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Substantial and increasing global losses of timber-producing forest due to wildfires

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One-third of global forest is harvested for timber, generating ~US$1.5 trillion annually. High-severity wildfires threaten this timber production. Here we combine global maps of logging activity and stand-replacing wildfires to assess how much timber-producing forest has been lost to wildfire this century, and quantify spatio-temporal changes in annual area lost. Between 2001 and 2021, 18.5–24.7 million hectares of timber-producing forest—an area the size of Great Britain—experienced stand-replacing wildfires, with extensive burning in the western USA and Canada, Siberian Russia, Brazil and Australia. Annual burned area increased significantly throughout the twenty-first century, pointing to substantial wildfire-driven timber losses under increasingly severe climate change. To meet future timber demand, producers must adopt new management strategies and emerging technologies to combat the increasing threat of wildfires.

Timber is a globally important natural resource used for construction materials, paper and energy. In 2015, the forestry sector contributed over US$1.5 trillion to national economies[1], and in 2020 at least one-third of all forest globally was being used for timber production[2]. Timber demand is expected to almost triple by 2050[3], via greater human demand and population growth, increasing urbanization, and as net-zero climate targets promote the replacement of carbon-intensive building materials, such as concrete and steel, with wood[4]. Ensuring that timber supply can meet future demand is therefore a key challenge in the twenty-first century.

Wildfires are a natural ecological process in many ecosystems. However, forest wildfires and associated forest loss have been increasing throughout the twenty-first century[5–7], with >110 million hectares (Mha) of forest lost to wildfires between 2001 and 2019[7]. Fire season length and fire extent are expected to increase significantly by 2100 because of climate change[8,9], placing forests under increasing threat of high-severity burning. Given the long-term nature of timber production, typically on 40–100+ year cutting cycles[10,11], future crops of timber trees will face a very different climate as they mature towards harvest.

We currently lack a robust understanding of how wildfires have influenced global timber production. High-severity, stand-replacing wildfires represent a large threat to timber stocks within forests managed for wood production[12], and the increasing frequency of such wildfires in the twenty-first century is a serious concern. Understanding where fire-induced losses of timber-producing forests occur and at what rate is therefore of critical importance in initiating efforts to ensure that timber production, and associated trade and financial investment, can be maintained in a more climatically hostile future. Here we combine spatial data detailing the global extent of forestry practices[6,13] with annual layers of forest loss due to wildfire[7] to conduct a global assessment of the threat of wildfire to timber production. We answer the following key questions: (1) how much timber-producing forest is being lost to stand-replacing wildfires globally, and where do these losses occur? and (2) what are the temporal trends in annual burned area of timber-producing forests since the turn of the century, at global, regional and national scales?

Wildfire impacts on the timber industry in the twenty-first century

To understand where timber-producing forests are burning, we used two datasets that map global logging activity from Lesiv et al.[13] and Curtis et al.[6], focusing primarily on clearcut logging of native forest and timber plantations. We overlaid these logging layers with global data on stand-replacing wildfires[7], where fire severity was high enough

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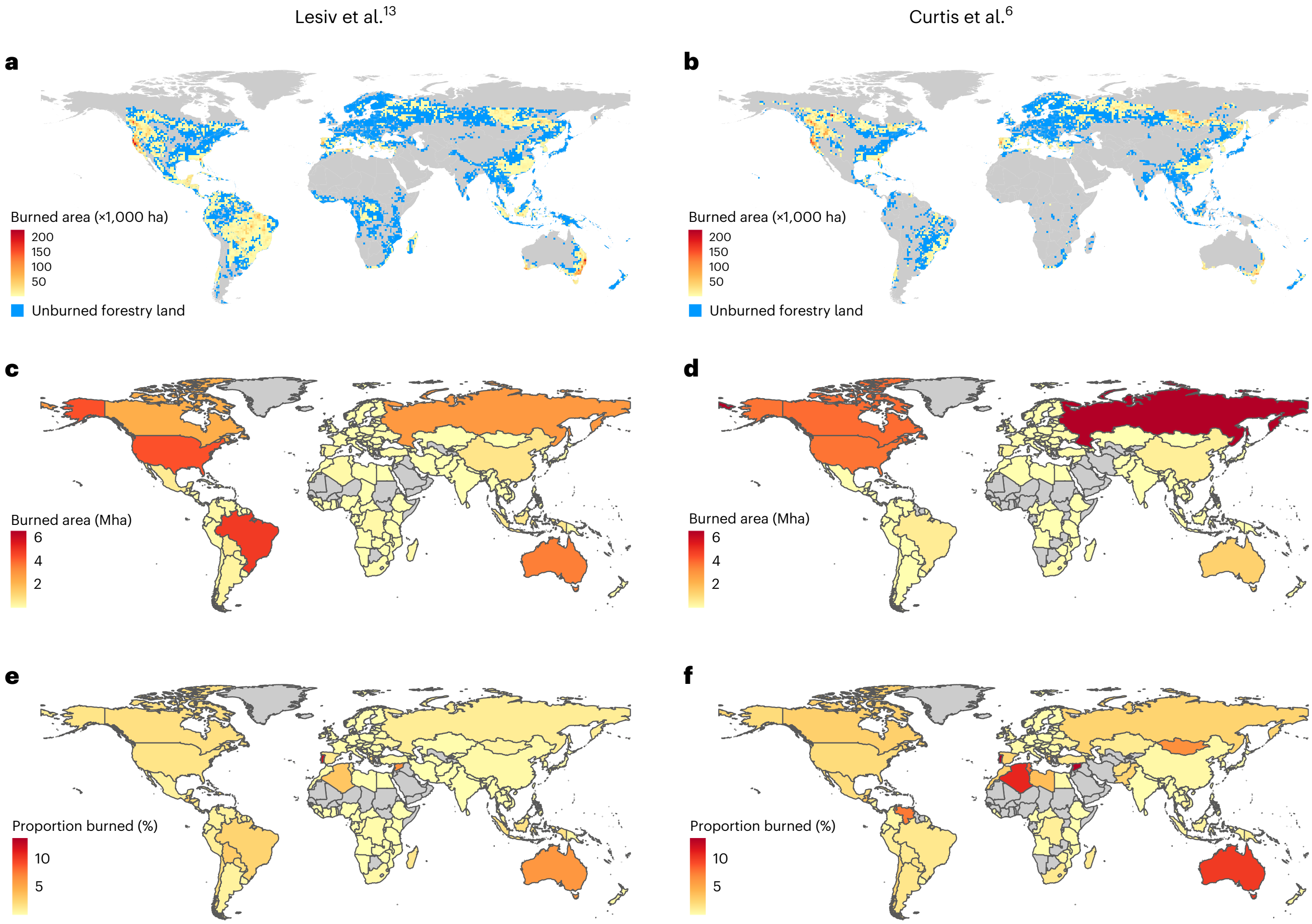

Fig. 1 | Global patterns of timber-producing forest loss through stand-replacing wildfires. a–f, Hotspots of severe burning in timber-producing forests (**a**,**b**), total area (**c**,**d**) and proportion (**e**,**f**) of forestry land severely burned nationally between 2001 and 2021, using the map of global forest management (**a**,**c**,**e**) by Lesiv et al.[13] and the map of forest loss due to forestry (**b**,**d**,**f**) by Curtis et al.[6]. In **a** and **b**, areas of warmer red represent increasing burn, blue represents areas where logging occurs but wildfires did not or were limited (<1,000 ha per cell) and grey represents areas where logging is not prevalent. The western USA and Canada, northeastern Russia, southeastern Australia and Brazil suffered particularly high losses of timber-producing forest to wildfire, while much of Central and northern Europe, and parts of South Asia and sub-Saharan Africa, experienced limited wildfire-induced losses.

to cause a detectable loss of tree cover, and thus timber (see Methods), and present the results from both layers together.

Since 2001, between 18.5 (s.e.m. 16.5–20.7) and 24.7 Mha (21.8–27.5) of timber-producing forest—an area roughly the size of Great Britain—has been lost due to wildfires (Fig. 1). This equates to between 1.0% (0.9–1.1%) and 1.7% (1.5–1.9%) of global forestry land burned since the turn of the century. Across both logging layers, fire-induced loss of timber-producing forest was particularly high in the northwestern USA and Canada, northeastern Russia, southeastern Australia and Brazil (Fig. 1a,b). Central and northern Europe experienced limited losses, as did parts of southern Asia and sub-Saharan Africa (see Extended Data Fig. 1 for a more spatially detailed map).

At the national scale, the three countries with the largest absolute wildfire-induced losses of timber-producing forest were Russia, the USA and Canada, where between 2.9 (2.6–3.4) Mha and 6.5 (5.8–7.2) Mha, 3.8 (3.4–4.1) Mha and 4.3 (3.9–4.8) Mha, and 2.3 (2.2–2.5) Mha and 3.9 (3.7–4.1) Mha were lost, respectively (Fig. 1c,d). This accounts for 1.1% (0.9–1.2%) to 2.6% (2.3–2.9%), 1.6% (1.4–1.7%) to 2.1% (1.9–2.3%) and 1.8% (1.7–2.0%) to 2.8% (2.7–3.0%) of their total national timber-producing forest, respectively. Portugal and Australia were characterized by the highest percentage of their forestry land lost, with 12.5% (11.1–14.0%) to 13.6% (12.1–15.2%) and 6.2% (5.9–6.5) to 10.1% (9.4–10.6%) burning, respectively (Fig. 1e,f). Such high losses of timber stock will leave a shortfall in internal timber supply, threatening timber-related jobs and probably forcing increased reliance on imports or shifts to faster wood production through plantations[14].

While reliable burn data are available since only the turn of the century, timber rotation times across the globe (and especially in much of the Northern Hemisphere) are often far longer than 21 years, indicating even greater timber losses across a whole rotation cycle. For example, rotation times in the boreal forests of Russia and Canada can be ~100 years[11], meaning fire-induced losses of timber forests could reach 5.1–12.3% and 8.7–13.5%, respectively, across one rotation cycle under current burn conditions. Similarly, losses in the areas of the USA that employ rotations of 80 years (for example, the northwest[15]) could reach 6–8% across a harvest cycle.

Most logging globally entails clearcutting of native forest and timber plantations[2], which is captured well by both logging layers used (see Extended Data Fig. 2 for a spatial comparison of the two). Additionally, Lesiv et al.[13] attempted to include selectively logged forest within their forest management map. Using this layer, we identified large areas of burned timber-producing forest across the tropics (~8.1 Mha; 7.0–9.1 Mha), particularly in Latin America (~6.8 Mha; 6.0–7.5 Mha). However, selective logging is far more difficult to detect via satellites than clearcutting or plantation forestry[16], so these results should be interpreted with caution.

While we find a concerningly large area of timber-producing forest has already been lost to wildfire this century (18.5–24.7 Mha), there are limitations in the available forest management data that will affect these results. Curtis et al.[6] had levels of high accuracy for mapped forestry areas (users: 87%; producers: 91%), but sample-based estimates suggest they slightly overestimated total forestry area. Conversely, the accuracy of the timber-producing forest classes mapped by Lesiv et al.[13] were lower (users: 58–71%; producers: 35–65%), and sample-based estimates conducted by the authors suggest that forestry areas were underestimated. A third product (Schulze et al.[17]) also maps patterns of forest use globally, but is based on Food and Agriculture Organization of the United Nations (FAO) data, where national self-reporting is inconsistent and forest-use classes do not allow for accurate spatial classification of all timber-producing forest. Nevertheless, global hotspots of timber-producing forest loss through wildfire identified using Lesiv et al.[13] and Curtis et al.[6] remain largely the same when using Schulze et al.[17] (Supplementary Information and Extended Data Fig. 3).

Increasing annual timber losses due to wildfire

Globally, the annual area of timber-producing forest lost to stand-replacing wildfires showed an increasing trend between 2001 and 2021 using both Lesiv et al.[13] (Mann–Kendall test, $P = 0.0008$, Sen's slope annual trend size = +68,400 ha yr^{-1}) and Curtis et al.[6] ($P = 0.02$, annual trend size = +37,800 ha yr^{-1}) forest management data, with strong correlation between the two layers in annual burned area ($r = 0.83$). In the past six years, mean annual loss from severe fire was 1.3–2.5 Mha, which is 2–4 times greater than in the previous 15 years (Fig. 2; see Extended Data Fig. 4 for raw data results). This increasing trend post-2015 is much sharper when using the Lesiv et al.[13] forest management dataset, which is probably due to a combination of widespread fires in Latin America after a strong El Ñino in 2015–2016 that were not identified in the Curtis et al.[6] layer, and possible under-reporting of burned timber production forest prior to 2014 in the Lesiv et al.[13] layer (Supplementary Information).

Changes to the forest-loss detection model employed by Global Forest Watch[18] that underpin the fire data used[7] have improved forest-loss detection in recent years, but we do not believe this impacts our observed increasing trends. First, the fire data our study employs[7] show no post-2015 spike in forest loss, which has been previously implicated as a clear signal of temporal inconsistencies in loss detection[19,20]. Second, the fire data uses v1.7 of the forest-loss data, where loss detection algorithms are consistent between 2011 and 2020. We find no sudden jump in the years after 2010, and while the introduction of the Landsat 8 Operational Land Imager imagery in 2013 may have improved detection rates, we still find increasing trends in annual forestry burned area when considering only the years 2013–2021 (Lesiv et al.[13]: $P = 0.029$, annual trend size = +237,000 ha yr^{-1}; Curtis et al.[6]: $P = 0.076$, annual trend size = +85,000 ha yr^{-1}). Finally, Tyukavina et al.[7] tested their fire data against another dataset that applied the newest forest-loss detection algorithms consistently across the whole period back to 2001, and found both methods demonstrated the same temporal trends[7]. This suggests algorithm inconsistencies between the 2001–2010 and 2011–2021 periods has little impact on observed trends in annual forest loss due to wildfires in the twenty-first century.

We found an increasing trend in annual wildfire-induced loss of timber-producing forest across all regions globally (Mann–Kendall test, $P \leq 0.05$), except for Eurasia, which exhibited no trend (Fig. 2; see Extended Data Fig. 5 for free-scaled bar chart of regional annual burn). North America and Eurasia, the two largest timber-producing regions globally[21], both exhibited the largest total losses across the period, between 6.6 (6.1–7.2) Mha and 7.6 (7.1–8.3) Mha, and 5.8 (4.7–7.1) Mha and 8.6 (7.4–9.9) Mha, respectively. Europe has suffered several major heatwaves and droughts across our study period (for example, in 2003, 2010 and 2017[22]), and has experienced strong increasing trends in heatwave frequency and intensity[23]. Nevertheless, this is not reflected in Eurasia's annual fire-induced loss of timber-producing forest, which remained stable across the period (Fig. 2). Similarly, droughts and heatwaves have become prominent in North America (particularly the extreme heatwave of 2021[24]), and burned area in the western USA and Canada has been steadily increasing across recent decades[12]. Unlike Eurasia, annual wildfire-induced losses of timber-producing forest in North America are increasing and were particularly high in the years 2016–2021, equating to a two- to fourfold increase relative to 2001–2015.

Latin America exhibited losses of between 0.8 (0.7–1.0) Mha and 7.9 (6.9–8.7) Mha, with a sharp increase in 2016–2017 after a strong El Ñino event in 2015–2016[25]. Australia and Oceania lost between 1.3 (1.2–1.4) Mha and 3.6 (3.4–3.7) Mha, the bulk of which occurred in 2019–2020, due to unprecedented wildfires across Australia[26], following years of drought[27]. Africa was characterized by a significant increasing trend in annual timber-producing forest lost due to fire, but total losses remained low compared with other regions at 0.1–0.8 Mha.

Increasing burning trends at global and regional scales suggest that the threat of wildfires to timber production will be exacerbated under future climate change. Wildfires are expected to become more frequent and severe across many regions[12], with regional models supporting increased fire activity in important timber-producing areas such as the western USA[28], Canada[29], boreal Russia[30], the Amazon[31] and Australia[32].

Three of the five largest timber-producing nations— the USA, Canada and Brazil, who together accounted for 33% of industrial roundwood production in 2021[21]— exhibited increasing trends in their annual area of timber-producing forest burned in at least one mapped product (Fig. 3). Increasing trends were also evident in many Latin American countries, Portugal, Italy, Ukraine, Australia, New Zealand, South Africa, Ethiopia, Kenya and Vietnam (Fig. 3).

There was some variation between mapped products in national level patterns. Canada showed a significant increasing trend using Curtis et al.[6], but no change over time with Lesiv et al.[13]. This result was possibly owing to Curtis et al.[6] mapping more logging activity in the fire-prone areas of western Canada[33]. In addition, many countries in sub-Saharan Africa and Latin America revealed an increasing burn trend using Lesiv et al.[13] but not Curtis et al.[6], probably because Curtis et al. mapped limited forestry activity in these areas due to the dominance of forest loss through shifting agriculture and commodity production[6]. Only a small number of countries, including Japan and the UK, were characterized by a decreasing trend across our study duration (Fig. 3a,b). In combination, therefore, countries showing a significant increasing trend in annual losses of timber-producing forest through stand-replacing wildfires together account for ~43–50% of global industrial roundwood production, whereas those that showed a decreasing trend accounted for only ~2–6%[21].

Improving management under increased fire risk

Stand-replacing wildfires have caused major losses of forest used for timber production, with an increasing trend in annual burned area between 2001 and 2021. Based on FAO data[21], these findings point to an estimated wildfire-induced loss of ~393–667 million m^3 of industrial roundwood timber across the period, which if exported at the 2021 global mean export price of US$115 per m^3, would be worth ~US$45–77 billion. Some burned timber may be harvested in post-fire 'salvage' logging operations. However, such wood is often of low quality, while salvage logging has strong negative environmental impacts[34,35] and can increase the likelihood of future forest disturbances[36].

Greater frequency and severity of wildfires under climate change[12] indicates that threats to global wood production will increase. Overlapping current timber production areas[6,13] with future fire prediction maps[8] suggests that ~29–62% of current production forest will

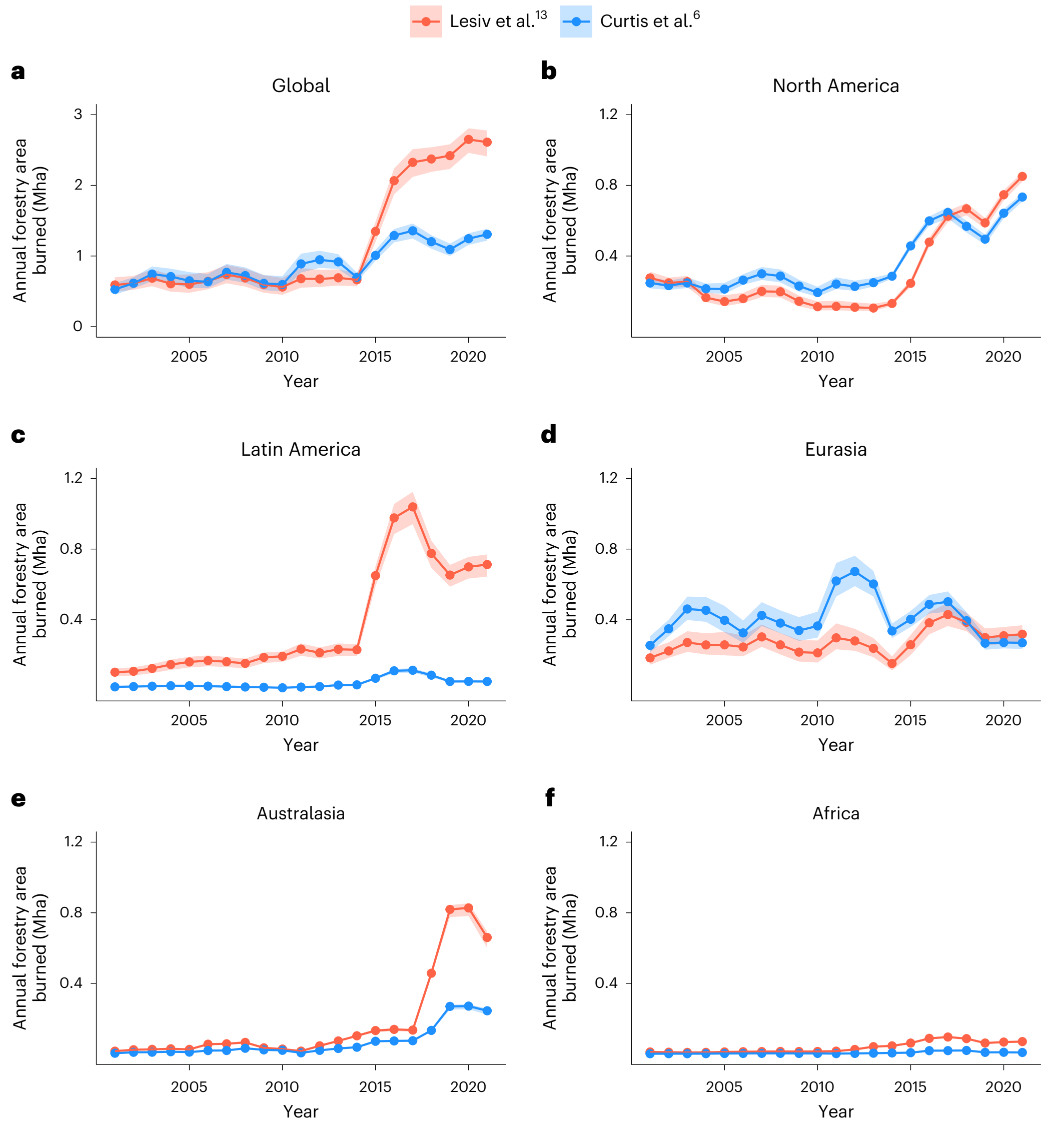

Fig. 2 | Global and regional three-year average annual area of timber-producing forest lost to wildfires in 2001–2021. a–f, Using the map of global forest management (red) by Lesiv et al.[13] and the map of forest loss due to forestry (blue) by Curtis et al.[6], split by global region: Global (**a**), North America (**b**), Latin America (**c**), Eurasia (**d**), Australasia (**e**) and Africa (**f**). Significant increasing trends in annual area of timber-producing forest burned are present globally and for all regions except Eurasia. Lines represent three-year rolling average, shaded areas represent three-year rolling average ± 1 s.e.m. Annual strength of trend from Sen's slope analysis and *P* value from two-sided Mann–Kendall test are as follows: Lesiv et al.[13] (Global: +68,000 ha yr^{-1}, $P = 0.0008$; North America: +18,500 ha yr^{-1}, $P = 0.05$; Latin America: +21,500 ha yr^{-1}, $P = 6.8 \times 10^{-6}$; Eurasia: no trend, $P = 0.22$; Australasia: +7000 ha yr^{-1}, $P = 0.0003$; Africa: +3500 ha yr^{-1}, $P = 2.9 \times 10^{-6}$); Curtis et al.[6] (Global: +38,000 ha yr^{-1}, $P = 0.002$; North America: +18,000 ha yr^{-1}, $P = 0.002$; Latin America: +1700 ha yr^{-1}, $P = 0.003$; Eurasia: no trend, $P = 0.83$; Australasia: +2700 ha yr^{-1}, $P = 0.001$; Africa: +450 ha yr^{-1}, $P = 1.2 \times 10^{-5}$).

experience an increase in fire-prone years, and ~44–80% will be subject to longer fire seasons by 2100. To ensure increasing timber demand is met[3], timber producers need to minimize the risk of fire to future timber crops today, via better selection of crop species, improved spatial planning, and adoption of new technologies for fire detection and suppression.

Plantations produce ~33% of global industrial roundwood[37] on ~3% of forest area[2] and this will probably increase as fast-growing timber is needed to meet rising demand[3], and regions move away from clearcut harvesting of natural forests[38]. Expanding production through plantations will decrease the risk of fire-induced timber losses, as harvest rotations are typically far shorter, providing a greater chance of producing a crop before it is lost to fire. Where possible, fast-growing timber species should be introduced in plantations, sparing large tracts of old-growth forest elsewhere to support biodiversity and carbon stocks[39,40]. However, timber plantations are highly flammable[41]. Shifting production in fire-prone regions from monocultures of highly flammable timber species (for example *Pinus radiata*[41], *Eucalyptus globulus*[42]) towards heterogenous mosaics of less-flammable species of varying ages will be vital in reducing timber losses through burning[43].

Improved spatial planning of forestry activities can reduce wildfire risk to timber. At the global scale, establishment of plantations in areas of high wildfire risk should be avoided in favour of regions less likely to burn. One concerning example is the recent rapid expansion of highly flammable *Eucalyptus* plantations in the Brazilian Cerrado[44], despite globally high wildfire prevalence in this region[5]. At a landscape scale, establishment of plantations on slopes, where fires burn more severely and spread rapidly, should be prevented[45]. Spatial contagion in fire can be reduced by avoiding large areas of contiguous plantations, with more 'fragmented' timber plantations interspersed with less flammable land-use types (for example, grazing lands) and 'green' firebreaks[38].

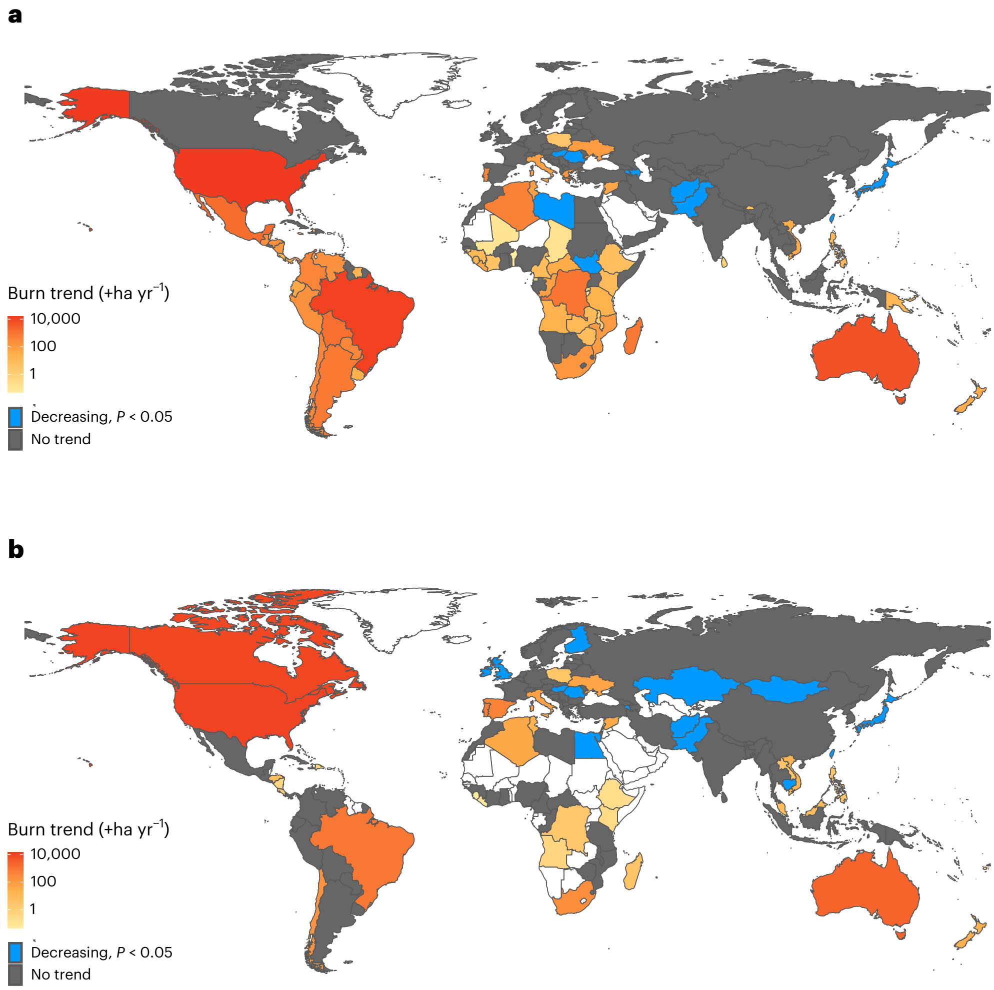

Fig. 3 | National trend in timber-producing forest lost due to wildfire annually between 2001 and 2021. a,**b**, Using the map of global forest management (**a**) by Lesiv et al.[13] and the map of forest loss due to forestry (**b**) by Curtis et al.[6]. Countries in orange–red demonstrated significant increasing trends in annual loss to wildfire (two-sided Mann–Kendall test, $P < 0.05$), with the scale representing the median slope of the trend across the period (in hectares burned per year). Countries in blue showed significant decreasing trends (two-sided Mann–Kendall test, $P < 0.05$, up to a maximum slope of -650 ha yr^{-1} in China). Dark grey represents countries with no significant trend in annual burned area across the time period, while countries shown in white have either limited mapped logging activity or forest-loss-inducing wildfires. Strong increasing trends are present in the USA, Brazil and Canada (using Curtis et al.[6]), as well as Australia and many Latin American countries.

The timber industry must also adopt emerging technologies to reduce the impact of wildfires where they occur. Improved modelling techniques allow for more accurate spatial prediction of fire ignitions[46], while adoption of infrared-sensing drones and on-the-ground camera networks could allow for swift, 24-hour detections[38]. Once detected, autonomous 'water gliders' could follow GPS signals to carry water or flame retardants to the ignition source and extinguish the fire before it has time to expand[38]. In areas that do burn, locally effective post-fire management practices will be required, as salvage logging and replanting post-fire can lead to more severe burning in the future[43,47].

Failure to adopt approaches such as those outlined above could lead to massive future timber losses, with falling timber supply driving higher prices. Concerningly, higher timber prices will increase the opportunity costs of conservation in tropical forests, especially in the Amazon and Congo Basin, making intensive selective logging economically attractive. Such economic feedbacks could make carbon-market payments prohibitively expensive[48], undermining global climate and biodiversity goals. We must urgently tackle the emerging timber production crisis to meet humanity's needs and prevent severe unintended environmental feedbacks.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-023-01323-y.

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Methods

To determine how much timber has already been lost to wildfires in recent years, we overlaid spatial data detailing the global extent of forestry practices[6,13] with annual layers of forest loss due to wildfire from 2001 to 2021[7]. For a summary of the different datasets used within the study, see Extended Data Table 1.

Logging layers

To understand where timber production occurs globally, we used the best available datasets that attempt to map global timber harvesting activity:

Global map of forest management. Lesiv et al.[13] used GeoWiki and classification algorithms to produce a global map of forest management type at 100 m spatial resolution. To make the classification, GeoWiki users and experts were asked to classify satellite images into different forest management types at 226,000 different points, before the outputs were then used to train classification algorithms to classify all areas of forest, using PROBA-V satellite imagery from the period 2014–2016. Multiple forest management types were included within the map, but to represent possible timber-producing forest, we included only the following three management classes: (1) naturally regenerating forest with signs of management, for example, logging, clear cuts and so on; (2) planted forests (rotation >15 years); and (3) plantation forests (rotation ≤15 years), covering a total of >2.4 billion ha of logged forest and timber plantations (see ref. 13 for full definitions). We also performed precautionary re-analyses, whereby we excluded both 'planted forests' and 'plantation forests' from the analysis. Results showed broadly the same patterns and are displayed in Extended Data Table 2.

Global map of forestry as the dominant driver of forest cover loss. This map from Curtis et al.[6] used satellite data and machine learning to classify the most dominant driver of forest loss between 2001 and 2019 at a spatial resolution of 10 km. Drivers were attributed as one of the following: urbanization, commodity-driven deforestation (for example, palm oil, soy), shifting agriculture, wildfire or forestry. We included all areas mapped as forestry in our analysis using this layer, which covered a total of ~1.6 billion ha of logged forest. Owing to the coarse spatial resolution of this layer, we applied a mask of forest cover in the year 2000[49], including only areas that had >10% tree cover (following the FAO definition of forest and the threshold used in Lesiv et al.[13]). This left a mapped area of 1.08 billion ha of clearcut logged forest and plantation area.

Global map of forest use. This third dataset, from Schulze et al.[17], was considered but not included in the main analysis. This map used national and sub-national forest management data and classification models trained with predictor variables to identify types of forest use globally at a 1 km resolution for the year 2000. However, the FAO's Forest Resources Assessment data used in this study are inconsistent between countries (which self-report their national statistics to the FAO) and the prevalence of the 'mixed use' forest class does not allow for accurate classification of all timber-producing forest globally. In addition, we identified multiple regions where timber production classification is inaccurate and large areas of logging concessions and plantations are not included within the map (for example, southeastern Australia[49]). The results from our analysis using this layer should thus be interpreted with caution, and are not included within the main text, but can be found in Extended Data Fig. 3. Owing to the coarse resolution of the map, we again applied a mask of forest cover for the year 2000[18], including only areas that had >10% tree cover (following the FAO definition of forest). Forest-use patterns are grouped into four different classes: production, mixed use, other and unknown. The FAO defined 'production' forest as "forest where the management objective is production of wood, fibre, bio-energy and/or non-wood forest products", while 'mixed use' is defined as "forest where the management objective is a combination of several purposes and where none of them is significantly more important than the other". For the analysis, we assumed 'production' forest to represent timber-producing forest. We also included 'multiple use' forest in our analysis. While 'multiple use' forest may not necessarily be used specifically for timber production, we included this management class as local forest definitions meant that many large timber-producing countries (for example, Canada, Australia, Germany) had limited to no mapped 'production' forest.

Fire layer

As our primary interest was in large, stand-replacing fires that deplete an area of forest of its timber stock, we used recent map layers describing stand-replacing wildfires[7], where fire severity was high enough to cause forest loss (defined as "the removal of woody vegetation exceeding 5 m in height"[7]). This layer is an extension of the work by Curtis et al.[6] and uses Hansen et al.[18] Landsat-based forest loss data and machine learning to identify whether wildfire or an alternative driver caused a forest loss event in the years 2001–2021, at a 30 m resolution. Classification models were trained on visually collected data, with separate models developed for five global regions (North America, Latin America, Africa, northern Eurasia, and combined South and Southeast Asia, Australia and Oceania). We elected not to implement the widely used MODIS Burned Area dataset[50] as our measure of fire activity, as these data map burned area without differentiating between stand-replacing fires and low-severity burns. Across many regions, low-severity burns may not cause enough damage to trees to render the majority of their timber unusable, so we focused on high-severity fires that would do so. In producing their map of wildfire-induced forest loss, Tyukavina et al.[7] undertook a sample-based area estimate and ensured the final map matched the sample-based area estimate for all global regions (except Africa) as well as providing maps containing the estimate ± s.e.m. This allows for estimation of burned area in timber-producing forests that matches sample-based area estimates, as well as inclusion of uncertainty through estimates of burn area ± s.e.m. for all regions except Africa.

Economic cost analyses of high-severity stand-replacing wildfires on timber-producing forests reveal extreme loss of timber stock and economic value. For example, severe wildfires in the Rocky Mountains in 2000 resulted in the burning of ~7 million m^3 of timber, of which <5% was salvaged[51]. Similarly, two wildfire events in southeastern Australia (2003 and 2006/2007) resulted in >AU$2 billion worth of lost timber, with salvage operations occurring across <4% of burned native forest[52]. In Russia, assessment of forests post-wildfire found that crown fires had dominated the burning, often resulting in total tree mortality[53]. Given the substantial environmental damage caused by salvage logging[34,35], and associated price depression when poor-quality salvaged timber floods the market[51], we assumed that the stand-replacing wildfires mapped in Tyukavina et al.[7] result in near-total loss of harvestable timber stock and economic value.

Data analysis

We completed all spatial data operations and analysis using R version 4.2.1. We downloaded the global map of forest management from Lesiv et al.[13] (https://doi.org/10.5281/zenodo.5879022), the global map of forest-loss by driver (Curtis et al.[6]) through the Global Forest Watch website (https://www.globalforestwatch.org/map/) and the global map of forest loss through wildfire from Tyukavina et al.[7] (https://glad.umd.edu/dataset/Fire_GFL/). We downloaded the global map of tree cover in 2000[18] through Google Earth Engine and reprojected to a 100 m resolution to match the highest resolution available for our logging data. We projected all spatial data in EPSG:4326 (WGS84) CRS and projected into ESRI:54009 where area calculations or intersections were computed. We used the following R packages: raster (v. 3.5.29)[54], sf

(v. 1.0.8)[55], terra (v. 1.6.7)[56], rnaturalearth (v. 0.1.0)[57], Kendall (v. 2.2.1)[58] and trend (v. 1.1.5)[59].

We divided the world into five regions (North America, Latin America, Eurasia, Africa, and Southeast Asia and Australasia), following the regional models of fire-induced forest loss used by Tyukavina et al.[7] For each region, we created a network of grid cells 0.25° in size for increased computational efficiency.

For each grid, we cropped the logging and fire raster data by the spatial extent of the grid using the terra package, and converted the resulting objects into simple features polygons using the sf package. For the Curtis et al.[6] logging layer, we then applied a forest mask using global forest cover for 2000[18], and retained only areas of timber-producing forest where tree cover was >10% (following the FAO definition of forest and the same masking threshold used by Lesiv et al.[13] when creating their map). We aggregated the total area of timber-producing forest in each grid to estimate the total global area of forest being used for timber production in each logging layer (Lesiv et al.[13]: 2.4 billion ha; Curtis et al.[6]: 1.08 billion ha).

Using the sf package, we calculated the total timber-producing forest present in each grid cell (for each logging layer used), as well as the intersection of timber-producing forest with wildfire-induced forest loss in each year of the time series. We then recorded the spatial extent of forest-loss-inducing fires for each year in timber-producing forests within the grid. We repeated this process using different combinations of pixel certainty in the Tyukavina et al.[7] dataset to also produce uncertainty estimates representing ± s.e.m.

Quantifying the spatial extent of wildfire-induced losses of timber-producing forest

We aggregated total burned area and total timber production area globally, regionally and nationally to create estimates of the global, regional and national area of timber-producing forest burned during our study period. For national level analysis, we used the R package rnaturalearth for country boundaries to determine the total area and proportion of timber production forest burned on a national scale. We calculated total area burned in square metres before conversion to hectares. For estimates of the proportion of timber-producing forest burned, we divided the total burned area of timber-producing forest across all years by the total area of timber-producing forest estimated from each logging dataset.

Temporal trends in annual burned area of timber-producing forests at various scales

We aggregated the total area of timber-producing forest burned by year of burn, to create an estimate of the annual burn area across the time period at global, regional and national scales (2001–2021). To estimate the trend in annual burn area, we used a Mann–Kendall test for monotonic trend in a time series from the Kendall package on the raw data and report these results. To estimate the size of the trend, we conducted a Sen's slope analysis using the trend package.

Data availability

All data originally used in this study are publicly available online: Tyukavina et al.[7] fire data (https://glad.umd.edu/dataset/Fire_GFL/), Curtis et al.[6] forestry data (https://data.globalforestwatch.org/documents/tree-cover-loss-by-dominant-driver/about), Lesiv et al.[13] forest management data (https://zenodo.org/record/5879022#.ZCa9IXbMKUk) and Hansen et al.[49] forest cover data (https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.7.html).

Code availability

The code used to generate the results is freely accessible and available at https://github.com/cbousfield/Bousfield_et_al_2023_Timber_losses_through_wildfire.git.

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Author contributions

C.G.B., D.B.L. and D.P.E. conceived the study and developed the methodology. C.G.B. performed the analysis and drafted the original paper. All authors contributed to reviewing and editing the paper.

Competing interests

The authors declare no competing interests.

Additional information

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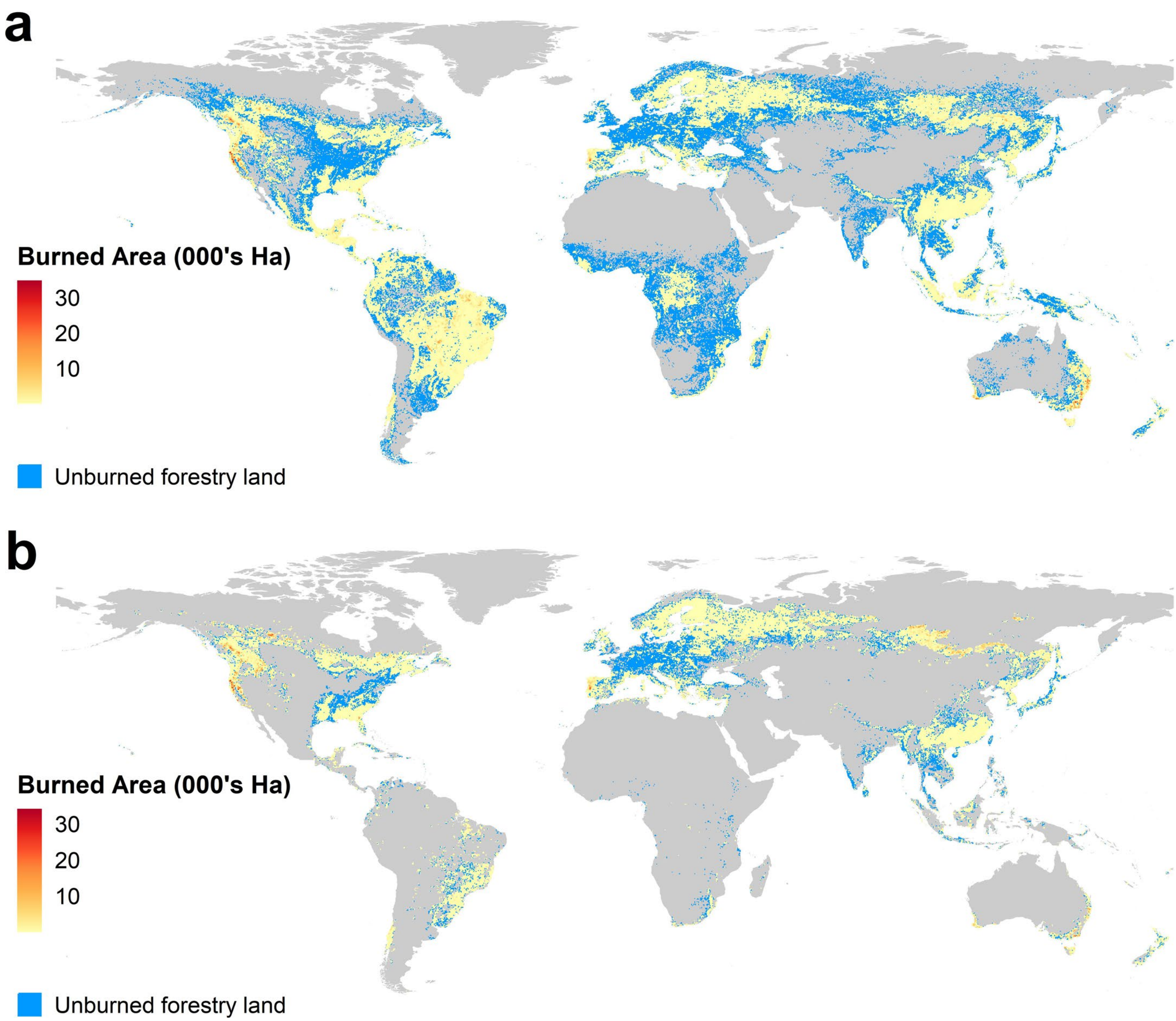

Extended Data Fig. 1 | Spatially explicit global map of timber-producing forest burned in each grid cell (000's Ha) between 2001–2021 at a spatial resolution of 0.25 degrees. Using Lesiv et al. forest management map (a) and Curtis et al. map of forestry as the dominant driver of forest loss (b). Areas of warmer red represent increasing burn, blue represents areas where logging occurs but wildfire did not, grey represent areas where logging is not prevalent.

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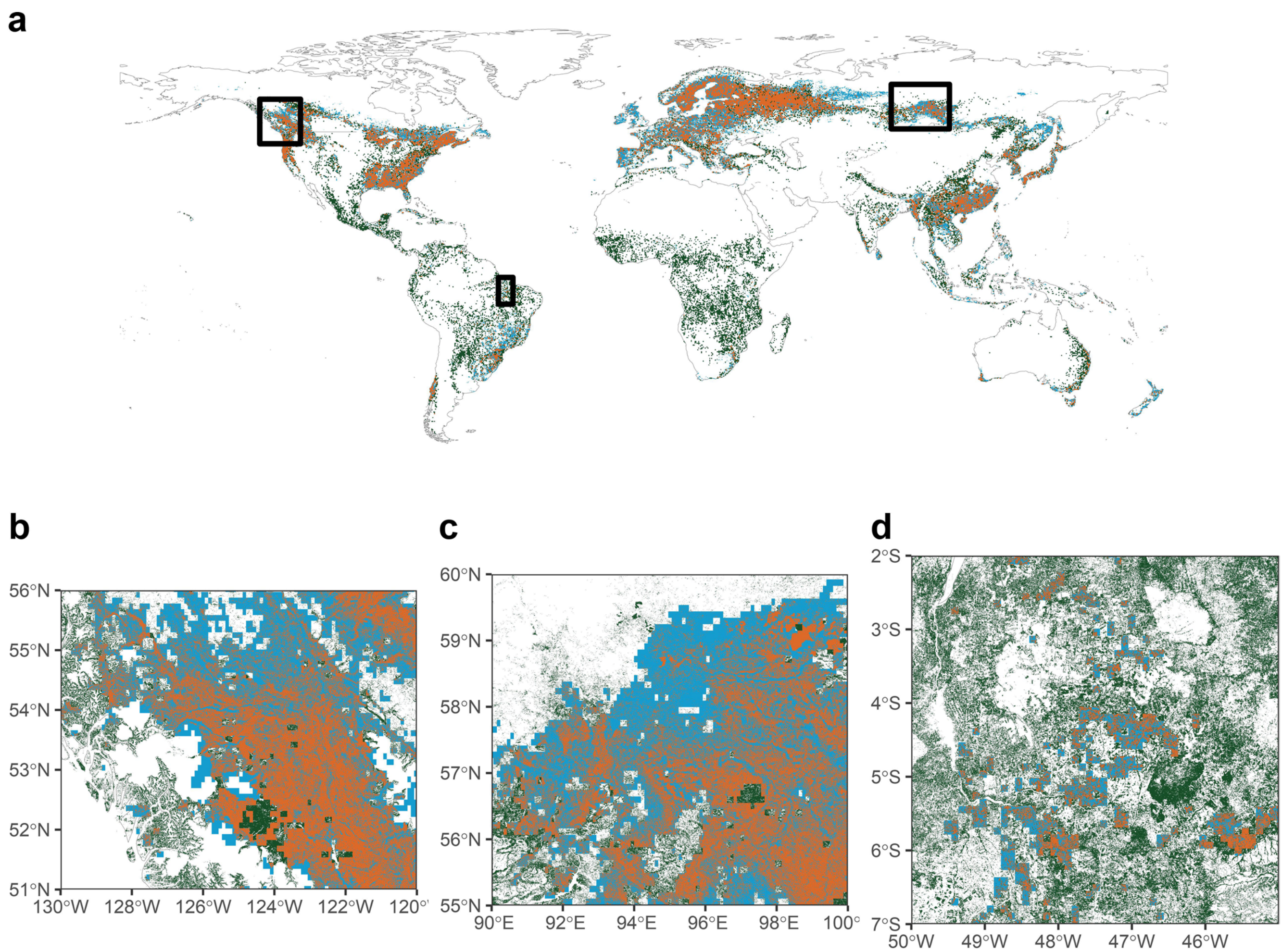

Extended Data Fig. 2 | Global comparison of forestry layers used in this study. Areas coloured in green represent forestry activity unique to Lesiv et al., areas in blue represent forestry activity unique to Curtis et al., whereas areas in orange represent forestry activity mapped by both layers (a). Zoom in insets show differences in greater detail for burning hotspots in the US/Canada (b), Russia (c) and Brazil (d).

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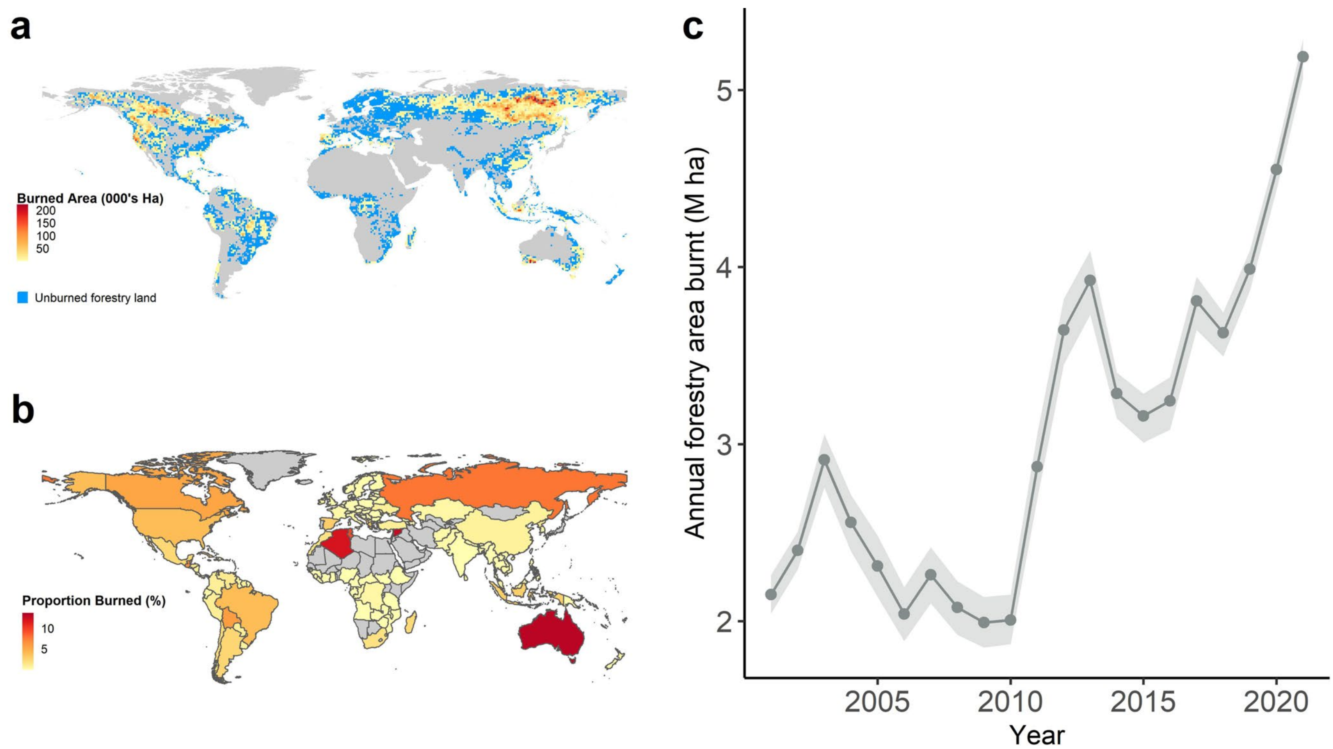

Extended Data Fig. 3 | Global patterns of timber-producing forest loss through stand replacing wildfires. Using Schulze et al. global map of forest management patterns. Hotspots of severe burning in timber-producing forests (a), proportion of forestry land severely burned nationally (b), and three-year average annual area of timber-producing forest burned in wildfires globally (c). Areas of warmer red represent increasing burn, blue represents areas where logging occurs but wildfire did not, grey represent areas where logging is not prevalent. Lines represent three-year rolling average, shaded areas represent three-year rolling average ± 1 SE.

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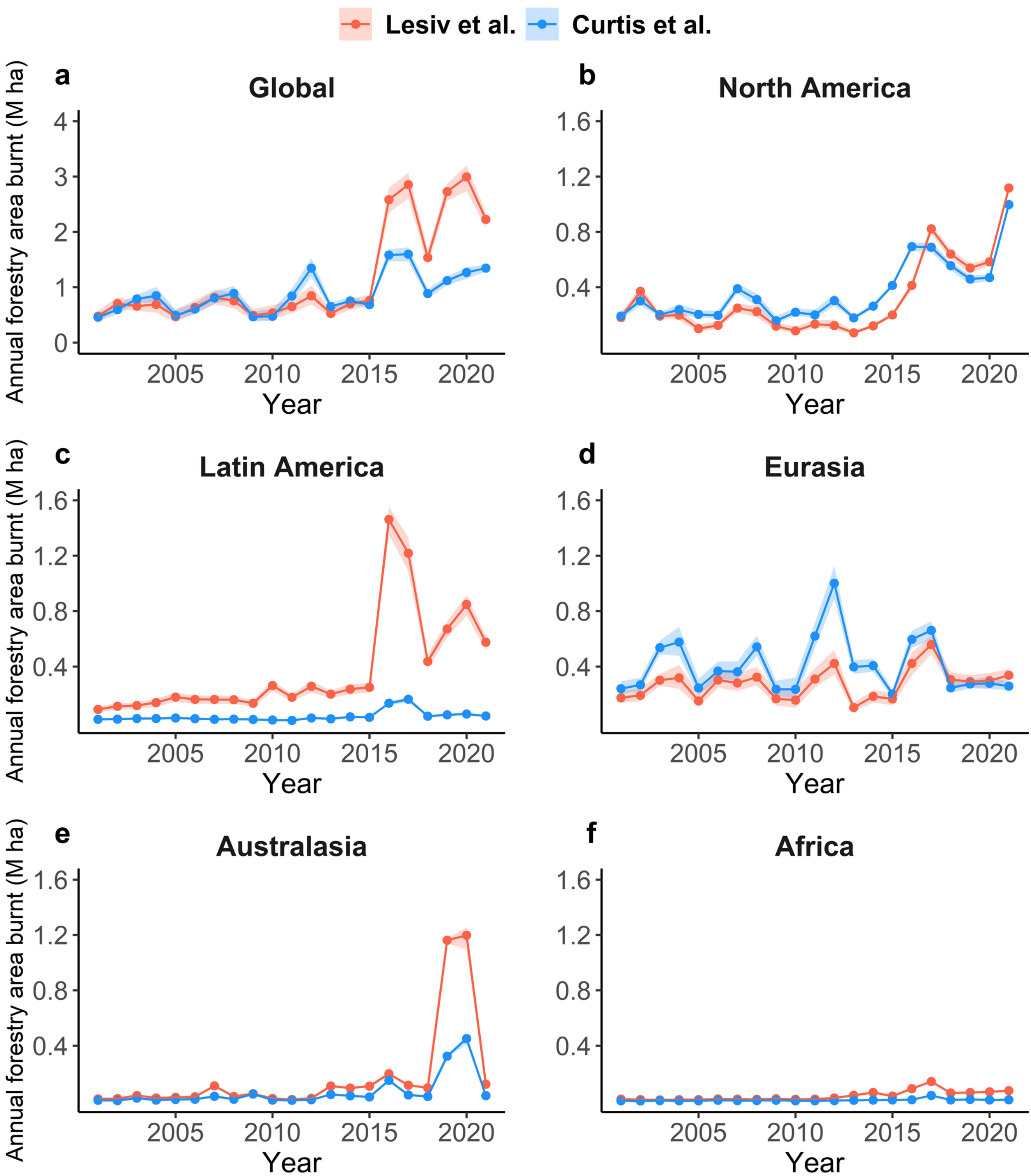

Extended Data Fig. 4 | Global and regional annual area of timber-producing forest lost to wildfires in the years 2001–2021. Using Lesiv et al. map of global forest management (red) and Curtis et al. map of forest loss due to forestry (blue), split by global region: Global (**a**), North America (**b**), Latin America (**c**), Eurasia (**d**), Australasia (**e**) and Africa (**f**). Significant increasing trends in annual area of timber-producing forest burnt are present globally and for all regions except Eurasia. Lines represent annual burn area, shaded areas represent annual burn area ± 1 SE. Annual strength of trend from Sen's slope analysis and p-value from two-sided Mann-Kendall test are as follows: Lesiv et al. (Global: +68,000 ha yr^{-1}, $p = 0.0008$; North America: +18,500 ha yr^{-1}, $p = 0.05$; Latin America: +21,500 ha yr^{-1}, $p = 6.8e^{-6}$; Eurasia: No trend, $p = 0.22$; Australasia: +7000 ha yr^{-1}, $p = 0.0003$; Africa: +3500 ha yr^{-1}, $p = 2.9e^{-6}$), Curtis et al. (Global: +38,000 ha yr^{-1}, $p = 0.002$; North America: +18,000 ha yr^{-1}, $p = 0.002$; Latin America: +1700 ha yr^{-1}, $p = 0.003$; Eurasia: No trend, $p = 0.83$; Australasia: +2700 ha yr^{-1}, $p = 0.001$; Africa: +450 ha yr^{-1}, $p = 1.2e^{-5}$).

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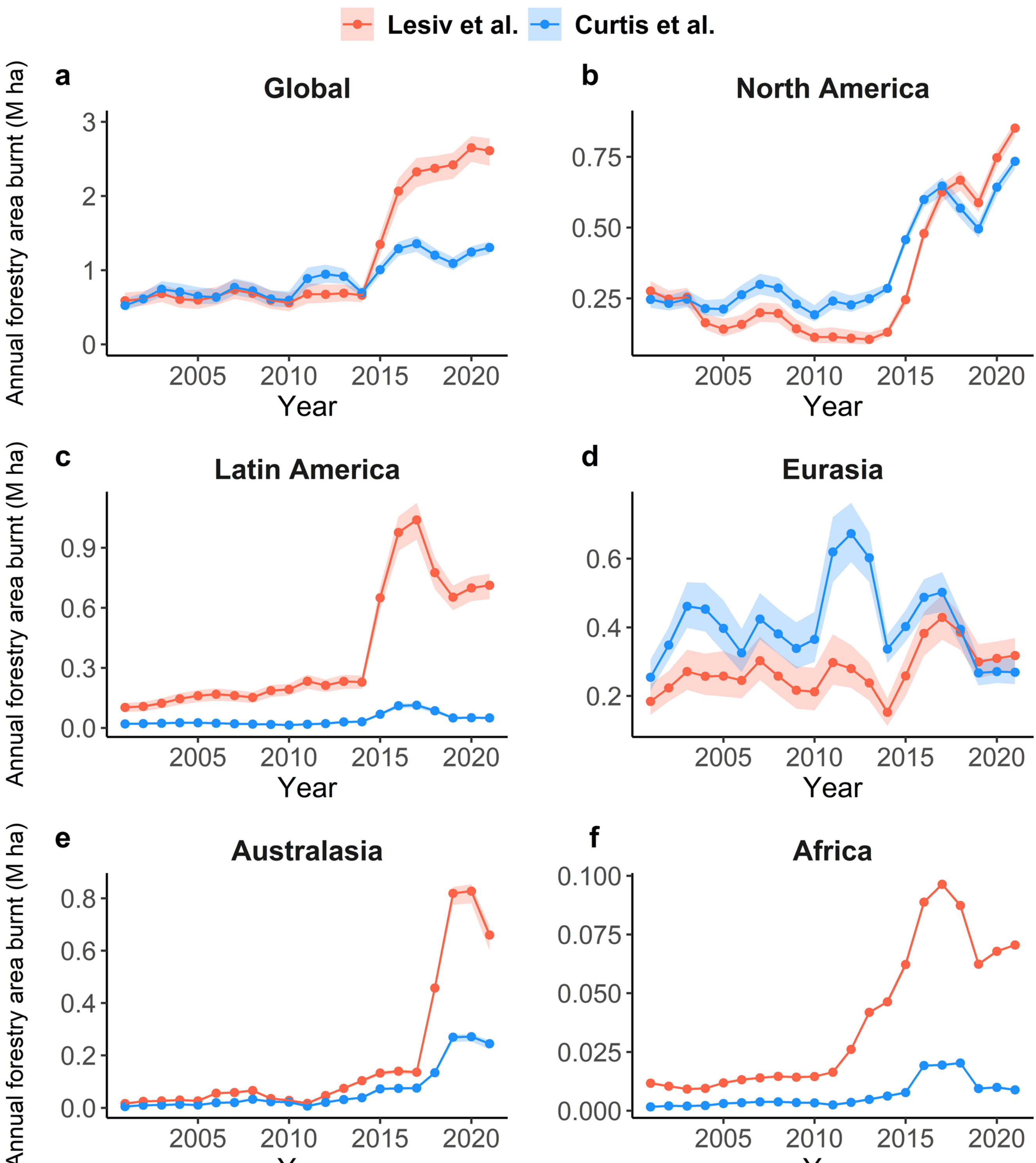

Extended Data Fig. 5 | Global and regional three-year average annual area of timber-producing forest lost to wildfires in the years 2001–2021. Using Lesiv et al. map of global forest management (red) and Curtis et al. map of forest loss due to forestry (blue), split by global region: Global (**a**), North America (**b**), Latin America (**c**), Eurasia (**d**), Australasia (**e**) and Africa (**f**). Significant increasing trends in annual area of timber-producing forest burnt are present globally and for all regions except Eurasia. Lines represent three-year rolling average, shaded areas represent three-year rolling average ± 1 SE. Annual strength of trend from Sen's slope analysis and p-value from two-sided Mann-Kendall test are as follows: Lesiv et al. (Global: +68,000 ha yr^{-1}, $p = 0.0008$; North America: +18,500 ha yr^{-1}, $p = 0.05$; Latin America: +21,500 ha yr^{-1}, $p = 6.8e^{-6}$; Eurasia: No trend, $p = 0.22$; Australasia: +7000 ha yr^{-1}, $p = 0.0003$; Africa: +3500 ha yr^{-1}, $p = 2.9e^{-6}$), Curtis et al. (Global: +38,000 ha yr^{-1}, $p = 0.002$; North America: +18,000 ha yr^{-1}, $p = 0.002$; Latin America: +1700 ha yr^{-1}, $p = 0.003$; Eurasia: No trend, $p = 0.83$; Australasia: +2700 ha yr^{-1}, $p = 0.001$; Africa: +450 ha yr^{-1}, $p = 1.2e^{-5}$).

Extended Data Table 1 | Summary of datasets included within the study, their uses and features

Data Source	Use	Summary	Additional Notes
Global map of forest management - Lesiv *et al.*, 2022 (*13*)	Logging activity layer	100-m resolution forest management map (2015) – based on remote-sensing and classification algorithms trained on 'expert' classified data.	Management classes used in this study to represent timber-producing forest: 1. Naturally regenerating forests with signs of forest management, e.g., logging, clear cuts etc. 2. Planted forests (rotation >15 years) 3. Plantation forest (rotation ≤15 years) Also attempts to include selective logging across the tropics, much harder to detect via remote sensing than clearcut and plantation forestry.
Global map of forest loss drivers – Curtis *et al.*, 2018 (*6*)	Logging activity layer	10-km resolution map of key driver of forest loss (2001-2019) – based on Hansen forest loss data and classification algorithms trained on visually inspected images.	Assigned forest loss to one of five drivers: urbanisation, commodity-driven deforestation (e.g. palm oil, soy), shifting agriculture, wildfire or forestry. Forestry class used in our study to represent timber producing forest. Classification based on forest loss detectable from Landsat, so forestry class represents chiefly clearcut and plantation forestry.
Global map of forest loss due to fire – Tyukavina *et al.*, 2022 (*7*)	Fire occurrence layer	30-m resolution map of where fire caused detectable forest loss (2001-2021) – extension of Curtis *et al*. work based on Hansen forest loss data and classification algorithms trained on visually inspected images.	Assigns forest loss event as caused by wildfire or some other driver. Maps date of burn to allow for temporal analysis of burn trends.
Global map of forest use – Schulze *et al.*, 2018 (*18*)	Logging activity layer (supplementary)	1-km resolution map of forest use type (2000) – based on FAO reported data and classification models trained with predictor variables.	Not included within our main analysis as FAO data unreliable and forest use definitions (production, mixed use) make it difficult to determine forests managed chiefly for timber.
Global forest change data – Hansen *et al.*, 2013 (*19*)	10% forest cover mask	100-m resolution map of % forest cover, gains and loss in years 2000-2012 – mapped global tree cover, loss and gain using Landsat data.	Used to mask Curtis *et al.* logging layer to include only areas marked as forestry with at least 10% tree cover in the year 2000 (according to FAO definition of forest, the same threshold was used in Lesiv *et al.*).

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Extended Data Table 2 | Comparison of total logging area, area burned, proportion burned and global annual burn trend between different logging layers used

	Lesiv – All logging forest types	Lesiv – Natural logged forest and Plantation	Lesiv – Natural logged forest only	Curtis	Schulze
Logged area (M ha)	2,415	2,208	2,126	1,076	1,567
Burned area (M ha)	24.7	23.6	22.8	18.5	63.9
Proportion burnt (%)	1.02	1.07	1.07	1.73	4.08
Annual trend	***	***	***	**	**

For Lesiv et al. the analysis was conducted including all three forestry-related categories (i) logging, clear cuts etc; (ii) Planted forests (rotation > 15 years); and (iii) Plantation forests (rotation ≤ 15 years). Two precautionary reanalyses were conducted, removing first the 'Planted forests' category, then removing both 'Planted forests' and 'Plantation forests' categories. The results are compared with using all three categories from Lesiv et al., as well as with Curtis et al and Schulze et al. Annual trend represents the significance level of the positive annual burn area trend, and is marked with ** (two-sided Mann-Kendall test, $0.001 \le p < 0.01$) and *** ($p < 0.001$).