year 2000. The map is color-coded to indicate the length of the forest edge within a grid cell size of 0.01°, with the histograms quantifying the total forest edge length at different latitudes and longitudes per 0.01°. **c** Global Forest Edge Length Difference

from 2020 to 2000: This panel illustrates the changes in forest edge extent between the years 2000 and 2020. The world map shows areas of increase (in blue) and decrease (in red) in forest edge length, with the histograms quantifying the net difference in total forest edge length at different latitudes and longitudes per 0.01° (the black dashed line is the zero line). Positive values indicate a growth in edge length, while negative values suggest a reduction. **d** Forest Areas and Edge Length Variations Over Time: The red line represents the dynamics of forest edge length, while the blue line represents changes in global forest area from 2000 to 2020. Geographic boundaries are made with Natural Earth. Free vector and raster map data at naturalearthdata.com.

strategies will be critical for preserving biodiversity, maintaining ecosystem function, and building resilience in a rapidly changing world.

Results and discussion

Forest edge dynamics across the globe

Global forest edge length declined from 323 million km in 2000 to 299 million km in 2020 (−7%; Fig. 1b). This net reduction reflects the disappearance of 90 million km of edges, partly offset by the formation of 66 million km of new edges (Supplementary Fig. 1). Among the newly formed edges, those resulting from forest loss (13% of the 2020 edge total) were more dominant than those emerging from forest expansion (9%) (Supplementary Fig. 1b, c). Conversely, more edge was removed by forest expansion (15% of the 2000 total) than by forest loss (13%) (Supplementary Fig. 1d, e). Area and edge co-declined during 2000–2015, then diverged in 2015–2020 as edge continued to fall while area rose slightly, with the strongest drop in 2000–2005, smaller changes in 2005–2015, and a sharper, decoupled changes in 2015–2020 (Fig. 1d). This net decline in global forest edge length is consistent with recent assessments of increasing fragmentation in the 21st century¹⁹, whereas our time-resolved analysis further suggests that the pace of edge reorganization has moderated in recent years, revealing temporal variability not captured by cumulative metrics alone.

Forest edge dynamics across climatic zones

We found substantial differences in forest edge length and its temporal dynamics across climate zones (see Methods). In the year 2000, Tropics and Subtropics together accounted for over 45% of global forest edges, while the Temperate and Boreal/Polar zones contributed 32% and 22%, respectively. In terms of temporal dynamics, the Polar zone remained highly stable, with over 2 million km of forest edge in 2000 and only a marginal 1% loss by 2020. In contrast, the Boreal zone, which contained over 68 million km of forest edges in 2000, experienced an 11% decline. Moderate decreases were observed in the Warm and Cool Temperate zones, encompassing around 47 and 55 million km of forest edges in 2000, with respective declines of 3% and 5%. The Tropical and Subtropical zones, starting with 76 million km and 68 million km of forest edges in 2000, saw a reduction of 8% and 9% by 2020 (Fig. 1).

Patterns of edge dynamics also varied by climatic zones. The Temperate zone contributed the largest share of new edges due to forest loss over 2000–2020 (40% of the global total for this dynamics class; see Methods), whereas the Subtropical and Tropical zones dominated new edges from forest loss (51%). By 2020, Temperate and Boreal regions accounted for the largest shares of edges lost due to forest gains (38% and 30%, respectively), while the Subtropical and Tropical zones contained the majority of edges lost due to forest loss (62%). Yet trajectories were not smooth: they changed in episodes and in several cases decoupled from area. In the temperate belts, area dropped sharply in 2000–2005, was broadly flat during 2005–2015 and rose markedly in 2015–2020; against this backdrop, edge kept contracting in Cool Temperate despite the late area rebound (decoupling), whereas Warm Temperate showed a joint rebound of area and edge after 2015 (re-coupling) (Supplementary Fig. 2a). The Subtropics

changed in 2015–2020 to a decoupled regime in which edge increased while area continued to fall. The Tropics largely co-declined throughout. The pace was pulsed, with a steep early step in 2000–2005 followed by milder changes thereafter. Boreal exhibited a strong early step-down with smaller subsequent changes, and Polar remained near-stationary (Supplementary Fig. 2a).

Forest edge dynamics across spatial scales

Forest edge patterns and dynamics also vary markedly across spatial scales from continental to subnational level. At the continent scale in 2000, more than 70% of the world's forest edge length was concentrated in Asia (28.8%), North America (21.7%), and Africa (21.6%), closely reflecting their shares of global total forest area (Asia 33.0%, North America 16.7%, and Africa 17.2%). Prominent concentrations occurred along the western coast of North America, the Amazon Basin, and across northwestern, central (Congo Basin), and eastern Africa (Fig. 1b). From 2000 to 2020, Africa and South America showed the largest net edge declines—8.7 million km (−12.5%) and 3.1 million km (−7.3%), respectively—largely associated with deforestation. Asia declined by 5.6 million km (−6.0%), North America by 5.0 million km (−7.1%), and Europe by 1.6 million km (−4.7%), whereas Australia registered a slight net edge gain of 0.06 million km (+0.5%) (Supplementary Fig. 2b). Beyond these totals, forest edge trajectories were episodic rather than gradual, with the magnitude and, in some regions, the direction of change shifting markedly among successive five-year intervals. In several continents, edge length also decoupled from forest area. Across most continents, the largest step occurred at the start of the record (2000–2005), followed by relatively mild changes during 2005–2015; after 2015, trajectories diverged (Supplementary Fig. 2b). In 2015–2020, North America and Europe decoupled, with forest area rebounding while edge length continued to contract. Asia, by contrast, showed a coupled rebound, with area and edge increasing together. Oceania decoupled in the opposite sense, with a pronounced increase in edge despite continued area loss. South America and Africa are largely co-declining across all time periods, with their steepest steps early in the record (Supplementary Fig. 2b).

Forest edge dynamics due to area change attribution further provide more insights. Asia and North America experienced substantial new edge formation from both forest gain and loss, with Asia leading in edge creation from forest expansion (11%). North America showed more mild edge changes (Supplementary Fig. 1). Conversely, Africa had the highest proportion of edge loss due to deforestation (14%), while Europe and Australia maintained high edge stability (72% and 90% of 2000 forest edges remained unchanged, respectively), reflecting effective forest conservation efforts²⁰.

At the country level, forest edge patterns largely mirrored continental changes but with important distinctions (Supplementary Data 1). The five most forested countries (Russia, Brazil, Canada, the United States of America (U.S.), and China)²⁰ also had the longest total forest edges. Russia stood out with the longest stable forest edges and the most new edge formation driven by both forest gain and loss. Although its total forest area declined only slightly (approximately 0.02%), edge length dropped by 10.6%, underscoring the importance

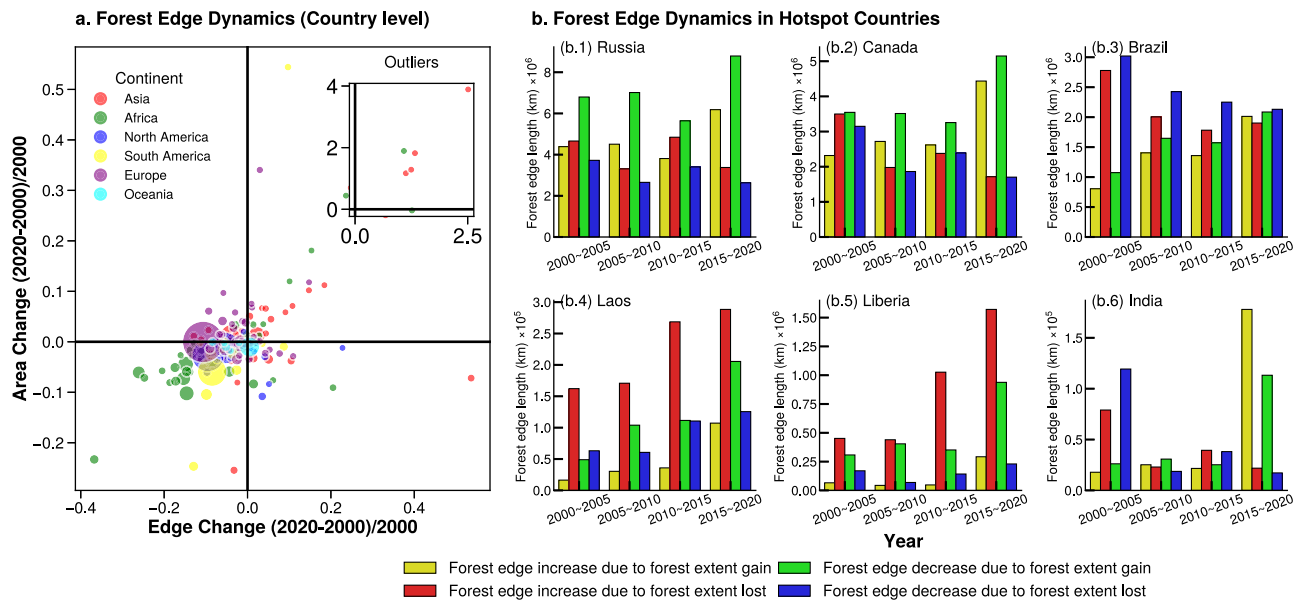


Fig. 2 | Forest dynamics at the country level from 2000 to 2020. **a** Forest Edge Dynamics (Country level): The bubble chart represents relative changes in forest area and forest edge length on a country level from 2000 to 2020 with the basis of 2000. Colors indicate the continent to which countries belong, as defined by Natural Earth classifications. The size of each bubble corresponds to the country's forest area. An inset shows outliers with substantial changes, all from countries with small forest areas. **b** Forest Edge Dynamics in Hotspot Countries: Bar charts

illustrate the contributions of forest edge dynamics due to forest extent dynamics across four periods: 2000–2005, 2005–2010, 2010–2015, and 2015–2020. Sub-panels **b.1** through **b.6** provide detailed shifts for the top three countries with net forest edge increases (Russia, Canada, and Brazil) and the top three countries with net forest edge decreases (Laos, Liberia, and India). Source data are provided as a Source Data file.

of tracking edge dynamics alongside area. Brazil experienced a 5.9% decrease in forest area and an 8.5% reduction in edge length, reflecting severe deforestation pressures. Canada saw a 2.8% reduction in forest area and a more pronounced 9.5% decline in forest edges, while the United States showed relatively minor declines in both forest area (1.2%) and edge length (5.4%). Uniquely, China was the only one among the top five countries to show a net increase in forest area (0.95%), albeit with a 3.6% decrease in forest edge length, likely due to afforestation in previously open areas with higher edge-to-area ratios²⁷. Among the countries, Laos presents a notable exception to global changes, with a net increase in forest edge length driven by widespread conversion of forest land to agriculture²⁸. Aggregated regionally, these country behaviors produce the continental signals above: many Asian countries register late-period increases, African countries tend to decline in both area and edge in line with expanding agricultural frontiers (Supplementary Fig. 1e), European countries commonly show edge decreases alongside relatively stable or rising area, and Oceania remains comparatively stable with small, mixed changes (Fig. 2a).

To illustrate forest edge dynamics and their varying processes at the subnational level, we examined spatial patterns within the five countries with the largest forest areas (Fig. 3b). In Russia, substantial forest edge increases due to forest loss were concentrated in Siberia, likely resulting from logging and fires²⁹. In contrast, the Russian Far East near the Pacific showed reductions in forest edge length associated with forest expansion across all time periods (Fig. 3b.4). In Brazil, widespread edge increases occurred in the Amazon Basin, driven by extensive forest loss from deforestation³⁰. Meanwhile, parts of southern Brazil showed localized forest expansion (Fig. 3b.3). In Canada, minimal forest loss in the west (e.g., British Columbia) contrasted with widespread forest gain in the east (e.g., Quebec and Labrador), where edge length decreased as forest cover expanded (Fig. 3b.5). In the United States, western landscapes show a sharp loss-driven edge pulse in 2000–2005 and weakens thereafter, which is likely tied to wildfires³¹; while in the East (Supplementary Fig. 3), the Northeast flips from 2000–2005 clearance to 2015–2020

afforestation, and the Southeast from early fragmentation to later merging. In China, southern areas such as the Yunnan-Tibet transition zone showed reduced edge length following forest expansion, while the northeast experienced considerable edge increases (Fig. 3d) from afforestation in areas that had previously undergone deforestation for agricultural expansion (Fig. 3b).

Implications for assessing global forest landscape pattern

To fully understand the impacts of global deforestation, reforestation, afforestation, and the change in forest landscape patterns, it is essential to go beyond tracking forest area alone and incorporate forest edge dynamics³². Because forest edge length scales with area following a power-law relationship^{33,34}, we employed a log transformation to both forest edge length and forest area and used linear regression to analyze their relationship across different countries, thereby avoiding the limitations of a simple edge-to-area ratio, which can misrepresent scale-dependent patterns and bias comparisons across regions of varying sizes (see “Methods”). As expected, we found a strong linear correlation between log-transformed forest edge length and forest area at the country level (Supplementary Fig. 5). Using the year 2000 as a baseline, we established a global average relationship to estimate expected forest edge lengths for each country in both 2000 and 2020. We then compared actual values to these expectations and quantified the residuals. Our analysis revealed substantial disparities in forest landscape patterns among countries (Fig. 4a).

Notably, tropical countries across Africa, Asia, and South America exhibited shorter-than-expected forest edges relative to the global edge–area relationship (see “Methods”), primarily due to the dominance of large, contiguous primary forests with less fragmented perimeters compared to secondary or managed forests. Interestingly, Japan and South Korea in temperate Asia also displayed shorter-than-expected forest edges, likely due to successful reforestation efforts and effective urbanization policies that support forest preservation³⁵. Equatorial Guinea and Suriname had the most negative residuals in 2000 and 2020, respectively, indicating highly intact forest

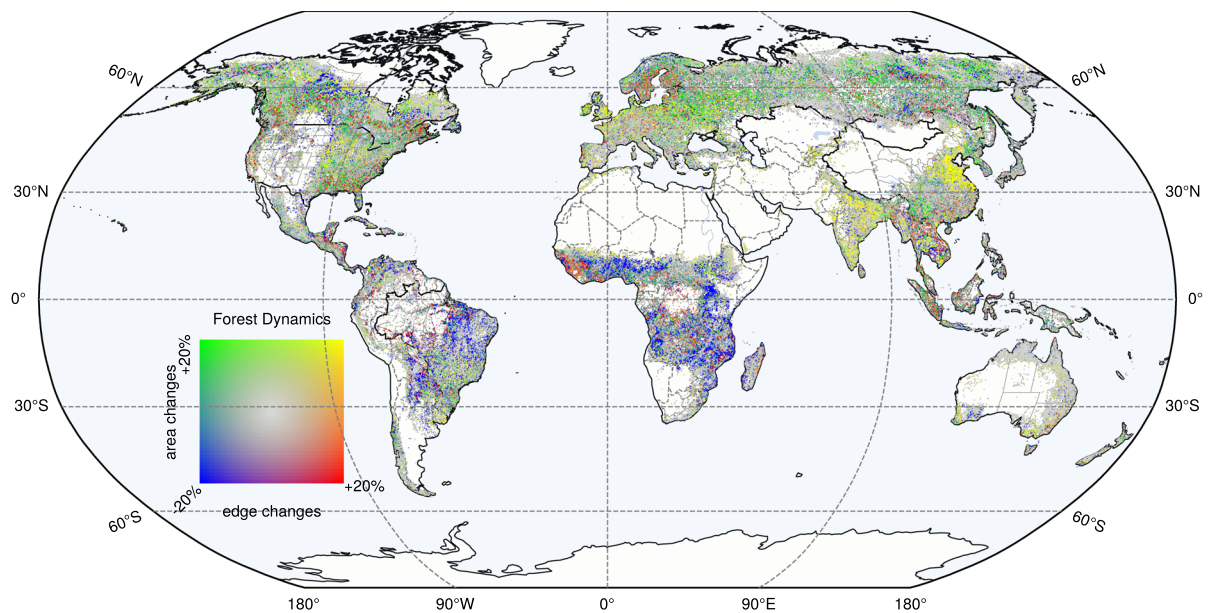
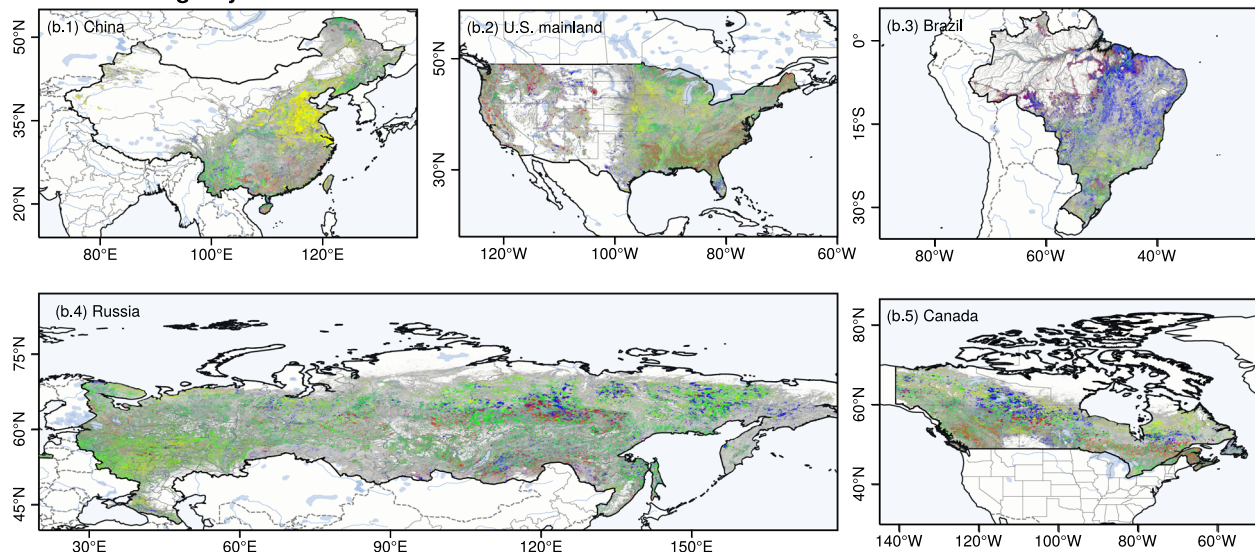
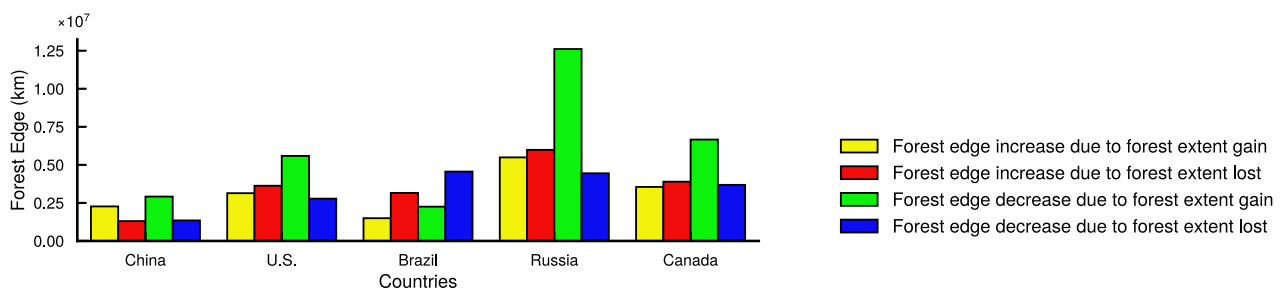
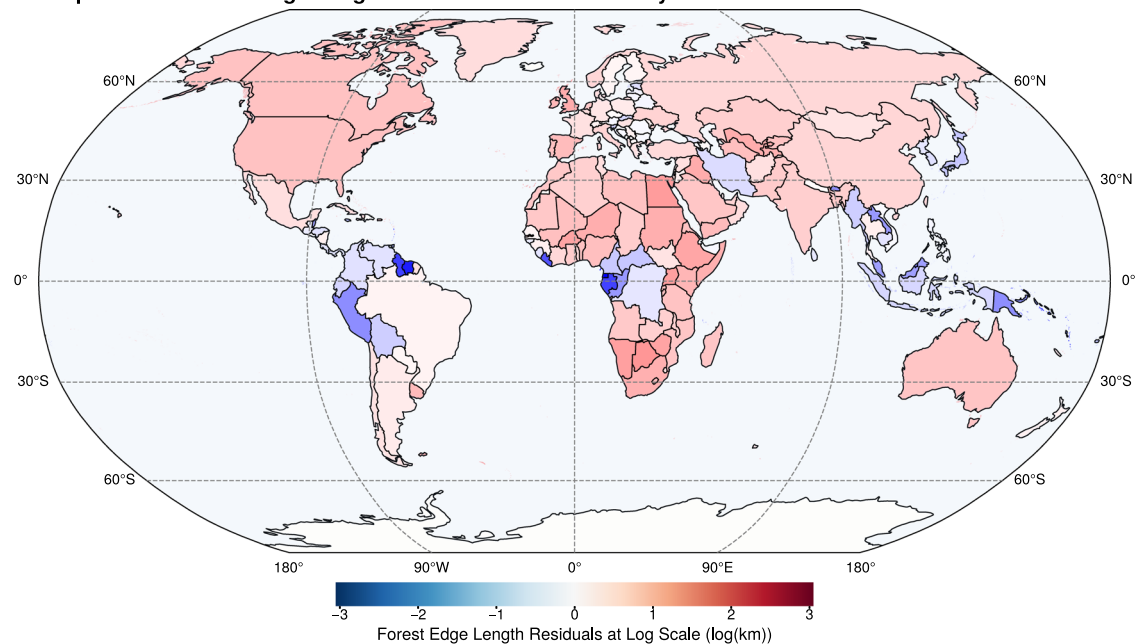
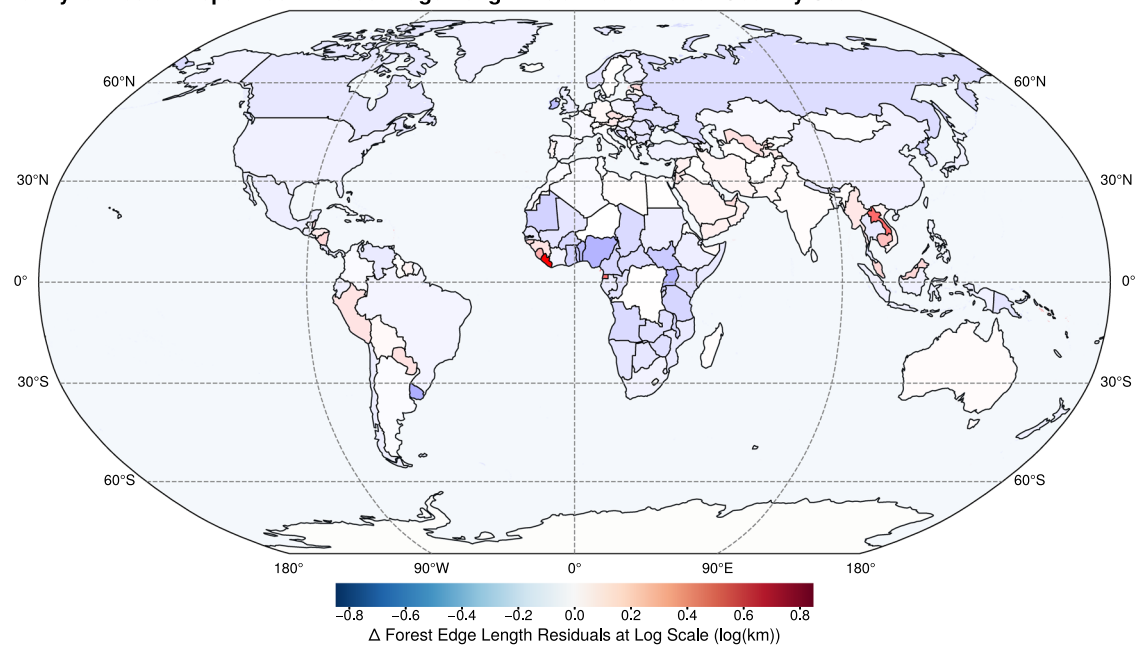
a. Global Forest Edge Dynamics**b. Forest Edge Dynamics in Different Countries****c. Forest Edge Dynamics Statistics**

Fig. 3 | Global forest edge dynamics between 2000 and 2020. a Global Forest Edge Dynamics: This map provides a global overview of forest edge dynamics, with color gradients representing the relative percentage change in forest edges. The scale ranges from forest edges large decrease with areas decrease (in blue) or forest edges large decrease with areas large increase (in green) to forest edges large increase with areas large decrease (in red) or forest edges large increase with areas large increase (in yellow), indicating regions where forest boundaries have contracted or expanded; the relatively stable edges are shown in gray. **b** Forest Edge Dynamics in Different Countries: Subpanels **b.1** through **b.5** offer a detailed view of

forest edge changes in China, the U.S. mainland, Brazil, Russia, and Canada, respectively. **c** Forest Edge Dynamics Statistics: This bar chart compares the forest edge dynamics among China, the U.S., Brazil, Russia, and Canada. Each country's edge dynamic is segmented into increase-increase (yellow bar), increase-decrease (red bar), decrease-increase (green bar), and decrease-decrease (blue bar) according to the definition (see "Methods"). Geographic boundaries are made with Natural Earth. Free vector and raster map data at [naturalearthdata.com](https://www.naturalearthdata.com). Source data are provided as a Source Data file.

a. Disparities in Forest Edge Length Relative to Area at Country Scale in 2000**b. Dynamics of Disparities in Forest Edge Length Relative to Area at Country Scale****Fig. 4 | Global forest landscape pattern and its dynamics at the country scale.**

a Disparities in Forest Edge Length Relative to Area at Country Scale in 2000: Colors show residuals from the global edge–area scaling relationship (see Methods), where red indicates countries with longer forest edges than expected given their forest area, and blue indicates shorter-than-expected edges. Positive residuals generally reflect more fragmented or boundary-complex forest configurations, whereas negative residuals indicate more contiguous forest landscapes. Color intensity reflects the magnitude of deviation. **b** Dynamics of Disparities in Forest

Edge Length Relative to Area at Country Scale: Colors represent changes in residuals over time (see “Methods”), where red indicates an increase in forest edge length relative to the global expectation, and blue indicates a decrease. Positive changes suggest increasing edge exposure or fragmentation, while negative changes suggest consolidation or reduced edge complexity. Color intensity reflects the magnitude of change. Geographic boundaries are made with Natural Earth. Free vector and raster map data at naturalearthdata.com. Source data are provided as a Source Data file.

landscapes. On the other end, Botswana (2000) and Egypt (2020) had the largest positive residuals, potentially due to extensive fragmentation or boundary complexity.

Globally, disparities in forest landscape patterns have evolved unevenly since 2000 (Supplementary Fig. 6). About 42% of countries with initially longer-than-expected forest edges experienced contractions by 2020, potentially reducing exposure to edge effects and other ecosystems. Conversely, 16% of countries with initially high edge

lengths saw further increases, suggesting ongoing fragmentation and forest exposure. Additionally, 25.5% of countries with initially shorter-than-expected edge lengths experienced further reductions, indicating the expansion of core forest areas. Notably, 16.5% of countries with initially lower-than-expected edge lengths are now showing increases, indicating rising forest exposure and shrinking core forest areas. This latter change is particularly concerning in tropical countries such as Liberia, Laos, and Equatorial Guinea, where rapid increases in forest

edge length are driven primarily by forest loss (Fig. 3a). These changes point to escalating deforestation and fragmentation of tropical primary forests, with significant implications for biodiversity, carbon storage, and ecosystem resilience.

Governance may override ecology in driving episodic forest edge dynamics

Our results suggest that global forest edge changes in the 21st century did not follow a continuous or ecologically gradual path; rather, they often exhibited episodic changes closely tied to land-use decisions and governance interventions (Supplementary Figs. 3 and 4). The strongest signals of forest area decline and edge expansion were concentrated in the early 2000s, whereas changes became progressively weaker after 2015, with a modest rebound in forest area and a slowing of edge reorganization. This pattern suggests a possible attenuation of fragmentation pressures in the most recent period, consistent with growing influence of forest governance, restoration initiatives, and natural recovery following earlier disturbances. These observed patterns suggest that policy, more than ecological processes alone, may play a dominant role in shaping forest landscape structure over decadal timescales.

For instance, major decreases in forest edge length due to forest loss in Africa were not evident until after 2005 but have since continued steadily. Meanwhile, natural processes such as fires have continued to influence edge dynamics, contributing to persistent edge expansion in West Africa and Siberia. In Europe and North America (especially the eastern U.S.), the direction and magnitude of forest edge dynamics shifted between 2000–2005 and 2015–2020, likely in response to evolving forest management practices and policy priorities^{36,37}. In several regions, the late-period stabilization or partial recovery of forest area coincides with expanded conservation programs and reforestation efforts, suggesting that policy actions may help moderate earlier trajectories of forest fragmentation. A particularly striking case is China, where large-scale afforestation initiatives launched after 2015 led to rapid gains and localized edge expansion, even though overall national forest edge length decreased²⁷. These patterns illustrate how policy changes, such as new conservation incentives, logging bans, or large-scale reforestation efforts, may be associated with pronounced changes in forest edge structure over relatively short periods.

These episodic transitions highlight the asymmetric pace at which human and ecological processes operate. Governance can rapidly alter disturbance regimes through policy, markets, and land-use decisions, whereas ecological responses such as forest regrowth and structural recovery typically unfold more gradually. As a result, forest landscapes may exhibit periods of rapid reorganization followed by phases of relative stabilization. Importantly, our analysis shows that forest edge length can decline even when changes in forest area are modest, underscoring that structural reconfiguration, including patch merging or infilling, can reduce edge exposure without large area gains. This decoupling emphasizes the value of tracking forest morphology alongside traditional area-based indicators.

Rather than implying direct causality, our findings point to a strong correspondence between changes in forest edge dynamics and broader socio-ecological changes, highlighting the role of governance as a key contextual factor shaping landscape trajectories. Effective conservation therefore requires moving beyond forest area targets to incorporate edge-sensitive perspectives that consider habitat configuration, connectivity, and exposure. The observed weakening of edge expansion and modest area recovery after 2015 provides cautious evidence that coordinated management and natural regeneration can slow or partially reverse fragmentation changes, although substantial regional variation remains. By providing a high-resolution, temporally explicit global record of forest morphology, this study offers a foundation for future analyses that integrate policy, disturbance, and

ecological processes to better understand the drivers of forest landscape change.

Methods

Defining the forest edge

The forest edge is defined as the boundary between the forest and neighboring non-forest land covers, such as grasslands, agricultural lands, or urban areas². Forest definitions vary depending on research purposes. In this study, we used the University of Maryland's definition²¹, which identifies any Landsat pixel representing tree heights of 5 m or above as forest, which is concordant with the FAO guidelines²⁰. Accordingly, we defined a forest edge pixel by the four-neighbor rule as any forest pixel that shares a boundary with a non-forest pixel in any of the four cardinal directions (up, down, left, or right).

Forest extent data

Resolution is important in forest edge mapping. Although various products are available for generating global land cover maps, creating a reliable global forest edge map is hampered by the coarse spatial resolutions (250–1000 m) of these satellite products: These resolutions miss the crucial edge effects, which vary with distance from the forest edge, being most prominent within the first 100 m^{38,39}. Conversely, high-resolution satellite data (<10-m resolution) may also be unsuitable for mapping forest edges due to the infinite coastline paradox, whereby increased resolutions lead to ostensibly limitless perimeter measurements such as mature tree canopies often span several meters across. Therefore, moderate-resolution sensors, such as Sentinel-2 and Landsat, with 10 to 30-m resolution, respectively, are more appropriate for forest edge mapping. To date, a few products have been developed with moderate-resolution data with time series, such as Hansen's forest cover map and Sentinel-2 10 m Land Use/Land Cover data^{22,40}. However, these products either primarily focus on tracking canopy cover loss and gain or provide data for only single years or relatively short periods compared to the lifespan of tree growth, thus impeding the ability to capture dynamic changes.

We used the medium-resolution forest extent data from the University of Maryland's Global Land Cover and Land Use Monitoring in Support of Environmental Sustainability project to map the forest edge²¹. This binary data provides forest extent for 2000 to 2020 with 5-year gaps, with an overall accuracy above 97% and a producer accuracy above 94%. It is structured on the WGS 1984 coordinate system, featuring a spatial resolution of 0.00025° (approximately 30 m near the equator and 10 m in the Arctic). All forest edge mapping and statistical analyses were conducted at this original resolution. The global forest extent data is stored as 261 10° × 10° chunks.

Limitations and potential uncertainty brought by land cover data

Although the high accuracy of the dataset minimizes potential misclassification, errors of omission (undetected forest pixels) and commission (misclassified non-forest pixels) may introduce minor biases in estimating forest edge dynamics. Omission errors could lead to a slight underestimation of forest edge length, whereas commission errors could marginally overestimate edge length by creating artificial boundaries where none exist. However, because our study tracks edge dynamics over multiple five-year intervals (2000, 2005, 2010, 2015, and 2020), rather than relying on a single-time-step comparison, the influence of individual misclassifications is minimized. The multi-temporal approach ensures that our results reflect actual forest-edge transitions rather than artifacts from classification inconsistencies. While classification-induced uncertainty is not explicitly quantified, we acknowledge that regional discrepancies, particularly in areas with

spectral confusion (e.g., between open woodlands and croplands) or persistent cloud cover, may have small, localized bias. Nonetheless, our methodology, grounded in a globally validated dataset with a consistent classification framework, ensures that overall changes in forest edge dynamics remain robust and reflective of real landscape changes rather than classification artifacts.

In addition, because the analysis is based on a Landsat-derived forest-extent product at 0.00025° resolution, it may not consistently capture individual trees, narrow woody features, or small patches of trees outside mapped forests, particularly in agricultural and urban landscapes. These features can contribute to tree cover and carbon storage but fall partly outside the operational forest definition used here⁴¹. Our estimates therefore represent the boundaries of mapped forests rather than all possible tree–non-tree interfaces. Despite these limitations, the use of a globally consistent forest definition, a common spatial resolution, and independent visual validation supports the interpretation of broad spatial and temporal patterns in forest edge dynamics.

Mapping the global forest edge and area

We used a raster-based method for mapping forest edges globally. First, we identified forest edge pixels based on the previously defined criteria of forest edge. Once forest edges were identified, we converted the spatial resolution from degrees to meters to obtain meaningful edge length values. Since each pixel in the original dataset measures 0.00025° × 0.00025°, its exact size in meters varies with latitude. To account for this, we used the geodesic distance function from the “geopy” package (<https://geopy.readthedocs.io/en/stable/#module-geopy.distance>) in Python to calculate pixel dimensions at different latitudes. Each pixel at the spatial resolution of 0.00025° was then assigned a value equal to the total length of its forest edges, and all non-edge pixels were set to zero. To ensure spatial continuity in edge mapping across the dataset’s 10° × 10° chunks, we applied the edge detection method consistently across both interior and exterior pixels. To prevent edge discontinuities at chunk boundaries, overlapping exterior pixels were spliced together, preserving a seamless global forest edge dataset. Independent validation using very high-resolution imagery confirms that the mapped forest edges and their temporal dynamics are consistent with observed landscape transitions (see “Manual validation of forest edge dynamics”). For visualization purposes, we aggregated the results to a coarser resolution of 0.01° (1 km²) using a sum aggregation method. This step was performed exclusively to enhance readability in figure visualization (Figs. 1, 3 and Supplementary Figs. 1, 3, 4) without altering the underlying high-resolution dataset used for analysis. Additionally, we calculated the area of each forest pixel at its original resolution (0.00025°). Since the forest extent data is stored in degrees, we used the geodesic distance function from the “geopy” package in Python to convert pixel dimensions into meters. This ensured that area calculations accounted for variations in pixel size due to latitude. The final forest area maps, like the edge length maps, maintain the original resolution but are presented in square meters for interpretability. All of the computations were done in the Center for High Throughput Computing at the University of Wisconsin-Madison⁴².

While our approach accurately captures forest edge dynamics at a high resolution, one limitation is that edge length calculations do not incorporate local terrain slope variations. The geodesic distance function we applied assumes a flat Earth surface, meaning that in mountainous regions, where forests are often restricted, actual edge lengths along the land surface may be underestimated. This effect is particularly relevant for forest edges created by natural disturbances such as landslides or avalanche chutes. Future refinements could

integrate high-resolution digital elevation models to improve slope-adjusted edge length calculations in topographically complex areas.

Forest edge dynamic mapping and statistics

Forest edge dynamics were quantified by jointly evaluating changes in forest edge length and forest area between two reference years, allowing edge changes arising from forest expansion, forest loss, and structural reconfiguration to be distinguished in a deterministic and spatially explicit manner. Based on the direction of change in forest edge length and forest area, we identified five types of forest edge dynamics: stable edges, new edges due to forest gains (increase-increase edges), new edges due to forest loss (increase-decrease edges), edges lost due to forest gains area (decrease-increase edges), and edges lost due to forest loss (decrease-decrease edges). Forest edge dynamics were computed for successive 5-year intervals (2000 to 2005, 2005 to 2010, 2010 to 2015, and 2015 to 2020), as well as for the full 2000 to 2020 period, with the earlier year in each comparison used as the baseline for quantifying changes in forest edge length and forest area.

Taking the 2000 vs. 2020 comparison as an example, we defined raster layers Area2000 and Area2020 to represent forest area, and Edge2000 and Edge2020 to represent pixel-level forest edge length for 2000 and 2020, respectively. Forest area and forest edge length were computed independently for each year using the same forest definition and spatial resolution. Edge dynamics therefore reflect differences between independently derived layers rather than iterative or cumulative calculations. For clarity, the following definitions describe how edge-dynamic classes are assigned at the pixel level based on the sign and magnitude of changes in forest area (ΔArea) and forest edge length (ΔEdge). Using 2000 as the baseline, the changes in the forest area, ΔArea , and forest edge length, ΔEdge , between 2000 and 2020 are calculated as below:

$$\Delta\text{Area} = \text{Area2020} - \text{Area2000} \quad (1)$$

$$\Delta\text{Edge} = \text{Edge2020} - \text{Edge2000} \quad (2)$$

We also define a function, $\text{Loc}(X)$, to identify the locations of pixels that satisfy the condition X . Then, we define the increase-increase edges pixels as the pixels with both larger forest edge lengths and larger areas in 2020 than in 2000, so that $\text{Loc}(\Delta\text{Area} > 0 \text{ and } \Delta\text{Edge} > 0)$, and the amount of the increase-increase edges, Edge_{ii} , equal to $\text{Edge}_{\text{stable}}$.

The increase-decrease edge pixels are defined as those with larger edge lengths but lower or same forest areas in 2020 than in 2000, which are the pixels at the location of $\text{Loc}(\Delta\text{Area} \leq 0 \text{ and } \Delta\text{Edge} > 0)$, and the amount of increase-decrease edge lengths, Edge_{id} , equal to $\Delta\text{Edge}(\text{Loc}(\Delta\text{Area} \leq 0 \text{ and } \Delta\text{Edge} > 0))$.

The decrease-increase edges pixels are defined as the pixels with the same forest area in 2000 and 2020 but a smaller edge length in the forest edge map in 2020, which are the pixels at the location of $\text{Loc}(\Delta\text{Area} \geq 0 \text{ and } \Delta\text{Edge} < 0)$, and the amount of decrease-increase edge lengths, Edge_{di} , so that $\Delta\text{Edge}(\text{Loc}(\Delta\text{Area} \geq 0 \text{ and } \Delta\text{Edge} < 0))$. $\Delta\text{Edge}(\text{Loc}(\Delta\text{Area} \geq 0 \text{ and } \Delta\text{Edge} < 0))$ is a non-positive value, but we took the absolute value of it as Edge_{di} in our summary.

The decrease-decrease edge pixels are defined as those with smaller forest edge lengths and areas in 2020 than 2000, so that $\text{Loc}(\Delta\text{Area} < 0 \text{ and } \Delta\text{Edge} < 0)$, and the amount of decrease-decrease edge lengths, Edge_{dd} , equal to $\Delta\text{Edge}(\text{Loc}(\Delta\text{Area} < 0 \text{ and } \Delta\text{Edge} < 0))$.

The stable edge pixels are defined as the pixels with the same edge lengths in 2000 and 2020, and their 2020 edge lengths are larger than zero ($\Delta\text{Edge}(\text{Loc}(\Delta\text{Area} < 0 \text{ and } \Delta\text{Edge} < 0))$). In some cases, local rearrangements of edges may occur within a pixel while the net edge length remains unchanged; such pixels are classified as stable edges

because they do not contribute to net edge gain or loss.

$$\begin{aligned} \text{Edge}_{\text{stable}} = & \text{Edge2000}(\text{Loc}(\Delta\text{Edge} = 0 \text{ and } \text{Edge2000} > 0)) \\ & + \text{Edge2000}(\text{Loc}(\Delta\text{Area} \leq 0 \text{ and } \Delta\text{Edge} > 0)) \\ & + \text{Edge2000}(\text{Loc}(\Delta\text{Area} \geq 0 \text{ and } \Delta\text{Edge} < 0)). \end{aligned}$$

Here, $\text{Edge}_{\text{stable}}$ represents the total edge length that does not contribute to net edge change over the interval, including pixels with zero net edge change as well as compensating edge losses and gains that cancel out at the pixel level.

Using the definitions above, we generated forest edge dynamic maps for each time interval, in which all forest edge pixels were unambiguously assigned to one of the five mutually exclusive edge-dynamic types, and summarized pixel-level edge lengths by edge-dynamic type.

Continents, climate zones, and country boundaries

Continental boundaries (Africa, Antarctica, Asia, Australia, Europe, North America, Oceania, and South America) were defined using ESRI Data & Maps. Country boundaries were obtained from Natural Earth at 10-m resolution shapefiles, with each country assigned to a United Nations world region code⁴³. Climate zones were defined using the 2020 World Climate Regions (WCR) map, which classifies the global land surface into six domains (tropical, subtropical, warm temperate, cool temperate, boreal, and polar) at 250-m resolution⁴⁴.

Using continent, country, and climate zone boundaries, we aggregated both forest area and forest edge length, and edge-dynamic components for all reference years (2000–2020 at 5-year intervals). Below we illustrate the aggregation using the 2000–2020 comparison as an example:

$$\Delta\text{Area}_k = \text{Area2020}_k - \text{Area2000}_k \quad (3)$$

$$\Delta\text{Edge}_k = \text{Edge2020}_k - \text{Edge2000}_k \quad (4)$$

$$\Delta\text{Area}\%_k = \Delta\text{Area}_k / \text{Area2000}_k \quad (5)$$

$$\Delta\text{Edge}\%_k = \Delta\text{Edge}_k / \text{Edge2000}_k \quad (6)$$

$$\text{Edge}_{\text{ii}}\%_k = \text{Edge}_{\text{ii}_k} / \text{Edge2020}_k \quad (7)$$

$$\text{Edge}_{\text{id}}\%_k = \text{Edge}_{\text{id}_k} / \text{Edge2020}_k \quad (8)$$

$$\text{Edge}_{\text{di}}\%_k = \text{Edge}_{\text{di}_k} / \text{Edge2000}_k \quad (9)$$

$$\text{Edge}_{\text{dd}}\%_k = \text{Edge}_{\text{dd}_k} / \text{Edge2000}_k \quad (10)$$

Where k denotes data for the k th region in continent, country or climate zone; $\text{Edge}_{\text{ii}}\%_k$ and $\text{Edge}_{\text{id}}\%_k$ represents the share of the increase-increase and increase-decrease forest edge in the total forest edge length in 2020 of the k th region, respectively; and $\text{Edge}_{\text{di}}\%_k$ and $\text{Edge}_{\text{dd}}\%_k$ represents the share of the decrease-increase and decrease-decrease forest edge in the total forest edge length in 2000 of the k th region, respectively.

Dynamics of disparities of forest edge length relative to area at country level

Given that about three-quarters of the world's forests are publicly owned²⁰, governments are the mainstay of forest governance. Forest area and edge length for each country were derived from the country boundaries and 0.00025° edge maps (We deleted countries with zero forest area) for 2000 to 2020 with a 5-year gap. Given the power law relationship between perimeter and area of similarly shaped fractal geometries in two dimensions, it could also be applied to the

distribution of forests³³. We performed a logarithmic transformation on both forest area and edge length for the 188 countries and regions. This transformation not only facilitates the linearization of the relationship but also helps to mitigate the numerical disparities in forest area and edge length across different countries, making the data more comparable across varying scales. We selected the year 2000 data as our baseline for analysis. A linear regression was conducted on the log-transformed data from this year to estimate the parameters of the model, defined by the equation:

$$\log(\text{Estimated Forest Edge})_i = \text{intercept} + \text{slope} \cdot \log(\text{Forest Edge Area})_i \quad (11)$$

Where i indexes the countries. This regression helps establish a global standard of forest edge length relative to forest area, against which deviations in other years can be measured.

To quantify the deviations in forest landscape patterns at the country level, we calculated residuals from this baseline regression model, which is calculated as:

$$\text{Residual}_i = \log(\text{Forest Edge})_i - \log(\text{Estimated Forest Edge})_i \quad (12)$$

These residuals indicate the extent to which actual forest edge lengths deviate from those predicted by the model. A positive residual indicates that a country has a longer forest edge than the global average expected for its given forest area. Conversely, a negative residual suggests a country has a shorter forest edge than the global average expected. We analyzed these residuals for both 2000 and 2020 to track changes over time, and is calculated as:

$$\Delta\text{Residual}_i = \text{Residual2020}_i - \text{Residual2000}_i \quad (13)$$

Where i indexes the countries align with the definition above. A positive $\Delta\text{Residual}_i$ indicates an increase in forest edge length relative to the global average expected value based on area, and a negative $\Delta\text{Residual}_i$ reflects a decrease in forest edge length relative to what is expected at the global average.

The country-scale edge disparities assessment provides a morphological evaluation of forest edge exposure, comparing observed edge lengths to expected values based on total forest area. Although this approach offers insights into whether forests in a given country exhibit higher or lower edge effects than expected, it does not explicitly differentiate between fragmentation-driven edge increases and deforestation-driven edge loss. To interpret these results in the context of forest transformation processes, we integrate them with our edge dynamics classification, which tracks edge changes at finer spatial scales and distinguishes between small-scale patch proliferation, large-scale patch loss, and afforestation-induced edge formation.

Manual validation of forest edge dynamics

To evaluate the reliability of the mapped forest edge dataset and its temporal dynamics, we conducted an independent validation using very high-resolution (VHR) imagery available in Google Earth. 100 validation sites were selected globally using a stratified random sampling approach from the 0.01° (~1 km at the equator) analysis grid, with each site representing a local landscape window centered on a sampled pixel, including dense forests, sparse woodlands, and regions experiencing edge expansion, contraction, or stability (Supplementary Fig. 7).

Visual interpretation focused on evaluating whether mapped forest–nonforest boundaries and their changes through time corresponded to observable landscape patterns. Because forest delineation is inherently definition-dependent, particularly in sparsely vegetated or transitional ecosystems, validation emphasized structural agreement rather than strict pixel-level correspondence. In open or

heterogeneous landscapes, it can be difficult to determine visually whether vegetation meets the forest definition (tree height larger than 5 m), and such ambiguity reflects the gradual nature of forest boundaries rather than mapping errors. These uncertainties are expected to be greatest in sparse forests and ecotonal regions and were considered when interpreting agreement.

Temporal availability of VHR imagery varies geographically and historically. For each reference year, we used the most recent available imagery within approximately two years of that year to represent ground conditions, prioritizing scenes acquired during the growing season and excluding images with substantial cloud cover. When multiple images were available, the most recent cloud-free growing-season image was selected. Sites lacking sufficient imagery coverage were excluded from dynamic validation to avoid introducing interpretation uncertainty. In addition, because the forest edge maps are produced at five-year intervals and represent conditions aggregated over a period rather than a single acquisition date, some rapidly changing landscapes may exhibit partial temporal mismatches between observed imagery and mapped conditions.

To evaluate edge dynamics, we compared the temporal evolution of forest patterns in the VHR imagery with the corresponding periods represented by the forest edge dataset. Specifically, we aligned the analysis window with the time span over which high-resolution imagery was available and assessed whether observed changes indicated expansion, contraction, fragmentation, merging, or stability. Only sites with interpretable temporal sequences were included in dynamic agreement assessments.

Interpretation was conducted independently by two reviewers to reduce subjective bias. Inter-reviewer agreement was evaluated, and discrepancies were resolved using a conservative decision rule, whereby the lowest-quality assessment was retained whenever disagreement occurred.

Static edge presence showed high consistency with visual interpretation, with an overall agreement of 96.5% across all comparisons (Supplementary Data 2 and Supplementary Fig. 8). Year-specific match rates ranged from 91.3% in 2000 to 98.9% in 2020, reflecting both improvements in imagery availability and clearer delineation of persistent forest boundaries. For sites with interpretable change signals, the direction of edge dynamics showed full agreement between mapped products and visual interpretation.

We note that discrepancies may arise in areas undergoing rapid or ongoing land-cover change. Small discrepancies are expected in regions undergoing rapid or continuous change because very high-resolution imagery captures conditions at specific acquisition dates, whereas the forest edge dataset represents annual conditions within five-year intervals. Such temporal differences likely make agreement estimates conservative. It is also important to recognize that the validation relies on visual comparison between high-resolution (~1 m) imagery and Landsat-derived (~30 m) forest edge maps, which operate at fundamentally different spatial scales. For example, narrow linear features such as small roads and trails are clearly visible in sub-meter resolution imagery but may not be resolved at Landsat resolution, particularly during the growing season when tree canopies overhang and obscure these features (Supplementary Fig. 9). Consequently, some apparent inconsistencies between predicted edges and high-resolution imagery reflect inherent scale differences rather than mapping errors. This scale mismatch further supports the conservative nature of our accuracy estimates.

Because the edge detection algorithm is a deterministic transformation of a validated forest extent product, this validation primarily evaluates whether derived edge patterns and their temporal evolution correspond to observable landscape structure rather than model parameter uncertainty. Overall, the results indicate that the forest edge dataset robustly captures both spatial configuration and dynamic

changes of forest boundaries at the global scale while acknowledging expected uncertainty in transitional environments. These considerations reflect inherent challenges in global forest monitoring and do not affect the interpretation of large-scale patterns in forest edge dynamics.

Reporting summary

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

Data availability

The Global Land Cover and Land Use Change 2000–2020 forest-extent data used in this study are publicly available from the Global Land Analysis and Discovery laboratory through the official GeoTIFF download page at <https://storage.googleapis.com/earthenginepartners-hansen/GLCLU2000-2020/v2/download.html>. These data are available without access restrictions. The official GLAD documentation describes the dataset as a global 30-m product and provides the corresponding download resources. Because the forest-area and forest-edge data generated in this study consists of numerous large tiled raster files, the files are hosted in the Chen Lab data repository (<https://gofile.me/7glzu/enA1L3vRY>) rather than directly within a single Zenodo record. The dataset description, directory manifest, file-format information, and access instructions have been deposited in Zenodo <https://doi.org/10.5281/zenodo.21346632>. Source data are provided with this paper.

Code availability

The code developed for this project can be found at GitHub repository: https://github.com/UW-GCRL/Global_forest_edge_dynamics. The version used in this study has been permanently archived in Zenodo <https://doi.org/10.5281/zenodo.21346993>.

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Author contributions

Conceptualization: H.Y., F.J., and M.C.; Methodology: H.Y., M.J., and M.C.; Visualization: H.Y., F.J., and V.C.R.; Funding acquisition: M.C.; Project administration: M.C.; Supervision: T.P., V.C.R., G.H., and M.C.; Writing—original draft: H.Y.; Writing—original draft: H.Y.; Writing—review and editing: H.Y., F.J., T.P., V.C.R., G.H., M.J., and M.C.

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Competing interests

The authors declare no competing interests.

Additional information

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