# Abrupt increase in harvested forest area over Europe after 2015

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Forests provide a series of ecosystem services that are crucial to our society. In the European Union (EU), forests account for approximately 38% of the total land surface[1]. These forests are important carbon sinks, and their conservation efforts are vital for the EU's vision of achieving climate neutrality by 2050[2]. However, the increasing demand for forest services and products, driven by the bioeconomy, poses challenges for sustainable forest management. Here we use fine-scale satellite data to observe an increase in the harvested forest area (49 per cent) and an increase in biomass loss (69 per cent) over Europe for the period of 2016–2018 relative to 2011–2015, with large losses occurring on the Iberian Peninsula and in the Nordic and Baltic countries. Satellite imagery further reveals that the average patch size of harvested area increased by 34 per cent across Europe, with potential effects on biodiversity, soil erosion and water regulation. The increase in the rate of forest harvest is the result of the recent expansion of wood markets, as suggested by econometric indicators on forestry, wood-based bioenergy and international trade. If such a high rate of forest harvest continues, the post-2020 EU vision of forest-based climate mitigation may be hampered, and the additional carbon losses from forests would require extra emission reductions in other sectors in order to reach climate neutrality by 2050[3].

Forests provide a series of both tangible and intangible services to society and to human well-being, ranging from the production of raw materials and regulation of water flows to the protection of soils and conservation of biodiversity[4]. In the countries that form the EU, forests account for approximately 38% of the total land surface, out of which more than 95% are managed[1] with practices that vary broadly across countries[5,6]. Emerging wood markets driven by the bioeconomy—economic activities that use renewable biological resources to produce food, materials and energy—are challenging the current balance between wood demand and the need to preserve key ecosystem services[7]. In particular, in recent decades forests are increasingly considered to be a key asset for meeting climate mitigation targets[2]. Despite the mixed biophysical impacts of forests on climate[8–10], carbon sequestration by forests remains the most important negative climate forcing provided by forests at the global level[11]. In addition, further climate mitigation by forests may come from the increasing use of wood and wood-based residues for material and energy substitution, respectively[12].

On the policy side, the conservation and expansion of the forest carbon sink is an important element in the Paris Agreement[13], as these activities are expected to help countries to reach their individual mitigation goals and globally to achieve the required balance between anthropogenic greenhouse gas emissions and removals in the second half of the century[3]. Similarly, according to the recent European Green Deal[14], the EU's forested area needs to improve, both in quality (biodiversity and management) and in area, to reach climate neutrality and a healthy environment.

The amount of carbon sequestered by forest carbon sinks in the EU has remained stable over the last 25 years and currently offsets about 10% of total EU greenhouse gas emissions[15]. Most of this sink occurs in the living biomass, directly reflecting the difference between forest growth and forest harvest, mortality and natural disturbances. The rate of forest harvest is, therefore, a key parameter in forest management as it largely controls the forest carbon budget[16,17] and also affects ecosystem services such as the conservation of biodiversity, soils and water resources. In recent decades, harvested volumes in Europe's forests have been substantially lower than net annual growth[18], resulting in an increasing carbon stock. Given the fundamental relevance of the harvest rate, timely, consistent and robust assessments of the spatial patterns and temporal trends of the harvest rate are required in order to inform management policies and track economic and environmental progress towards a sustainable bioeconomy. However, official annual forest-harvest statistics typically do not cover the most recent years, their estimates are usually provided at a somewhat coarse spatial scale (by national or regional administrative units) and in some cases they are not regularly updated or are incomplete[19,20].

Currently, the combination of high-resolution satellite records and cloud-computing infrastructures that can handle 'big data' provides a complementary asset for quantifying harvested forest area that is independent from official statistics and overcomes some of the limitations of national inventories. Using such datastreams and information technologies, we assessed the recent changes (2004–2018) in harvested forest area based on the Hansen maps of Global Forest Change

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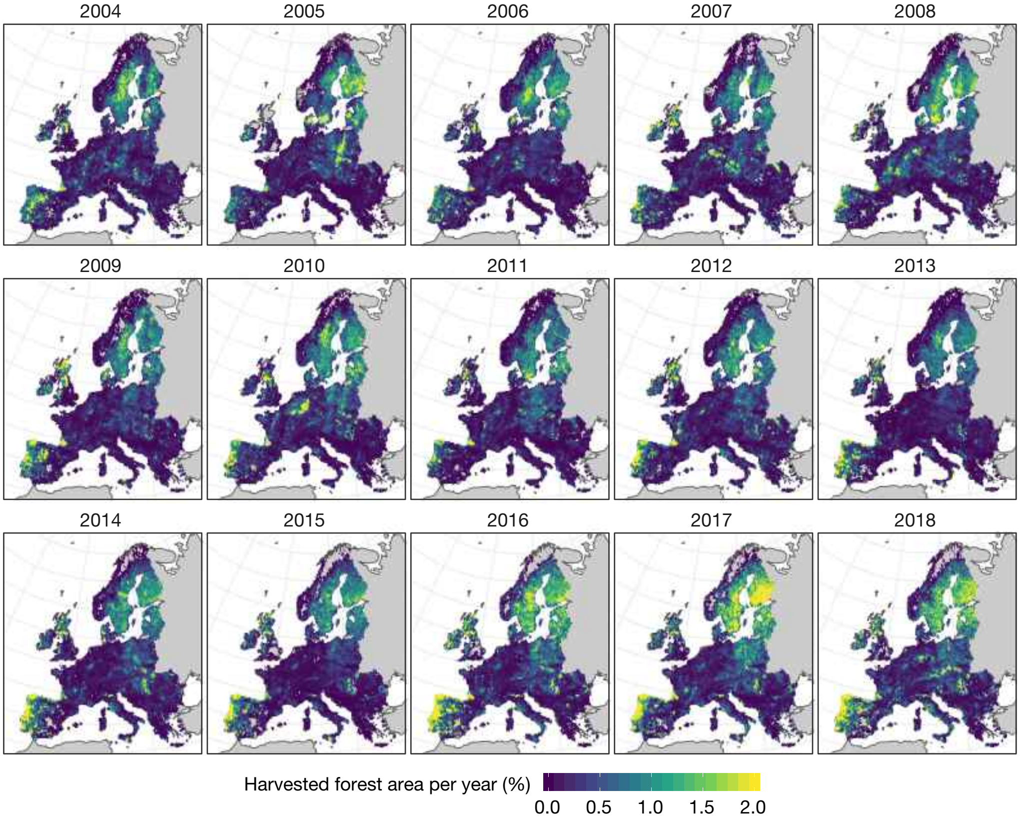

**Fig. 1 | Harvested forest area per year.** Percentage of harvested forest area (expressed as the relative amount of forest area affected by management practices) per year in a 0.2° grid cell, excluding forest losses due to fires and major windstorms and areas with sparse forest cover. For the generation of this map, land areas were classified only as forests when the tree cover exceeded a 20% threshold, uniformly throughout EU26, whereas the rest of the analysis was performed on the basis of a country-based tree-cover threshold as explained in Methods. Grey areas represent countries not included in the analysis. Map generated using GEE[22].

(GFC)[21], a map product with a 30-m resolution based on Landsat satellite data, which provides yearly estimates of tree cover and tree-cover loss (details in Methods section 'Forest mapping'). This evidence-driven assessment targets three questions: (1) whether, following the recent boost in the bioeconomy, the area of harvested forests is changing throughout the EU, and if so in which countries and to what degree; (2) which forests, in terms of biomass and plant cover type, show the largest changes in harvested rate; and (3) whether the modality of forest management in the EU is changing in terms of the size of harvested forest patches.

Here we estimate the changes in forest cover across 26 EU countries—including the UK and excluding Cyprus and Malta (herein referred to as EU26)—using the GFC maps implemented in Google Earth Engine[22], a big data Earth observation platform that enables seamless parallel computing and geospatial operations (details in Methods section 'Cloud-computing platform: Google Earth Engine'). Losses owing to forest fires and major windstorms (details in Methods section 'Spatial aggregation and major windstorm removal') are factored out. We assume that the annual loss in forest cover detected by the GFC maps is a reasonable proxy for the harvested forest area, because we remove losses related to fires or major windstorms. We note that the GFC dataset is sensitive to clear-cuts instead of the actual wood harvest, which can be complemented by thinning operations that may not be seen by the satellite—such as when the change in crown cover is not large enough to be detected.

Validation using a sample of high-resolution data (details in Methods section 'Validation of the GFC maps with high-resolution imagery') confirms the capacity of the GFC maps to detect forest loss, even though uncertainties are lower in some years compared to others, (for example, 2017 has lower uncertainty than 2012) and also lower for large patches (forest patch size greater than 0.27 ha) than in fragmented areas (patch size less than 0.27 ha) (Supplementary Fig. 1). The classification accuracy is particularly high (more than 82% correct detection) for patches larger than 4.5 ha, representing more than 60% of the detected harvested area in EU26. Henceforth, we refer to the forest-loss area as the harvested area.

In answering the first question, our results show that the intensity in harvest, defined here as the percentage of harvested forest area per year, was very stable in magnitude and spatial pattern across most EU26 countries from 2004 to 2015 (Fig. 1). Conversely, we observed a sudden increase in the mean value for the years 2016–2018: 43% with respect to the mean of the years 2004–2015 and 49% with respect to the mean of the years 2011–2015, with particular contributions from large EU domains such as the regions of Finland, Sweden, Lithuania, Latvia, Estonia and Poland, and the western part of the Iberian Peninsula. We acknowledge the uncertainty and the potential bias of the GFC maps, and in particular variations in the availability of observational data before and after 2012, owing to the frequency of Landsat acquisitions (see Methods section 'Forest mapping'). Nonetheless, we consider our findings reliable because abrupt changes in harvested forest area occurred in 2016–2018. We argue that these recent variations in harvested forest areas are due to changes in management and not to increased rates of natural disturbances from windstorms or fires, as these natural disturbances have been factored out from the analysis. This striking rise in harvested forest area is particularly marked in countries that have relevant forestry-related economic activities (for example, the bioenergy sector, paper industries), such as Sweden, Finland, Poland, France, Latvia, Portugal and Estonia. Although an

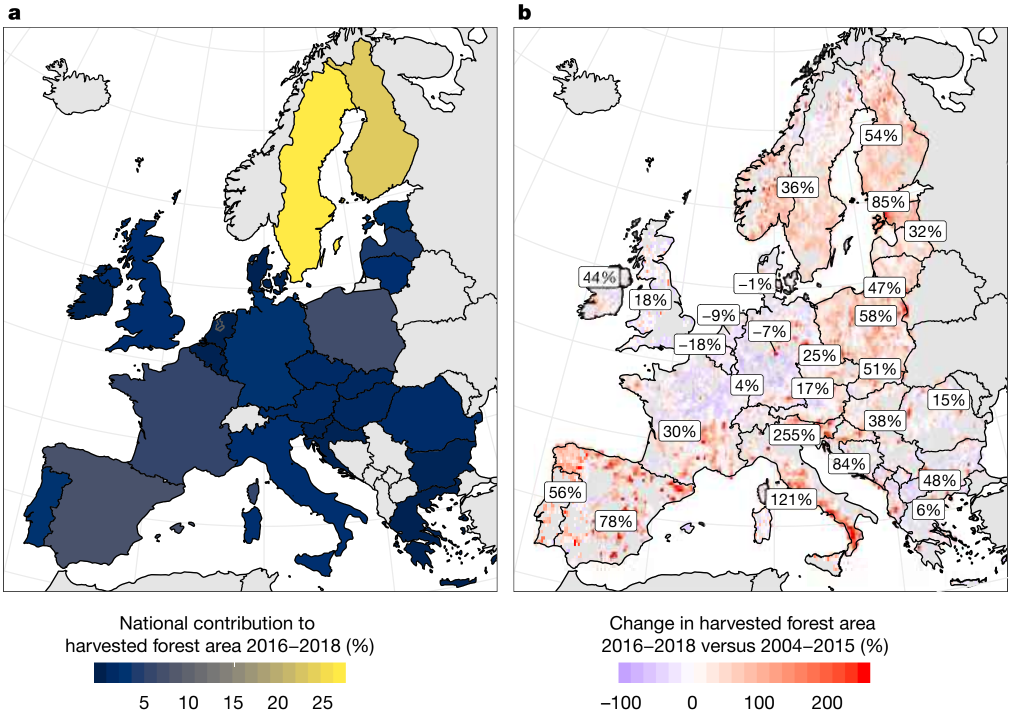

**Fig. 2 | Spatial statistics of European harvested forest area. a**, Percentage national contribution to the total harvested forest area of EU26 during 2016–2018. **b**, Percentage variation of European harvested forest area within each 0.2° × 0.2° grid cell, for 2016–2018 versus 2004–2015 (labels refer to aggregated national values). Grey areas represent countries not included in the analysis. Maps generated using GEE[22].

increased fraction of mature forests in the EU[18] is expected to drive a moderate increase in harvest rate in the coming decades[23], the magnitude and speed of change observed in 2016–2018 instead suggests an increase in wood demand and/or a change in forest management[24].

The largest share of variation in harvested forest area during 2016–2018 compared to 2004–2015 among the 26 EU countries was recorded in Sweden and Finland, which together accounted for more than 50% of the total increase in harvested area observed in recent years (Fig. 2a). Poland, Spain, France, Latvia, Portugal and Estonia accounted for about 30% in total. Needleleaf forests accounted for more than 50% of the detected harvested area in the 26 EU countries according to the European Space Agency (ESA) GlobCover global map on forest type[25], in agreement with the Eurostat report[26] (Extended Data Fig. 4). The analysis of the percentage variation (Fig. 2b) of the annual harvested forest area during 2016–2018 compared with the reference period (2004–2015) shows a general increase, with exceptions in Belgium, the Netherlands, Denmark and Germany, which show minor negative variations. The variation in harvested areas within each 0.2° × 0.2° grid cell confirms a widespread increase in harvested areas in Finland, Sweden, Latvia, Lithuania, Estonia, Poland, and the Iberian peninsula.

The assessment of the rate of forest harvest was quantified in terms of biomass loss by combining the GFC layer with a global map of above-ground biomass (AGB) in living trees for the year 2010, estimated from Earth observation data[27] (details in Methods section ‘Above-ground biomass analysis’). Results show that the patterns in biomass loss (Extended Data Fig. 8 and Supplementary Fig. 4) strongly resemble those of harvested area (Figs. 1, 2a). The increase of annual harvested forest biomass for the period 2016–2018 with respect to 2011–2015 is 69%, higher than the increase in harvested area during the same period. This implies that the areas harvested in the most recent years were characterized by a higher biomass density than those harvested in the reference period.

The 43% increase in annual harvested forest area observed for the years 2016–2018 relative to 2004–2015 was also accompanied by an increase in forest losses owing to natural disturbances from fires and windstorms, although these events were not included in the harvest-area statistics we report. An exceptional number of fires (an approximately 210% increase) were detected for the years 2016–2018 compared with the average number of fires observed during the 2004–2015 period (Fig. 3a). Major windstorms exhibited a rise of the order of 90%, especially in 2018, although the areas hit in 2016–2017 were generally smaller than those hit in 2005, 2007 and 2010.

The analysis of the time series of harvested forest area was carried out at EU26 country level and compared with existing statistics on harvested volume from FAOSTAT, further corrected to account for possible inconsistencies[17]. For this analysis we normalized the harvested volume to enable a comparison with harvested forest area (Extended Data Fig. 6). Overall, on the basis of a country-level analysis, we can conclude that remote-sensing estimates of harvested area are consistent with the statistics for harvested volume. Where inconsistencies were detected, country-specific circumstances—generally independent of the approach we propose here—were identified (details in Methods section ‘Harvested forest area at the country level and comparison with official harvest statistics’).

The second question we want to address is which forests—in terms of biomass and type—are undergoing the largest changes in their harvested area. Across EU26, we computed the average harvested forest area for five different biomass-density classes and the three major forest types (Fig. 3b). The analysis was carried out also for four selected countries (Supplementary Figs. 5 and 6): the two countries with the largest harvested areas (Sweden and Finland), one representative country in central Europe (Poland) and one country in southern Europe (Italy). Generally, the largest increase in harvested area during the period 2016–2018 occurred in needleleaf forests, followed by mixed and broadleaf forests, and the largest increase in the percentage of harvested area occurred in regions with 50–200 t ha$^{-1}$ of biomass. The patterns of harvested biomass are different for different countries, reflecting the variability of forest types and management strategies

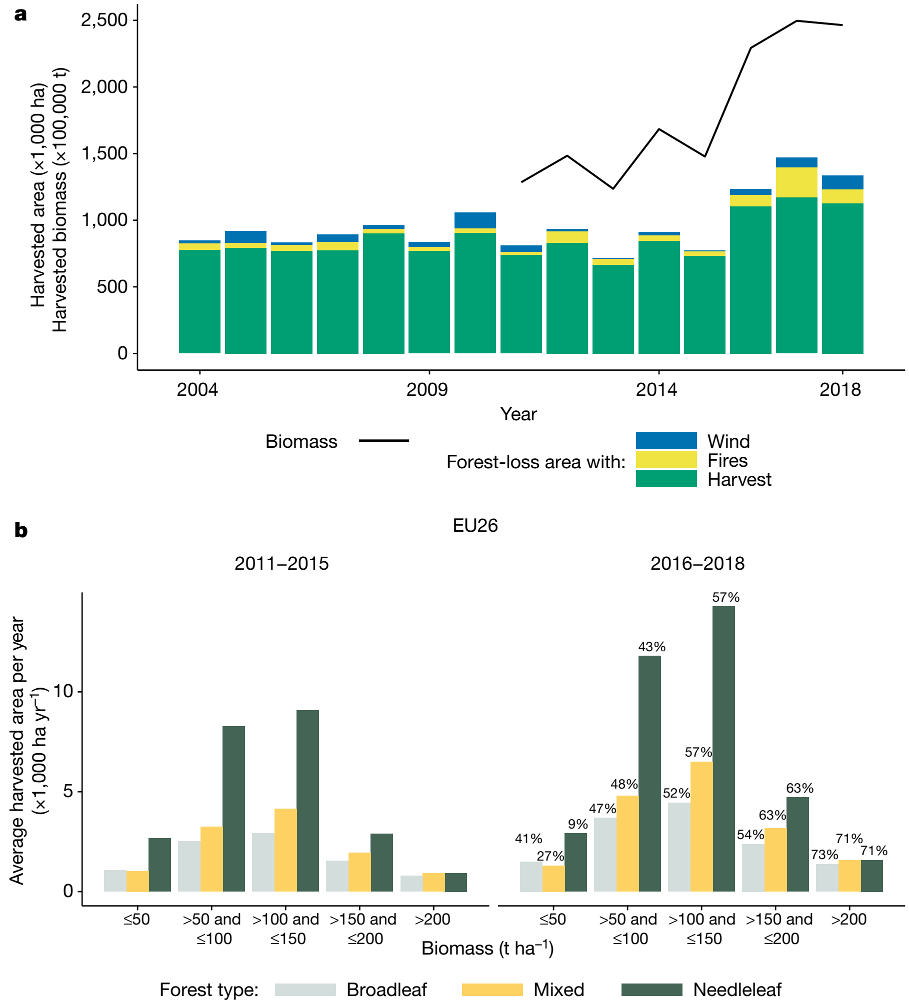

**Fig. 3 | Temporal trends of forest harvests. a**, Time series of forest biomass and area loss due to forest fires, major windstorms and harvested. **b**, Mean yearly harvested area for five biomass-density classes for the periods 2011–2015 (left) and 2016–2018 (right) for EU26, by forest type. Percentage labels at right show the variation (all are increases) for 2016–2018 compared with the reference period 2011–2015 for each biomass class.

across EU26. Both Finland and Sweden show a peak in harvested area for needleleaf forests with biomass density in the range 50–150 t $\mathrm{ha}^{-1}$, whereas in Poland and Italy the maximum harvest values occur in mixed and broadleaf forests, respectively, that have higher biomass density (100–200 t $\mathrm{ha}^{-1}$). This distribution of harvested area reflects the lower biomass stock of forest in the northern European countries compared with those in central Europe and also reflects the prevalence of broadleaves in southern Europe.

Taking advantage of the high spatial and temporal resolution of satellite records, we produced country statistics for the temporal trends of the size of harvested forest patches (that is, the median gap size), and the corresponding percentage variation in the median harvested patch size between 2004 and 2018 (Fig. 4). This analysis addresses our final question regarding ongoing changes in spatial patterns of harvested forest area. The size of harvested patches depends on the topography and silvicultural practices of the country, with larger patches observed in the case of massive clear-cuts, and smaller patches seen for group selection (in which groups or small patches of harvested area are created by the removal of adjacent trees) and shelterwood (in which young trees are grown under the shelter of older trees removed by successive cuttings) systems. The size of harvested patches may affect the impact of forest management on the provision of ecosystem services: generally, larger patches have stronger effects on ecosystems through habitat disruption, soil erosion and water regulation[28,29].

Satellite observations reveal that, overall, the median patch size has increased by 34% across EU26 (on the basis of the mean of the percentage changes of the individual EU26 countries for the years 2016–2018 compared with 2004–2015, weighted by total national forest area). The majority of this increase is attributable to large forest patches (>7.2 ha) (Extended Data Fig. 5). In 21 out of the 26 EU countries, the size of the harvested patches increased by more than 44% between the studied years. Portugal and Italy exhibit an abrupt rise in the median patch size for the period 2016–2018 compared with 2004–2015 (more than 100%). Also, the median patch size is substantially larger in Finland, Sweden, the UK and Ireland than in central or southern EU26 countries.

Exploring the reasons for the recent increase in harvested area, we identify three potential drivers: the ageing of European forests, an increase in salvage logging (owing to natural disturbances), and variations in socio-economic context, such as market demand and policy frameworks. Although harvest volumes can increase because of forest ageing[23], according to the most recent statistics[30] this cannot explain more than 10% of the observed increase in harvest area (details in Methods section 'Potential drivers of change in harvested forest area'). Moreover, the abrupt increase in harvested area as detected from satellite records is not consistent with the gradual trend expected from the effect of ageing. Additionally, although natural disturbances (such as forest fires, salvage logging after major windstorms and insect outbreaks) have affected inter-annual variations and trends, they have been factored out from the analysis. Thus, the socio-economic context

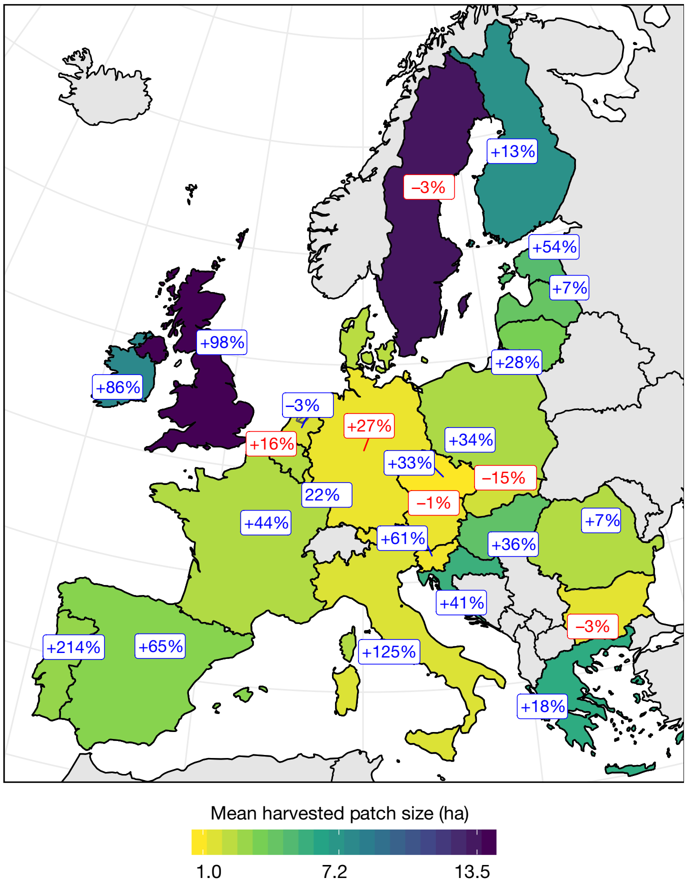

**Fig. 4 | Mean harvested-patch size and recent change by country.** Mean forest harvested patch size and the percentage variation for 2016–2018 compared with 2004–2015. The colour of the label indicates the agreement in sign between the variation in patch size and the total harvested forest area (red when in opposition, blue when in agreement with the harvest variations given in Fig. 2b). Grey areas represent countries not included in the analysis. Map generated using GEE[22].

and policy framework are most probably the most important drivers of harvest area increase, even if a causal connection is difficult to prove and quantify[31]. Although the effect on the harvest rate from a socio-economic stimulus or policy may vary from one country to another (including country-specific patterns of import and export), all economic indicators of wood demand and market (that is, FAOSTAT[30], Eurostat[32] and UNECE[33]) confirm a substantial expansion of the forest sector during the last years (details in Methods section 'Potential drivers of change in harvested forest area'). For example, the output of forestry and connected secondary activities (Extended Data Fig. 7) increased by 13% in 28 EU countries from 2012 to 2016 (as of the years of interest, thus including the UK). This is possibly linked to new legislation (at both EU and country levels) promoting the use of wood in the context of the bioeconomy[34], in particular in the use of renewable energy[35], which has been criticized for the potential impact on global forests[36].

Overall, our analysis shows that Earth observation can provide timely, independent, transparent and consistent monitoring of harvested forest areas across large geographical areas. Complementing national forest inventories with Earth observation has several benefits: (1) it increases transparency because governments or civil society (such as research centres and universities) can better track forest management, both spatially and temporally; (2) it supports the calculation of spatially explicit estimates of greenhouse gas emissions and removals, as required in recent EU land-related legislation[37]; (3) it enables increasing frequency of assessments, facilitating early warnings and timely policy responses; and (4) it assists in validating official statistics by enabling independent checks.

Our methodology, built on the large body of literature regarding the use of satellite remote sensing in the assessment of deforestation[38–40], was developed to deal with the specificity of forest management (such as different management types, no land usage change) and is thus a useful tool supporting the sustainable management of forests[41]. In the future, the interoperability of the NASA Landsat satellite with the ESA Copernicus Sentinels mission, which both provide high-resolution imagery under "complete, free and open"[42,43] licenses, will further increase data availability for monitoring forest management (for example, under the planned EU Observatory on changes in the world's forest cover)[44].

In summary, our results reveal a striking increase in forest harvesting in 26 European countries—a 49% increase in harvested forest area and a 69% increase in harvested biomass—for the years 2016–2018 compared with the average for 2011–2015, with potential implications for climate change mitigation from forest carbon sequestration and other ecosystem services. This type of timely and transparent monitoring of forest harvests is key for implementing more effective forest-based climate mitigation policies and for tracking the progress of country-based climate-mitigation targets. We contend that the carbon impact associated with increased forest harvesting in Europe, as observed in this study, will have to be counted towards post-2020 country-based EU climate targets[23,37]. We believe that the approaches we outline here for the monitoring of natural resources with big data will support future assessments of the potential trade-offs arising from the increasing demands on European forests from economic and ecological services. In addition, such approaches will improve the implementation of forest-related policies under the European Green Deal[14] and in meeting the greenhouse gas reporting and verification requirements under the Paris Agreement.

## Online content

Any methods, additional references, Nature Research 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/s41586-020-2438-y.

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# Methods

## Forest mapping

In Europe, the characteristics of forests change considerably along climate gradients and among forest types. Consequently, there is not a common definition of a 'forest' but each country has adopted the definition that best fits national circumstances. The establishment of a national definition of a forest is essential to monitor changes in forest area and a prerequisite to develop a consistent monitoring system. The United Nations Framework Convention on Climate Change (UNFCCC) proposed that a 'forest' is an area of land of at least 0.05–1 ha and a minimum tree-crown cover of 10–30%, with trees that reach, or could reach, a minimum height of 2–5 m at maturity[45]. Inside these limits, EU countries selected their national forest definition for reporting purposes; EU regulation 2018/841 regarding land use, land use change and forestry[37] reports tabular values of the different tree-cover thresholds for each country. However, even small differences in forest definition might have amplified effects on amounts of biomass or stored carbon amongst others.

Forest cover and the relative changes were obtained combining data from the GFC maps[21] (which provide estimates on tree cover in the year 2000) with forest-area statistics from FAOSTAT. It should be noted that Hansen et al.[21] in their work refer to tree cover. As a consequence, a tree-cover threshold that defines forest cover must be selected to map forest cover from the GFC maps.

**The Hansen maps of Global Forest Change.** The Hansen maps of Global Forest Change[21] (GFC) version 1.6 are the results of a time-series analysis of the Landsat archive characterizing forest extent and forest change with a spatial resolution of about 30 m (the spatial resolution slightly varies along the latitude). The GFC maps consist of three layers: '2000 Tree Cover', 'Forest Loss Year' and 'Forest Cover Loss/Gain'. '2000 Tree Cover' is a global map of tree canopy cover (expressed in percentage) for the year 2000, where a 'tree' is defined as the canopy closure for all vegetation taller than 5 m in height. 'Forest Loss Year' refers to the year of gross forest-cover-loss event. Encoded as either 0 (no forest loss) or else a value in the range 1–18, representing forest loss detected primarily in the years 2001–2018, respectively. 'Forest Cover Loss/Gain' is defined as a stand-replacement disturbance or the complete removal of tree-cover canopy at the Landsat pixel scale. 'Gain' is defined as the inverse of loss, or a non-forest to forest change entirely within the period 2000–2012. Although forest-loss information is reported annually (in other words, there are annual maps for forest-loss disturbances), forest gain is reported as a 12-yr total, that is, it refers to the period 2000–2012 and is a unique layer that does not report the timing of the gain.

Our approach has limitations in the detection of small-scale silvicultural practices. Although the GFC clearly does not require full clear-cuts to detect forest-cover loss, it is not able to reliably capture partial removal of trees caused by forest thinning, selective logging, short cycle forestry (that is, less than 10 yr) or forest degradation when the tree-cover change is smaller than the Landsat spatial resolution. In addition, most changes occurring below the canopy cannot be detected by optical instruments, potentially leading further to an underestimation of actual harvest wood. It should also be noted that our analysis encompasses the 2004–2018 period, thus excluding the 2001–2003 period. The GFC dataset is based on the Landsat archive, and the temporal coverage throughout Europe for the first years is sparser, which can cause artefacts when calculating trends. Also, the GFC product is not fully consistent over the entire 2000-onward period. The ingestion of Landsat 8 from 2013 onwards leads to improved detection of global forest loss.

In terms of data acquisition, the analysis of Landsat images shows that the number of cloud-free images (defined as images with cloud cover less than 20%) over Europe gradually increases from 2013 to 2018 (Extended Data Fig. 9a). In particular, in the 2016–2018 period there is a 15% increase in Landsat image availability with respect to the preceding 3-yr period (2013–2015). In 2012, the number of images dropped substantially, owing to the decommission of Landsat 5.

However, our analysis shows that there is complete and frequent cloud-free land coverage of Landsat in Europe with more than seven cloud-free acquisitions per tile every year during the study period (2004–2018; Extended Data Fig. 9b). According to the authors of the GFC product, a minimum of seven acquisitions per year is sufficient to detect forest loss in Europe[46]. In fact, in temperate and boreal regions, forest recovery after harvesting (if occurring) is a much slower process compared to that occurring in tropical and subtropical regions, and the change in spectral signature persists for several months after the loss of vegetation and soil exposure. For these reasons we conclude that variation in image availability did not affect the results of our analysis, as the number of images collected was above the threshold required for a robust classification throughout the entire time series.

The only exceptions occurred in 2012, with longer satellite revisiting time in northern Europe, and in 2008 with a data gap in Fennoscandia, but this area presented marginal forest cover and forest loss throughout the whole study period.

**FAOSTAT.** The FAOSTAT Forestry database[30] provides annual production and trade statistics for forest products, primarily wood products such as roundwood, sawnwood, wood panels, pulp and paper. For many forest products, historical data are available from 1961. These statistics are provided by countries through an annual survey conducted by the FAO (Food and Agriculture Organization of the United Nations) Forestry Department. Within this study, we used 'Area of forest' data from FAOSTAT for each European country for the years 2000, 2005, 2010 and 2015[47].

## From tree cover to forest cover

In this study, we present a simple approach towards defining for each EU26 country the minimum tree cover (percentage) that qualifies as forest using the GFC maps. For each country, we found that the tree-cover threshold needed to define a forest that minimizes the difference between national forest-area statistics from FAOSTAT and GFC estimates (Extended Data Fig. 1a). Specifically, we computed for 15 tree-cover classes—from 10% to 80% in 5% steps—the corresponding forest areas and selected the class that minimizes the difference between the national forest-area statistics collected in the FAOSTAT report for the year 2015 (hereafter FAOSTAT-2015); using the last published dataset is a common approach. To match the FAO definition of forest, we used a minimum mapping unit (MMU) of approximately 0.5 ha with a moving-window kernel. Specifically, in a square kernel 100 m × 100 m, we retain the forest only if there are more than 5 forest pixels in the GFC map, corresponding to about 0.45 ha. To explore the sensitivity of our analyses to the choice of tree cover, we replicated the analysis above using high and low tree-cover thresholds. A forest threshold sensitivity, $S$, (Extended Data Fig. 1b) was computed as

$$S = \frac{\text{Forest}_{\text{max}} - \text{Forest}_{\text{min}}}{\text{Forest}_{\text{rightThreshold}}} \times 100 \quad (1)$$

Where $\text{Forest}_{\text{min}}$ represents the forest area obtained using a tree-cover threshold equal to 10%, $\text{Forest}_{\text{max}}$ represents the forest area obtained using a tree-cover threshold equal to 70% and $\text{Forest}_{\text{rightThreshold}}$ represents the forest area obtained using the correct tree cover (that is, the threshold that minimizes the difference with FAOSTAT-2015 estimates).

In other words, the forest threshold sensitivity represents how much the forest area would change by choosing strict or less strict thresholds (10% and 80% of tree cover) normalized by the actual forest area. If the forest sensitivity is, for instance, 120%, then using the two extreme thresholds for a forest definition (that is, tree cover equal to 10% and

70%) corresponds to forest areas that differ by 1.2 times the value of the actual forest area (as defined in Supplementary Fig. 1).

The results of this analysis show that national forest-areas change considerably according to the choice of the minimum tree-cover threshold and that this threshold varies by country, making it inappropriate to use a single threshold for the whole of Europe.

It should be noted that the GFC definition of forest is land-cover based, whereas the national forest inventories employ a land-use definition. For example, orchards are considered as forests in the GFC, whereas they are excluded from national forest inventories. Conversely, bare ground which has been affected by harvest operations is still called forest if it is expected to revert to forest by national forest inventories (land-use approach). Thus, the GFC maps can be used to produce a map of forest cover, with some caveats[48–50].

We note that the geographical extent of this study included 26 member states of the EU, including the UK, and excluding Cyprus and Malta—for which there are no data available from official government sources, or the forest coverage is scarce.

### Comparing forest cover with different data streams

We compared our estimates of forest cover with estimates from the two existing datasets for EU26: FAOSTAT and LUCAS. FAOSTAT provides forest-area estimates for the years 2000 and 2010. LUCAS, the Land Use and Cover Area frame Survey carried out by Eurostat[51] (the statistical office of the EU), is an EU26-wide regular point-sample survey with a 2-km grid size that provides estimates for the years 2009, 2012 and 2015. Note that we used forest area from FAOSTAT for the year 2015 to define the tree-cover thresholds. However, a comparison using different years (see below, and Extended Data Fig. 2) gives further verification of our forest assessment.

To compare our calculated forest cover over the same years, we computed forest cover for the years 2000, 2009, 2010 and 2012 using the country-based tree-cover thresholds and considering a MMU of approximately 0.5 ha. We also took into account forest-gain information.

Extended Data Fig. 2 shows the comparison between FAOSTAT and GFC-derived forest area for 2000 and 2010. Note that for the GFC maps the temporal evolution of the forest area is always decreasing, whereas FAOSTAT often shows an increasing trend. This is probably because forest gain is difficult to capture with remote-sensing data. A decreasing trend in forest area for both GFC and FAOSTAT data is visible only for Finland and Portugal. The comparison shows a high level of agreement between the two datasets, which lends confidence to the assessment of remote-sensing-derived forest area.

The scatterplot analysis performed with FAOSTAT was also carried out with LUCAS data for 2009, 2012 and 2015, to have another independent source of information on forest area (Extended Data Fig. 2). The LUCAS data tend to provide larger estimates of forest area compared with GFC data. Such differences between forest estimates are probably due to the methodology: the LUCAS definition of forest is different from the FAO definition. Specifically, LUCAS uses a low tree-cover threshold—10%—and no MMU to define a forest (labelled as 'wooded area' in the dataset). In addition, changes in survey protocol for the 2009, 2012 and 2015 LUCAS campaigns might cause inconsistencies when datasets are compared over time.

### Validation of the GFC maps with high-resolution imagery

We validated the GFC maps using high-resolution imagery from Google Earth. We performed two validation exercises aimed at testing the capability of the GFC for the detection of harvest patches of different sizes, designed as follows.

**Validation exercise 1.** We tested the GFC capabilities for forest-harvest patches of various sizes (hereafter, general validation). The purpose of this general validation was to assess the accuracy of the harvested area as derived from the GFC dataset (that is, the user accuracy). We did not attempt to quantify the omission errors. The general validation was carried out by analysing 620 patches of harvest with various size, randomly selected from seven countries (Poland, Ireland, France, Italy, Estonia, Sweden and Finland) for 2012 and 2017 to better sample the range of variability represented by different countries, climatic conditions, forest type and management system (620 patches in both 2012 and 2017). 26% and 37% of the patches for 2012 and 2017, respectively, could not be validated for lack of high-resolution imagery.

**Validation exercise 2.** This second validation effort was aimed specifically at testing our methods on big harvest patches (larger than 4.5 ha, hereafter the big-patch validation), as the increased occurrence of larger harvest areas is one of the main issues raised by this study. For the big-patch validation, we compared data from the same seven countries used in the general validation, and compared 2012 and 2017. For this exercise, forest patches consisted of at least 50 contiguous pixels (with a four-neighbours rule), that is, at least approximately 4.5 ha. We found 188 and 260 patches for 2012 and 2017, respectively.

For both the general and big-patch validations, samples were classified, using visual image interpretation, into four categories: 1) correct classification: the high-resolution images confirm the forest loss detected by the GFC maps in shape, position and timing (that is, the loss area in the high-resolution images is more than 50% of the loss area detected by GFC); 2) wrong classification: the forest loss detected by GFC is not visible in the high-resolution images; 3) partially correct (location and extent mismatch): the loss area in the high-resolution images is less than 50% of the loss area detected by GFC, mostly owing to image misregistration; and 4) partially correct (temporal mismatch): there is a temporal lag of maximum one year in the detection of GFC forest loss (generally, the actual loss happened the year before the loss reported by the GFC data).

Extended Data Fig. 3a reports the validation results by large (that is, $\geq$0.27 ha) and small (that is, <0.27 ha) forest-loss patches. It emerges that the classification capabilities are better in the year 2017 than in 2012, probably because Landsat 8 entered operation. As expected, the classification of small patches show a larger uncertainty (that is, the error in classification is 29% of cases instead of the 13% error observed for large patches in 2017). From these results we determine that, despite the larger uncertainty in the classification of small patches, the overall impact on our findings is limited, because patch sizes smaller than 0.27 ha represent less than 3% of the detected total harvested area in EU26 (Supplementary Fig. 1). The results of the big-patch validation clearly show that more than 84% of big forest patches ($\geq$4.5 ha) are correctly classified and only 5% are wrongly classified (third row of Extended Data Fig. 3b). The remaining patches are either recorded with one year of delay (3%) or refer to harvest areas of different size (7%), owing to image misregistration.

This evidence confirms the robustness of our retrievals on the recent trend in harvest areas.

### Spatial aggregation and major windstorm removal

To identify anomalies in forest management and to exclude extraordinary losses owing to natural disturbances that are not related to the normal management regime, we computed the annual percentage of forest loss at a 0.2° spatial resolution as the ratio between the area of forest loss during 2004–2018 and the area of forest cover in the year 2000, within each grid cell. Regions affected by forest fires, as detected by the European Forest Fire Information System (EFFIS) dataset, were masked out. EFFIS provides European Commission services and the European Parliament with updated information on wildland fires in Europe[52]. EFFIS provides shapefiles for European forest fires using remote-sensing imagery; specifically it maps burned areas by analysing daily images from MODIS at 250-m spatial resolution. Small burnt or unburnt areas below the spatial resolution of the MODIS imagery are not mapped; however, the area burned by fires detected by MODIS represents about 75% to 80% of the total area burned in the EU.

To generate Fig. 1 at the European scale, a common tree-cover threshold of 20% (instead of a country-specific threshold as used in the rest of the analysis) was used to define a 'forest'. We also excluded areas with sparse forest cover—that is, where forest cover in a gridcell of 0.2° is less than 10%. Aggregating to 0.2° also has another advantage, namely that this scale is simpler to map and visualize at the EU level, as shown in Figs. 1, 2b.

What is detected by satellites is a change in the percentage of forest cover that can either be attributed to forest management (that is, harvest) or disturbances (for example, pests, biotic disturbances and windstorms), and so we filtered out from our analysis areas affected by major windstorms. To do so, we assumed that major windstorms generally cause larger losses than the losses caused by forest management[53]. For each 0.2° grid cell we computed a threshold of the percentage of forest loss, which is calculated as:

$$\mathrm{Threshold}_{\mathrm{wind}} = \mathrm{median}(x) + 3 \times \mathrm{MAD}(x), \qquad (2)$$

where $x$ is the time series of the percentage of forest loss from 2001 to 2018 and MAD is the median absolute deviation.

When the annual percentage of forest loss is greater than $\mathrm{Threshold}_{\mathrm{wind}}$, the the forest loss is attributed to windthrow. With this formula, we excluded major windstorms from our analysis. The resulting maps only remove major windstorms; forest loss from small and localized windstorms, pests and other diseases are not masked out. Note that $\mathrm{Threshold}_{\mathrm{wind}}$ was computed including the 2001–2003 period (later excluded from the analysis) to obtain more robust statistics.

Major windstorms are masked in Figs. 1, 2b. Patterns of major windstorms detected with our scheme show a good overlap with the tracks of major windstorms events in 2005, 2007 and 2009[53].

The major windstorms removal scheme has a major limitation, namely that short rotation forestry[54]—that is, areas characterized by intensive management—can be erroneously classified as major windstorms and thus excluded from our analysis. However, this limitation does not undermine the main findings of this study, as the rise in harvested forest area in the EU might be underestimated by excluding short-rotation forests.

A note of warning in Fig. 1 is warranted for Portugal, as during the period 2016–2018 the country experienced intense fires[52] that might have been only partially detected in our analysis (possibly owing to the limited spatial extent of individual events) and therefore erroneously considered as harvest area.

### Land cover

The land cover data layer (at a resolution of 300 m) was obtained from the ESA GlobCover map[25] and harmonized to the 30-m$^2$ grid using a nearest-neighbourhood algorithm.

### Patch size

We computed for each year and for each EU26 country the number of contiguous pixels—using a four-connected rule—of forest loss and its distribution. We excluded from the analysis regions affected by forest fires (using the EFFIS dataset) or major windstorms. For each year we computed the median of the number of connected pixels of forest loss. This median value is representative of the average patch size of harvested forest patches (Fig. 4). Combining country-level variations in harvested patch size and harvested forest area (as shown in Fig. 2a), it is possible to identify countries where the signs of the variation in harvested patch size and area are in opposition (that is, both patch size and area are either increasing or decreasing), as indicated by blue labels in Fig. 4, or not (red labels). Interestingly, in seven countries out of the 26, variations in the harvest area and patch size are in opposition. For example, in Sweden, the harvested area increased and the patch size decreased, although slightly (approximately 3%). Similarly, Austria, Bulgaria and Slovakia show an increase in the harvested forest area and at the same time a reduction in the patch size. This could suggest an increase in harvested forest area in smaller regions (for example, by private owners) or the application of less intensive management practices. Conversely, Belgium and Germany show an increase in the patch size and at the same time a reduction in the harvested area.

### Silvicultural practice and harvest patch size

We conducted an analysis of changes in forest harvest size both at the European and also at the country level. We investigated the annual distribution of harvested forest area for five different classes of patch size, ranging from small patches (harvested forest area less than 0.27 ha) to large ones (harvested forest area greater than 7.2 ha) across all EU26 (Extended Data Fig. 5a) and at country level (Extended Data Fig. 5b). We note that the patterns for all EU26 and Finland are similar, with a major contribution from large patches of harvested forest. Conversely, Italy displays a dominance of harvested forest patches of size less than 3.6 ha, despite an increase in the number of big patches (>7.2 ha), which doubled from 2004 to 2016. These data provide information on the most common forest management practices applied at country level. On the one hand we have countries, such as Sweden, UK, Finland and Ireland, where larger harvested forest areas prevail, suggesting the application of clear-cut as the main management system. On the other hand, in Italy other silvicultural systems clearly prevail (such as the shelterwood system or a single-tree selection system): this is as a result of both the uneven age structure of the trees and to the smaller sizes of privately owned forests. It should be noted that, owing to calculation constraints, the sizes of the patches are calculated from the GFC map on a geographic coordinate system (that is, EPSG:4326) and not on an equal-area projection. As a consequence, slight errors in the area occur along latitude.

### Harvested forest area at the country level and comparison with official harvest statistics

For each EU26 country, we compared the harvested forest area derived from the GFC maps and the amount of harvest volume removals reported by FAOSTAT. Harvest removals (that is, 'total roundwood production') are provided by FAOSTAT for each European country for the years 2004–2018, further corrected to account for possible inconsistencies, according to a previous analysis[17]. Harvest removals are expressed as volumes.

For this analysis, we excluded areas affected by forest fires (that is, the EFFIS archive), whereas areas affected by major windstorms were retained. In this way, we assume that storm-damaged timber is harvested and so that we are consistent with national harvest removal statistics that take into account salvage logging associated with wind damage; these generally exclude fires.

In Extended Data Fig. 6, the black line (normalized between zero and the maximum value of the harvested area for clarity) shows the harvest removals. Finally, the difference between Earth observation data and inventories is shown for the two countries with the largest forest sectors in the EU: Finland[55] and Sweden[56] (Supplementary Fig. 3), for which we have information on harvested forest area up to 2018 and 2016, respectively.

On the basis of this comparison between harvested forest area, official harvest removals (Extended Data Fig. 6) and National Forestry Action Programmes and other data sources (such as the National Forestry Accounting Plans (NFAP) recently published by the EU countries), we performed the following country-based analysis.

**Austria.** The GFC maps accurately reproduce the trend reported by harvest removals ($r = 0.65$; $r$, coefficient of correlation). This is also a result of the specific management system applied at national level, where the annual share of the final cut (the last of a series of cuts) of the total harvest is generally higher than 80% (NFAP Austria)[57]. These data series include both the amount of wood removed from salvage logging after major windstorms (in 2007–2008)[58], and also the area affected by those disturbance events.

**Belgium.** Uncertainties in official harvest removal data, and the peak in 2010—probably due to a windstorm[59]—reported only by the GFC, may explain the lack of correlation between the two time series.

**Bulgaria.** The high uncertainty in official harvest removal data[60], the effects of unregistered logging and heterogeneous silvicultural systems applied at country level (including simple coppices and coppices in conversion to high forests) may explain the low correlation between GFC and harvest removals.

**Croatia.** The poor correlation with the GFC maps is probably due to the specific forest management systems applied at national level, including the shelterwood system (largely applied to broadleaves), and the selective cut system (applied to unevenly aged forests, which cover about 20% of the total forest area). Moreover, silvicultural treatments are still partially influenced by ongoing demining activities, owing to the war that involved Croatia during the 1990s (NFAP Croatia)[61].

**Czech Republic.** The GFC maps represent fairly well the amount of harvest provided by final cut (on average, 43% of the total removals) and, partially owing to salvage logging, equal to about 41% of the total removals during the last decade (NFAP Czechia)[62]. The peak of harvest as reported by both these time series since 2016 is probably the result of salvage logging, as a consequence of windstorms and bark beetle attacks that have occurred during recent years[63].

**Denmark.** The lack of correlation with the GFC data is due to both some uncertainty in the estimates reported by harvest removal data (generally underestimated before 2014), and also to the increasing amount of primary residues removed from forests from 2011 onward (NFAP Denmark)[64]. Owing to this activity, recent harvest removal data also include wood used for energy, mainly provided by branches and other wood materials.

**Estonia.** Data from the GFC are consistent with harvest removals, and probably include the amount of area affected both by final cut and also by salvage logging after major disturbance events.

**Finland.** Harvest data reported by official statistics is well correlated with data from the GFC ($r = 0.56$). Taking into account the information reported by the 2018 statistical yearbook for forestry in Finland[55] (Supplementary Fig. 3), we can infer that the GFC can be compared to the area affected by clear-cut (about 135 kha yr$^{-1}$ for the period 2001–2016) and final removals within the shelterwood system (about 43 kha yr$^{-1}$ for the period 2001–2016). Both these data series, however, are only partially correlated with the annual amount of harvest removed at country level ($r = 0.53$). This is probably due to the following: (1) the harvest from thinnings is not negligible, because thinning represents about 66% of the total area affected by fellings at country level (average of the period 2004 and 2015); and (2) the different biomass density per unit of area between the northern and southern part of the country certainly reduces the correlation between the two variables. Nevertheless, the increasing amount of harvest detected by the GFC during recent years was recently confirmed by the data reported by the National Resource Institute of Finland[65], highlighting that in 2018, a total of 78.2 million cubic meters of roundwood was harvested from Finnish forests, 8% more than in the previous year and, compared with the average of the preceding ten-year period, amounted to an increase of nearly 25%.

**France.** The GFC represents fairly well the amount of harvest from final cut and salvage logging after major natural disturbances (indeed, they clearly highlight the effect of the windstorm that occurred in 2009, which explains the peak of harvest removals reported for 2010). Owing to the complex structure and heterogeneity of the management systems applied in France (including coppice with standards, and mixed forests where coppices and high forests coexist in the same area), and also the difficulty in determining the different biomass densities per unit of area, the GFC can probably detect only part of the silvicultural treatments and of the overall harvest applied at the country level ($r = 0.33$).

**Germany.** Harvest data reported by official statistics is well correlated with data from the GFC ($r = 0.56$), and can be compared with the amount of harvest from final cut and salvage logging after major natural disturbances (the data clearly highlight the effect of the windstorms that occurred in 2007 and 2010).

**Greece.** Harvest data reported by official statistics is partially correlated with data from the GFC ($r = 0.42$). This is due both to the high uncertainty of harvest statistics[19,20] and also to the specific characteristics of this country, which is mainly covered by unevenly aged forests that are generally treated with selective cut systems.

**Hungary.** The GFC maps do not reproduce the pattern in the forest harvest data, probably because it cannot reproduce the sharp increase in total forest area as reported in official statistics[66] (between 2000 and 2015 the total forest area grew by 8%, from 1,908 kha in 2000 to 2,069 kha in 2015)[1].

**Ireland.** As for Hungary, the GFC does not reproduce the trend in the harvest data, probably because it cannot reproduce the sharp increase in total forest area as reported in official statistics (between 2000 and 2015 the total forest area grew by 19%, from 635 kha in 2000 to 754 kha in 2015)[1].

**Italy.** Owing to the high uncertainty of official harvest removal data[19,20] and to the specific characteristics of this country (unevenly aged forests cover about 30% of the total forest area)[67], and because the biomass density may vary within the country owing to different climatic conditions, the GFC can only partially reproduce the trend reported by harvest statistics.

**Latvia and Lithuania.** Even if the average share of harvest provided by clear cut is equal to about 70–80%[17], the GFC can only partially reproduce the trend reported by harvest removal data. This is specifically due to the decreasing amount of area affected by harvest detected by GFC maps between 2012 and 2015. For both these countries, even if the absolute amount of harvest has been generally increasing since 2010, the relative share of final cut to thinnings decreased, at least for some species (NFAP Lithuania)[68].

**Luxembourg.** The GFC maps can reasonably reproduce the trend reported by harvest removal data ($r = 0.60$). This is due to the specific management system applied at national level, where the annual share of the final cut is generally higher than 90%[17].

**The Netherlands.** The lack of statistical correlation between official harvest removals and GFC data may be due to different reasons. The data for harvest removals was extremely homogeneous in time until 2013, when, owing to an abrupt increase of coniferous wood removals, the total amount of harvest increased by about 16%[69]. Conversely, GFC data shows a peak in 2010 (when removals increased by 6% compared to 2009), and no major variation is reported after 2013. Neither the

GFC nor harvest removal data highlight any substantial deviation in 2007 when about 0.25 million m$^3$ in biomass volume was damaged by windstorms.

**Poland.** Overall, the GFC can reproduce the trend reported by harvest removal data ($r = 0.62$), at least for the quota compared to the amount of harvest provided by clear cut, equal to about 48% of average annual removals reported by the country since 2004 (NFAP Poland)[70].

**Portugal.** Despite the very heterogeneous silvicultural systems applied at country level (including unevenly aged forests), the GFC is well correlated with official harvest removal data ($r = 0.75$). This is probably also due to the relatively high proportion of *Eucalyptus* plantations among all forest area, many of which are managed through clear cuts.

**Romania.** Large uncertainties in official harvest statistics[19,20], unregistered logging and the various silvicultural treatments applied at country level (including unevenly aged forest systems) considerably reduce the correlation between GFC data and the official harvest removal data ($r = 0.39$).

**Slovakia and Slovenia.** The GFC data can adequately reproduce the trend reported by harvest removal data ($r = 0.73$ for both these countries). This is also due to the specific management system applied at a national level, which is largely based on clear cut (for Slovakia, the annual share of harvest provided by the final cut is generally higher than 70%)[71].

**Spain.** Owing to the specific characteristics of this country, which is largely covered by unevenly aged forests that are managed through a single tree selection system, the GFC maps can only partially reproduce ($r = 0.44$) the trend reported by harvest removal data[72].

**Sweden.** The lack of correlation between the GFC data and harvest-removal data is probably due to: (1) when large disturbance events occurred, salvage logging (for sanitary reasons) had the priority on clear cut, the area of which was indirectly reduced (for this reason, probably, the GFC does not highlight the effect of the two windstorms that occurred in 2005 and 2007); (2) remote-sensing estimates and harvest statistics at the country scale may not show a statistical correlation because the biomass density per unit of area differs greatly over the country in space (that is, between the northern or southern part of Sweden); and (3) for this country, final felling covered (in terms of area) about 37% of the area annually affected by fellings between 2000 and 2015[56]. This area is not statistically correlated with the total amount of wood removed during the same period, as reported by the same data source ($r = 0.48$). Despite that, official statistics on the notified area (larger than 0.5 ha), affected by final felling are consistent with the GFC (see Supplementary Fig. 3) and highlight that the size of this area increased by 13% in 2018 in comparison with the previous year, and compared with the average of the period 2011–2015, increased by nearly 17%. Considering that these statistics only report the "notified area larger than 0.5 ha"[56], whereas the GFC probably includes a broader share of management practices, we can infer that in Sweden the GFC maps adequately represent the variation in the relative amount of area affected by final felling.

**United Kingdom.** Overall, the GFC maps can reproduce the trend reported by harvest removal data ($r = 0.44$). Some peaks reported by the GFC in 2012 could be due to the indirect effect of exceptional fires that were not properly filtered out by the preliminary analysis performed on these disturbances[73].

Inconsistency between remote-sensing-based estimates (that is, the harvested area) and national statistics on harvest removals may be due to the specific silvicultural practices of the country and to the accuracy and time resolution of official harvest statistics. Concerning specific silvicultural practices, owing to the spatial scale of the GFC dataset, the detected harvested area is limited to management schemes that lead to the complete removal of trees on a minimum spatial scale of 30 m. Small-scale silvicultural practices such as thinning or selective logging—which are relevant in some EU countries—could therefore not be fully detected. The second aspect refers to the limitation of official statistics, which in some countries may be suboptimal because they are infrequently updated or are incomplete owing to unregistered or illegal logging. In these cases, the use of independent remote-sensing data, such as that provided by this study, could help in improving and act as a complement to national statistics.

We also performed a country-based assessment on the impact of thinning and selective logging on the total harvest (Supplementary Table 1). In this analysis, we reported the share of final cut for the managed area or, in the case of the Carbon Budget Model[17], volume from the evenly aged forests. National statistics highlight how thinnings or selective logging (on evenly and unevenly aged forests, respectively) is relevant only for a few EU countries (for example, Italy, France, and Croatia, as indicated in the previous sections). Also, low values of the share of clear cut (for example, as in Italy) may not hamper GFC statistics, because they partially include forest thinnings and other silvicultural practices such as salvage logging.

### Potential drivers of change in harvested-forest area

Increasing harvest demand, as detected by our study, is potentially due to the combined effect of endogenous and exogenous drivers.

**Endogenous drivers.** are those deriving from forest characteristics (such as age–class distribution) that may affect the amount and temporal dynamic of the wood available for harvest even under a constant management system.

**Exogenous drivers.** include on one hand natural disturbances such as forest fires, heavy snow load and windthrow (which affect both the age structure and management practices), and, on the other hand, political, social or economic factors that lead to a modification of management practices applied with respect to a reference period, for example, to satisfy an increasing wood demand.

Quantifying and disaggregating the impact of the single drivers is challenging. Taking into account the effect of ageing and assuming the continuation of current management practices applied by the 26 studied EU countries between 2000–2009, it is estimated that, at the EU level, harvest volumes are expected to increase by 9% in the period 2021–2030 relative to the period 2000–2009[23]. Assuming a gradual increase in the harvest owing to ageing we should therefore expect a 0.45% increase per year. Similarly, another work[74] foresees a sustainable increase in harvest of 19%, owing to ageing, for the period 2009–2050 (equivalent to 0.46% per year).

Considering that the increase observed with satellite records occurred in the latter half of the decade (2016–2018), we estimate that over this timespan a maximum increase of about 4% by volume could be ascribed to forest ageing, which corresponds to about 8% of the observed increase in the harvested biomass. From this we can infer that endogenous drivers, as defined above, have had only a minor role in the recent sharp increase in harvest and that exogenous factors dominated.

Among exogenous drivers, the expansion of activities on the basis of demand for wood products (economic drivers) might have affected the forest sector, as reported in official statistics from UNECE and FAO[33] and Eurostat[75]. In fact, forest harvest is unlikely to increase when there is no rise in market demand for wood products. In northern and central–eastern Europe, where the relative contribution of the forest sector to GDP is the largest (2.1% and 1.3%, respectively, in 2010)[1], the higher demand from sawmills during the last years was probably one of the major drivers of the increasing timber harvest[33]. For example, in Croatia sawn-hardwood production grew by 89% in the five years to 2017, and in the Czech Republic and Slovakia particleboard production grew by 10% and 6.5%, respectively, in 2017 compared with the previous year[33]. In addition, fuelwood removals increased at the EU26 level from around 70 $\mathrm{Mm}^3$ to about 99 $\mathrm{Mm}^3$ (+41%) between 2000 and 2015[76]. UNECE[33] also confirms a substantial increase of EU harvest in 2013–2017 compared to 2007, with three countries standing out: Poland (+19.5%), Finland (+12.2%) and Sweden (+7.5%).

International trade, sometimes linked to political factors, may also affect the harvest demand at the national level. This was, for example, the case in some north European countries (such as Finland and Estonia), where, since 2009, the collapse of exports of roundwood from Russia indirectly affected internal harvest demand. Conversely, in some central European countries (such as the Czech Republic, Hungary and Slovenia), exports have strongly increased since 2014, encouraged not only by increasing roundwood demand coming from Germany (where imports increased by 30% since 2014), but also by from other EU26 countries (such as the UK and Croatia), and more recently, from China.

Concerning the increase in wood demand and its market, in the EU the application of the 'Energy from Renewable Sources' directive[35] and the bio-economy strategy[34] (started in 2012) are setting binding targets and increasing wood demand for bioenergy needs, with an established target of at least 32% renewable energy by the year 2030[34]. Specifically, the EU renewable energy directive[35] raised concerns about increasing harvested wood for bioenergy use[36]. In the ongoing shift from coal to biomass, wood is currently responsible for more than 60% of the renewable energy supply in Europe[75].

The outputs of forestry and connected secondary activities (Extended Data Fig. 7) increased by 13% in EU28 from 2012 to 2016[32], whereas in countries that show the largest increases in harvest—such as Poland, Portugal, Romania, Slovenia, Finland and Sweden—the rise was almost twofold (even if, for all these countries, statistics refer to the period 2008–2016).

The percentage of change in harvest area from 2008 to 2016 (or from 2012 when 2008 data is not available) as retrieved from remote sensing and from forestry market statistics are reported in brackets in the labels of Extended Data Fig. 7. Note that the quality of the Eurostat data varies from country to country, and some outliers (for example, France in 2014) seem questionable. Both UNECE and Eurostat indicators on wood products are heavily influenced by many other factors that can independently affect the true amount of forest harvest. However, these statistics give an overall indication of existing trends and potential drivers.

Concerning the potential effects of policy changes, the key role of the forest sector within the bioeconomy market has been supported by specific political initiatives in several EU countries. For example, this is the case in Slovenia, where specific financial incentives have actively supported the forest sector during recent years[77]. By contrast, in Sweden[78], as in other north European countries where production subsidies were abolished, the increase in felling during recent years is probably due to the increasing demand for forest raw materials by the forest industry.

A relevant recent element in the policy context is the EU regulation for the Land Use, Land Use Change and Forestry sector in the EU 2030 climate target[37], which aims to improve the assessment of the carbon impact of additional actions in "managed forest land"[23]. This regulation sets forest reference levels: country-based estimates of greenhouse gas emissions and removals in managed forest lands. The regulation has been strongly debated in scientific and policy contexts, and sometimes perceived as a possible limitation on potential future increases in harvest[79,80]. This knowledge might have triggered a more rapid increase in forest harvest in some countries, compared with what would have otherwise occurred. However, we could not find any direct evidence that this EU regulation is a reason for the increase in harvest.

A final set of exogenous drivers that may have affected forest-harvest intensity include natural disturbances such as windstorms, heavy snow load, forest fires and pest outbreaks. If the medium-term trend is mainly controlled by economic, political and legislative factors, salvage logging can represent the main driver affecting year-to-year fluctuations in total harvest at the country, regional or even at the EU level. As highlighted in Extended Data Fig. 7, this was the case in Austria (2007–2008), Czech Republic (2016–2018), France (2009–2010), Finland (2017–2018), Germany (2007 and 2010), Slovakia (2005), Slovenia (2014) and Sweden (2005 and 2007). Estimating the effect of natural disturbances on harvest statistics is challenging, because a fraction of the biomass will be directly removed through salvage logging, and the remaining will be harvested during the following years through normal silvicultural practices such as thinnings and clear-cuts. Despite this uncertainty, it is important to notice that at the EU level the amount of harvest owing to salvage of storm residue is somewhat limited. For instance, in the period 2000–2012 forest harvest owing to storms was on average equal to 13 $\mathrm{Mm}^3\,\mathrm{yr}^{-1}$—that is, about 2.7% of the average total amount of harvest removed within the same period[17]. These events can generate large spatial and inter-annual variability so that at the country scale and for selected years the importance of salvage logging can be very relevant. For example, for the Czech Republic, the share of harvest provided by salvage logging in 2007 and 2017 was equal to about 83% and 60%, respectively. However, during the recent years characterized by an abrupt increase of harvest rate, there have been no major windthrow events at the European scale that may have contributed substantially to the observed trend. Moreover, as highlighted above, generally there is a mutual relation between salvage logging (for sanitary reasons) and ordinary management practices (such as clear cut) the affected area of which is indirectly reduced when large disturbance events occur.

Summarizing these considerations, we can conclude that the largest share (up to 90%) of the increasing amount of harvest detected during recent years is most probably due to exogenous drivers, whereas about 10% was the result of forest ageing. At the European scale, natural disturbances (which have probably affected inter-annual variations and trends) have been factored out from the analysis. Ultimately, recent changes in socio-economic and political contexts are thus the most probable driver of the observed patterns.

### Above-ground biomass analysis

AGB values for harvested forest were obtained from ESA GlobBiomass, a global dataset of forest biomass at a resolution of 100 m for the year 2010[27]. Specifically, the AGB analysis quantifies the mass of all living trees excluding stump and roots, expressed as the oven-dry weight of the woody parts (stem, bark, branches and twigs) in units of $\mathrm{Mg\,ha^{-1}}$. The AGB estimates were obtained from space-borne synthetic-aperture radar (ALOS PALSAR, Envisat ASAR), optical (Landsat 7), lidar (ICESat) and auxiliary datasets with multiple estimation procedures[27]. The AGB map was resampled at the spatial resolution of the GFC (that is, resampled from 100 m to 30 m) and (as the AGB map refers to 2010) to update it to the year of forest loss from 2011 onwards, we assigned an AGB value of zero to those pixels with forest loss, meaning that forest loss was considered as a total AGB loss.

Forest biomass growth was retrieved from ref. [1]. The average biomass growth rate (Gr, expressed as an annual percentage) has been computed for five geographical regions in Europe (north, central west, central east, south west and sout east; see Extended Data Fig. 10a) as

$$\mathrm{Gr} = \frac{\mathrm{Gs}_{2015} + F_{2010\text{–}2015} - \mathrm{Gs}_{2010}}{\mathrm{Gs}_{2010}} \times \frac{1}{\mathrm{Ys}} \tag{3}$$

$\mathrm{Gs}_{2010}$ and $\mathrm{Gs}_{2015}$ are the total growing stock in 2010 and 2015, respectively, Ys is the number of years between 2010 and 2015 (five) and $F_{2010\text{–}2015}$ is the total amount of fellings removed within the same period. We converted relative into absolute biomass growth rates (from percentage to t ha$^{-1}$ yr$^{-1}$) on the basis of the AGB map and forest-area estimates by country from the GlobBiomass[27] and GFC[21] datasets, as shown in Extended Data Fig. 10b. As expected, the results show that absolute growth rates are higher in the temperate forests of central Europe and lower in boreal and Mediterranean regions.

Again, regions affected by forest fires (from EFFIS data) and major windstorms were excluded from our analysis. We note that resampling the biomass data from 100 m to 30 m is an approximation that introduces uncertainty in the biomass-loss estimates.

The analysis of AGB loss was carried out at the European and country level. Extended Data Fig. 8 shows the percentage of AGB harvested per year in a 0.2° grid cell, Supplementary Fig. 2 shows the pixel-wise $R^2$ regression between harvested forest area and biomass, and Supplementary Fig. 4 shows the percentage national contribution of the European harvested forest biomass during 2016–2018.

As expected, the pixel-wise correlation between harvested forest area and harvested forest biomass is high over the spatial domain (Supplementary Fig. 2), because harvested forest area and biomass are closely linked.

Supplementary Figs. 5 and 6 show the average harvested area for five biomass-density classes for the period 2011–2015 (left) and 2016–2018 (right) for Finland, Sweden, Poland and Italy. The patterns of Supplementary Fig. 5a show that the contribution of evergreen forests in the AGB range 50–150 t ha$^{-1}$ dominate, whereas the contribution from forests with very high AGB (that is, greater than 150 t ha$^{-1}$) is negligible. Sweden (Supplementary Fig. 5b) shows patterns that are similar to those in Finland, although the quota of harvested biomass greater than 200 t ha$^{-1}$ is higher. Conversely, Poland (Supplementary Fig. 6a) exhibits a dominance of mixed forests in the range 100–200 t ha$^{-1}$, indicating a different distribution of forest age and structure.

### Cloud-computing platform: Google Earth Engine

Google Earth Engine is a cloud-based infrastructure that enables "access to high-performance computing resources for processing very large geospatial datasets"[22]. It consists of "a multi-petabyte analysis-ready data catalogue co-located with a high-performance, intrinsically parallel computation service"[22]. The data catalogue hosts a large repository of publicly available geospatial datasets, including the Landsat archive, the GFC maps[21], and land-cover, topographic and socio-economic datasets. From 2015, the Copernicus Sentinel sensor data are also included. The catalogue is accessed and controlled through an Internet-accessible application programming interface (API) that enables prototyping and visualization of results.

All data extraction for this study was performed in Google Earth Engine, which provides the ability to compute pixel-level or country-based statistics and analyse the entire data records of the GFC maps as well as ancillary land cover data with high computational efficiency, and without the need to retrieve and download huge amounts of data.

## Data availability

To ensure full reproducibility and transparency of our research, we provide all of the data analysed during the current study. The data are permanently and publicly available on a Zenodo repository, https://doi.org/10.5281/zenodo.3687090.

## Code availability

To ensure full reproducibility and transparency of our research, we provide all of the scripts used in our analysis. Codes used for this study (Google Earth Engine and R scripts, the harvest-removals dataset and shapefiles of the validation) are permanently and publicly available on a Zenodo repository, https://doi.org/10.5281/zenodo.3687096.

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**Competing interests** The authors declare no competing interests.

**Additional information**

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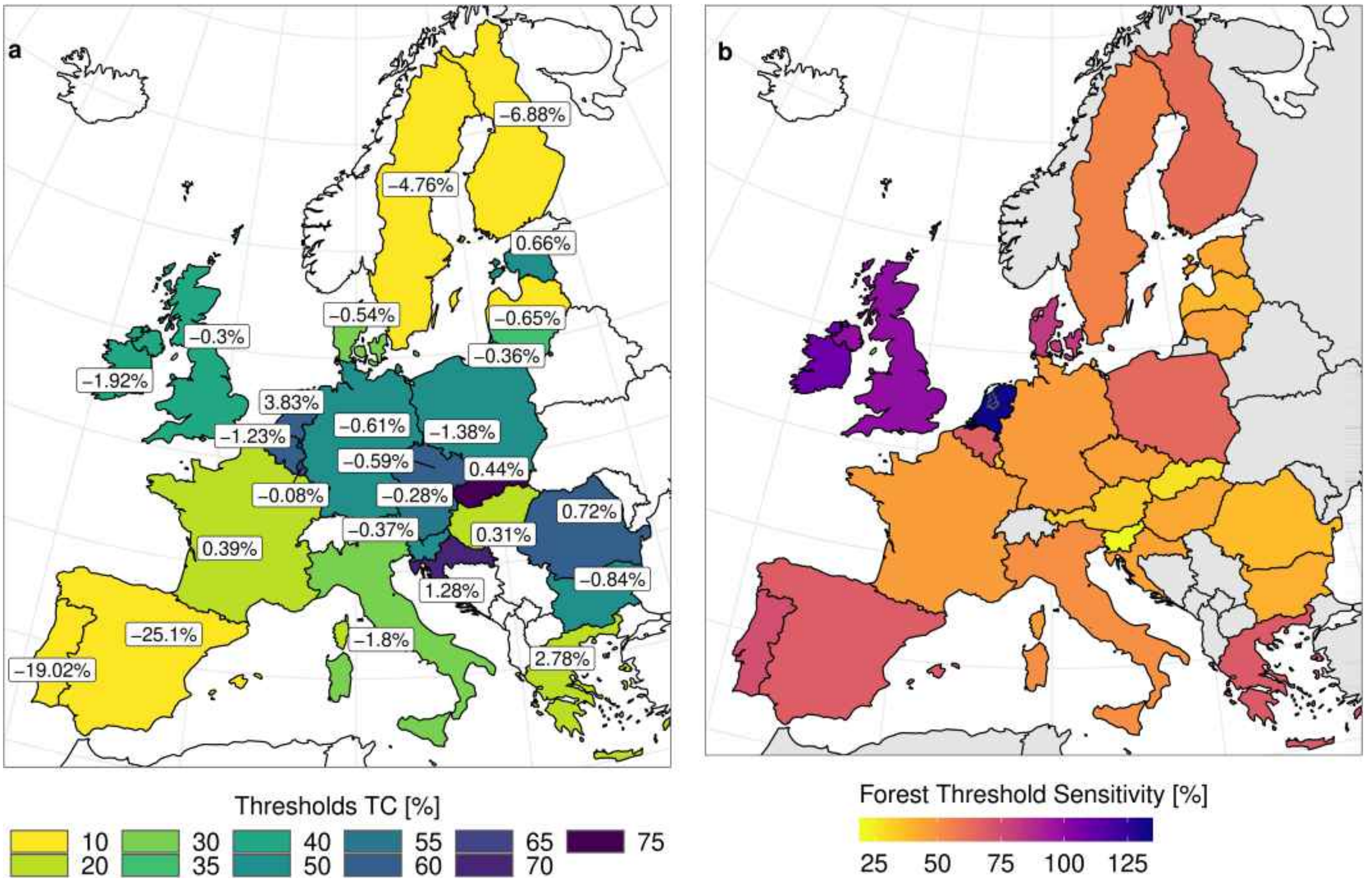
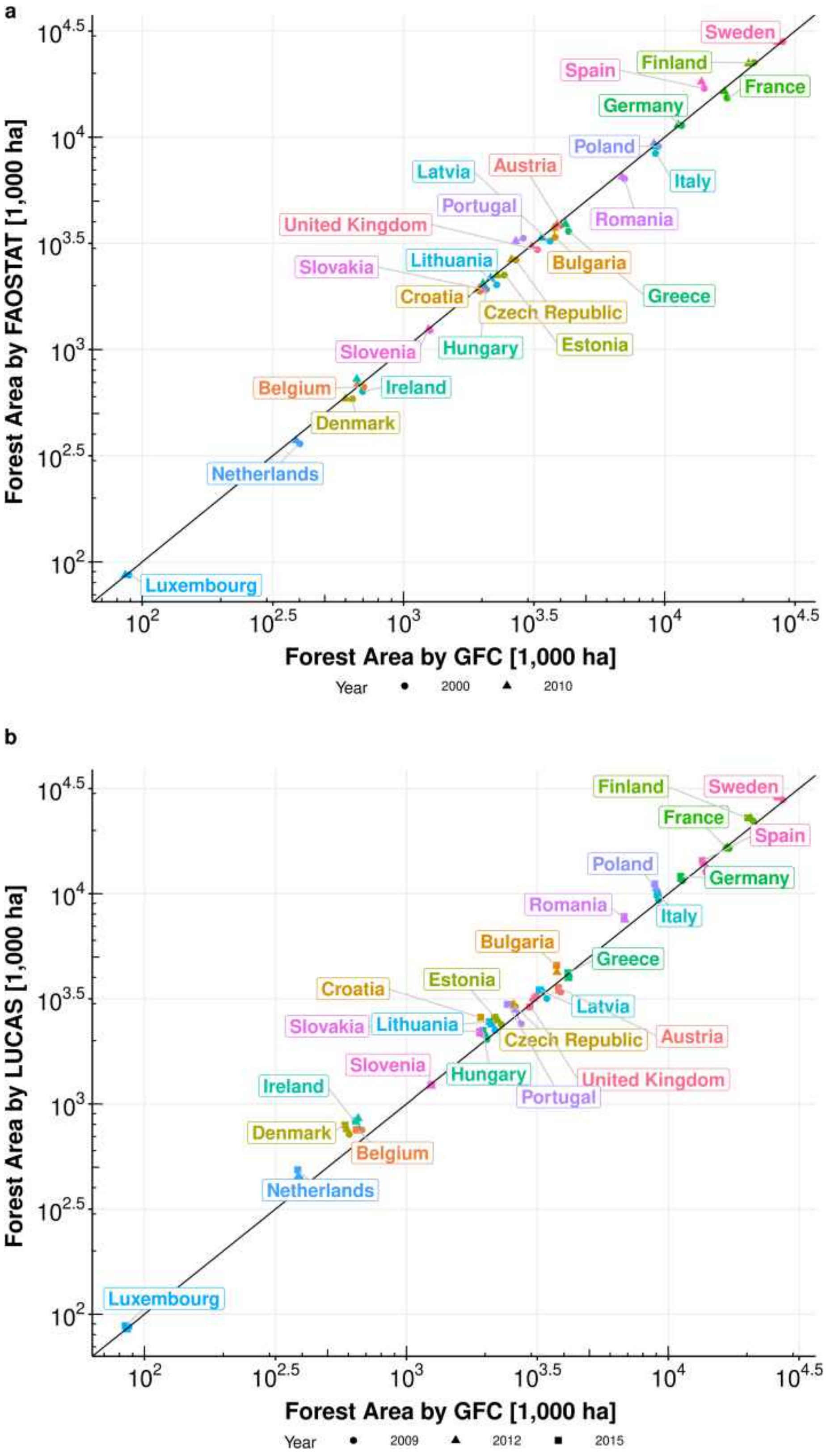
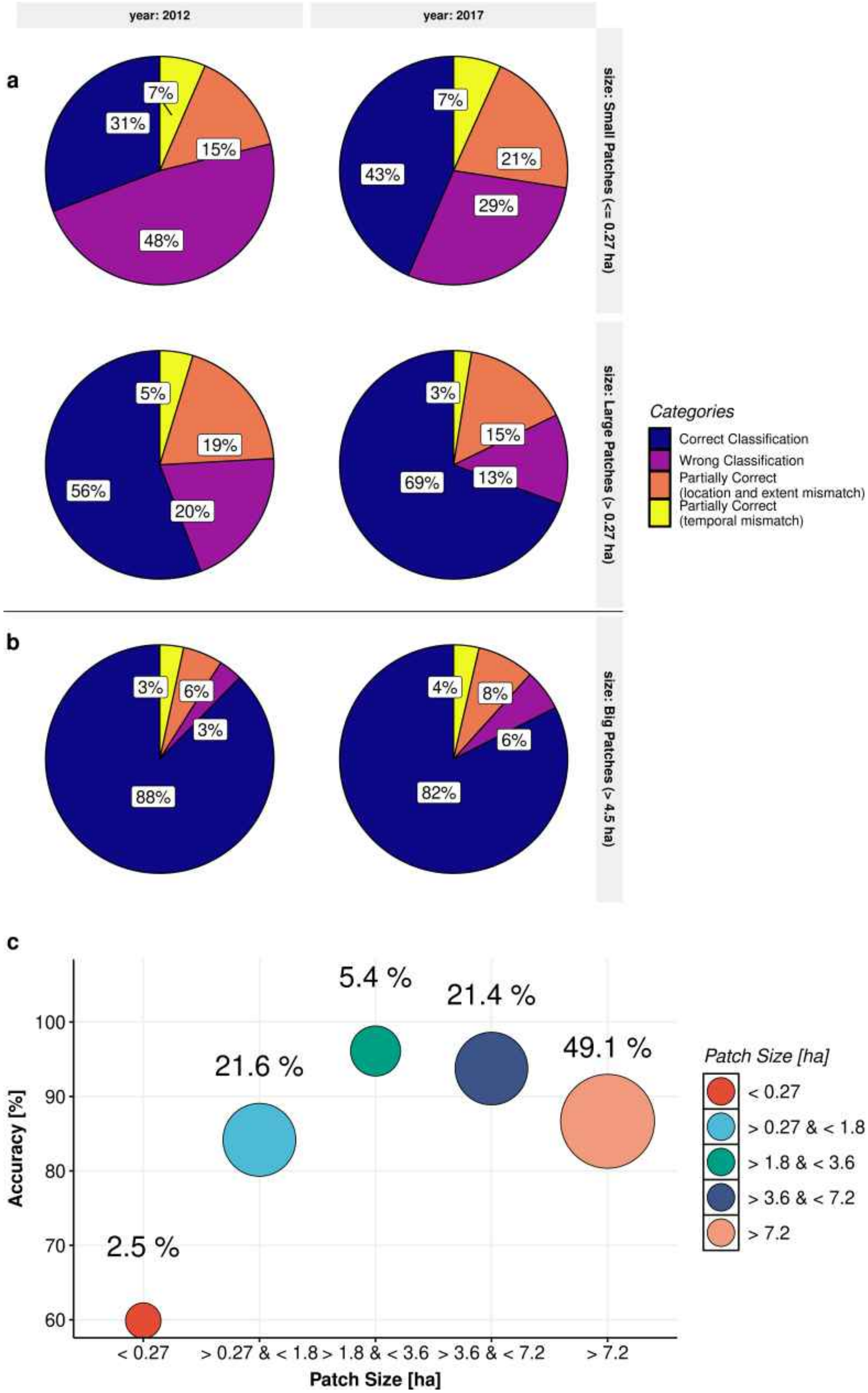


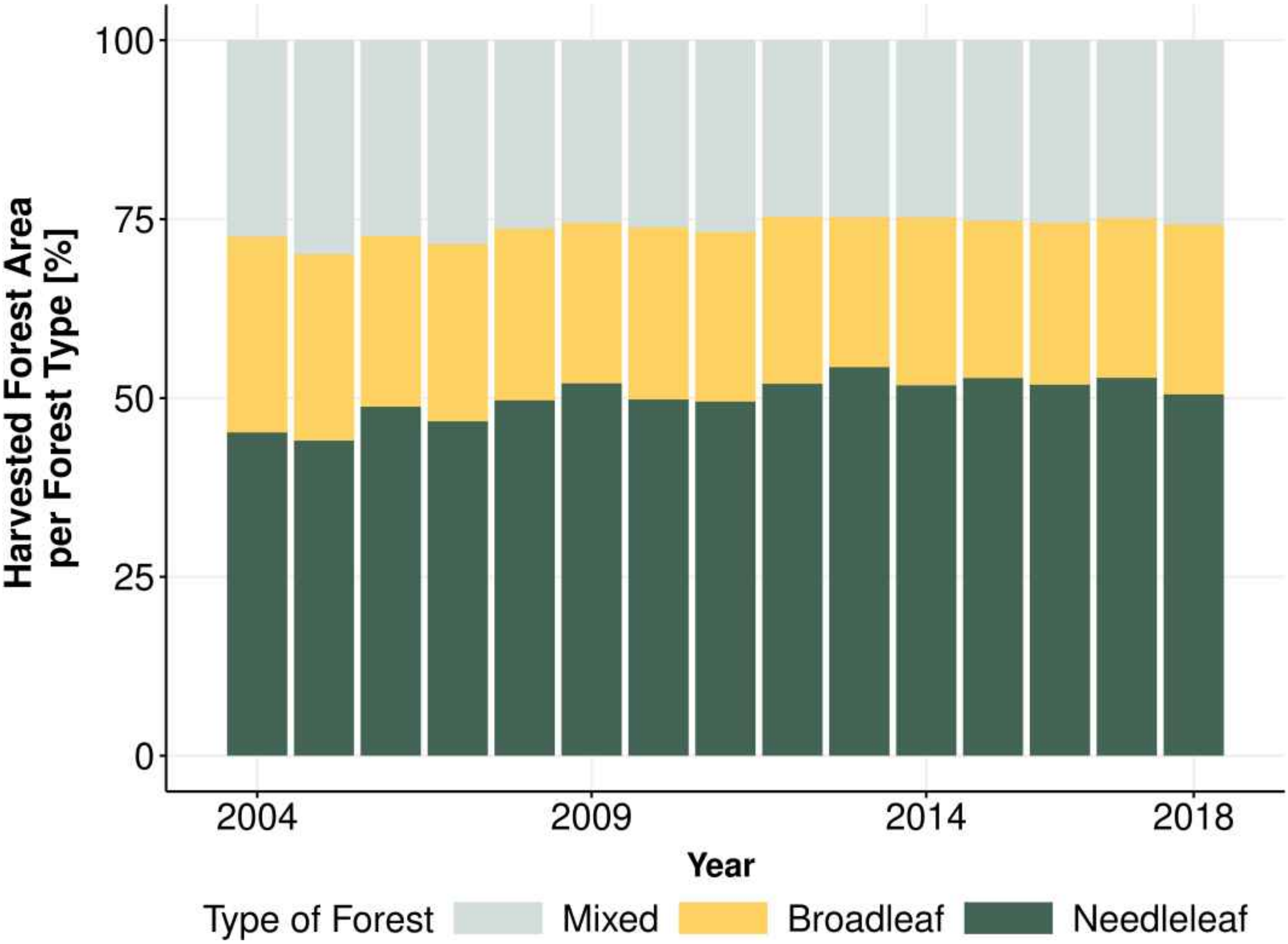
**Extended Data Fig. 1 | From tree cover to forest cover. a**, Tree-cover threshold needed to define a forest (colours) and percentage error between FAOSTAT-2015 and remote-sensing-based forests (labels). **b**, Forest threshold sensitivity. Maps were generated using GEE[22].



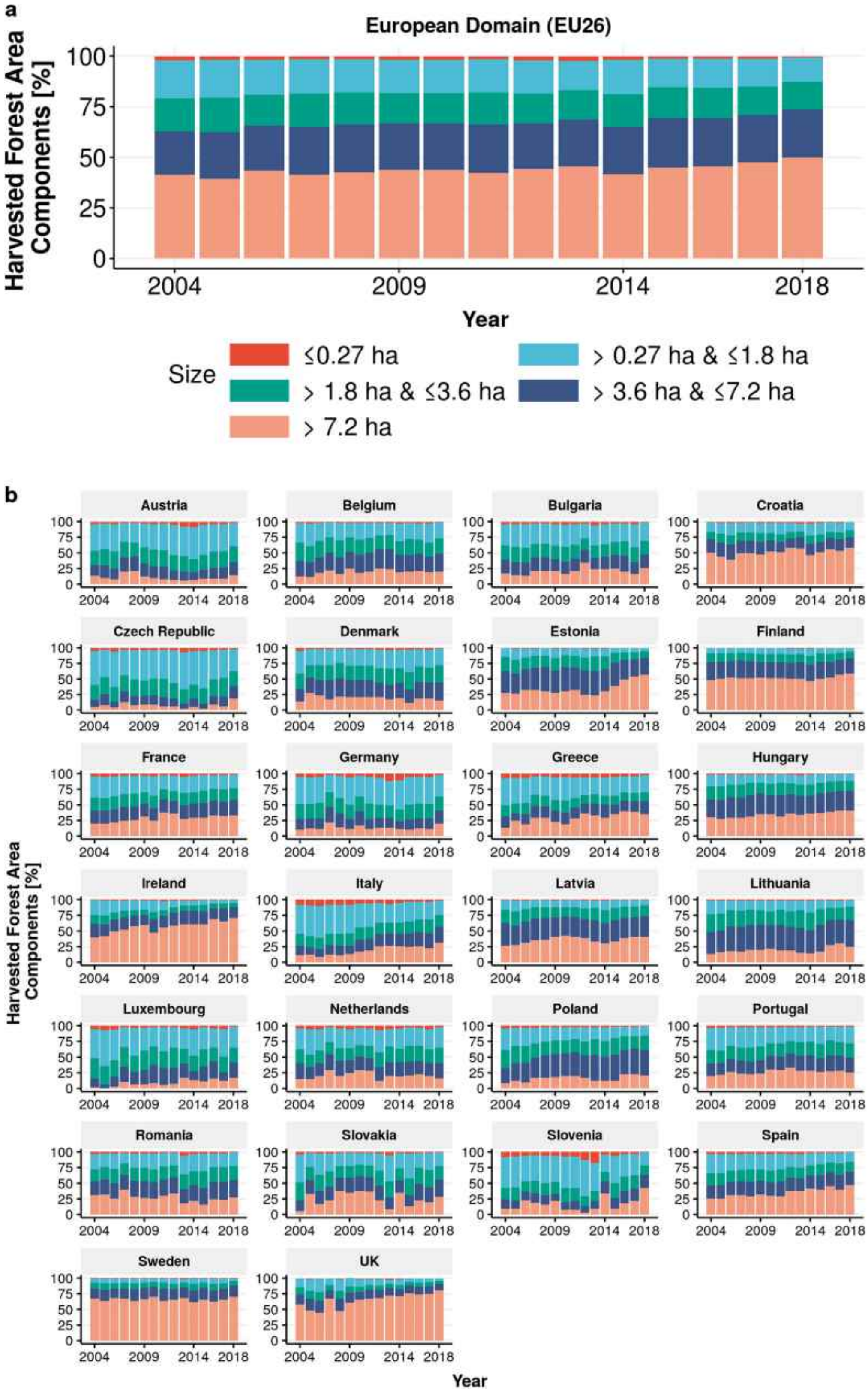
**Extended Data Fig. 2 | Verification of EU forest area. a**, GFC data versus FAOSTAT for 2000 and 2010. **b**, GFC data versus LUCAS for 2009, 2012 and 2015.



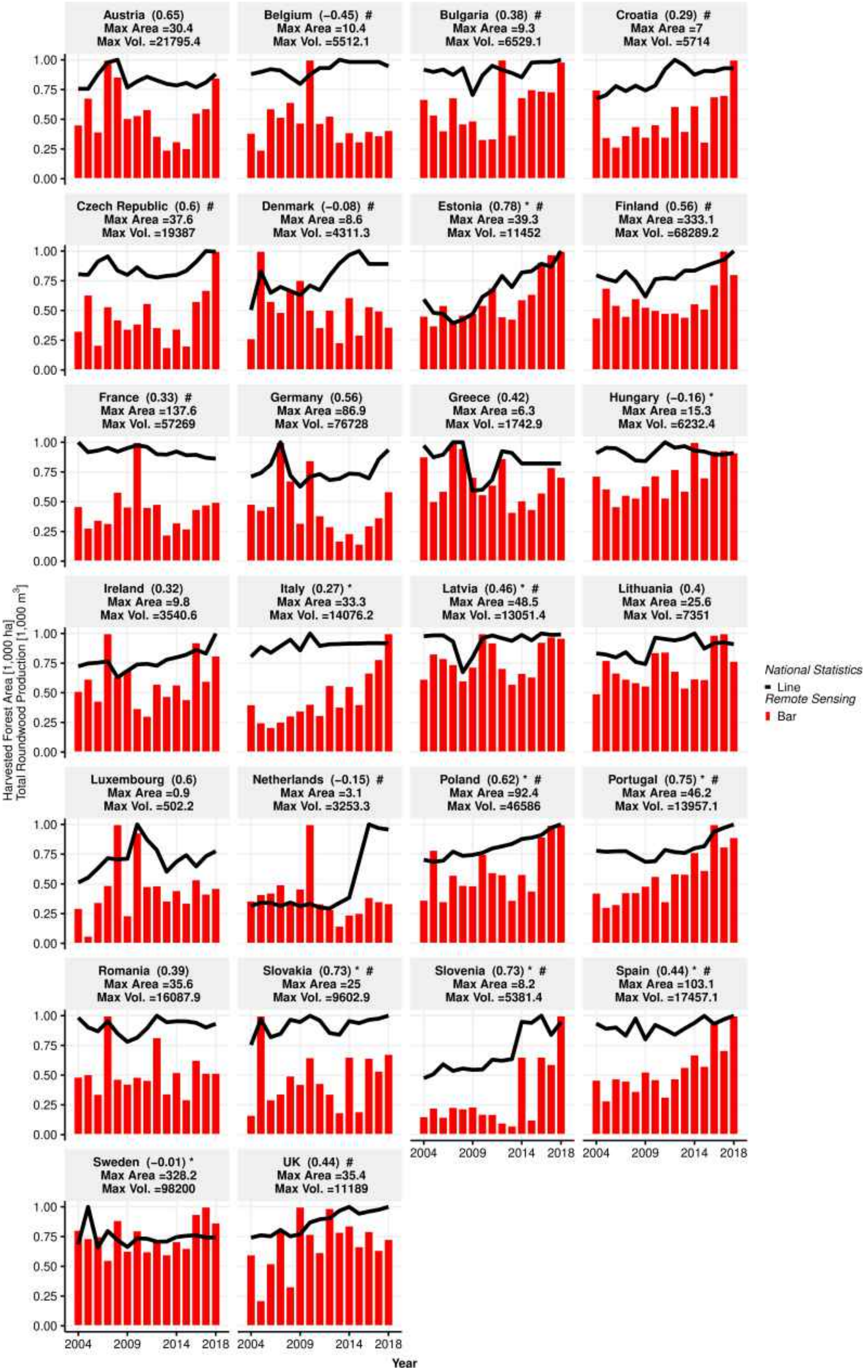
**Extended Data Fig. 3 | Validation of GFC-derived forest loss with high-resolution data. a**, **b**, Validation of the classification of harvested areas in the years 2012 and 2017 by forest patches of sizes small (≤0.27 ha) and large (>0.27 ha and ≤4.5 ha; **a**), and big (>4.5 ha; **b**). **c**, Accuracy of harvest area derived from GFC-derived forest loss versus patch size (labels and circle size refer to the EU26-wise cumulative harvested forest).



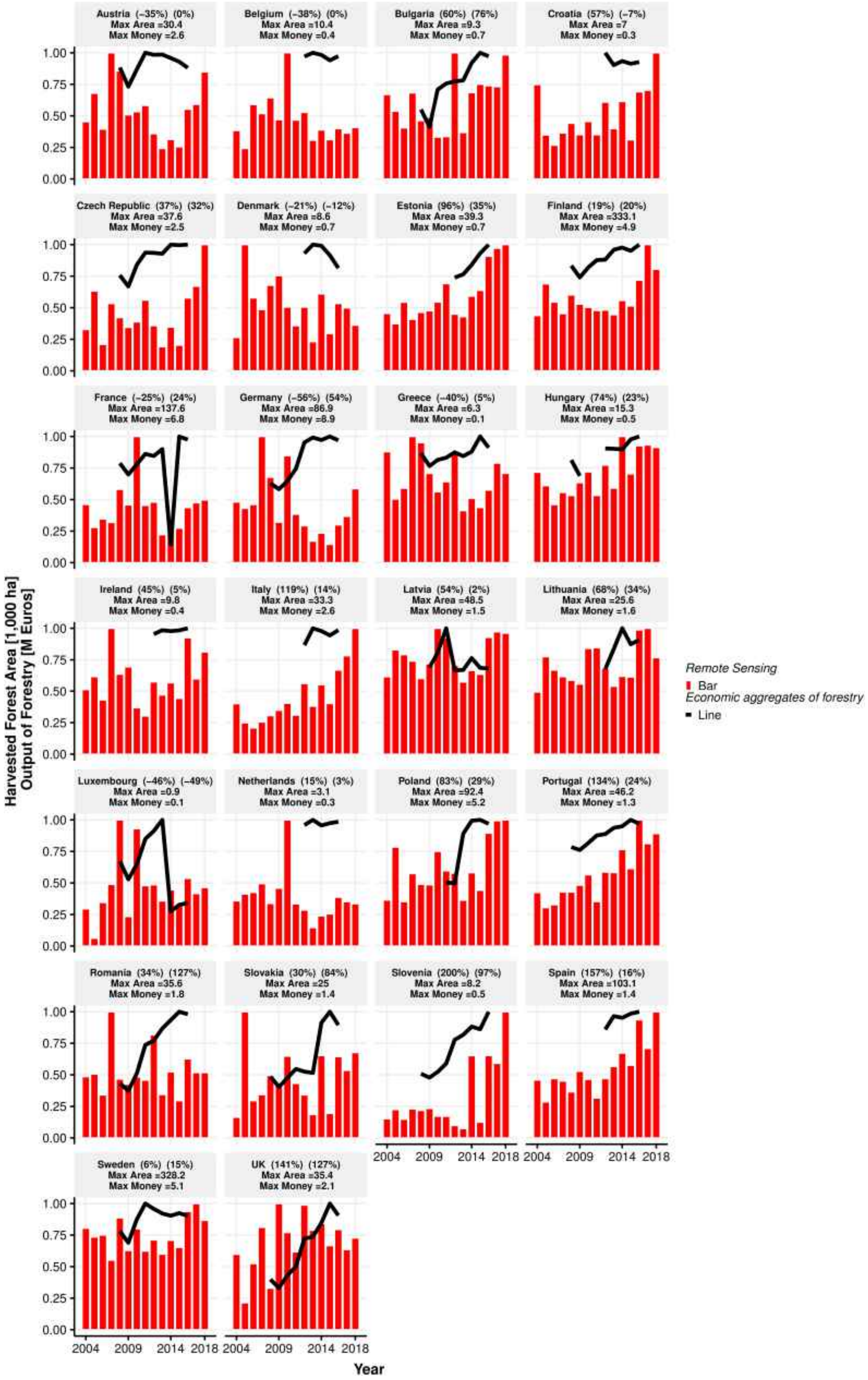
**Extended Data Fig. 4 | Harvested forest area by forest type.** Time series of land cover type (from GlobCover)[25] for EU26. Colours refer to the three forest types: mixed, broadleaf and needleleaf.



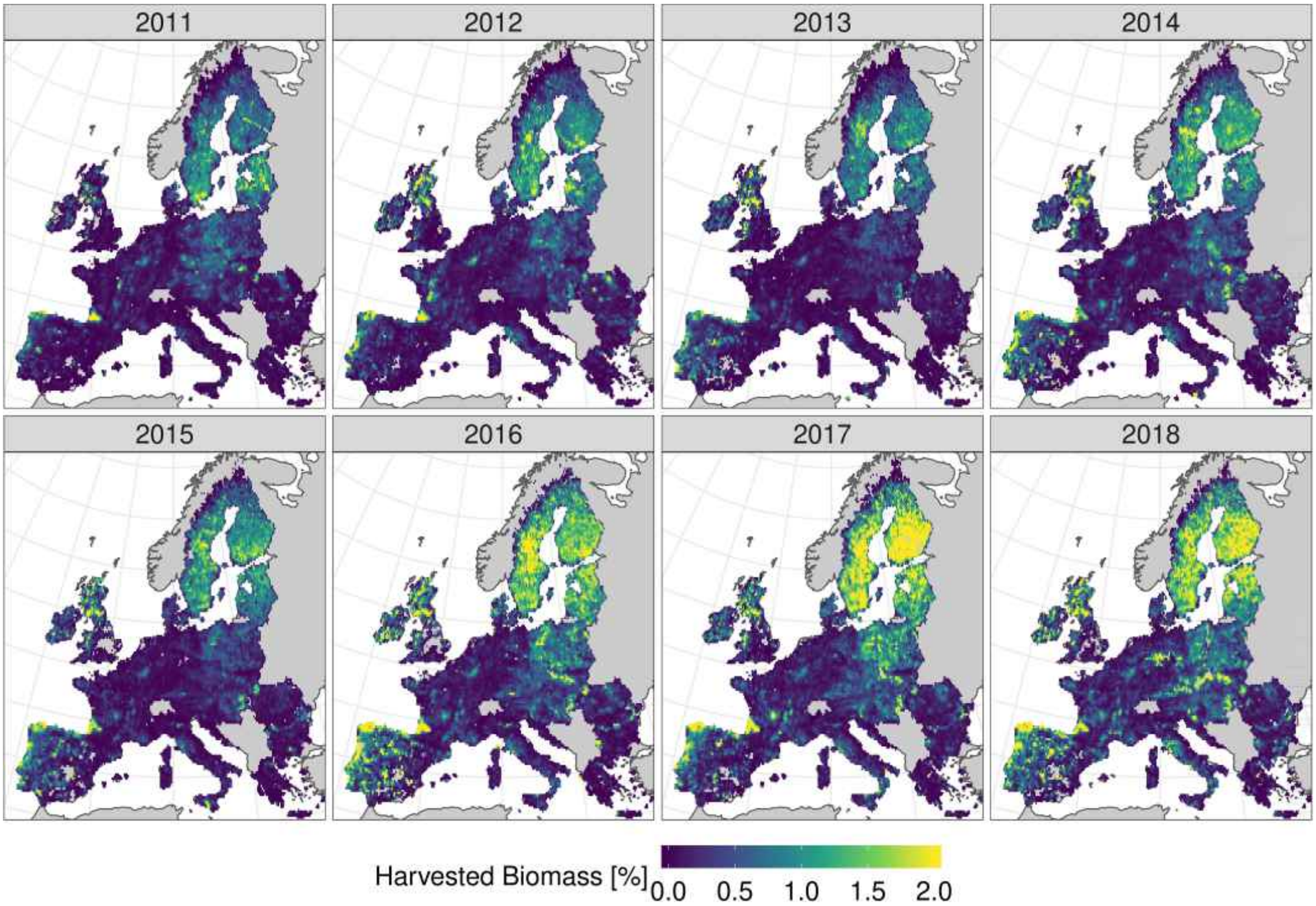
**Extended Data Fig. 5 | Harvested forest area components. a**, **b**, Annual distribution of harvested forest for different classes of patch size, ranging from small patches (harvested forest area less than 0.27 ha) to big patches (harvested forest area greater than 7.2 ha) for all of EU26 (**a**), each EU26 country (**b**).



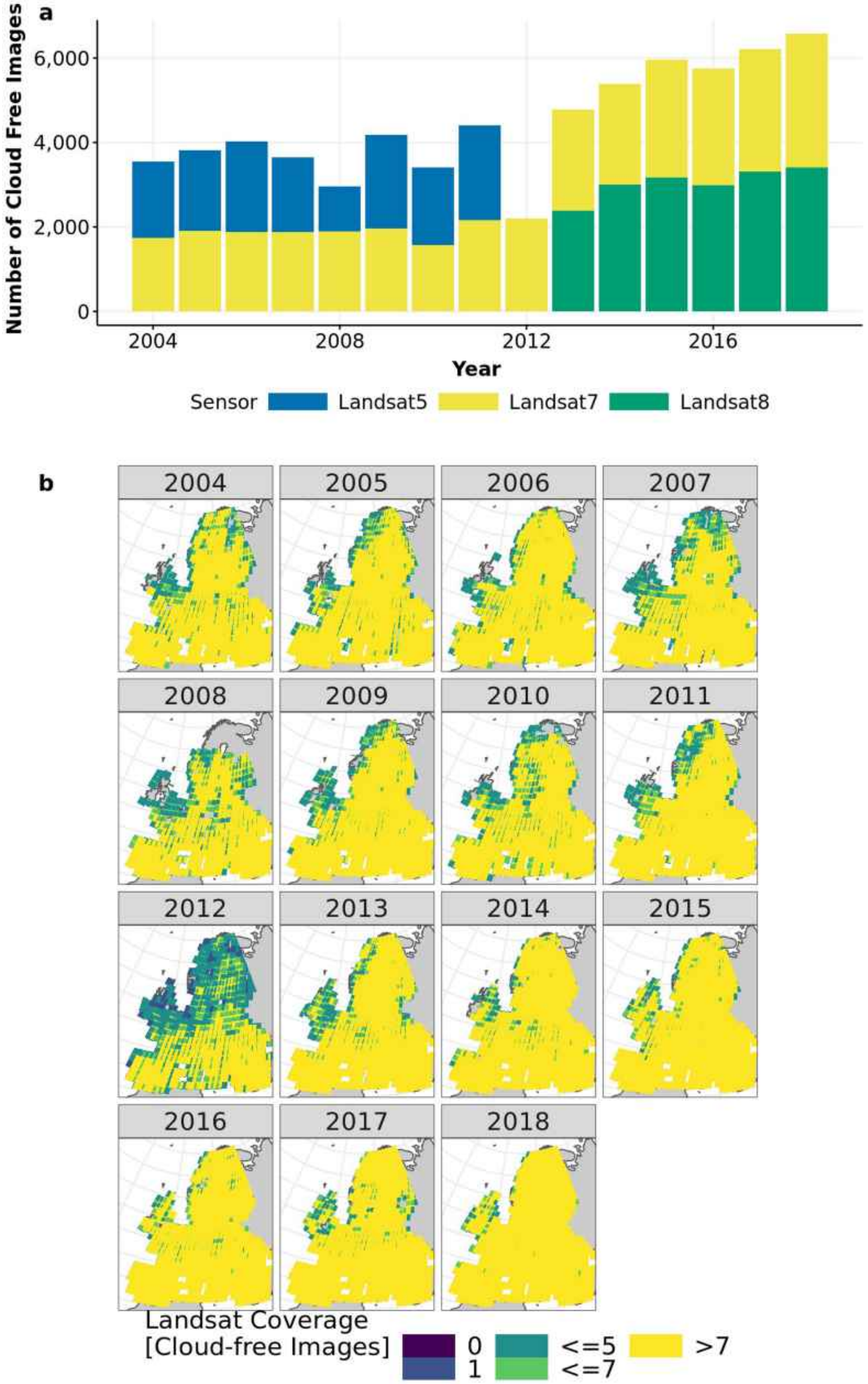
**Extended Data Fig. 6 | GFC-derived harvested forest area versus official harvest removal data.** Harvested forest area from the GFC maps (red bars, normalized between 0 and 1) and volumes of harvest removals from national statistics (black lines, normalized between 0 and 1). We excluded areas affected by forest fires and retained areas affectedby major windstorms because they appear in the harvest removal data. Statistical significance at $P = 0.05$ for remote sensing and national statistics is indicated by an asterisk and a hash, respectively, in the country label panels. The value in brackets is the correlation coefficient, $r$. Maximum values of harvested forest area and official harvest removal data for each country are reported in the second and third lines of each label, respectively.



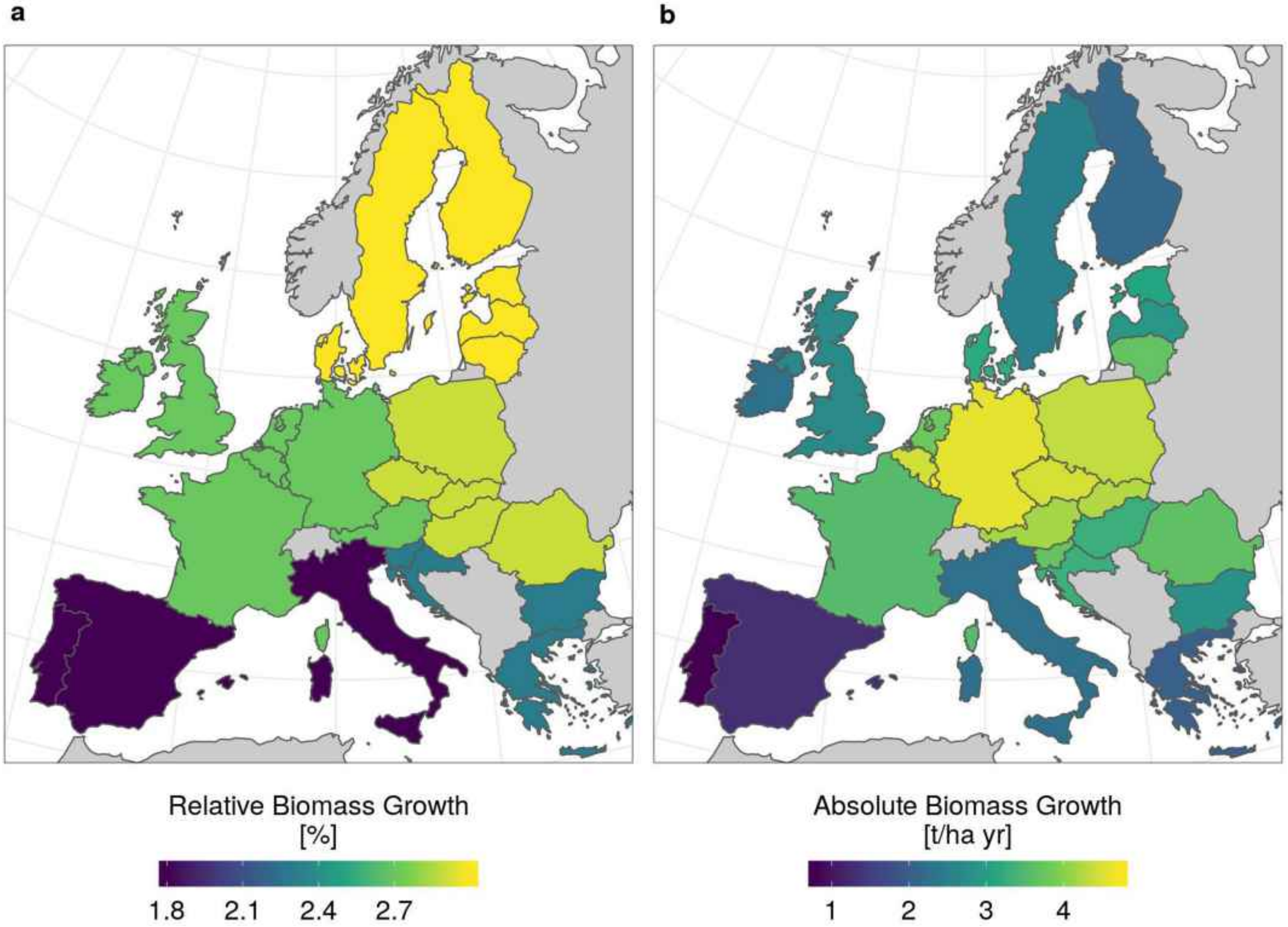
**Extended Data Fig. 7 | Harvested forest area versus Eurostat[32] economic aggregates.** Harvested forest area from the GFC maps (red bars, normalized between 0 and 1) and volumes of economic aggregates of forestry from Eurostat data (black lines, normalized between 0 and 1). We excluded areas affected by forest fires and retained areas affected by major windstorms because they appear in the harvest removal data. Percentages in the first and second brackets after the country label refer to the percentage change 2008–2016 (or 2012–2016 when 2008 records are not available) of remote sensing and market value, respectively. Maximum values of harvested forest area and volumes of economic aggregates of forestry for each country are reported in the second and third lines of each label, respectively.



**Extended Data Fig. 8 | Harvested forest biomass per year.** Percentage of AGB harvested (expressed as relative amount of biomass affected by management practices) per year in a 0.2° grid cell excluding forest losses due to fires and major windstorms and areas with sparse forest cover. As in Fig. 1 but measuring biomass instead. This map was generated using GEE[22].



**Extended Data Fig. 9 | Cloud-free land coverage of Landsat in Europe.** **a**, Time series of cloud-free Landsat scenes (cloud cover less than 20%) for EU26. **b**, Spatial distribution of cloud-free Landsat images over Europe. Grey areas indicate where no data was available for the selected year using satellite imagery. Map and time series were generated using GEE[22].



**Extended Data Fig. 10 | Growth rates of forest biomass. a**, **b**, Relative (**a**) and absolute (**b**) growth rate of forest biomass as derived from the *State of Europe's Forests 2015* report[1] in combination with GlobBiomass[27] and GFC[21] data. The data in **a** are given over five European regions, with colours corresponding to the colour scale: north (yellow), central west (green), central east (lime), south west (purple) and south east (blue). Maps were generated using GEE[22].