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Tropical montane forest loss dominated by increased 1–10 hectare-sized patches

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Abstract

Tropical forest loss continues across mountain regions at alarming rates, threatening biodiversity, carbon storage and ecosystem sustainability. To improve our understanding of the dynamics of tropical mountain forest loss, this study focuses on the trends in patch sizes of forest loss during the 21st century. The annual area of tropical mountain forest loss surged from 0.7 million hectares in 2001–2003 to >2.5 million hectares in 2019–2021. There was an increase across all categories in terms of the size of forest loss patches, but strikingly, more than half of this increase was attributed to the proliferation of intermediate-sized forest loss patches spanning 1–10 hectares. Concurrently, there was a diminishing proportion of small-scale montane forest loss patches (<1 ha) across all tropical continents over time. Despite their reduced overall proportion, the annual area of small forest loss patches increased, primarily influenced by trends in the Asia-Pacific region. Our study provides up-to-date and spatially explicit information on the scale of tropical mountain forest loss, and temporal trends associated with these patterns, which is crucial for assessing the sustainability of mountain forest ecosystems, highlighting the need for targeted, region-specific strategies to slow or reverse forest loss.

Keywords

Tropics, forest loss, patch size, mountain forest, Landsat

1. Introduction

Tropical montane forests play a crucial role in global ecosystem services, including carbon sequestration, climate mitigation, biodiversity conservation, and regulation of the water cycle (Bruijnzeel *et al.*, 2011; Spracklen and Righelato, 2014; Zeng *et al.*, 2021). However, increasing rates of forest cover loss resulting from land-use changes across tropical mountains threaten the provision of these essential services (Feng *et al.*, 2022; Smith *et al.*, 2023; He *et al.*, 2023). The spatial pattern of fragmentation and loss could amplify negative effects on tropical ecosystems. For example, evidence shows that the loss or fragmentation of mountain forests can lead to biodiversity loss as tropical mountain forests serve as important refuges for endemic species (Newmark, 1988; Burgess *et al.*, 2002; Ponce-Reyes *et al.*, 2013). Therefore, spatially explicit information on the scale of forest loss in mountainous areas, along with an understanding of how these patterns have changed over time, is of great importance for developing effective strategies to preserve tropical montane forests and to maintain related ecosystem services.

The dynamics of forest loss are not static over time (Kalmadeen *et al.*, 2018). Forest fragmentation alters ecological functioning and species composition (Laurance *et al.*, 2011), reducing the amount of carbon stored at forest edges (Chaplin-Kramer *et al.*, 2015). A shift from small-scale to large-scale deforestation could modify the mechanisms and patterns of regional precipitation (Chambers and Artaxo, 2017; Khanna *et al.*, 2017). The size of a forest clearing activity is often used as a proxy for characterizing small-scale activities or large commercial and industrial-scale operations (Austin *et al.*, 2017). Assessing the size of forest loss patches may therefore be helpful in understanding changing mountain forest landscapes (Malhi *et al.*, 2014).

Extensive studies have been conducted in tropical forests to quantify the sizes of deforested areas or forest fragmentation (Austin *et al.*, 2017; Hansen *et al.*, 2020). In lowland areas, for example, significant declining rates of large-scale deforestation were observed in the Amazon, while a pervasive rise of small clearings occurred over time (Rosa *et al.*, 2012; Godar *et al.*, 2014; Kalamandeen *et al.*, 2018). Similarly, in the Congo Basin, small-scale deforestation for agriculture has increased over time (Tyukavina *et al.*, 2018). Across tropical mountain regions, however, despite some local or regional assessments of remaining forest patches (Cayuela *et al.*, 2006; Canale *et al.*, 2012), a comprehensive and consistent analysis on the size of forest loss is still lacking.

In this study, we used time series of forest loss and quantified this loss in terms of forest loss patch sizes from 2001 to 2021 across tropical mountains (Figure 1). The objectives of this work are to analyse how much forest loss was associated with patches of different sizes and to determine whether the distribution of clearing sizes has changed over time. This study provides spatially explicit quantification of forest loss patches over tropical mountains, which can inform conservation policy where there is a desire to maintain larger and contiguous patches of forest cover.

2. Methods

We used the Global Forest Change (GFC) data (Hansen *et al.*, 2013) to investigate how mountain forest loss patch sizes varied in the tropics (24°S–24°N) in the 21st century. Tree cover loss was defined by Hansen *et al.* (2013) as a stand-replacement disturbance or the complete removal of tree cover canopy at a pixel scale of 30 m based on Landsat imagery. To define a pixel as forested, we used a 25% tree-cover threshold, following Hansen *et al.* (2010). In the GFC dataset, only the first occurrence of a forest loss event in each pixel has been reported. This means that forest loss was only detected when it happened for the first time, and each pixel was marked only once to indicate the time of the initial forest loss in that area.

Our study relies on the GFC v1.9 dataset, which covers the period from 2001 to 2021 for analysis. To assess the accuracy of the GFC data in mountain regions, we applied a stratified random-sample approach for validation (Olofsson *et al.*, 2014; Feng *et al.*, 2022). This approach for accuracy assessment is recognized as one of the most robust means of examining loss trends in the GFC product and can mitigate inconsistencies arising from changes in detection algorithms and satellite sensors (Weisse and Potapov, 2021). Our study involved a total of 3,628 pixels in mountains, comprising 2,458 loss pixels and 1,170 non-loss pixels, across three tropical continents (Supplementary Data). Following the best practice guidance of Olofsson *et al.* (2014), we then constructed the error matrix of sample counts (Table S1) and estimated area proportions (Table S2) from the reference data. Next, we determined the overall accuracy (OA), user's accuracy (UA) and producer's accuracy (PA) of the GFC-derived forest loss (Supplementary Methods). Generally, the GFC data exhibited high performance in tropical mountains, with OA, UA, and PA values of forest loss being 98.86%, 82.86%, and 92.30%, respectively. The estimated area of forest loss based on the reference data was 35.97 million ha (95% confidence interval: 33.18–38.76 million ha) across tropical mountains. In this study, we calculated three-year moving averages of annual forest loss for time-series analysis, following recommendations from prior research (Tyukavina *et al.*, 2018; Kleinschroth *et al.*, 2019; Weisse and Potapov, 2021). The three-year moving average was calculated by taking the mean of annual forest loss patches over the middle year and the adjacent year before and after.

Mountain extent in the tropics was mapped by a series of mountain polygons developed by the Global Mountain Biodiversity Assessment (GMBA) inventory (v1.2; Körner *et al.*, 2017). GMBA defines a 2.5′ pixel to be mountainous if the difference between the highest and lowest points of 30″ within the pixel exceeds 200 m. According to this definition, there are 304 mountain regions in the tropics (Figure 1), occupying 8.76 million km^2 (14%) of tropical land surface.

We defined the forest loss patch as a contiguous area (eight neighbour rule) of forest that was cleared within a year (Figure S1). We used annual forest loss maps to determine the area of forest loss each year during 2001–2021 and the size distribution of forest loss patches in that year. On the choice of the minimum mapping unit for forest loss patches, we tested 1, 3 and 5 pixels by comparing the GFC mapped forest loss area with our sample-based estimates. Since the total mapped area using 3 pixels was closest to our sample-based area estimation, we applied a minimum mapping unit of 3 pixels in this analysis. Forest loss patches were classified into four categories: small (<1 ha), intermediate (1–10 ha), large (10–100 ha), and very large (>100 ha). We used the Theil-Sen estimator to identify trends in size of forest loss patches over time. The Theil-Sen estimator, a non-parametric regression method, relies on the median of slopes for all pairs of ordered data points (Sen, 1968). Due to its robustness in trend detection and insensitivity to outliers, the Theil-Sen estimator has been employed in studies related to forest change (He *et al.*, 2023; Feng *et al.*, 2022). To visualise the spatial distribution of sizes of forest loss patches, we aggregated the annual data to 5 × 5 km grids over our study area. The mean forest loss patch size was calculated as the total forest loss area divided by the number of loss patches.

We also analysed tropical mountain forest loss patches in different elevational bins. A high-resolution elevation dataset (30 m) from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM; v3) was used in the analysis (Tachikawa *et al.*, 2011; NASA, 2019). Tropical mountain forest loss was divided into four elevation ranges: <1,000 m; 1,000–2,000 m; 2,000–3,000 m; and >3,000 m.

To understand how the distributions and trends of forest loss patch sizes vary across different forest biomes, we utilized the map of biomes provided by Olson *et al.* (2001) to separate tropical mountain forests. This global map encompasses a total of 14 biomes, including forests, grasslands, and deserts. In this analysis, three primary biomes were considered: moist broadleaf forests, dry broadleaf forests and coniferous forests. We compared the variations among the three biomes.

3. Results

Between 2001 and 2021, tropical mountain forests lost 8% compared to their extent in 2000. There was a reduction in the proportion of tropical mountain forest loss associated with small patches (<1 ha), from 37% in 2001 to 26% in 2021 (Figure 2a). Conversely, over the same period, there were increases in the proportion of tropical mountain forest loss associated with intermediate (1–10 ha) and large patches (10–100 ha), with intermediate patches increasing from 47% to 53% and large patches increasing from 12% to 18%. These results suggest that the increase in tropical mountain forest loss during the period was driven by increases in the area cleared in patches of 1–100 ha (Figure 2e).

The Asia-Pacific region experienced a rapid increase in annual forest loss over time. On average, about 0.38 million hectares of mountain forest were lost annually in the Asia-Pacific region during 2001–2003. This annual loss increased to an average of 1.56 million hectares between 2019 and 2021 (Figure 2f). The total area per year of small forest loss patches (<1 ha) also increased, but the overall increase in the annual area of forest loss was driven principally by intermediate and large patches, which comprised 61% of forest loss in 2001 and 72% in 2021 (Figure 2b). The proportion of very large-scale (>100 ha) patches of total forest loss is greater in the Asia-Pacific region than that in the other regions. Over the study period, 78% of very large forest loss patches (>100 ha) across all tropical mountains as a whole, occurred in the Asia-Pacific region.

Africa had the highest proportion of small-scale forest loss, with 46% at the beginning of the 21st century, but decreasing to 32% in 2021 (Figure 2c). Similarly, the Americas witnessed a >10 percentage point decline in the proportion of small forest losses over the two decades, decreasing from 39% in 2001 to 26% in 2021 (Figure 2d). Concurrently, the combined proportion of intermediate and large-scale forest loss increased in Africa (13%) and the

Americas (11%).

Between 2001 and 2021, the mean forest loss patch size was 1.24 ha. We found that a majority (72%) of forest loss patches were below 1 ha, but in area terms, patches below 1 ha only accounted for 26% of total forest loss across our study period. In Asia-Pacific and Africa, the area of small forest loss patches showed an increase in the 2010s compared to the 2000s (Figure 3b,c). Conversely, in the Americas, the occurrence of small forest loss events remained relatively stable during the two decades of the 21st century (Figure 3d). There were pronounced increases in intermediate forest loss patches (1–10 ha) in 2016 or 2017 across all tropical regions, with a minor decline in subsequent years (Figure 3).

Spatially, the mean forest loss patch size on the Malay Peninsula was the greatest; other areas with a relatively large mean forest loss patch size included Indonesia, Laos, and Vietnam in Asia-Pacific, Brazil, Bolivia, and Peru in the Americas, as well as Guyana in Africa (Figure 4a). Considerable changes were also observed in the geographical pattern of forest loss patch size between 2001 and 2021. The trend of mean forest loss patch size was greatest in mainland Southeast Asia and western Africa (Figure 4b). Despite the larger average patch size in insular Southeast Asia (including Indonesia, Brunei and Malaysia), there was a decreasing trend in mean forest loss patch size in the region, particularly evident in Sumatra and Sulawesi within Indonesia (Figure 4a,b). The distribution of median forest loss patch size was similar to that of mean forest loss patch size, but the maximum forest loss patch size had a different pattern, which showed that Southeast Asian mountains had the greatest absolute maximum forest loss patch size and the highest time-series trend of increasing maximum patch size (Figure 4).

Tropical mountain forests situated below 1000 m constituted 62% of the total area, but the loss incurred below this elevation comprised >75% of total loss, showing most forest loss in tropical mountains tended to be at lower elevations (Figure 5). The pattern of increased medium-scale forest loss patches, as observed above, was evident at lower elevation ranges (Figure 5a,b). Compared to lower elevations, a higher proportion of small-scale forest loss was found above 2,000 m (<1 ha; Figure 5c,d), likely as a result of natural disturbances such as windthrow, landslides or other events that tend to be more frequent at higher elevations (Kramer *et al.*, 2001; Liu *et al.*, 2021). There were notable differences in forest loss patches across elevation ranges in different regions. In tropical Asian mountains, intermediate patches accounted for a large proportion of the total area of forest loss patches below 2,000 m, with a significant increase since 2012 (Figure S2a,b), likely as a result of widespread deforestation for agricultural expansion such as corn, rubber and oil palm plantations (Zeng *et al.*, 2018a; He *et al.*, 2023). In Africa, shifting cultivation was evident (Doggart and Loserian, 2007; He *et al.*, 2023), leading to a significant rise in small-scale forest loss, especially at elevations >1,000 m (Figure S2e,f). Across the Americas, intermediate forest loss patches were the most prominent at elevations <2,000 m, while above this altitude, both intermediate and small forest loss patches accounted for a large proportion (Figure S2g-j). The variations in the sizes of forest loss patches at different elevations can also be attributed to geographic and political factors, as well as conservation policies (Liu *et al.*, 2022).

By analysing the forest loss patch size distributions and trends across three different biomes – moist broadleaf forests, dry broadleaf forests and coniferous forests, we discovered similar patterns of forest loss patch sizes among these biomes (Figure S3). The highest proportion of forest loss patches fell within the intermediate size of 1–10 ha, accounting for over 50% in all biomes. In terms of forest loss area, ~90% of the total loss was observed in moist broadleaf forests, while the loss in coniferous forests was the smallest (0.8 million ha). Among these three biomes, coniferous forests exhibited the highest proportion of small-scale forest loss (31%; Figure S3). On the temporal scale, the trends in moist broadleaf forests and dry broadleaf forests were very similar, both experiencing an increase followed by a decrease, peaking in the year 2016 (Figure S4). The peak in 2016 was primarily attributed to forest loss in Asian mountains (He *et al.*, 2023). Notably, coniferous forests had a relatively low average forest loss for small patches between 2001–2015 but experienced a large rise in such forest loss since 2016.

4. Discussion

In this study, our results revealed the dominance of tropical montane forest loss by increased numbers and proportion of intermediate-sized patches (1–10 ha). These increased forest loss patches could lead to an acceleration in forest fragmentation and strong increases in tropical forest edge areas (Fischer *et al.*, 2021). The overarching implications extend beyond the immediate ecological consequences, with potential repercussions for global climate patterns, biodiversity, and the well-being of local communities. We also showed a decrease in the proportion of small montane forest loss patches (<1 ha) across all tropical continents, even though the total annual area of small clearings increased. Our finding of a declined proportional role played by small patches of forest loss over tropical mountain regions contrasts with previous research utilizing the same forest loss dataset and similar analysis methods, which showed an increased proportion of small-scale deforestation in the lowland Amazon in recent years (Kalamandeen *et al.*, 2018). This disparity highlights distinctly different patterns between mountainous and lowland regions.

Natural disturbances, such as fire, wind, geomorphic activity, flooding, snow and ice-induced damage, as well as insect and pathogen outbreaks, are important causes of tropical mountain forest loss (Peterson *et al.*, 2000). These natural disturbances are very widespread and common in tropical montane forests, affecting canopy turnover, patterns of forest structure and tree species regeneration. Due to the complexity of environments in mountains, tropical montane forests tend to experience more disturbance types than lowland forests in a given area (Fahey *et al.*, 2016). Tropical montane forests are more susceptible than tropical lowland forests to landslides and larger, potentially catastrophic, disturbances such as cyclones, forest die-back, and fires (Anderson et al., 2002; Crausbay and Martin, 2016). Under the influence of climate change and land-use modification, natural forest disturbances are becoming more frequent, intense, and widespread in many parts of the world (Seidl *et al.*, 2017; Lindenmayer and Taylor, 2020; Collins *et al.*, 2021; Viljur *et al.*, 2022). Another contributor to mountain forest loss is human-induced land-use change. Currently, higher land-use pressure especially agricultural expansion has encroached into tropical mountains, leading to a reduction of mountain forests since the 21st century (Zeng *et al.*, 2018a, b; Feng *et al.*, 2021, 2022; He *et al.*, 2023). Consequently, it is important to consider multiple interactive drivers, including natural disturbances and land-use and management, for understanding tropical mountain forest loss regimes.

We found larger forest loss patches in Southeast Asian mountains, which are likely to be linked to the production of oil palm in this region (Pendrill *et al.*, 2022). A recent study by Wang *et al.* (2023) also highlighted the significant contribution of rubber plantations to extensive forest loss in Southeast Asia, especially in Indonesia, Thailand and Malaysia. Alarmingly, >1 million ha of rubber plantations established in 2021 were located within Key Biodiversity Areas, putting biodiversity at risk (Su *et al.*, 2019; BirdLife International, 2022). However, in Africa and the Americas, a lot of small-scale forest loss patches were observed, consistent with the evidence that shifting cultivation remains widespread in these regions (Heinimann *et al.*, 2017). Under climate change, these mountains will experience increased pressure, which potentially have significant impacts on mountain ecosystems and the essential services they provide

(Nsengiyumva, 2019).

Our analysis underscores the significance of the loss in moist broadleaf forests compared to dry broadleaf forests and coniferous forests in contributing to tropical mountain forest loss. The difference was likely due to the fact that various tropical mountain forest biomes exhibit distinct sensitivities to natural disturbances. Tropical moist forests are particularly vulnerable to fires, which often inflict severe damage, followed by slow recovery processes (Asbjornsen *et al.*, 2005; Martin *et al.*, 2011), and conversely, drier forest ecosystems have evolved to be resilient to surface fire regimes.

With regard to uncertainties in our analysis, the change in detection methodology and variations in satellite data sources (Landsat 7 and Landsat 8) may result in inconsistencies of the GFC data during the study period. To address this potential concern, we used a stratified random-sample approach to validate the data and analyse trends in forest loss area. However, we cannot reduce the omission and commission errors. As noted by Hansen *et al.* (2013), the accuracy of the disturbance year is ~75%, with >95% of the disturbance occurring within one year before or after the mapped disturbance year in the GFC data. Consequently, we calculated 3-year moving averages of annual forest loss for our time-series analysis. In addition, the UA value of 82.86% indicates the GFC mapped forest loss area could be overestimated. To reduce the uncertainty, in our analysis we applied a larger mapping unit of 3 pixels for forest loss patches, meaning that very small patches of just 1 or 2 pixels in size were excluded. We also calculated the percentage of forest loss patches in different sizes using 1, 3 and 5 pixels to test the effect of minimum mapping units on our results. We found little change in the statistics, and different minimum mapping units did not alter the main finding that intermediate-sized forest loss patches (1–10 ha) were dominant (Figure S5). Additional uncertainty related to the GFC data is likely attributed to its temporal resolution (annual). For example, forest loss that occurs in December and extends into January may constitute a single disturbance event but is unfortunately split into two distinct years. To reduce these uncertainties, future studies could integrate higher-resolution satellite and lidar datasets, together with field work, to generate forest dynamics more accurately. More research on proximate drivers of forest cover change is also needed.

5. Conclusion

Using a high-resolution satellite-based forest change dataset, this study examined the dynamics of forest loss patches over tropical mountains in the 21st century. The results revealed a notable increase in the proportion of medium-sized patches contributing to tropical mountain forest loss. There was a simultaneous decrease in the proportion of smaller patches, but the total area per year of small forest losses also increased. In addition, lower-elevation forests of mountains have been disproportionately cleared. By comparing the patterns among different tropical mountain forest biomes, this analysis further demonstrates the dominant role of the loss in moist broadleaf forests than dry broadleaf forests and coniferous forests. These insights indicate that more attention should be brought on land-use change in tropical montane forests. We call for collaborative, cross-disciplinary efforts to develop strategies that not only halt the decline of tropical montane forests but also promote sustainable coexistence between human activities and these vital ecosystems.

Data availability statement

The Global Forest Change (GFC) data v1.9 can be downloaded from https://storage.googleapis.com/earthenginepartners-hansen/GFC-2021-v1.9/download.html. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) v3 can be accessed from https://earthdata.nasa.gov/. Global Mountain Biodiversity Assessment (GMBA) Mountain Inventory v1.2 is available at https://ilias.unibe.ch/goto_ilias3_unibe_cat_1000515.html. The distribution map of biomes is obtained from https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world.

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Figure Legends

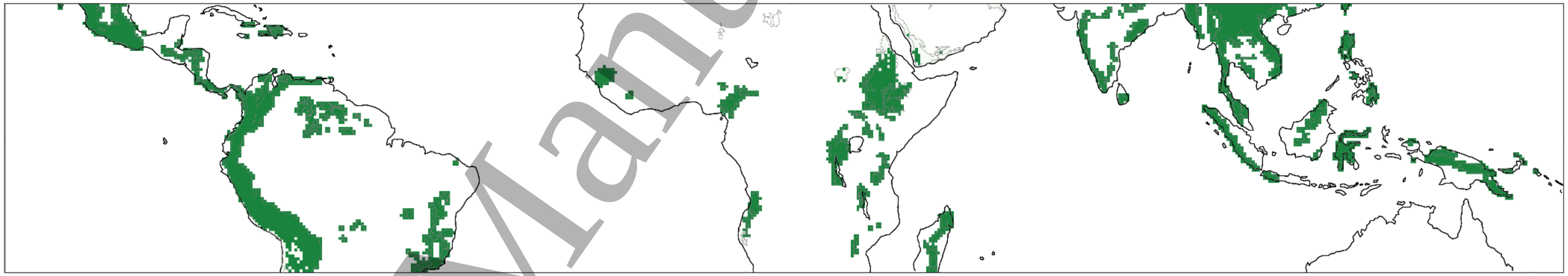
Figure 1. The extent of tropical mountain forests in the year 2000. Green areas show the location of forested area where tree-cover >25%. Grey lines indicate mountain extent defined by Global Mountain Biodiversity Assessment (GMBA) inventory data. Total area of tropical mountain forests in 2000 was 431 million ha.

Figure 2. Patterns of forest loss patches of different sizes across tropical mountains from 2001 to 2021. Percentage (a–d) and area (e–h) of forest loss patches in different sizes in the tropics (a, e), Asia-Pacific (b, f), Africa (c, g) and Americas (d, h).

Figure 3. Three-year moving average of annual mountain forest loss area in terms of different patch sizes for the tropics (a) and by region within the topics (b–d).

Figure 4. Spatial pattern of forest loss patches across tropical mountains during the period 2001–2021.

Figure 5. Area of forest loss patches of different sizes across tropical mountains in different elevational bins. A three-year moving average was used for the time-series analysis.



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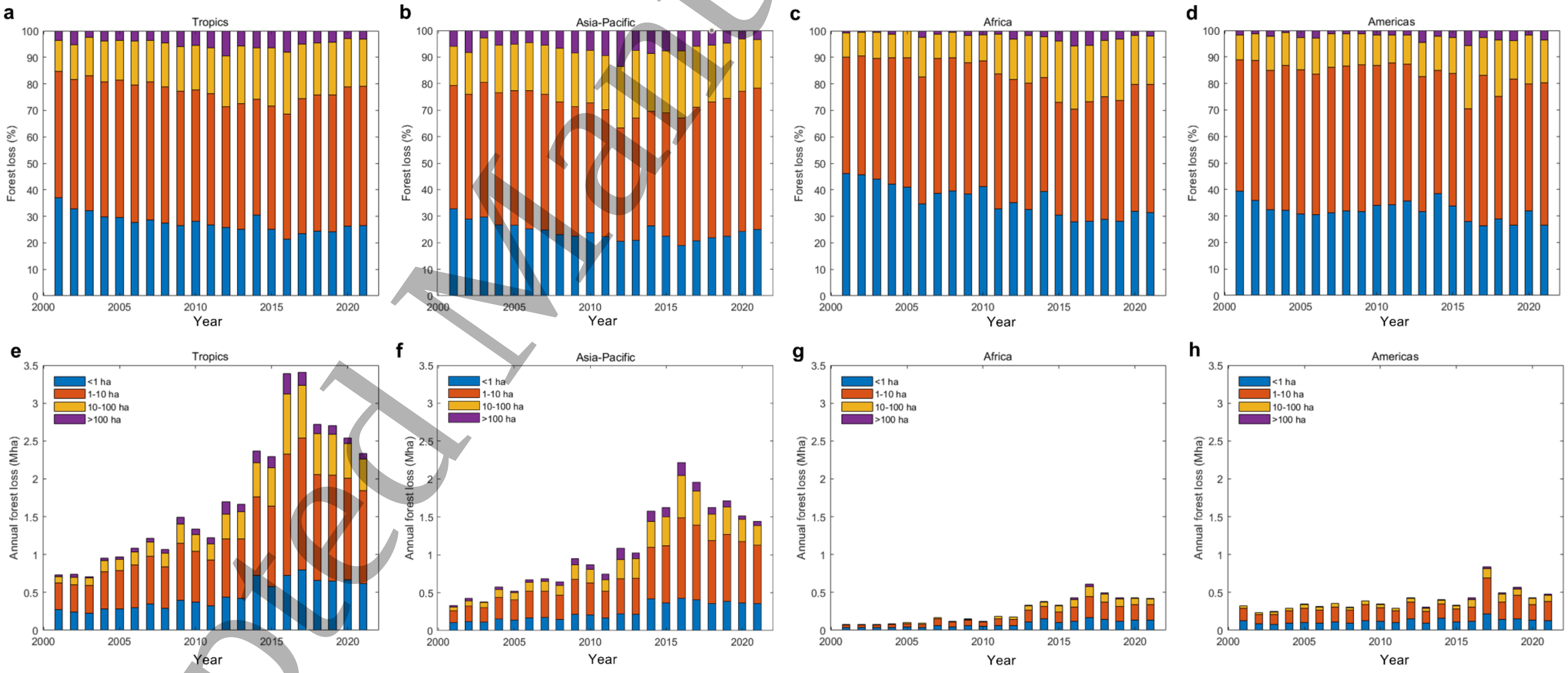

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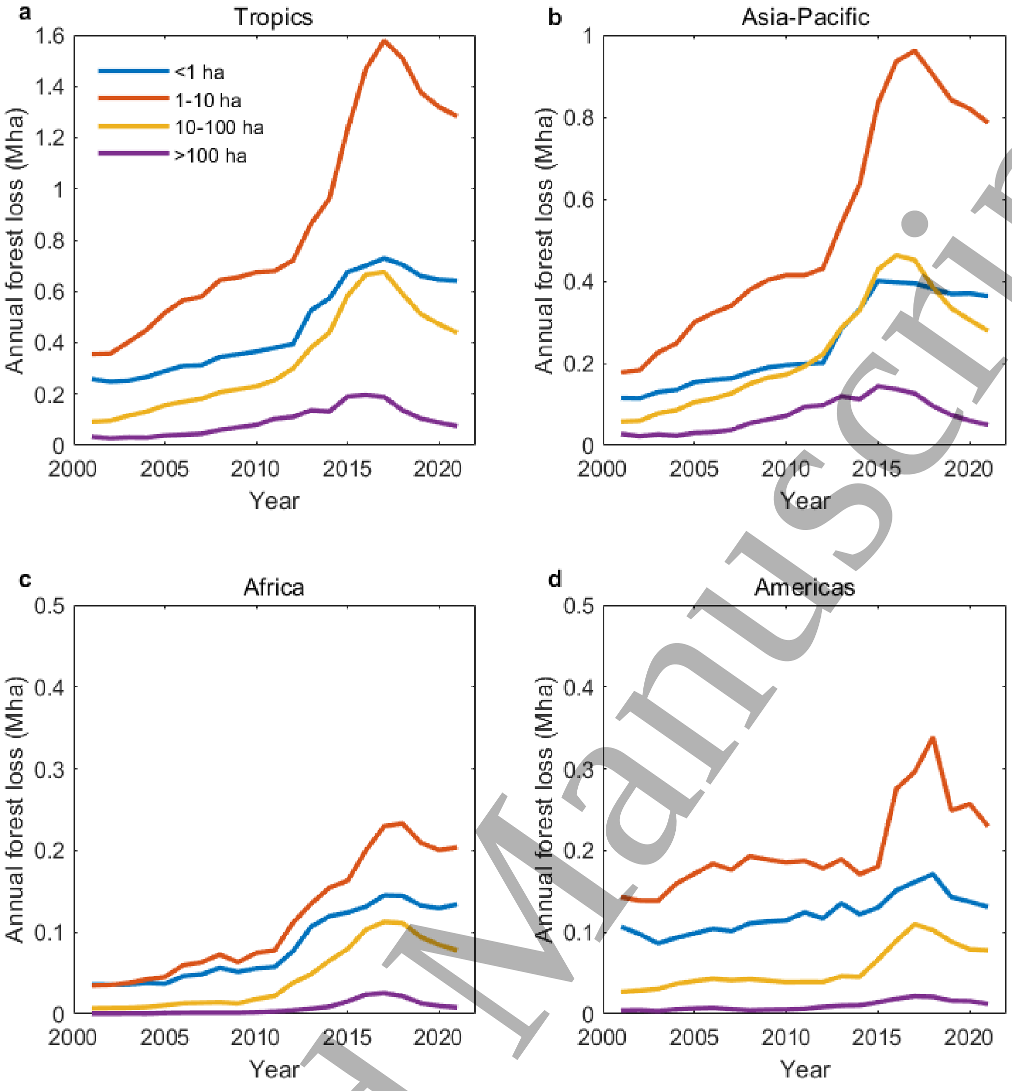

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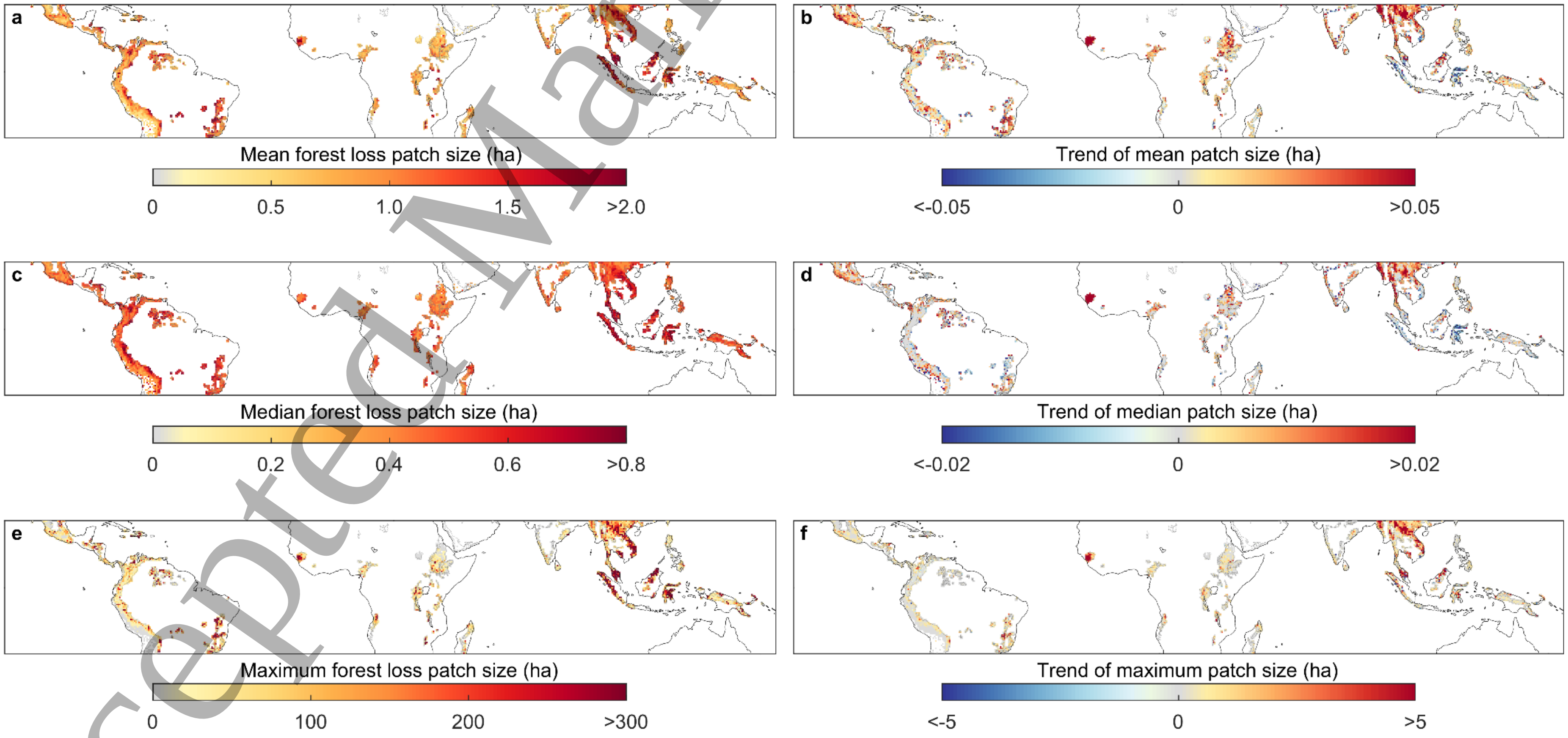

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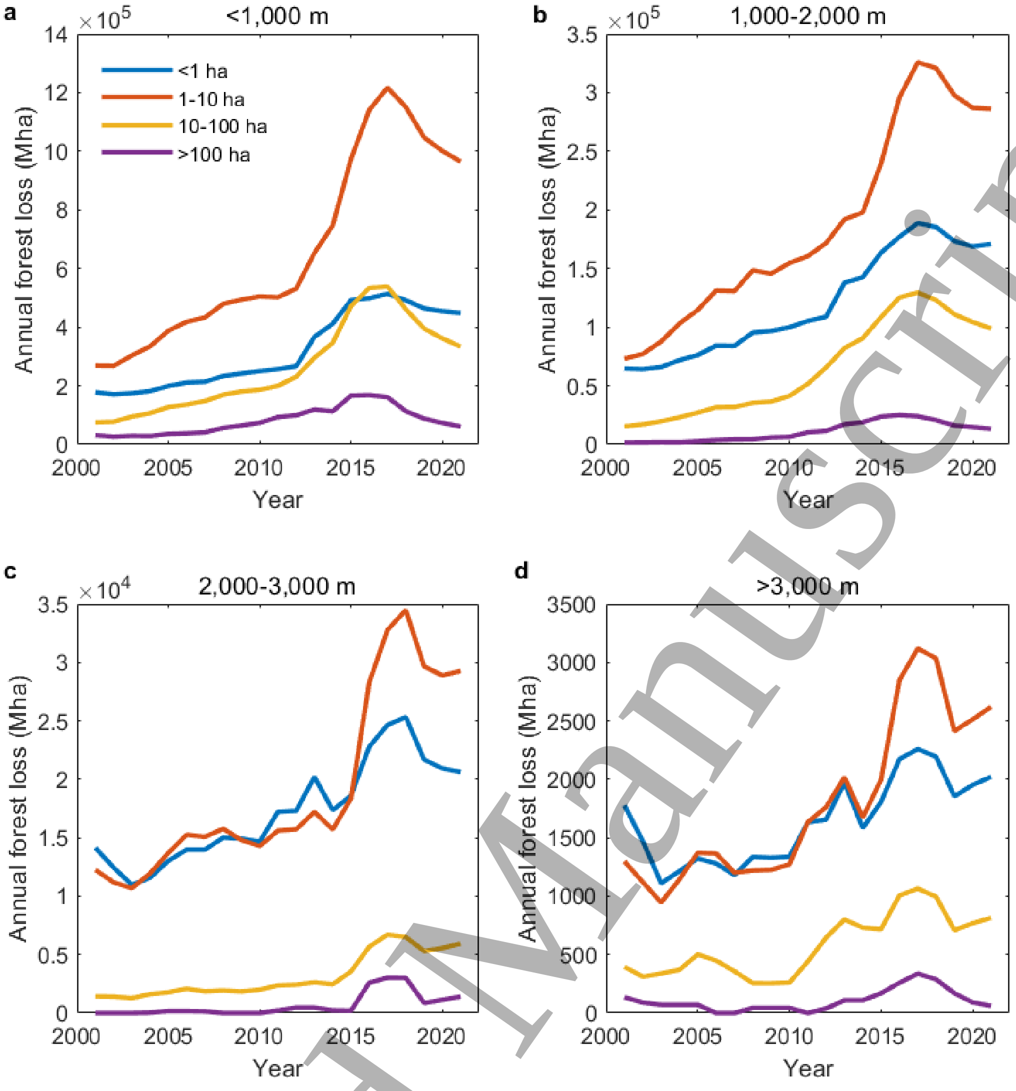

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