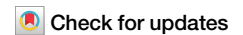


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# Forest loss persists despite certification and protection



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Forest loss is a significant global problem. Forest certification schemes and protected areas are two key approaches for improving forest conservation and management outcomes, but their effectiveness in reducing national-level forest loss remains unclear. Here, we analysed an 11-year high-resolution satellite dataset on tree canopy removal from 2013 to 2023 to assess associations between forest loss, certification, protection, and economic factors globally. We found that forest loss persisted globally with no evidence of decline in countries with higher levels of certification under the Forest Stewardship Council (FSC) or the Programme for the Endorsement of Forest Certification (PEFC). Forest loss was lower in higher-income countries (measured by gross domestic product per capita) and higher where industrial roundwood and fuelwood production was greater. While forest certification may improve management of certified forests, our results suggest limited effectiveness in reducing overall forest loss. Strengthening certification and protected-area strategies will be essential to slow global forest loss.

Forest loss, including permanent forest conversion to other forms of land cover (viz: deforestation), is a major global issue with numerous negative impacts, including increased carbon emissions<sup>1</sup>, biodiversity loss<sup>2</sup>, and disruption of hydrological regimes<sup>3</sup>. The problem of forest loss is recognised globally<sup>4</sup>. In response, economic trading blocs such as the European Union have implemented policies aimed at eliminating supply chains underpinned by deforestation<sup>5</sup>. Slowing forest loss and preventing deforestation is also a major objective of international declarations, such as the Glasgow Leaders' Declaration on Forests and Land Use, endorsed at COP26 in 2021 by 144 countries, which committed signatories to strengthen collective efforts to halt deforestation and land degradation<sup>6</sup>.

Understanding the factors associated with forest loss and deforestation is critical to the successful implementation of global initiatives to mitigate these problems, such as those agreed under COP26<sup>6</sup>. Two key approaches to improve forest conservation and management outcomes are to establish formal protected areas and to implement forest management certification schemes outside protected areas<sup>7,8</sup>. Forest management certification schemes, like those developed by the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC), were instigated almost three decades ago in response to public concerns about both the globally concerning rates of deforestation (particularly in the tropical regions of the world<sup>9</sup>) and the need for improved forest management practices<sup>10</sup>. These schemes are voluntary, market-based instruments that aim to independently ensure the quality of forest management and promote the trade of products sourced from certified forests<sup>9,11</sup>. By 2019, ~426 million ha

or ~10% of the world's forests (including plantations) had been certified (after accounting for dual forest management certification)<sup>12–15</sup>.

Protected areas are critical for effective conservation efforts across the world's forests<sup>16,17</sup>, with 168 nation states recognising the role of protected areas in Article 8 of the 1992 Convention on Biological Diversity (CBD)<sup>18</sup>. They have been credited with conserving considerable amounts of biodiversity<sup>19</sup>, with populations of many plant and animal species being larger inside reserves than outside them<sup>20</sup>, and rates of vertebrate species decline five times lower in reserves than outside reserves<sup>21</sup>. Protected areas are intended to exclude industrial-scale extractive activities as well as land clearing for agricultural or urban development<sup>18</sup>. The International Union for Conservation of Nature (IUCN) has been pivotal in coordinating global protected areas through their World Commission on Protected Areas<sup>22</sup>. As of 2021, at least 22.5 million km<sup>2</sup> of land and inland water was within protected areas and other area-based conservation measures<sup>23</sup>. Specifically for forests, about 7.26 million km<sup>2</sup> or 18% of global forest areas were in protected areas worldwide<sup>12</sup>.

Several studies have evaluated the effectiveness of forest certification schemes and protected areas in reducing forest loss. Yamamoto and Matsumoto<sup>24</sup> found no significant association between the expansion of forest certification (2002 and 2011) and reductions in forest cover loss, after accounting for country and year fixed effects. Furthermore, they reported evidence of leakage of forest loss into non-certified areas<sup>24</sup>. In contrast, Damette et al.<sup>25</sup> showed that forest management certification, especially the FSC, was negatively related to deforestation, while countries where logging

was more prevalent tended to experience larger deforestation rates than others. Shah et al.<sup>26</sup> found that protected areas established between 2000 and 2012 reduced forest loss by ~72% compared with unprotected areas, although effectiveness varied across regions and income groups. Similarly, Heino et al.<sup>27</sup> reported that forest loss within protected areas between 2000 and 2012 was lower than the global average (3% vs. 5%), yet such rates were still considered relatively high given the protection status of these forests. However, Neal<sup>28</sup> found that protected areas prevented about only 30% of forest loss occurring between 2000 and 2022 that would have occurred if the protected areas were not in place, although with significant heterogeneity between countries.

Building on previous work, we examine forest loss and its associations with both forest certification and protected areas for the period of 2013 to 2023. Using globally consistent and high-resolution spatial data for this 11-year period, we sought to answer four key questions:

1. What are the overall global trends of forest loss by fire and non-fire disturbances, protected areas, forest management certification, and forest product commodities?
2. Which countries and subregions contribute most to these trends?
3. Is forest loss less in countries where there is formal forest protection and where forest management certification schemes have been implemented?
4. What other factors are associated with the rate and spatial extent of forest loss?

To answer these four questions, we quantified spatio-temporal changes in disturbance-related forest loss between 2013 and 2023 and across all forested nations worldwide. We then intersected data on forest loss with data on spatio-temporal patterns in forest certification, levels of forest protection, and other country-level data on natural disturbances like wild-fire, human population density, and national Gross Domestic Product (GDP) (Table 1). Our results are indicative of the effectiveness of forest management certification schemes and forest protection across nations globally.

## Results

### What are the overall global trends of forest loss by fire and non-fire disturbances, protected areas, forest management certification, and forest product commodities?

Between 2013 and 2023, global annual forest canopy loss ranged between 21 to 32 million ha per year (Fig. 1). Linear models indicated that total forest canopy loss did not change significantly over the period (Fig. 1A,  $\beta = 1.57$ ,  $R^2 = 0.09$ ,  $P = 0.192$ ). Fire-related canopy loss showed a marginally positive trend, with an estimated annual increase of 1.28 million ha (Fig. 1A,  $\beta = 1.28$ ,  $R^2 = 0.29$ ,  $P = 0.052$ ), whereas non-fire canopy losses showed no directional trend (Fig. 1A,  $\beta = 0.29$ ,  $R^2 < 0.01$ ,  $P = 0.731$ ). The expansion of forests under formal protection increased from ~868 million ha in 2013 to ~990 million ha in 2023 (Fig. 1B,  $\beta = 13.6$ ,  $R^2 = 0.97$ ,  $P < 0.001$ ). FSC-certified forest area showed no significant change over the period (Fig. 1C,  $\beta = 1.22$ ,  $R = 0.04$ ,  $P = 0.537$ ), while PEFC-certified area increased significantly, from 262 million ha in 2013 to 300 million ha in 2023 (Fig. 1C,  $\beta = 6.15$ ,  $R^2 = 0.58$ ,  $P = 0.007$ ). PEFC increased its total certified area globally between 2013 and 2023, despite suspending its certificates in Russia in response to that nation's invasion of Ukraine in 2022<sup>29</sup>; therefore gains in PEFC certification elsewhere offset the losses in Russia (Fig. 1C). There was a net decrease in the total area certified under the Forest Stewardship Council (FSC) between 2013 and 2023, due primarily to the suspension of FSC certificates in Russia and Belarus following Russia's invasion of Ukraine<sup>30</sup>.

Industrial roundwood production increased significantly over the decade between 2013 and 2023 (Fig. 1D,  $\beta = 0.016$ ,  $R^2 = 0.44$ ,  $P = 0.016$ ), and fuelwood production increased even more strongly over this time (Fig. 1E,  $\beta = 0.0066$ ,  $R^2 = 0.83$ ,  $P < 0.001$ ). By contrast, global agricultural land area showed no consistent change between 2013 and 2023 (Fig. 1F,  $\beta = 0.50$ ,  $R^2 = 0.03$ ,  $P = 0.606$ ).

### Which countries and subregions contribute most to these trends?

We found that forest canopy loss between 2013 and 2023 was highly concentrated in a small number of countries. The Russian Federation (~57 Mha), Brazil (~36 Mha), Canada (~34 Mha), and the United States (~23 Mha) accounted for almost half of all global forest canopy loss (Fig. 2A, Table S3). Canopy loss from fire-related disturbances dominated in boreal regions such as Russia and Canada, whereas non-fire disturbances accounted for most losses in tropical nations including Brazil, the Democratic Republic of the Congo (DRC), and Indonesia.

Brazil supported the largest area of forest under protection by 2023 (~228 Mha), followed by Russia (~93 Mha) and Canada (~59 Mha), which together comprised ~38% of the world's protected forest area (Fig. 2B). Forest management certification coverage was similarly concentrated; nearly half of the FSC-certified forest was in the Russian Federation and Canada (prior to the withdrawal of certificates in the Russian Federation), while ~40% of PEFC-certified forest was located in Canada (Fig. 2C, D). Industrial roundwood production was dominated by the United States, Russia, and China (Fig. 2E). Fuelwood production was highest in tropical countries such as India and Brazil (Fig. 2F). The extent of agricultural land in 2023 was greatest in China, followed by the USA, Australia, and Brazil (Fig. 2G).

Between 2013 and 2023, total forest canopy loss (Fig. 3A) was highest in northern Asia (Russian Federation) (57.3 Mha), South America (56.2 Mha), and North America (57.0 Mha). Fire-driven forest canopy loss (Fig. 3B) was greatest in northern Asia (Russian Federation) (43.0 Mha), North America (30.6 Mha), and South America (11.7 Mha), whereas non-fire-related forest canopy loss (Fig. 3C) was largest in South America (44.5 Mha), south-eastern Asia (31.9 Mha), and North America (26.5 Mha).

By 2023, the largest areas of protected forests at the subregion level (Fig. 3D) were in South America (367.1 Mha), eastern Africa (105 Mha), North America (103.9 Mha), and northern Asia (Russian Federation) (93.3 Mha). The largest of FSC-certified forest areas at the subregion level by 2023 (Fig. 3E) were in North America (60.1 Mha), northern Europe (28.5 Mha), and South America (16.2 Mha), while the largest PEFC-certified forest areas (Fig. 3F) were concentrated in North America (163.7 Mha), northern Europe (49.1 Mha), and western Europe (20.9 Mha).

The total industrial roundwood production between 2013 and 2023 (Fig. 3G) was highest in North America (5.69 billion m<sup>3</sup>), northern Asia (2.15 billion m<sup>3</sup>), and South America (2.62 billion m<sup>3</sup>), whereas fuelwood production (Fig. 3H) was highest in southern Asia (4.20 billion m<sup>3</sup>), eastern Africa (3.40 billion m<sup>3</sup>), and western Africa (2.26 billion m<sup>3</sup>). Finally, agricultural land area in 2023 (Fig. 3I) was largest in eastern Asia (638.2 Mha), South America (531.8 Mha), and North America (478.7 Mha).

The maps we created (see Fig. 4) illustrate estimated trends in proportional forest canopy loss ( $\beta$ ) between 2013 and 2023, derived from country-level beta regression models. Positive  $\beta$  values indicated an increase in the rate of forest canopy loss, while negative  $\beta$  values indicated a decline in the rate of forest canopy loss over time. Across much of central and eastern Europe, including Germany,  $\beta$  estimates were positive, reflecting accelerating fire- and non-fire-related forest canopy loss. In contrast, several African nations, such as Kenya and Tanzania, exhibited negative  $\beta$  estimates, suggesting that the rate of forest canopy loss had slowed. Large areas of southeast Asia and parts of South America showed accelerating losses of forest canopy primarily associated with fire. While most countries fell within a moderate range of  $\beta$  values, two extreme outliers stood out: Niger ( $\beta \approx -8.83$ ) and Seychelles ( $\beta \approx +5.99$ ). Because these arose from countries with very small total forest areas, they were excluded from the mapped summaries for visual clarity.

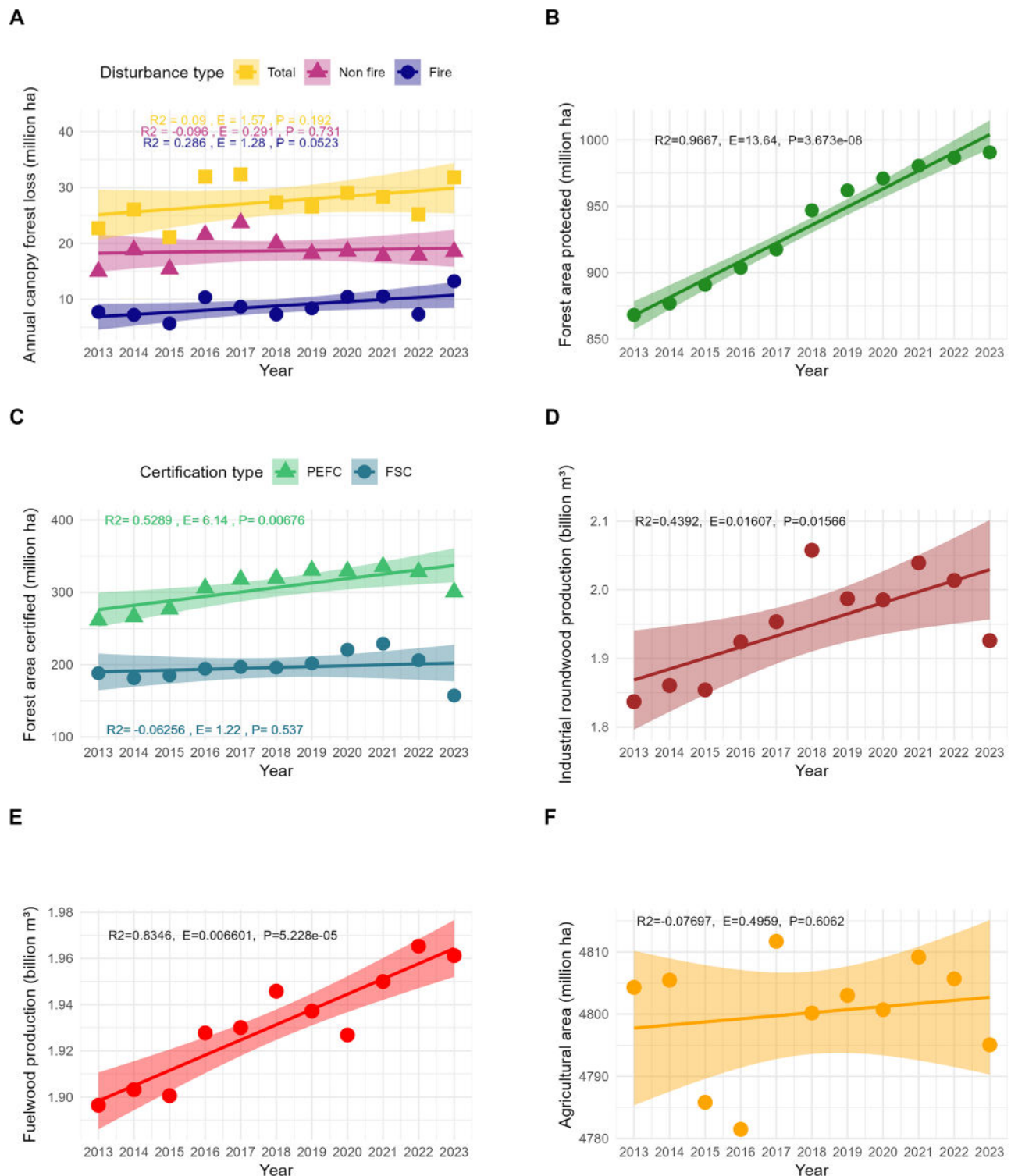
### Is forest loss less in countries where there is formal forest protection and where forest management certification schemes have been implemented?

Our panel data analysis revealed that across countries from 2013 to 2023, there was no evidence for a relationship between forest protection and certification and reductions in forest canopy loss (Table S5, Fig. 5).

**Table 1 | Variables used in the panel data analysis**

| Variable type | Name                            | Transformation                                  | Brief summary                                                                                                                                                                                                  | Source                                                                                                            |
|---------------|---------------------------------|-------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|
| Response      | Forest loss (total)             | Proportion of total land area                   | Annual forest canopy/loss due to both fire and non-fire disturbance, per country and year, expressed as a proportion of total land area.                                                                       | Global Land Analysis and Discovery (GLAD) laboratory in partnership with Global Forest Watch (GFW) <sup>4</sup> . |
|               | Forest loss (fire)              | Proportion of total land area                   | Annual forest canopy/loss due to fire disturbance, disaggregated from other causes, expressed as a proportion of total land area.                                                                              | Hansen et al. <sup>4</sup> dataset disaggregated for fire-related disturbance.                                    |
|               | Forest loss (non-fire)          | Proportion of total land area                   | Annual forest canopy/loss due to non-fire disturbance, expressed as a proportion of total land area. The input data were calculated by subtracting canopy/loss due to fire disturbance from total canopy loss. | Hansen et al. <sup>4</sup> dataset disaggregated for non-fire disturbance.                                        |
| Predictor     | FSC-certified area (lagged)     | Proportion of total land area, lagged by 1 year | Annual area certified under FSC, expressed relative to national land area. Lagged by one year.                                                                                                                 | FSC International, annual country-level data <sup>50</sup> .                                                      |
|               | PEFC-certified area (lagged)    | Proportion of total land area, lagged by 1 year | Annual area certified under PEFC, expressed relative to national land area. Lagged by one year.                                                                                                                | Programme for the Endorsement of Forest Certification (PEFC) <sup>15</sup> .                                      |
|               | Protected forest area (lagged)  | Proportion of total land area, lagged by 1 year | Annual extent of formally protected forest in each country, expressed relative to national land area. Lagged by one year.                                                                                      | World Database on Protected Areas (WDPA), January 2023 release <sup>23</sup> .                                    |
|               | Forest area                     | Proportion of total land area                   | Baseline forest extent per country, expressed relative to national land area.                                                                                                                                  | FAO Global Forest Resources Assessment (via FAOSTAT) <sup>58</sup> .                                              |
|               | Agricultural area               | Proportion of total land area                   | Agricultural land per country, expressed relative to national land area.                                                                                                                                       | FAOSTAT <sup>58</sup> .                                                                                           |
|               | Fuelwood production             | Density (m <sup>3</sup> per ha of land area)    | Annual reported fuelwood harvest volume, expressed relative to land area.                                                                                                                                      | FAOSTAT <sup>58</sup> .                                                                                           |
|               | Industrial roundwood production | Density (m <sup>3</sup> per ha of land area)    | Annual reported industrial roundwood harvest volume, expressed relative to land area.                                                                                                                          | FAOSTAT <sup>58</sup> .                                                                                           |
|               | GDP per capita (lagged)         | Standardised, lagged by 1 year                  | Gross domestic product per person, lagged by one year.                                                                                                                                                         | FAOSTAT <sup>58</sup> .                                                                                           |
|               | Population density (lagged)     | Persons per ha, lagged by 1 year                | National population per unit land area, lagged by one year.                                                                                                                                                    | FAOSTAT <sup>58</sup> .                                                                                           |
|               | Year                            | Standardised                                    | Linear effect of year on annual forest canopy loss.                                                                                                                                                            | –                                                                                                                 |
|               | Year <sup>2</sup>               | Standardised                                    | Quadratic effect of year on annual forest canopy loss.                                                                                                                                                         | –                                                                                                                 |
|               | Country                         | Categorical                                     | Included as a fixed effect.                                                                                                                                                                                    | –                                                                                                                 |

All predictors were scaled to a mean of zero and standard deviation of one for modelling.



**Fig. 1 | Trends in global results from 2013 to 2023. A** Forest canopy loss (total, fire-related, and non-fire-related), **B** protected forest area, **C** certified forest area under FSC and PEFC schemes, **D** industrial roundwood production, **E** fuelwood

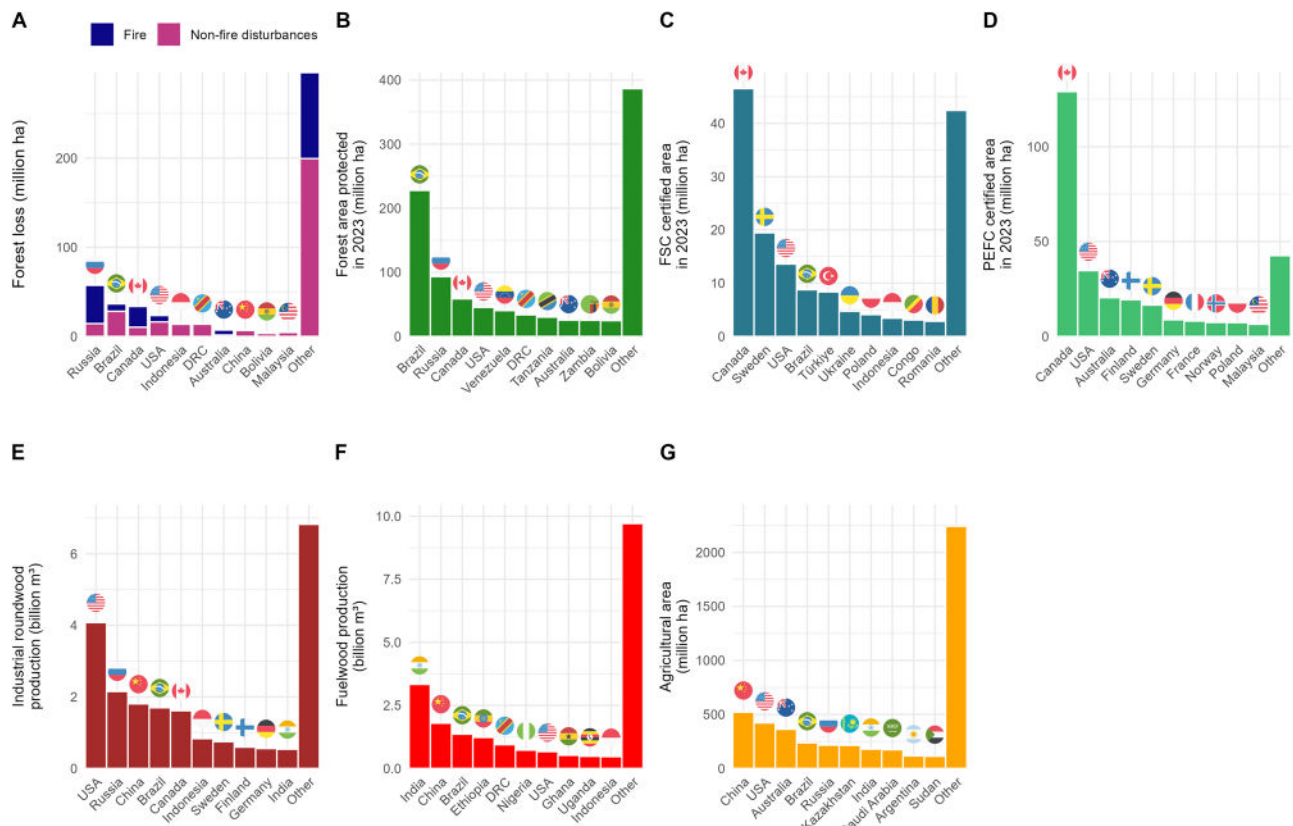
production, and **F** agricultural area. We fitted linear regressions for each category to estimate annual trends. Lines represent fitted values; slope estimates,  $R^2$ , and p-values are shown in each panel.

### What other factors are associated with the rate and spatial extent of forest loss?

For non-fire-related forest canopy loss, industrial roundwood density ( $\beta = 0.24 \pm 0.09$ ), and fuelwood density ( $\beta = 0.35 \pm 0.13$ ) were the strongest positive predictors (Fig. 5). GDP per capita (lagged;  $\beta = -0.53 \pm 0.13$ ) was negatively associated with non-fire forest canopy loss. For fire-related

forest canopy loss, GDP per capita ( $\beta = -1.56 \pm 0.4$ ) was the only significant predictor (Fig. 5).

Our heterogeneity modelling revealed that, of the 36 interactions tested, only three were statistically significant, and none involved FSC certification (Fig. S3, Table S6). PEFC certification showed no significant interactions except with forest proportion for fire-related loss ( $\beta = 1.63$ ,  $P = 0.036$ ), where



**Fig. 2 | Country-level forest canopy loss and forestry-related indicators from 2013 to 2023.** **A** Total forest canopy loss for the years 2013 to 2023 is shown by cause (fire vs. non-fire disturbance) in all areas, **B** Protected forest area extent in 2023, **C** FSC-certified areas in 2023, **D** PEFC-certified areas in 2023, **E** total industrial roundwood

production for the years 2013 to 2023, **F** total fuelwood production for the years 2013 to 2023, **G** and agricultural area in 2023. Listed countries represent the top 10 contributors to global totals. Circular flags are plotted using the ‘ggflags’ package<sup>62</sup> in R<sup>63</sup> and are sourced from EmojiOne (CC-BY-4.0 licence, Brad Erickson).

the positive coefficient indicates PEFC was associated with higher fire loss in more heavily forested countries. Protected areas showed significant positive interactions with fuelwood ( $\beta = 0.46$ ,  $P = 0.010$ ) and industrial roundwood production density ( $\beta = 0.26$ ,  $P = 0.004$ ) for non-fire loss, suggesting that protection may be less effective in countries with high wood extraction pressure. None of the total GDP interactions were significant.

## Discussion

Understanding the drivers of forest loss is key to developing effective strategies to limit deforestation globally. We analysed satellite-derived spatio-temporal patterns of forest loss (defined as stand-replacing tree canopy removal) over an 11-year period and found that global total fire- and non-fire forest loss showed no significant overall trend between 2013 and 2023 (Fig. 1). The Russian Federation experienced the largest amount of forest loss, primarily due to fire, followed by Brazil, where non-fire disturbances dominated (Fig. 2). Over the same period, the total area of protected forests has increased, and the area of forest certified under the PEFC has generally increased, although FSC certified area has declined (Fig. 1), largely due to certificate suspensions in Russia and Belarus. However, countries with higher levels of forest management certification under FSC or PEFC did not experience lower rates of non-fire forest loss. We further discuss these and other key results in the remainder of this paper and conclude with commentary on how forest management certification schemes might be improved to reduce forest loss.

## Forest loss, forest management certification, forest protection and other effects

Our analyses indicated that although substantial proportions of forest are certified under FSC and PEFC in some subregions and countries, forest management certification did not translate into significant reductions in

non-fire forest loss at the country level (Fig. 5). Despite these results, it remains possible that forest management certification prevented larger losses than might otherwise have occurred.

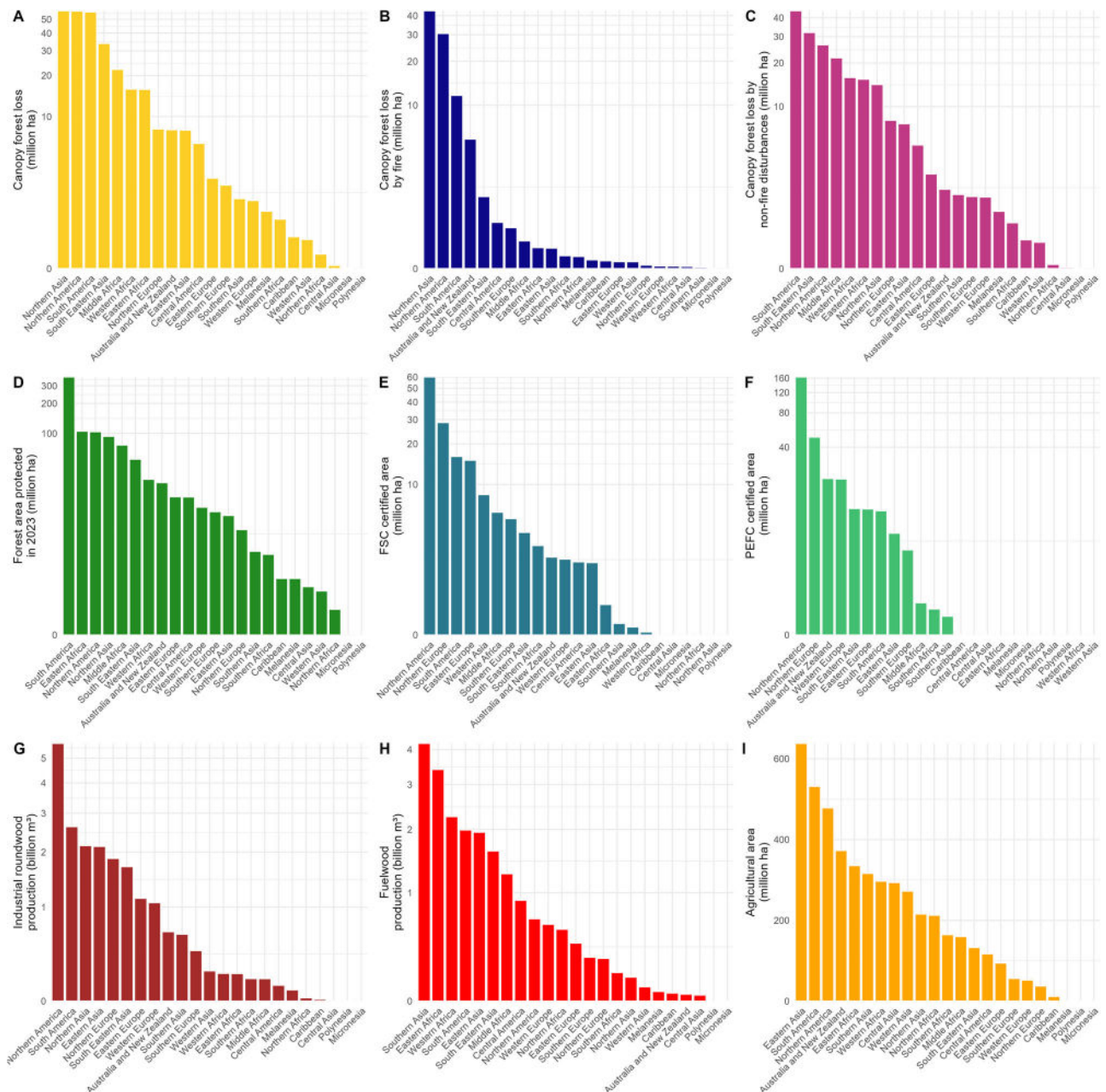
Global industrial roundwood production increased between 2013 and 2023 (Fig. 1D). At a country level, higher industrial roundwood production was positively associated with non-fire related forest loss (Fig. 5). This association likely reflects the direct impacts of logging as a driver of forest canopy removal.

Global fuelwood production increased steeply between 2013 and 2023 (Fig. 1E). We found a positive relationship between fuelwood production and forest loss. To address concerns over unsustainable fuelwood harvesting, the FSC has sought to promote responsible fuelwood and charcoal production under its forest management certification. Namibia, for example, has seen 1.6 million ha of land awarded FSC forest management certification, partly due to increasing European demand for FSC-certified charcoal<sup>31</sup>. Notably, fuelwood producers in Namibia became the first in Africa to obtain an FSC group chain-of-custody certificate<sup>32</sup>.

Finally, we found evidence that non-fire-related forest loss was higher in lower GDP per capita countries (Fig. 5). We suggest this likely reflects stronger deforestation pressures in less economically developed nations; a well-documented pattern of deforestation<sup>5,33</sup>.

## Comparison with other studies

Our results show a continuation of the trend in forest management certification as observed by Yamamoto and Matsumoto<sup>24</sup>, who found no significant relationship between the expansion of forest management certification between 2002 and 2011 and rates of forest loss over the same period. Damette and Delacote<sup>25</sup> observed that countries with higher levels of roundwood removal tended to experience greater deforestation, which aligned with our results. However, they found that forest management



**Fig. 3 | Subregion-level forest canopy loss and forestry-related indicators from 2013 to 2023.** **A** Total forest canopy loss between 2013 and 2023, **B** Total forest canopy loss by fire between 2013 and 2023, **C** Total forest canopy loss by non-fire disturbances between 2013 and 2023, **D** Protected forest extent in 2023, **E** FSC-

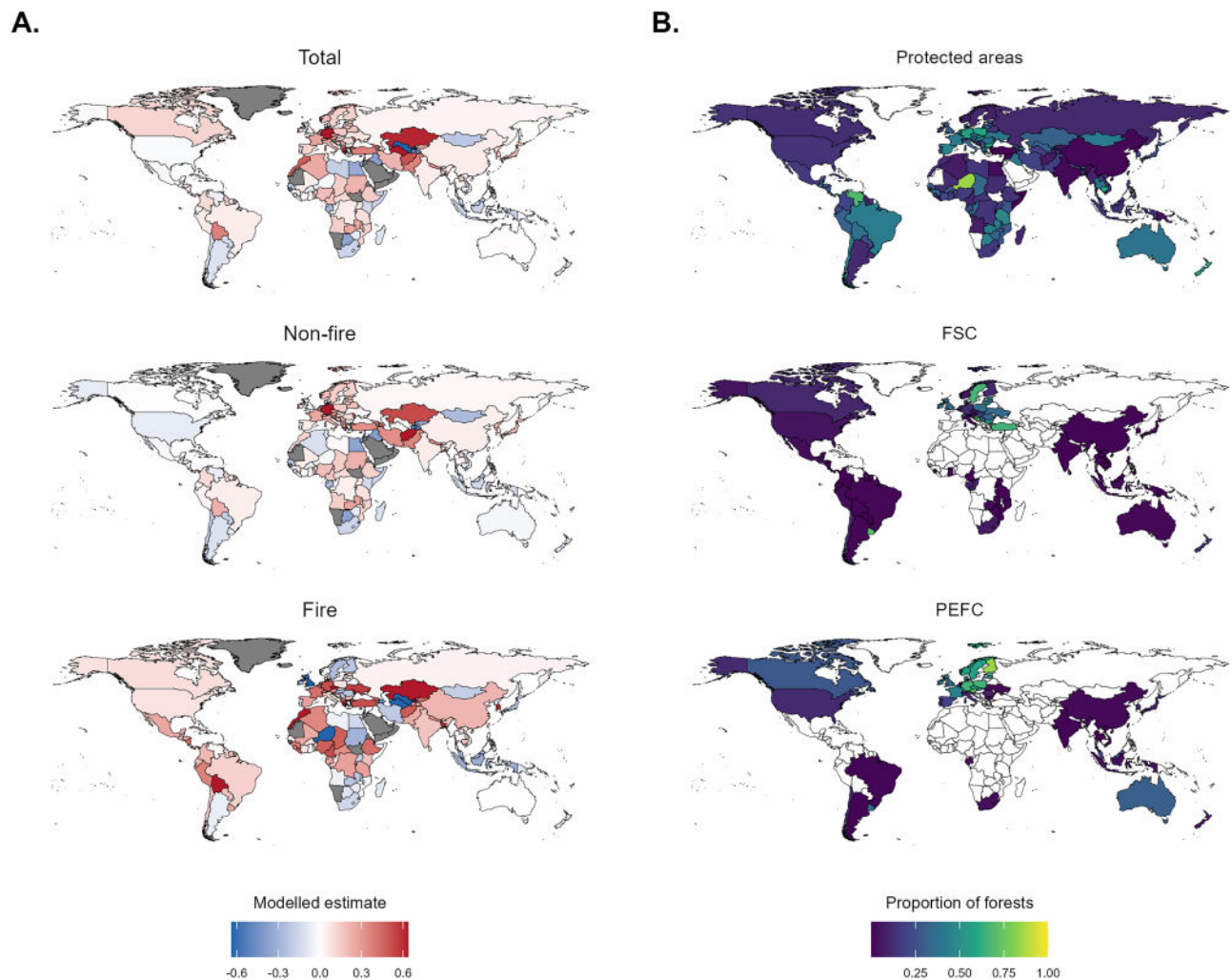
certified areas in 2023, **F** PEFC-certified areas in 2023, **G** Total industrial roundwood production between 2013 and 2023, **H** Total fuelwood production between 2013 and 2023, and **I** agricultural area in 2023. The y-axes in (A-H) are  $\log(x + 1)$  transformed.

certification, particularly countries with large areas of FSC forest management certification, was negatively associated with deforestation. This divergence regarding forest management certification may be explained by differences in data sources, periods of analysis and by using a panel and cross country analysis. Both our study and that of Yamamoto and Matsumoto<sup>24</sup> used high resolution global forest loss data sourced from Hansen et al.<sup>4</sup>, whereas Damette and Delacote<sup>25</sup> relied on the FAO country level estimates of decreases in net forest cover. Their study also included an earlier period of 1972 to 1994 for their analysis, when forest management certification schemes were only beginning to emerge toward the end of their analysis period (1990–1994)<sup>34</sup>. As certification was too recent to be incorporated into their panel analysis, Damette and Delacote<sup>34</sup> also examined certification using a cross country approach based on the proportion of forest area certified under FSC and PEFC in 2005.

Some studies have shown global forest area has declined over time. Estoque et al.<sup>35</sup> found that between 1960 and 2019 the world lost 81.7 million ha of forest, with losses exceeding gains. With an increase of 4.68 billion people over the same period, global forest area per capita fell by more than 60% (from 1.4 to 0.5 ha). Estoque et al.<sup>35</sup> argue their results were consistent with forest transition theory, as forest losses were concentrated in lower-income tropical countries and forest gains occurred mainly in higher-income extratropical countries.

### The need to strengthen and integrate forest management certification schemes

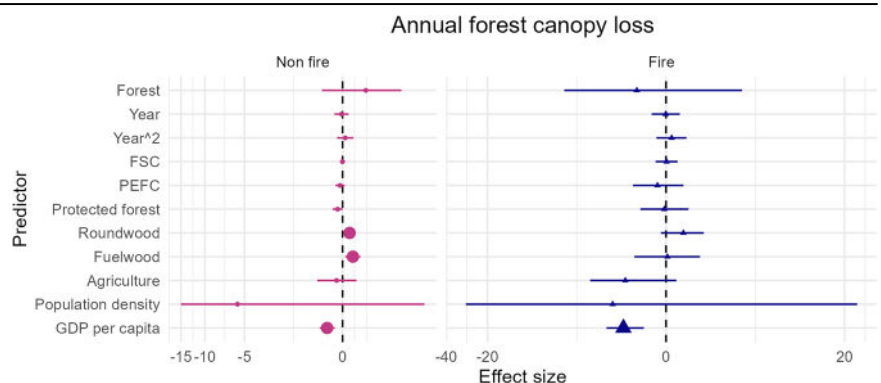
Several studies have highlighted the value of forest management certification programmes, such as in protecting particular high-profile species<sup>36</sup> or in a complementary role with community forests to enhance human well-being



**Fig. 4 | Country-level trends in forest canopy loss (2013-2023) and global distribution of forest protection (2023).** **A** Country-level trends in forest canopy loss between 2013 and 2023, estimated from panel data models separately for total forest canopy loss, fire-related forest canopy loss, and non-fire-related forest canopy loss. Colours represent the coefficient estimate for Year from a beta-regression fitted separately for each country; red indicates increasing forest canopy loss over time, and blue indicates decreasing loss. Colour scales are truncated at the 97.5th percentile to

reduce the influence of outliers and improve visual interpretation. Countries shown in grey had insufficient data to fit a reliable model or returned non-converging estimates. **B** Global distribution of forest protection in the final year of analysis (2023), showing the proportion of forest area under formal protection, and the proportion certified under FSC and PEFC schemes. The colour scale indicates the proportion of each country's forest area under protection. Countries without reported certified or protected forest area are shown in white.

**Fig. 5 | Modelled effect sizes from panel data analysis regressing the proportion of forest canopy loss due to non-fire- and fire-related forest canopy loss against all predictor variables.** Effect sizes represent the coefficient estimates from the full models (Table S5). Error bars represent 95% confidence intervals. We interpreted effects as significant if the error bars did not cross the zero-effect line. Larger points represent those effects considered significant and smaller points represent those effects considered non-significant.



from neighbouring forests<sup>37</sup>. Therefore, despite our finding of no association between forest management certification schemes and forest loss at the broader country level, we do not advocate dispensing with forest management certification programmes. Rather, we urge revisiting their role in

broader efforts to reduce forest loss. For example, forest certification schemes are based around a series of standards, the most important of which cover the certification of forest management and the tracking of forest commodities from certified forests to points of sale through Chain of

Custody certification<sup>34</sup>. Forest management certification schemes are market-based schemes that fall within the domain of private governance<sup>11</sup>. In contrast, the vast majority of protected and conserved areas are governed by national governments and other state actors<sup>38</sup>. Forest management certification is intended for wood production forests and plantations, while formal protection typically excludes industrial wood production. The two entities have historically been treated as parallel but separate strategies, often without integration at the landscape scale. In some cases, the establishment of protected areas has been used as a justification to intensify industrial logging operations and agricultural land use expansion in places outside protected areas<sup>39,40</sup>.

Some land management approaches have proven to be effective in reducing forest loss. One is Indigenous-led management on Indigenous People's Lands (IPL), including those areas not formally recognised under IUCN categories. While inclusion of IPLs was beyond the scope of our study, we acknowledge their conservation value. Recent studies have shown that Indigenous-led conservation can outperform other strategies. For example, Simkins et al.<sup>40</sup> found that Key Biodiversity Areas outside IPLs have experienced higher tree cover loss than those within IPLs. Camino et al.<sup>41</sup> showed that IPLs with secure legal tenure in the Dry Chaco region in South America experienced substantially lower forest loss than both insecure IPLs and surrounding public lands. Sze et al.<sup>42</sup> reported that forests under Indigenous-led management had the highest protective effect on forest integrity and the lowest land-use intensity relative to other land uses across the tropics. These studies reinforce the importance of recognising and securing Indigenous land rights as a conservation strategy, particularly in hotspots of forest loss.

We argue there is a need for complementary approaches between forest management and land management strategies. Only a comparatively small area of forest is under forest management certification (~10% of the world's forests [including plantations])<sup>12,15,34</sup>. Therefore, it is important to strengthen and strategically expand forest management certification in ways that complement other land management strategies, like Indigenous Peoples Lands and formal protected areas, particularly given that the IUCN World Conservation Congress have implored governments to protect at least 30% of the planet by 2030<sup>43</sup>. No one incentive can work in isolation and forest loss has been observed even occurring in protected areas across many countries globally<sup>28,44</sup>. How forest management certification integrates with protected areas, Indigenous People's Lands, especially outside of wood production areas, is an area for future study.

### Study limitations

A key limitation of this study was the relatively limited period where data were either consistent and/or available. Many regions worldwide experienced deforestation or ecological disturbances long before our analysis period, meaning that significant land-use changes over past decades may not be fully reflected in our results<sup>45</sup>. Furthermore, government and market-based efforts to curb deforestation have had varying effects across different regions, particularly in more recent decades<sup>46</sup>. As a result, our 11-year sample may not capture longer-term deforestation trends before our study period, nor does it account for potential future changes in forest loss dynamics.

Another limitation pertains to potential underestimation of forest loss by fire<sup>47</sup>. We selected fire forest loss pixels with medium and high certainty for analysis. This may have resulted in an underestimation of forest loss by fire. For example, in Australia, our analysis identified over 124,965 ha of non-fire forest loss in protected areas in 2020, coinciding with extensive wildfires across eastern Australia<sup>48</sup>. Given Australia's comparatively strong enforcement against land clearing and logging in protected areas<sup>49</sup>, it is unlikely that this loss resulted from deforestation or forestry operations. Instead, we attribute this unclassified forest loss to low-intensity fires and prescribed burns, which may not have been detected as fire-driven loss in the dataset due to remote sensing limitations. Thus, we interpret our findings as indicative rather than definitive, recognising that fire-related losses may be

underrepresented or misclassified, particularly where forest degradation rather than complete canopy removal has occurred.

Finally, our observational panel design has limitations for causal inference. Although we controlled for country-level heterogeneity and time-varying confounders through fixed effects and country  $\times$  year interactions, certification adoption is not random. Countries and forest managers that adopt certification may differ systematically from those that do not. Additionally, conditioning on variables such as GDP per capita may introduce bias if these act as mediators on the causal pathway between certification and forest loss, or are influenced by unobserved confounders. Our heterogeneity analyses found no evidence that certification effectiveness varies by income or industrial context, but unmeasured confounding cannot be ruled out.

### Conclusions

Our study analysed spatio-temporal patterns of forest loss (defined as stand replacing canopy removal) from 2013 to 2023. Over this period, total global non-fire forest loss showed no consistent trend, while fire-related loss rose marginally (Fig. 1). The global extent of protected forest areas increased, the PEFC certified area grew, and the FSC certified area declined (Fig. 1). However, forest loss was not reduced in countries with higher levels of forest management certification under the FSC and/or the PEFC schemes. We found forest loss was negatively associated with increasing GDP per capita. Non-fire-related forest loss was positively associated with both industrial roundwood and fuelwood production (Fig. 5).

While it remains possible that forest management certification prevented larger forest loss than might have otherwise occurred, our findings suggest that FSC and PEFC may not be as effective in reducing forest loss at the country level. These results highlight the challenges facing the global community in achieving the objectives of international agreements such as the Glasgow Leaders' Declaration on Forests and Land Use<sup>6</sup>, and underscore the need for stronger, complementary approaches to forest protection and sustainable management<sup>46</sup>.

### Materials and methods

We investigated country- and subregion-level associations between forest loss and the area of forest certified under the FSC<sup>50</sup> and PEFC<sup>15</sup>, as well as the extent of forest within formally protected areas over the period 2013 to 2023<sup>51</sup>. We selected this period to align with the launch of Landsat 8 in 2013, which significantly improved the consistency and accuracy of global forest loss detection<sup>52</sup>. Earlier studies have focused on the previous 2001–2012 period<sup>24,26,27</sup>, and here we extend the analysis to the subsequent decade, taking advantage of enhanced satellite image acquisition and classification accuracy.

### Data acquisition and processing

We obtained forest cover and loss data from the Global Forest Change (GFC) dataset<sup>4</sup> which provides annual, ~one arc second resolution raster maps of tree cover and forest loss across 128.8 million km<sup>2</sup> of global land (excluding Antarctica and select Arctic islands). The dataset is structured into 10°  $\times$  10° tiles, each comprising unsigned 8-bit values with a spatial resolution of one arc-second per pixel. Tree cover is mapped for the year 2000 as percent canopy closure for all vegetation  $\geq$  5 m in height. To differentiate forest cover from non-forest cover, we referred to the FAO definition of forest "as land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use."<sup>12</sup> Guided by the Food and Agriculture Organization definition<sup>12</sup>, we defined forest as cells with greater than 10% canopy cover in the year 2000. We re-projected raster tiles into a metric coordinate system and resampled to 50  $\times$  50 m cells for spatial consistency and computational efficiency.

In the Global Forest Change 2000–2023 dataset, forest loss is defined as a stand-replacing disturbance resulting in complete canopy removal and was recorded for each year from 2001 to 2023<sup>4,53</sup>. Each raster cell was

encoded as 0 (no loss) or an integer from 1 to 23, corresponding to the year of loss (2001 = 1, ..., 2023 = 23). Stand-replacing disturbances included high-severity fire, clearcut logging, conversion to agriculture or urban areas, and natural events such as windthrow. Forest degradation not resulting in complete canopy loss (e.g., low-intensity logging or fire) was not captured in this dataset<sup>4,53</sup>. For our analysis, we considered loss occurring only within forested pixels (defined as having >10% canopy cover in 2000). We excluded losses in areas below this threshold from analysis.

To isolate fire-driven forest loss from other kinds of forest loss, we incorporated the supplementary dataset produced by Tyukavina et al.<sup>47</sup> which disaggregates gross forest loss data into fire and non-fire components using Landsat-based spectral and temporal classifiers<sup>4</sup>. This dataset identified stand-replacing loss caused specifically by fire, excluding low-intensity or understory burns. For our analysis, we retained only medium- and high-certainty fire pixels and, consistent with Hansen et al.<sup>4</sup>, counted only the first recorded instance of stand-replacing loss per pixel within areas classified as forest in 2000 (>10% canopy cover). We encoded fire-driven loss in the same manner as Hansen et al.<sup>4</sup>, with raster values 1–23 corresponding to years 2001–2023. We assigned cells with no detected fire-driven loss a zero value. A limitation was that in Africa, the fire/no-fire classifier produced only binary outputs (0 or 100% probability), where uncertainty estimates were limited, and small high-severity fire patches may have been under-represented. To calculate non-fire driven forest loss, we subtracted the fire-driven forest loss from the total forest loss.

We obtained country-level forest management certification data from the FSC and the PEFC<sup>54,55</sup>. These data represent the total certified forest area (ha) per country as reported by each scheme. Our analysis included only forests certified under the forest management standards of FSC and PEFC. We excluded Controlled Wood or Chain of Custody certifications due to lack of publicly available data. Neither the FSC nor the PEFC certification schemes provide spatial data delineating the full extent of certified forest management units. While FSC maintains spatial data internally, they are not made publicly accessible. Geolocation data provided by FSC are voluntarily submitted and do not represent all certified areas<sup>56</sup>. As such, it was not possible to spatially overlay forest management certification boundaries with forest loss data, and instead we used country-level statistics.

Protected areas were those areas identified as protected under the World Database for Protected Areas (WDPA)<sup>57</sup>. The WDPA accepts data on protected areas as defined by the IUCN and the Convention on Biological Diversity (CBD). Under the IUCN, a protected area is a clearly defined geographical space, recognised, dedicated, and managed through legal or other effective means to achieve the long-term conservation of nature with associated ecosystem services and cultural values. The CBD defines a protected area as a geographically explicit area that is designated or regulated and managed to achieve specific conservation objectives<sup>57</sup>. Protected areas designations in the WDPA include national parks, Indigenous Protected Areas, regional parks, wildlife refuges and private nature reserves<sup>57</sup>. Following the methods used by Maxwell et al.<sup>50</sup>, we included only protected areas from the WDPA database that have a status of ‘Designated’, ‘Inscribed’ or ‘Established’. We removed all points and polygons with a status of ‘Proposed’ or ‘Not Reported’, or designated as ‘UNESCO MAB Biosphere Reserves’, as they do not meet the IUCN definition of a protected area.

We obtained data on forest product commodities from the Food and Agriculture Organization of the United Nations<sup>58</sup>. We focused on two key forestry commodities: industrial roundwood and fuelwood. Industrial roundwood includes aggregate production of sawlogs and veneer logs, pulpwood (round and split), and other industrial roundwood used in wood-processing industries. Fuelwood refers to wood extracted primarily for energy production, such as in cooking, heating, and power generation. Fuelwood includes stems, branches, and wood intended for charcoal, pellets, and similar agglomerates. We selected these commodities as explanatory variables due to their direct relevance to commodity supply chains regulated by forest certification schemes. While agricultural drivers of deforestation, such as beef and crop production, are undeniably important, they fall

outside the mandate of forest management certification. We therefore did not include beef and crop production in our forest management certification-specific analysis. However, we recognise the broader influence of agricultural expansion on forest loss and therefore included, at the country level, the amount of agricultural area, population density, and GDP per capita to account for broader socio-economic pressures on forests (see Supplementary Materials 1–5, Table S2)<sup>58</sup>.

## Data structure and panel design

We structured our dataset as a panel comprising country-year observations for the period 2013–2023, with records nested within its corresponding subregion and country to enable multilevel analysis. Our primary response variables were forest loss due to fire and forest loss excluding fire. To assign protected area status, we temporally aligned each pixel’s year of forest loss with the year of its protected area designation. If forest loss occurred in a pixel before its designation as a protected area, we classified the pixel as unprotected at the time of loss. If forest loss occurred after the pixel had been designated within a protected area, we classified it as protected. We treated pixels within areas already protected by 2013 as protected throughout the study period, while we treated pixels never designated as protected as unprotected. This temporal matching ensured that each forest loss event was attributed the correct protection status at the time it occurred. We then aggregated these pixel-level classifications to the national-level and sub-region level for panel data analysis. An equivalent pixel-level procedure could not be applied across certified areas under the FSC or PEFC because no spatial data on certified areas were publicly available. Certified area was therefore included only as a country-level covariate.

## Statistical analysis

1. What are the overall global trends of forest loss by fire and non-fire disturbances, protected areas, forest management certification, and forest product commodities?

To answer question 1, we first fitted linear models of overall trends from 2013 to 2023 inclusive of annual canopy forest loss in total (million ha), by non-fire disturbances (million ha), and by fire (million ha); the amounts of protected (million ha), FSC-certified (million ha), and PEFC-certified (million ha) forests globally; the amounts of industrial roundwood and fuelwood production (billion m<sup>3</sup>); and the amount of land as agriculture (million ha).

2. Which countries and subregions contribute most to these trends?

To answer question 2, we provided summary statistics of our spatial analysis, plotting forest loss, protected area, FSC area, PEFC area, industrial roundwood production, fuelwood production, and agricultural area for the top 10-contributing countries, as well as by subregion.

To visualise spatial variation in temporal trends, we fitted beta regression models (glmmTMB, beta family, logit link) with a zero-inflation term (ziformula = ~1) separately for forest canopy loss due to fire non-fire disturbances, and total loss. We modelled each country independently, using Year as the sole predictor to estimate annual trends in proportional canopy loss. We then extracted the estimated coefficients and plotted them on a world map to show the direction and magnitude of temporal change. The general structure of the models was:

$$\text{Forest loss}_{cy} = \beta_0 + \beta_1 Y_y + \epsilon \quad (1)$$

where subscripts *c* and *y* represent country and year, respectively;  $\beta_0$  is the intercept and  $\beta_1$  is the annual change in proportional canopy loss; and  $\epsilon$  is the residual error term.

In parallel, we mapped the spatial distribution of forest protection measures in 2023, including the proportion of forest area formally protected, and the proportions certified under FSC and PEFC

schemes. These maps allowed comparison between recent forest loss trajectories and current protection and forest management certification coverage.

3. Is forest loss less in countries where there is formal forest protection and where forest management certification schemes have been implemented?
4. What other factors are associated with the rate and spatial extent of forest loss?

To answer questions 3 and 4, we conducted a panel data analysis, using generalised linear models<sup>59,60</sup>. To reduce skewness inherent in area-based data and ensure comparability across countries of different sizes, we expressed most variables as proportions relative to total land area (e.g., FSC-certified area per unit land area, forest loss per unit land area). This transformation allowed us to model forest loss independently of country size. We filtered out countries with very low forest extent (<10,000 ha in 2000) to avoid inflating proportional loss estimates from countries with negligible forest area. We also filtered out countries that did not have any FSC- or PEFC-certified forest during the time of the study. This filtering left us with 91 countries to analyse.

To evaluate the influence of forest management certification on forest loss, we analysed annual proportional forest loss due to fire and non-fire disturbance. For each country and year, we calculated fire-related forest loss proportion, and non-fire-related forest loss proportion, each as a fraction of total land area. We focused on lagged predictors for forest management certification variables, under the assumption that forest management certification and socioeconomic variables may affect forest loss in the following year. Specifically, we lagged the following predictors by one year: FSC-certified area, PEFC-certified area, protected forest area, population density, and GDP per capita. We retained other predictors (e.g., forest cover proportion, agricultural land proportion, fuelwood and industrial roundwood extraction) as non-lagged variables, reflecting concurrent land-use and extraction pressures. We scaled all predictors prior to modelling.

We fitted generalised linear models for both response variables using the glmmTMB package<sup>61</sup> in R, assuming a beta family error distribution with a logit link for the proportional response variables and including a zero-inflation term ( $\text{ziformula} = \sim 1$ ) to account for structural zeros in the data. We controlled for unobserved heterogeneity by including country-level fixed effects in all models and country  $\times$  year interactions to absorb country-specific time-varying shocks and mitigate country-time specific biases. The general structure of our model was:

$$\begin{aligned} \text{Forest loss}_{cy} = & \beta_0 + \beta_1 \text{FSC}_{c(y-1)} + \beta_2 \text{PEFC}_{c(y-1)} + \beta_3 \text{PA}_{c(y-1)} \\ & + \beta_4 \text{Forest}_c + \beta_5 Y_y + \beta_6 Y_y^2 + \beta_7 F_{cy} + \beta_8 R_{cy} \\ & + \beta_9 \text{Ag}_{cy} + \beta_{10} \text{GDPP}_{c(y-1)} + \beta_{11} \text{Pop}_{c(y-1)} \\ & + \beta_n \text{Country}_c + \beta_m \text{Country}_c Y_y + \beta_o \text{Country}_c Y_y^2 + \epsilon \end{aligned} \quad (2)$$

where subscripts  $c$  and  $y$  refer to country and year respectively.  $\beta_0$  is the intercept and  $\beta_1$  to  $\beta_o$  are the associated regression coefficients representing the effects of the predictors including FSC proportion in previous year ( $\text{FSC}_{c(y-1)}$ ), PEFC proportion in previous year ( $\text{PEFC}_{c(y-1)}$ ), protected area proportion in previous year ( $\text{PA}_{c(y-1)}$ ), forest land area in 2000 ( $\text{Forest}_c$ ), year ( $Y_y$ ), quadratic term of year ( $Y_y^2$ ), fuelwood production density ( $F_{cy}$ ), industrial roundwood production density ( $R_{cy}$ ), agricultural land proportion ( $\text{Ag}_{cy}$ ), gross domestic product per person in previous year ( $\text{GDPP}_{c(y-1)}$ ), population density in previous year ( $\text{Pop}_{c(y-1)}$ ), and the fixed factor variables for country ( $\text{Country}_c$ ) and their interactions with time ( $\text{Country}_c Y_y + \text{Country}_c Y_y^2$ ).

To test whether the effects of forest management certification and protected areas on forest loss were moderated by economic, land-use, or demographic context, we conducted a series of heterogeneity analyses using interaction terms. Specifically, we fitted additional models that included

two-way interactions between each of the certification/protection variables (FSC-certified area, PEFC-certified area, and protected forest area) and potential moderating variables: GDP per capita, forest proportion, agricultural land proportion, industrial roundwood production density, fuelwood production density, and population density. For each moderating variable, we fitted separate models for fire-related and non-fire-related forest loss, retaining the same fixed-effects structure as the main models (country fixed effects and country  $\times$  year interactions). We interpreted significant negative interactions as evidence that certification or protection was more effective at reducing forest loss in countries with higher values of the moderating variable, and significant positive interactions as evidence that certification or protection was less effective in such contexts.

## Data availability

All data and code are available at <https://doi.org/10.6084/m9.figshare.31225177>.

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## Author contributions

C.T. contributed equally to conceptualisation, data curation, formal analysis, methodology, and writing—review & editing. M.J.E. and C.T. contributed equally to formal analysis, methodology, writing—review & editing. D.B.L. led the writing—original draft, and funding acquisition, and contributed equally to conceptualisation, methodology, and writing—review & editing.

## Competing interests

The authors declare no competing interests.

## Additional information

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