Abrupt Increase in Forest Harvested Area over Europe After 2015

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Abstract:

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 to achieve climate neutrality by 2050 [2]. However, the increasing demand for forest services and products driven by the bio-economy is posing new challenges to the sustainable forest management. Here, we use fine-scale satellite data to show a striking increase of the forest harvested area (+49%) and biomass loss (+69%) over Europe for the period of 2016-2018 relative to 2011-2015, particularly for the Iberian Peninsula and the Nordic and Baltic countries. Satellite imagery further reveals that the average harvested patch size increased by 34% across Europe, with potential impacts on biodiversity, soil erosion, and water regulation. The increase in harvest rate is resulting from the recent expansion on the wood markets, as emerging from econometric indicators on forestry, wood-based bioenergy and international trade. If such a high rate of forest harvest continues, it might hamper the post-2020 EU vision on forest-based climate mitigation, and the additional carbon losses from forests would require extra emission reductions in other sectors so as to reach climate neutrality in 2050 [3].

Main

Forests provide a series of both tangible and intangible services to society and human well-being, ranging from the production of raw materials, the regulation of water flows, the protection of soils and the conservation of biodiversity [4]. In the European Union (EU), forests account for approximately 38% of the total land surface, out of which more than 95% are managed [1] with practices that broadly vary across countries [5,6]. Emerging wood markets driven by the bio-economy 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 as a key asset to meet climate mitigation targets [2]. Despite mixed biophysical impacts of forests on climate [8–10], carbon sequestration (i.e. forest carbon sink) remains the most important negative climate forcing provided by forests at the global level [11]. In addition, further mitigation by the forest sector 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 the enhancement of the anthropogenic forest sink is an important element in the Paris Agreement, as it is 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 EU Green Deal [13], the EU's forested area needs to improve, both in quality and quantity, to reach climate neutrality and a healthy environment.

The forest carbon sink in the EU has remained rather stable over the last 25 years and currently offsets about 10% of the total EU greenhouse gas emissions [14]. Most of this sink occurs in the living biomass, directly reflecting the difference between forest growth on one side and harvest, mortality and natural disturbances on the other. The harvest rate is, therefore, a key parameter in forest management since it largely controls the forest carbon budget [15,16] and a series of additional ecosystem services like the conservation of biodiversity, soils, and water resources. In recent decades, harvested volumes in Europe's forests have been substantially lower than the net annual increment in growth[17], resulting in an increasing carbon stock. Given the fundamental relevance of the harvest rate, timely, consistent and robust assessments of its spatial patterns and temporal trends are required so as to inform management policies and track economic and environmental progress towards a sustainable bio-economy. Yet, official annual forest harvest statistics typically do not cover the most recent years, their estimates are usually provided at a rather coarse spatial scale (national or regional administrative units) and in some cases they are not regularly updated nor complete [18,19].

Nowadays, the combination of high-resolution satellite records and cloud-computing infrastructures to handle big data provides a complementary asset to quantify forest harvested area that is independent from official statistics and overcomes some of the limitations of national inventories. Based on these datastreams and information technologies, we assessed the recent changes (2004-2018) in forest harvest area based on the Global Forest Change layer (GFC)[20], a map product at 30 m resolution based on the Landsat satellite that provides yearly estimates on tree cover and its loss (details in Methods 'Forest mapping'). This evidence-driven assessment targets three questions: i) following the recent boost in the bio-economy, is the forest harvested area changing throughout the EU, and if so in which countries and to what degree? ii) which forests, in terms of biomass and plant cover type, show the largest changes in harvested rate? iii) is the modality of forest management in EU changing in terms of the size of harvested forest patches?

Here we estimate the changes in forest cover across 26 EU countries using Google Earth Engine [21], a big data Earth Observation platform that allows seamless parallel computing and geospatial operations (details in Methods 'Cloud-computing platform'). The losses due to forest fires and major windstorms (details in Methods 'Spatial aggregation and major windstorm removal') are factored out. We assume that the annual loss in forest cover detected in GFC, which is not related to fires or major windstorms, is a reasonable proxy for forest harvested area. Note that the GFC dataset is sensitive to clear-cuts rather than the actual wood harvest, which can be complemented by thinning operations that may not be seen by the satellite (e.g. if the crown cover change is not large enough to be detected).

Validation using a sample of high-resolution data (details in Methods 'Validation of Hansen map of Global Forest Change with High-Resolution Imagery') confirms the capacity of the GFC to detect forest loss, even though uncertainties are lower in some years (e.g. 2017 has lower uncertainty than 2012) and for large patches (i.e. when the patch size is greater than 0.27 ha) than in fragmented ones (i.e. when the size is less than 0.27 ha) (Fig. S1). Classification accuracy is particularly high (more than 82% of correct detection) for patches larger than 4.5 ha, representing more than 60% of the detected harvested area in EU. Henceforth, we refer to the forest loss area as harvested area.

Results show that the intensity in harvest, defined here as the percentage of forest harvested area per year, was rather stable in magnitude and spatial pattern across most European countries from 2004 to 2015 (Fig. 1). Conversely, for the years 2016-2018 we observed a sudden increase (+43% with respect to 2004-2015, + 49% with respect to 2011-2015) in large EU domains such as the Nordic and Baltic countries and the western part of the Iberian Peninsula. We acknowledge the uncertainty and the potential bias of the GFC product, in particular before and after 2011, due to variations in the availability of observational data. Nonetheless, we consider our findings reliable since abrupt changes in forest harvested area occurred in 2016-18. We argue that these recent variations in forest harvested areas are due to the change in management and not to an increased rate of natural disturbances from windstorms or fires, which 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 (e.g. bio-energy sector, paper industries) such as Sweden, Finland, Poland, France, Latvia, Portugal, and Estonia. Although an increased fraction of mature forests in EU [17] is expected to drive a moderate increase in harvest rate in the coming decades [22], the magnitude and speed of change observed in 2016-2018 rather suggests an increase in wood demand and/or a change in forest management [23].

The largest share of variation in harvested forest area during 2016-2018 in 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%. Needleleaf forests accounted for more than 50% of the detected harvested area in the 26 EU countries according to a global map on forest type (ESA GLOBCOVER [7]), in accordance with the Eurostat report [24] (Extended Fig. 4). The analysis of the percentage variation (labels in Fig. 2b) of the annual harvested forest area during 2016-2018 compared with the reference period (i.e. 2004-2015) show a general increase, with the only exception of Belgium and Germany which show minor negative variations. The variation in harvested areas within each 0.2° x 0.2° grid cell confirms the widespread increase in harvested areas for the Nordic and Baltic countries and the Iberian peninsula.

The assessment on forest harvest rate was quantified in terms of biomass loss by combining the Global Forest Change layer with a global map of Above Ground Biomass (AGB) in living trees for the year 2010 estimated from Earth Observation data [25] (details in Methods 'Above Ground Biomass analysis'). Results show that the patterns in biomass loss (Extended Fig. 8 and S4) strongly resemble those of harvested area (Fig. 1 and 2a). The increase of annual harvested forest biomass for the period 2016-2018 with respect to 2011-2015 is equal to 69%, therefore higher than the increase in harvested area during the same period. This entails that the areas harvested in the most recent years were characterized by a higher biomass density than those harvested in the reference period.

The striking 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 due to natural disturbances from fires and windstorms, which were however factored out from harvest statistics reported above. An exceptional number of fires (~ 210% increase) were detected for the years 2016-18 compared with the average of fires observed during the 2004–2015 period (Fig. 3a). Major windstorms exhibit a rise in the order of 90%, especially in 2018, yet, areas hit in 2016-17 are generally smaller than in 2005, 2007 and 2010.

The analysis of the time series of harvested forest area was carried out at country level and compared with existing statistics on harvested volume from FAOSTAT, further corrected to account for possible inconsistencies [16]. For this scope we normalized harvested volume to allow a comparison with harvested forest area (Extended Fig. 6). Overall, based on a country-level analysis, we can conclude that remote sensing estimates of harvested area are coherent with the statistics on harvested volume. Where some inconsistency was detected, country-specific circumstances, generally independent by the approach proposed within the present study, were identified (details in Methods 'Harvested forest area at country level and comparison with official harvest statistics').

The second question we want to address is: which stands, in terms of biomass and forest type, are undergoing the largest changes in harvested area? Across the

European domain, we computed the average harvested forest area for five different biomass classes and the three major forest types (Fig. 3b). The analysis was carried out also for 4 selected countries (Fig. S5 and S6): two countries with the largest harvested area (i.e. Sweden and Finland), one representative for Central Europe (i.e. Poland) and one for Southern Europe (i.e. Italy). Generally, the largest increase in harvested area during the period 2016-2018 occurred in needleleaf, followed by mixed and broadleaf forests, whereas the largest increase in percentage and harvested area occurred in stands with 50-200 t/ha of biomass. Patterns of harvested biomass are distinct for different countries, reflecting the variability of forest types and management strategies in Europe. Finland and Sweden show a peak for needleleaf forests in the range 50-150 t/ha, whereas Poland and Italy show maximum harvest values for mixed and broadleaf forests, respectively, with higher biomass (i.e. 100-200 t/ha). This distribution of harvested area reflects the lower biomass stock of forest in the Nordic and Baltic countries compared with those in Central Europe and the prevalence of broadleaves in Southern Europe.

Taking advantage of the high spatial and temporal resolution of satellite records, we produced country statistics on the temporal trend in the size of the harvested forest patches (i.e. median gap size), and the corresponding percentage variation for the years 2004-2018 (Fig. 4). This analysis addresses our last question about the ongoing changes in the spatial patterns of the forest harvest. The size of patches depends on the topography and silvicultural practices of the country, with larger patches in case of massive clear-cuts and smaller patches for group selection and shelterwood systems. Patch size may affect the impact of forest management on the provision of ecosystem services: generally, larger patches have stronger impacts on ecosystems through habitat disruption, soil erosion, and water regulation.

Satellite observations reveal that overall the gap size has recently increased by 34% across the EU (i.e. average of percentage changes of individual EU countries for the years 2016-2018 compared with 2004-2015, weighted by the national forest area). Such an increase occurred mostly in large forest patches (> 7.2 ha) (Extended Fig. 5). In 21 out of 26 EU countries the size of harvested patches has increased by more than 44% in recent years. Portugal and Italy exhibit an abrupt rise in the average gap size for the period 2016-2018 compared with 2004-2015 (more than 100%). Also, the patch size is substantially larger in Finland, Sweden, the UK and Ireland than in Central or Southern Europe.

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 due to natural disturbances, and variations in the socio-economic context such as market demand and policy frameworks. While harvest volumes can increase because of forest ageing [22], according to the most recent statistics (i.e. FAOSTAT), this cannot explain more than 10% of the observed increase in harvest area (details in Methods 'Potential Drivers of Changes in Harvested Forest Area'). Moreover, the abrupt increase in harvest detected from satellite records is not coherent with the gradual trend expected from the ageing effect. On the other hand, although natural disturbances (i.e. 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. This leaves the socio-economic context and the policy framework as the likely most important drivers, even if a causal connection is difficult to prove and quantify [26]. Whereas the reaction of harvest rate to a socio-economic stimulus or policy may vary from one country to another (including country-specific patterns of import/export), all economic indicators of wood demand and market (i.e. FAOSTAT, EUROSTAT, and UNECE) confirm a substantial expansion of the forest sector during the last years (details in Methods 'Potential Drivers of Changes in Harvested Forest Area'). For example, output of forestry and connected secondary activities (Extended Fig. 7) increased by 13% in EU-28 from 2012 to 2016. This is possibly linked to new legislation (at EU and country levels) promoting the use of wood in the context of the bio-economy [27] , and in particular the use of renewable energy [28], which have been criticized for the potential impact on global forests (e.g. [29]).

Altogether, our analysis shows that Earth Observation can provide timely, independent, transparent and consistent monitoring of forest harvest areas across large geographical areas. Complementing national forest inventories with Earth Observation has several benefits: i) it increases transparency as governments or civil society can better track forest management, both spatially and temporally; ii) it supports the calculation of spatially-explicit estimates of greenhouse gas emissions and removals, as required in recent EU land-related legislation [30] ; iii) it increases the frequency of assessments, allowing early warnings and timely policy responses; and iv) it complements official statistics with independent checks.

Our methodology, built on the large body of literature regarding the use of satellite remote sensing in the assessment of deforestation [31–33], was developed to deal with the specificity of forest management (different management types, no land-use change, etc.) and thus represents an innovative tool supporting a sustainable management of forests [34]. In the future, the interoperability of the NASA Landsat satellite with the ESA Copernicus Sentinels mission, providing high-resolution imagery under “free, full and open” licenses, will further increase data availability for monitoring forest management (e.g. under the planned EU Observatory on changes in the world’s forest cover [35]).

In summary, our results reveal a striking and previously undocumented increase (+49% for area, +69% for biomass) in EU forest harvesting in 2016-2018 compared with the average 2011-2015, with relevant potential impacts on the forest mitigation potential and other ecosystem services. This type of timely and transparent monitoring of forest harvest is key for implementing more effective forest-based mitigation policies and for tracking progress toward country climate mitigation targets. In fact, the carbon impact associated with increasing harvest in the EU, such as the one observed in our study, will have to be fully counted towards post-2020 EU country climate targets [22,30]. We believe that these novel approaches to the monitoring of natural resources with big-data will support the assessment of the potential trade-offs arising from increasing demands for economic and ecological services on EU forests. In addition, it will improve the implementation of forest-related policies under the new EU Green Deal [13] and the greenhouse gas reporting and verification needs under the Paris Agreement.

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Methods

Forest mapping

In Europe, the forest characteristics change considerably along climate gradients and forest types. Consequently, there is not a common definition of forest but each country has adopted the definition that fits best the national circumstances. The establishment of a national definition of "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 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 [36]. Inside these limits, EU countries selected their national forest definition for reporting purposes and the "EU legislation n.841 on Forest and Bioeconomy" [30] 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 Hansen Map of Global Forest Change layer (GFC)[20], a map product providing estimates on tree cover in the year 2000 (details in Hansen Map of Global Forest Change) with forest area statistics from FAOSTAT. It should be noted that Hansen et al.[20] in their work refer to tree cover. As a consequence, to map forest cover from the GFC product, a tree cover threshold must be selected (that defines forest cover).

Hansen Map of Global Forest Change (GFC)

Hansen maps of Global Forest Change [20] version 1.6 (hereafter GFC) are the results of time-series analysis of the Landsat archive characterizing forest extent and change with a spatial resolution of ~ 30 m (the spatial resolution slightly varies along the latitude). GFC consists of three layers: "treecover2000", "lossyear" and "gain".

Treecover2000 is a global map of tree canopy cover (expressed in percentage) for the year 2000, where tree is defined as the canopy closure for all vegetation taller than 5m in height. Lossyear 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 year 2001–2018, respectively. Forest loss 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. Whereas forest loss information is reported annually (in other words there are annual maps for forest loss disturbances), forest gain is reported as a 12-year total, i.e. it refers to the period 2000-2012 and it is a unique layer without reporting the timing of the gain.
Our approach has limitations in the detection of small scale silvicultural practices. While 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 (i.e. less than 10 years) 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 further leading 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 artifacts 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 Fig. 9a). In particular, in the 2016 - 2018 period there is a 15% increase of Landsat image availability with respect to the preceding 3-year period (2013 - 2015), while in 2012 the number of images dropped significantly due 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 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[37] . 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 since the number of images collected were always 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

FAOSTAT-Forestry online database [38] 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 FAO Forestry Department. Within this study, we used the “Area of Forest” from FAOSTAT for each European country for the year 2000, 2005, 2010 and 2015 [39].

From tree cover to forest cover

In this study, we present a simple approach to define for each European country the minimum tree cover (percentage) that qualifies as forest using the GFC map. For each country, we found the tree cover threshold needed to define a forest that minimizes the difference between national forest area statistics from FAOSTAT and GFC estimates (Extended Fig. 1a). Specifically, we computed for 13 tree cover classes - from 10% to 70%, with a 5% step - the corresponding forest areas and we selected the class that minimizes the difference with the national forest area statistics collected in the FAOSTAT report for the year 2015 (hereafter FAOSTAT-2015) as using the last published dataset is a common approach. In order to match the FAO definition of forest, we used a minimum mapping unit (MMU) of ~ 0.5ha with a moving window kernel. Specifically, in a square kernel of 100m x 100m, we retain the forest only if there are more than 5 forest pixels in the GFC map, corresponding to ~0.45 ha. To explore the sensitivity of our analyses to the choice of the tree cover, we replicated the analysis above using high and low tree cover thresholds. A forest threshold sensitivity (Extended Fig. 1b) was computed as

$$S = \frac{Forest_{max} - Forest_{min}}{Forest_{rightThreshold}} \times 100$$

Where $Forest_{min}$ represents the Forest Area obtained using a tree cover threshold equal to 10%, $Forest_{max}$ represents the Forest Area obtained using a tree cover threshold equal to 70% and $Forest_{rightThreshold}$ represents the Forest Area obtained using the right tree cover (i.e. the threshold that minimizes the difference with FAOSTAT-2015 estimates).

In other words, the Forest sensitivity represents how much the forest area would change by choosing tight or loose thresholds (10% or 70% of tree cover) normalized by the actual forest area. If the Forest sensitivity is for instance 120% it means that by using the two extreme thresholds for forest definition (i.e. tree cover equal to 10% and 70%) the corresponding forest areas differ by 1.2 times the value of the actual forest area (as defined in Fig. S1).

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

It should be noted that GFC definition of forest is land cover based while the national forest inventories employ a land use definition. For example, orchards are considered as forests in the GFC, while they are excluded from national forest inventories. Conversely, bare ground which had 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 map can be used to produce a map of forest cover with some caveats [40–42].

Note that the geographical extent of this study included 26 Member States of the European Union (hereafter European domain of EU26) excluding Cyprus and Malta where 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 dataset for the European domain: (i) FAOSTAT and (ii) LUCAS. FAOSTAT provides forest area estimates for the years 2000 and 2010. LUCAS is the acronym of Land Use and Cover Area frame Survey carried out by Eurostat [43], the statistical office of the European Union. LUCAS is an EU26-wide regular point sample survey (with a 2 km grid size) which provides estimates for the years 2009, 2012 and 2015. Note that forest area from FAOSTAT for the year 2015 was used to define the tree cover thresholds. However, a comparison with a different period gives a further verification of our forest assessment.

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

Extended Figure 2 shows the comparison between FAOSTAT and GFC-derived (Hansen) forest area for 2000 and 2010. Note that for Hansen the temporal evolution of the forest area is always decreasing, while FAOSTAT often shows an increasing trend. This is probably due to the fact that forest gain is difficult to capture with remote sensing data. A decreasing trend for both GFC and FAOSTAT forest area 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 remotely sensed derived forest area.

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

Validation of Hansen map of Global Forest Change with High-Resolution Imagery

We validated the Hansen map of Global Forest Change (GFC) using high-resolution imagery from Google Earth. We performed two validation exercises aiming at testing the capability of GFC for the detection of harvest patches of different sizes. The two validation exercises are designed as follows:

Exercise 1): We want to test GFC capabilities for forest harvest patches of various sizes (hereafter general validation). The purpose of this validation was to assess the accuracy of the harvested area as derived from the GFC dataset (i.e. the user accuracy). We did not attempt to quantify the omission errors. The general validation was carried out analyzing 620 patches of harvest with various size, randomly selected from 7 countries (namely Poland, Ireland, France, Italy, Estonia, Sweden and Finland) for 2012 and 2017 in order to better sample the range of variability represented by different countries, climatic conditions, forest type and management system (620 patches for 2012 and 620 patches for 2017). 26% and 37% of the patches for 2012 and 2017, respectively, could not be validated for lack of high-resolution imagery.

Exercise 2): This second validation effort aimed specifically at testing our methods on big harvest patches (larger than 4.5 ha, hereafter big patch validation) since the increased occurrence of larger harvest area is one of the main issues raised by this study. For the big patch validation, we compared data from the very same 7 countries used in the validation Exercise 1 and compared 2012 and 2017. For this exercise forest patches consisted of at least 50 contiguous pixels (with a 4-neighbours rule), i.e. ~ 4.5 ha. We found 188 and 260 patches for 2012 and 2017, respectively.

For both 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 GFC in shape, position and timing (i.e. 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 due to image misregistration; 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 happens the year before the GFC loss).

Extended Figure 3 (first two rows of panel a and panel b) reports the validation results by large (i.e. >= 0.27 ha) and small (i.e. < 0.27 ha) forest loss patches. It emerges that the classification capabilities are better in the year 2017 than in 2012, likely due to the entering in operation of Landsat 8. As expected, the classification of small patches show a larger uncertainty (i.e. error in classification for 29% of cases instead of 13% observed for large patches in 2017). From these results we can evince that, despite the larger uncertainty in the classification of small patches, the overall impact on our findings is limited since gaps smaller than 0.27 ha represent less than 3% of the detected total harvested area in EU (Fig. S1). Results of the big patch validation clearly show that more than 84% of big forest patches (i.e. >= 4.5 ha) are correctly classified, while only 5% are wrongly classified (third row of Extended Fig. 3a). The remaining patches are either recorded with one year of delay (3%) or refer to harvest areas of different size (7%) due to image misregistration.

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

Spatial aggregation and major windstorm removal

In order to identify anomalies in forest management and to exclude extraordinary losses due to natural disturbances that are not related to the normal management regime, we computed the annual percentage of forest loss at 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 European Forest Fire Information System (EFFIS) dataset were masked out. EFFIS provides the European Commission services and the European Parliament with updated information on wildland fires in Europe [44]. EFFIS provides shapefiles for European forest fires using remote sensing imagery. Specifically, EFFIS maps burned areas by analyzing MODIS daily images 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 EU.

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

Since what is detected by satellites is a change in percentage of forest cover that can either be attributed to forest management (i.e. harvest) or disturbances (e.g. pests, biotic disturbances, windstorms, etc.), we filtered out from our analysis areas affected by major windstorms. To do so, we assumed that major windstorms are causing larger losses than those generally caused by forest management [45]. For each 0.2° grid cell we computed a threshold of the percentage of forest loss which is calculated as:

$$Threshold_{wind} = median(x) + 3 \times MAD(x) \quad (1)$$

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 the $Threshold_{wind}$the forest loss is attributed to windthrow. With this formula, we excluded major windstorms from our analysis. The resulting maps only remove major windstorms, while forest loss from small and localized windstorms, pests and other diseases are not masked out. Note that $Threshold_{wind}$ was computed including the 2001-2003 period (later excluded from the analysis) to get more robust statistics.

Major windstorms are masked in Fig. 1 and Fig. 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 [45].

The major windstorms removal scheme has a major limitation, namely: short rotation forestry [46] (i.e. 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 forest harvest 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 2016-2018 period the country suffered from intense fires[44] that might have been only partially detected in our analysis (possibly due to the limited spatial extent of the single events) and therefore erroneously considered as harvest area.

Land Cover

Land Cover data layer (at a resolution of 300m) was obtained from ESA GLOBCOVER and harmonized to the 30 m^2 grid using a nearest-neighborhood algorithm.

Patch size

We computed for each year and for each EU country the number of contiguous pixels - using a 4-connected rule - of forest loss and its distribution. We excluded from the analysis regions affected by forest fires (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 gap size of harvested forest patches (Fig. 4). Combining country-level variations in harvested patch size and forest harvested area (as shown in Fig. 2a) it is possible to identify countries where signs of variation in harvested patch size and area are in opposition (i.e. both gap size and area are either increasing or decreasing, indicated by blue labels in Fig. 4) or not (red labels). Interestingly, in 7 countries out of 26, variations in harvest area and patch size are in opposition. For example, in Sweden, the harvest increased while the gap size decreased, although slightly (in the order of 3%). Similarly, Austria, Bulgaria, and Slovakia show an intensification of the harvested forest area and at the same time a reduction of the patch size. This could suggest the increase in harvested forest area in smaller properties (e.g. by private owners) or the application of less intensive management practices. Conversely, Belgium and Germany show an increase of the patch size and at the same time a reduction of the harvested area.

Silvicultural practice and gap size

We conducted an analysis of changes in forest harvest size both at European and at country level. We investigated annual distribution of harvested forest area for five different classes of patch size ranging from small gaps (i.e. harvested forest area less than 0.27 ha) to big gaps (i.e. harvested forest area greater than 7.2 ha) (Extended Fig. 5) across the European domain (panel a) and at country level (panel b). Note that patterns for Europe and Finland are similar with a major contribution of big forest harvested patches. Conversely, Italy displays a dominance of forest harvested patches less than 3.6 ha, despite an increase in the quota of big patches that doubled from 2004 to 2016. This figure provides information on the most common forest management practices applied at country level. On the one side we have countries, like Sweden, UK, Finland, and Ireland, where larger harvested forest areas prevail, suggesting the application of a clear-cut as the main management system. On the other side, in Italy other silvicultural systems clearly prevail (such as the shelterwood system or a single tree selection system): this is due both to the uneven-aged structure and to the small size of forest ownership. It should be noted that due to calculation constraints, the size of patches is calculated from the GFC map on a geographic coordinate system (i.e. EPSG:4326) and not on an equal-area projection. As a consequence, slight errors in the area occur along latitude.

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

We compared for each EU country the harvested forest area derived from GFC and the amount of harvest volume removals reported by FAOSTAT. Harvest removals (i.e. “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 the analysis provided by [16]. Harvest removals are expressed as volumes.

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

The black line (normalized between zero and the maximum value of harvested area for the sake of simplicity) shows the harvest removals. Finally, the difference between Earth Observation and inventories is shown for two countries with the largest forest sectors in EU: Finland and Sweden (Fig. S3) where we have information on harvested forest area until 2016 and 2018, respectively.

Based on the comparison between harvested forest area, official harvest removals (Extended Fig. 6) and National Forestry Action Programmes and other data sources, such as the National Forestry Accounting Plans, recently published by the EU countries (hereafter NFAP) we performed the following country-based analysis. Austria: GFC can accurately reproduce the trend reported by harvest removals (r=0.65). This is also due to the specific management system applied at national level, where the annual share of the final cut on the total harvest is generally higher than 80% (NFAP [47]). These data series include, from one side, the amount of wood removed from salvage logging after main windstorms (i.e. in 2007-2008 [48]), and from the other side the area affected by the same disturbance events. Belgium: uncertainties on official harvest removals, and the peak in 2010, probably due to some windstorm [49] and only reported by GFC, may explain the lack of correlation between the two time series. Bulgaria: the high uncertainty of official harvest removals[50] also due to 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 GFC 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 uneven-aged forests, which cover about 20% of the total forest area. Moreover, silvicultural treatments are still partially influenced by the ongoing demining activities, due to the war which involved Croatia during the 90s (NFAP [51]). Czech Republic: GFC represents fairly well the amount of harvest provided by final cut (on average 43% of the total removals) and, partially of salvage logging, equal to about 41% of the total removals during the last decade (NFAP [52]). The peak of harvest reported by both these time series since 2016, is likely due to salvage logging, as a consequence of windstorms and bark beetle attacks that occurred during the last years [53]. Denmark: the lack of correlation with GFC is due both to some uncertainty on the estimates reported by harvest removals, generally underestimated before 2014, and to the increasing amount of primary residues removed from forests from 2011 onward (NFAP [54]). Due to this activity, recent harvest removals also include wood used for energy, mainly provided by branches and other wood materials. Estonia: data from GFC are consistent with harvest removals, and probably include both the amount of area affected by final cut and by salvage logging after major disturbance events. Finland: harvest reported by official statistics is well correlated with data from GFC (r=0.56). Taking into account the information reported by the Statistical yearbook for forestry in Finland (2018 [55], Fig. S3), we can infer that GFC can be referred to the area affected by clearcut (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 fact that (i) the harvest provided by thinnings is not negligible, since they cover about 66% of the total area affected by fellings at country level (average of the period 2004 and 2015) and (ii) the different biomass density per unit of area between the northern and southern part of the country, certainly reduce the correlation between the two variables. Nevertheless, the increasing amount of harvest detected by GFC during the last years, was recently confirmed by the data reported by the National Resource Institute of Finland (Luke [56]), highlighting that in 2018, a total of 78.2 million cubic meters of roundwood was harvested from Finnish forests, being 8 % more than in the previous year, and, compared with the average of the preceding ten-year period, the amount increased by nearly 25%. France: GFC represents fairly well the amount of harvest provided by final cut and salvage logging after major natural disturbances (indeed, they clearly highlight the effect of the windstorm occurred in 2009, which explains the peak of harvest removals reported for 2010). Due 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 on the same area), also determining different biomass densities per unit of area, GFC can probably detect only part of the silvicultural treatments and of the overall harvest applied at country level (r=0.33). Germany: harvest reported by official statistics is well correlated with data from GFC (r=0.56), and can be referred to the amount of harvest provided by final cut and salvage logging after major natural disturbances (they clearly highlight the effect of the windstorm occurred in 2007 and 2010). Greece: harvest reported by official statistics is partially correlated with data from GFC (r=0.42). This is due both to the high uncertainty of harvest statistics [18,19] and to the specific characteristics of this country, mainly covered by uneven-aged forests, generally treated with selective cut systems. Hungary: GFC does not reproduce the pattern in harvest likely because it cannot reproduce the sharp increase in total forest area as reported in official statistics [57] (since 2000 the total forest area grew by 8% - i.e. from 1908 kha in 2000 to 2069 kha in 2015, according to the State of Europe's Forests 2015 [1]). Ireland: as for Hungary, GFC does not reproduce the trend in harvest likely because it cannot reproduce the sharp increase in total forest area as reported in official statistics (since 2000 the total forest area grew by 19% - i.e. from 635 kha to 754 kha in 2015 [1]). Italy: due to the high uncertainty of official harvest removals [18,19] and to the specific characteristics of this country, where uneven-aged forests cover about 30% of the total forest area [58], and biomass density may vary within the country because of the different climatic conditions, 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% [16], GFC can only partially reproduce the trend reported by harvest removals. This is specifically due to the decreasing amount of area affected by harvest detected by GFC between 2012 and 2015. For both these countries, even if the absolute amount of harvest was generally increasing since 2010, the relative share of final cut to thinnings decreased, at least for some species (NFAP [59]). Luxembourg: GFC can reasonably reproduce the trend reported by harvest removals (r=0.60). This is also due to the specific management system applied at national level, where the annual share of the final cut is generally higher than 90% [16]. The Netherlands: the lack of statistical correlation between official harvest removals and GFC data can be due to different reasons. From one side the data series reported by harvest removals is extremely homogeneous in time until 2013, when, due to an abrupt increase of coniferous wood removals, the total amount of harvest increases by about 16% [60]. Conversely, GFC data shows a peak in 2010 (when removals increased by 6% compared to 2009), while no significant variation is reported after 2013. Neither GFC nor harvest removals highlight any significant deviation in 2007 when about 0.25 million m^3 were damaged by windstorms. Poland: overall, GFC can reproduce the trend reported by harvest removals (r=0.62), at least for the quota referred to the amount of harvest provided by clear cut, equal to about 48% of average annual removals reported by the country since 2004 (NFAP [61]). Portugal: despite the quite heterogeneous silvicultural systems applied at country level (including also uneven-aged forests), GFC is well correlated with official harvest removals (r=0.75). This is probably due also to the relatively high share of Eucalyptus plantations managed through clear cuts. Romania: large uncertainties on official harvest statistics [18,19], also due to unregistered logging, and the variety of silvicultural treatments applied at country level (also including uneven-aged forest systems), considerably reduce the correlation between GFC and official harvest removals (r=0.39). Slovakia and Slovenia: GFC can adequately reproduce the trend reported by harvest removals (r=0.73 for both these countries). This is due also to the specific management system applied at a national level, largely based on clear cut (i.e. for Slovakia, the annual share of harvest provided by the final cut is generally higher than 70%, NFAP [62]). Spain: due to the specific characteristics of this country, largely covered by uneven-aged forests, managed through a single tree selection system, GFC can only partially reproduce (r=0.44) the trend reported by harvest removals (NFAP [63]). Sweden: the lack of correlation between GFC and harvest removals, is probably due to the fact that: (i) when large disturbance events occurred, salvage logging (for sanitary reasons) had the priority on clear cut whose area was indirectly reduced (for this reason, probably, GFC does not highlight the effect of the two windstorms occurred in 2005 and 2007); (ii) remote sensing estimates and harvest statistics, at the country scale, may not show a statistical correlation even because the biomass density per unit of area largely differs in space (i.e. between the northern or southern part of Sweden); (iii) for this country, final felling covered (in terms of area) about 37% of the area annually affected by fellings between 2000 and 2015 (SLU Swedish University of Agricultural Sciences, National Forest Inventory, [64]). 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 GFC (see Fig. S3) and highlight that this area has increased by 13% in 2018 in comparison with the previous year, and, compared with the average of the period 2011-2015, the amount increased by nearly 17%. Considering the fact that these statistics only report the "notified area larger than 0.5 ha", while GFC probably includes a broader share of management practices, we can infer that, also for this country, GFC can adequately represent variation on the relative amount of area affected by final felling in Sweden. United Kingdom: overall, GFC can reproduce the trend reported by harvest removals (r=0.44). Some peaks reported by GFC in 2012 could be due to the indirect effect of exceptional fires not properly filtered out by the preliminary analysis performed on these disturbances [65].

Inconsistency between remote sensing-based estimates (i.e. 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, due 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 30m. 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 that in some countries may be suboptimal because infrequently updated or incomplete due to unregistered or illegal logging. In these cases, the use of independent remote sensing data, such as the ones provided by this study, could help improving and complementing national statistics.

We also performed a country-based assessment on the impact of thinning and selective logging on the total harvest (Tab. S1). In this analysis, we reported the share of final cut on either the managed area or volume (in the case of the Carbon Budget Model from Pilli et al.[16] - hereafter CBM) from the even-aged forests. National statistics highlight how thinnings or selective logging (on even-aged and uneven-aged forests, respectively) is relevant only for a few EU countries (Italy, France, Croatia, etc.). Also, low values of the share of clear cut (e.g. Italy) may not hamper GFC statistics since they partially include forest thinnings and other silvicultural practices such as salvage logging.

Potential Drivers of Changes in Harvested Forest Area

An 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, like the 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 from one side natural disturbances like forest fires, heavy snow load and windthrow, which affect both the age structure and the management practice and, from the other side, political, social or economic factors, which lead to a modification of management practices applied with respect to a reference period, e.g. 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 the current management practices applied by 26 EU countries between 2000 -2009, Grassi et al. [22] estimated that, at EU level, harvest volumes are expected to increase by 9% in the period 2021 -2030, relative to the period 2000–2009. Assuming a gradual increase in the harvest due to ageing we should therefore expect a 0.45% increase per year. Similarly, Nabuurs et al.[66] foresee a sustainable increase of harvest due to ageing of 19% for the period 2009-2050 (equivalent to 0.46% per year).

Considering that the increase observed with satellite records occurred in the last three years (2016-2018) of the decade, we estimate that over this timespan a maximum increase of about 4% in volume could be ascribed to forest ageing, which roughly 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 of harvest, while the dominant role was played by exogenous factors.

Among exogenous drivers, the expansion of activities based on wood products (economic drivers) might have impacted the forest sector as reported in official statistics from UNECE/FAO and EUROSTAT. In fact, forest harvest is unlikely to increase when there is no rise in market demand for wood products. In North and Central-East Europe, where the relative contribution of the forest sector to GDP is the largest (2.1% and 1.3% in North and Central-East Europe, respectively, in 2010, according to the Ministerial Conference on the Protection of Forests in Europe 2015[1]), the higher demand from sawmills during the last years, was likely one of the major drivers of the increasing timber harvest (UNECE/FAO 2017-2018 [67]). For example, in Croatia the sawn wood hardwood production grew by 89% in the five years to 2017; in Czech Republic and Slovakia, the particleboard production grew by 10% and 6.5%, respectively, in 2017, compared with the previous year (UNECE/FAO 2017-2018 [67]). In addition, also fuelwood removals increased at European level from around 70 Mm^3 to about 99 Mm^3 (+41%) between 2000 and 2015 [68]. UNECE[67] 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 of some North European countries (i.e. Finland and Estonia), where the collapse of export of roundwood from Russia since 2009, indirectly affected also the internal harvest demand. Conversely, in some Central European countries (i.e. Czech Republic, Hungary and Slovenia), the export has strongly increased since 2014, encouraged by the increasing roundwood demand coming from Germany (where the import increased by 30% since 2014) and from some other EU countries (i.e. UK and Croatia), and more recently, also from China.

Concerning the increase of wood demand and market, in EU the application of the new Renewable Energy Directive (2018/2001) and the bio-economy strategy (started in 2012) are setting binding targets and increasing wood demand for bioenergy needs, with an established target of at least 32% renewables energy for the year 2030 [69]. Specifically, the EU Renewable Energy Directive raised concerns about increasing harvested wood for bioenergy use[29]. In the ongoing shift from coal to biomass, wood is currently responsible for more than 60% of the renewable energy supply in Europe [70].

Output of forestry and connected secondary activities (Extended Fig. 7) increased by 13% in EU-28 from 2012 to 2016 (EUROSTAT [71]), while for countries that are showing the largest increase in harvest like 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) .

Percentages of change in harvest area during 2008-2016 (or 2012 when 2008 is not available) as retrieved from remote sensing and from forestry market statistics are reported in brackets in the labels of Extended Fig. 7. Note that the quality of the EUROSTAT data varies from country to country, and some outliers (e.g. France in 2014) seem at least questionable. Both UNECE and EUROSTAT indicators on wood products are heavily influenced by many other factors that can impact independently the actual amount of forest harvest. However, these statistics give an overall indication of existing trends and/or potential drivers.

Concerning the potential impact of policy changes, the key role of the forest sector within the bio-economy market has been supported by specific political initiatives in several EU countries. For example this is the case of Slovenia, where specific financial incentives actively supported the forest sector during the last years (NFAP of Slovenia [72]). In contrast, in Sweden (NFAP of Sweden [73]), as in other North European countries, where production subsidies were abolished, the increase in felling during the last years is likely due to the increasing demand for forest raw materials by the forest industry.

A relevant recent element in the policy context is the new EU Regulation 2018/841, including the Land Use, Land-Use Change and Forestry (LULUCF) sector in the EU 2030 climate target [30] , which aims to improve the assessment of the carbon impact of additional actions in “managed forest land” [22]. The Regulation is setting 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 potential limitation on future potential increase in harvest [74,75]. This might have triggered a more rapid increase in forest harvest in some countries relative to what would have occurred without EU regulation. 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 harvest intensity are natural disturbances like windstorms, heavy snow load, forest fires and pest outbreaks. If the medium-term trend is mainly controlled by economic/political/legislation factors, salvage logging can represent the main driver affecting the year to year fluctuations in total harvest, at country, regional, or even at EU level. As highlighted in Extended Fig. 7, this was the case of Austria (in 2007-2008), Czech Republic (since 2016), France (in 2009-2010), Finland (2017-2018), Germany (in 2007 and 2010), Slovakia (2005), Slovenia (2014) and Sweden (in 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, while the remaining will be harvested during the following years through normal silvicultural practices (i.e. thinnings, clear-cuts, etc.). Despite this uncertainty, it is important to notice that at EU level the amount of harvest due to salvage of storm residues is rather limited. For instance, in the period 2000 – 2012 it was equal on average to 13 Mm^3 yr^{-1}, i.e. about 2.7% of the average amount of harvest removed within the same period (Pilli et al. [16]). These events can generate large spatial and inter-annual variability so that at 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 the abrupt increase of harvest rate, there have been no major windthrow events at 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 (i.e. clear cut) whose area 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 the last years is most probably due to exogenous drivers, whereas about 10% was due to forest ageing. At continental scale, natural disturbances, which have likely affected the inter-annual variations and trends, have been factored out from the analysis. Ultimately, the recent changes in socio/economic and political context are therefore the most likely driver of the observed patterns.

Above Ground Biomass analysis

The Above Ground Biomass (AGB) of the harvested forest was obtained from the European Space Agency GlobBiomass product, a global dataset of forest biomass at a resolution of 100 m for the year 2010. Specifically, it quantifies the mass, expressed as oven-dry weight of the woody parts (stem, bark, branches, and twigs) of all living trees excluding stump and roots (unit: Mg/ha). The AGB estimates were obtained from space-borne SAR (ALOS PALSAR, Envisat ASAR), optical (Landsat-7), LiDAR (ICESat) and auxiliary datasets with multiple estimation procedures [25]. The AGB map was resampled at the spatial resolution of GFC (i.e. from 100m to 30m) and, to update it to the year of forest loss, from 2011 onwards (the AGB map refers to 2010) we assigned to pixels with forest loss a value of AGB equal to zero, meaning that forest loss was considered as a total AGB loss.

Forest biomass growth was retrieved from the State of Europe's Forests 2015[1]. The average biomass growth rate (*Gr*, expressed as annual percentage) has been computed for five geographical regions in Europe (Extended Fig. 10a) as:

$$Gr = \frac{Gs_{2015} + F_{2010-2005} - Gs_{2010}}{Gs_{2010}} * \frac{1}{Ys} \quad (1)$$

Where Gs_{2010} and Gs_{2015} are the total growing stock in 2010 and 2015, respectively, Ys the number of years between 2010 and 2015 (five) and $F_{2010-2015}$ is the total amount of fellings removed within the same period. We converted relative into absolute biomass growth rates (i.e. from percentage to t/ha/year) based on the AGB and forest area estimates by country from the ESA-GlobBiomass and GFC datasets, as shown in Extended 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 and major windstorms were excluded from our analysis. Note that resampling biomass from 100m to 30m is indeed an approximation that introduces some uncertainty in the biomass loss estimates.

The analysis of AGB loss was carried out at European and at country level. Extended Fig. 8 shows the percentage of AGB harvested per year in a 0.2° grid cell; Fig. S2 shows the pixel-wise R^2 regression between harvested forest area and biomass; and Fig. S4 shows the percentage national contribution of the European harvested forest biomass during 2016-2018.

As expected, the pixel-wise correlation between harvest forest area and harvested forest biomass is high over the spatial domain (Fig. S2) since harvested forest area and biomass are closely linked.

Figures S5 and S6 show the average harvested area for five biomass classes for the period 2011-2015 (left panel) and 2016-2018 (right panel) for Finland, Sweden, Poland, and Italy. Patterns of Fig. S5a shows that the contribution of evergreen forests in the AGB range 50-150 t/ha are dominating, while the one from forest with very high AGB (i.e. greater than 150 t/ha) is negligible. Sweden (Fig. S5b) shows patterns that are similar to those of Finland, although the quota of harvested biomass greater than 200 t/ha is higher. Conversely, Poland (Fig. S6a) exhibits a dominance of mixed forests in the range 100-200 t/ha, thus indicating a different forest age and structure.

Cloud-computing platform: Google Earth Engine

Google Earth Engine is a Cloud-based infrastructure that allows access to high-performance computing resources for processing very large geospatial datasets[21]. It consists of a multi-petabyte analysis-ready data catalog co-located with a high-performance, intrinsically parallel computation service. The data catalog hosts a large repository of publicly available geospatial datasets, including Landsat archive, the Hansen Map of Global Forest Change[20], land cover, topographic and socio-economic datasets. Since 2015, Copernicus Sentinel sensor data are included. The catalog 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 because it provides the ability to compute pixel-level or country-based statistics and analyze the entire data records of Hansen Map of Global Forest Change 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 dataset analysed during the current study. Dataset are made permanently and publicly available on Zenodo repository so that results are entirely reproducible: 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 (Google Earth Engine / R scripts, the harvest removals dataset, and shapefiles of validation) used for this study are made permanently and publicly available on Zenodo repository so that results are entirely reproducible: 10.5281/zenodo.3687096.

Acknowledgments

The views expressed are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

Author's contribution

GC and AC conceived the idea and designed the methodology; GC analyzed the data and wrote the Google Earth Engine / R scripts; GC and AC wrote the manuscript with contributions from GD, GL, VA, RP and GG. All authors contributed critically to the interpretation of the results and gave final approval for publication.

Competing interests

The authors declare no competing financial interests.

Fig. 1. **Harvested forest area per year**. Percentage of harvested forests (expressed as 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 was larger than a 20% threshold, uniformly throughout the whole European domain, while the rest of the analysis was based on country-based tree cover threshold as explained in Methods. This map was generated using GEE [21].

Fig. 2. **Spatial statistics of European harvested forest area**. (a) Percentage national contribution of the European harvested forest area during 2016-2018; (b) percentage variation of the harvested forest area within each 0.2° x 0.2° grid cell - 2016-2018 vs 2004-2015 (labels refer to aggregated national values). Maps were generated using GEE [21].

Fig. 3. **Temporal trends of forest harvest**. Time series of a) biomass and area of forest fires, major windstorms and harvested forests and b) average harvested area for five biomass classes for the period 2011-2015 (left panel) and 2016-2018 (right panel) for the European domain. Colors refer to the three forest loss factors (a) and types (b). Labels over the bars in the right panel in Fig. 3b show the percentage variation during 2016-2018 compared with the reference period 2011-2015 for each biomass class.

Fig. 4. **Country mean harvest patch size and its recent change**. Average harvest patch size and percentage variation in size for the year 2016-2018 compared with 2004-2015. The color of the label refers to the agreement in sign between variations in size and in harvested forest area (red when in opposition, blue when concordant with harvest variations of Fig. 2b). This map was generated using GEE [21].

Extended Figure 1. **From Tree Cover to Forest Cover.** a) Tree Cover Threshold needed to define a forest and percentage error between FAOSTAT-2015 and Remote Sensing based Forests (label); b) Forest Threshold Sensitivity. Maps were generated using GEE [21].

Extended Figure 2. **Verification of EU forest area.** GFC vs. FAOSTAT for 2000 and 2010. GFC vs. LUCAS for 2009, 2012 and 2015.

Extended Figure 3. **Validation of GFC forest loss with high-resolution data.** Validation of the classification of harvested areas in the years 2012 and 2017 by small and large (a), and big (b) forest patches; accuracy of harvest area derived from GFC forest loss versus patch size (labels and circle size refer to the EU-wise cumulative harvested forest) (c).

Extended Figure 4. **Harvested Forest Area per Forest Type.** Time series of land cover type (from GlobCover) for the European domain. Colors refer to the three forest types.

Extended Figure 5. **Harvested Forest Area Components.** Annual distribution of harvested forest for different classes of patch size ranging from small gaps (i.e. harvested forest area less than 0.27 ha) to big gaps (i.e. harvested forest area greater than 7.2 ha) for the European domain (a), each EU26 country (b).

Extended Figure 6. **Harvested Forest Area vs. Official Harvest Removals.** Harvested Forest Area from GFC (bars, normalized between 0 and 1) and volumes of Harvest Removals from National Statistics (lines, normalized between 0 and 1). We excluded areas interested by Forest Fires, while we retained areas interested by major windstorms because they appear in the Harvest Removals. Statistical significance for remote sensing and national statistics at p=0.05 is reported with an asterisk and a hashtag, respectively in the country label panels. Maximum values of Harvested Forest Area and Harvest Removals for each country are reported in the second and third lines of each label, respectively.

Extended Figure 7. **Harvested Forest Area vs. EUROSTAT Economic Aggregates.** Harvested Forest Area from GFC (bars, normalized between 0 and 1) and volumes of Economic aggregates of forestry from EUROSTAT (lines, normalized between 0 and 1). We excluded areas interested by Forest Fires, while we retained areas interested by major windstorms because they appear in the Harvest Removals. Percentages in brackets 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 Figure 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. Same as Fig. 1 but referring to Biomass instead. This map was generated using GEE [21].

Extended Figure 9. **Cloud-free land coverage of Landsat in Europe.** Time series of cloud free Landsat scenes (i.e. where cloud cover is less than 20%) for the European domain (a); spatial distribution of cloud-free Landsat images over Europe (b). Map and time series were generated using GEE [21].

Extended Figure 10. **Growth rates of forest biomass.** Relative (a) and absolute (b) growth rate of forest biomass as derived from the State of Europe's Forests 2015 in combination with the GlobBiomass and GFC dataset. Maps were generated using GEE [21].

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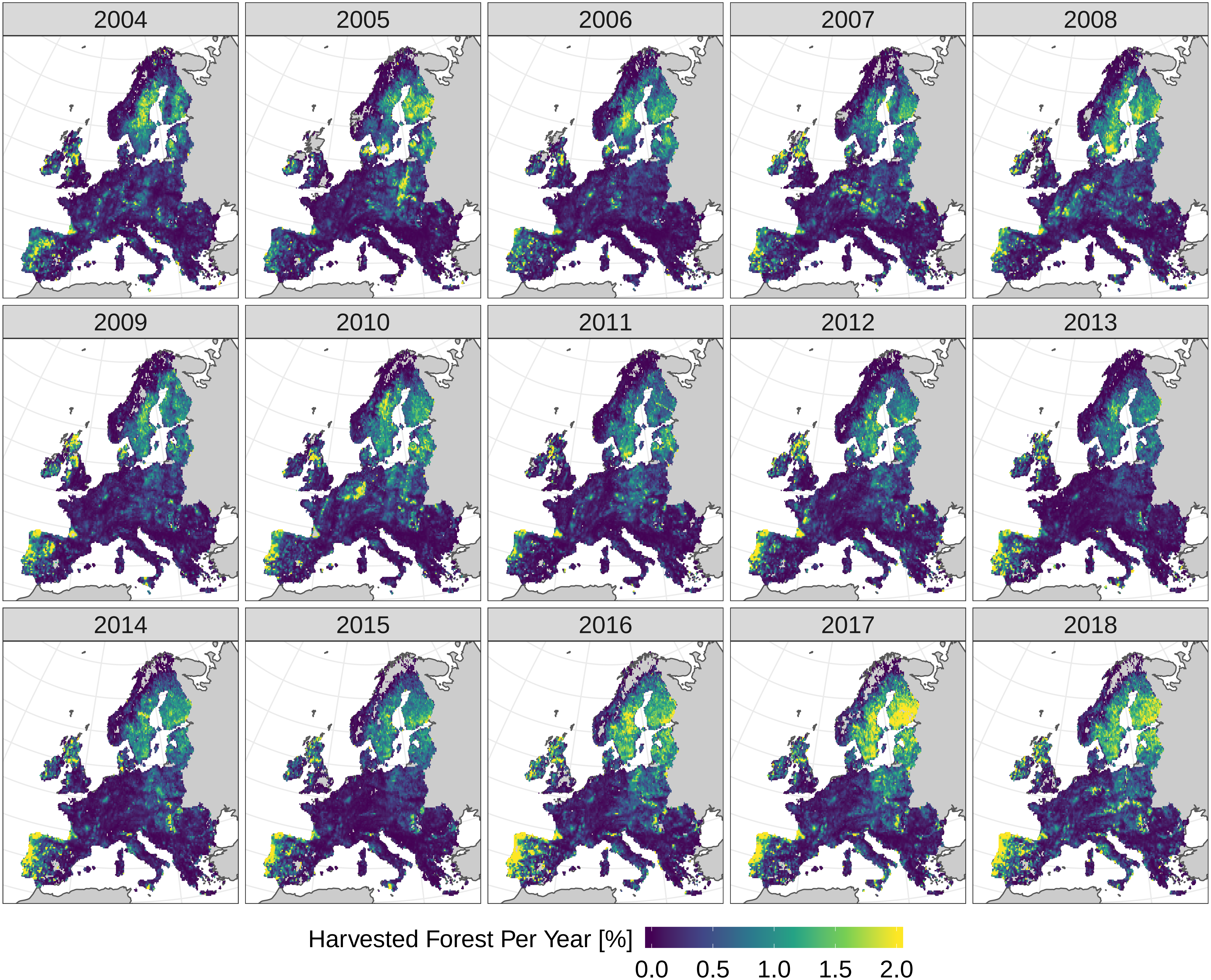
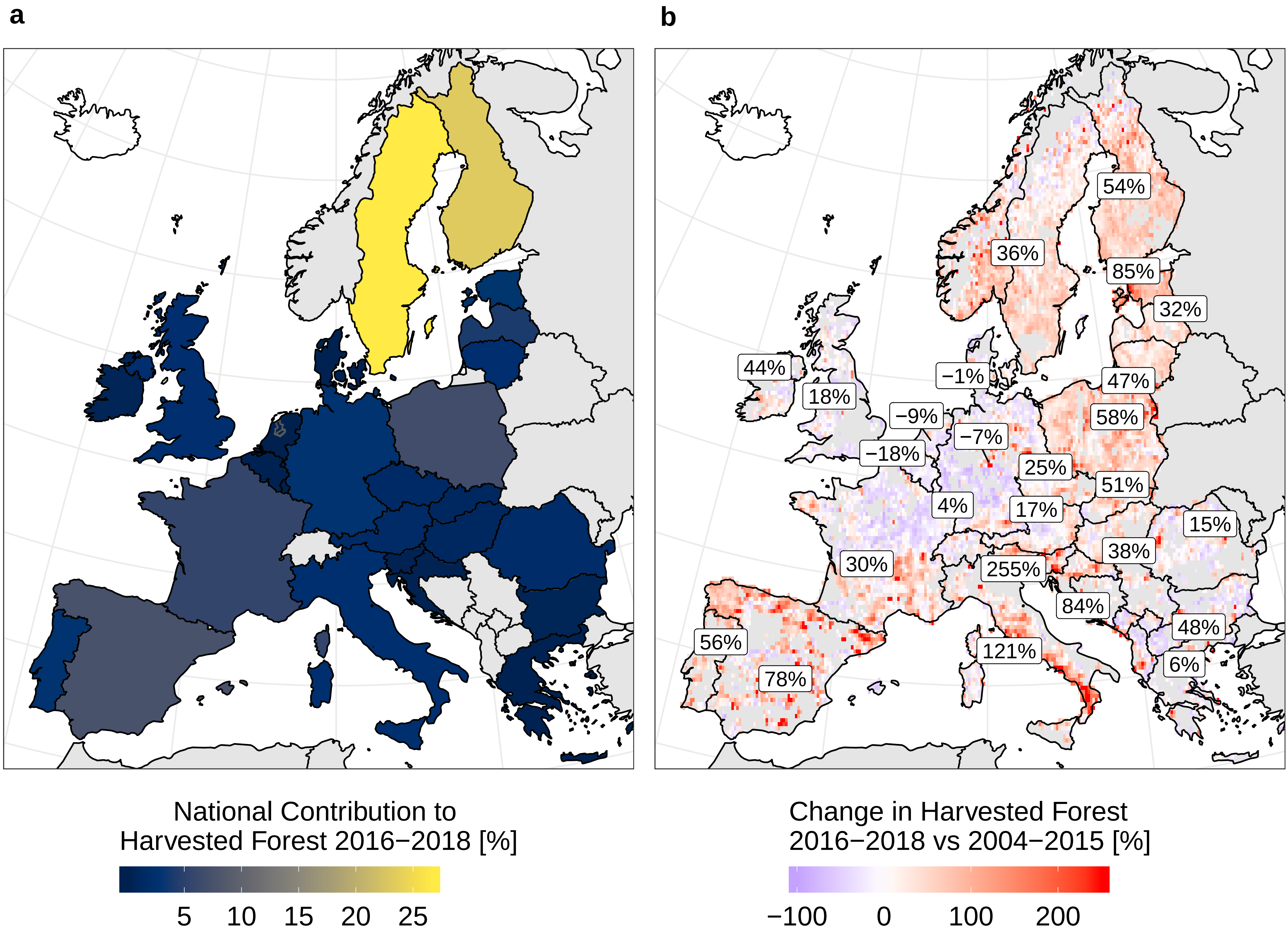
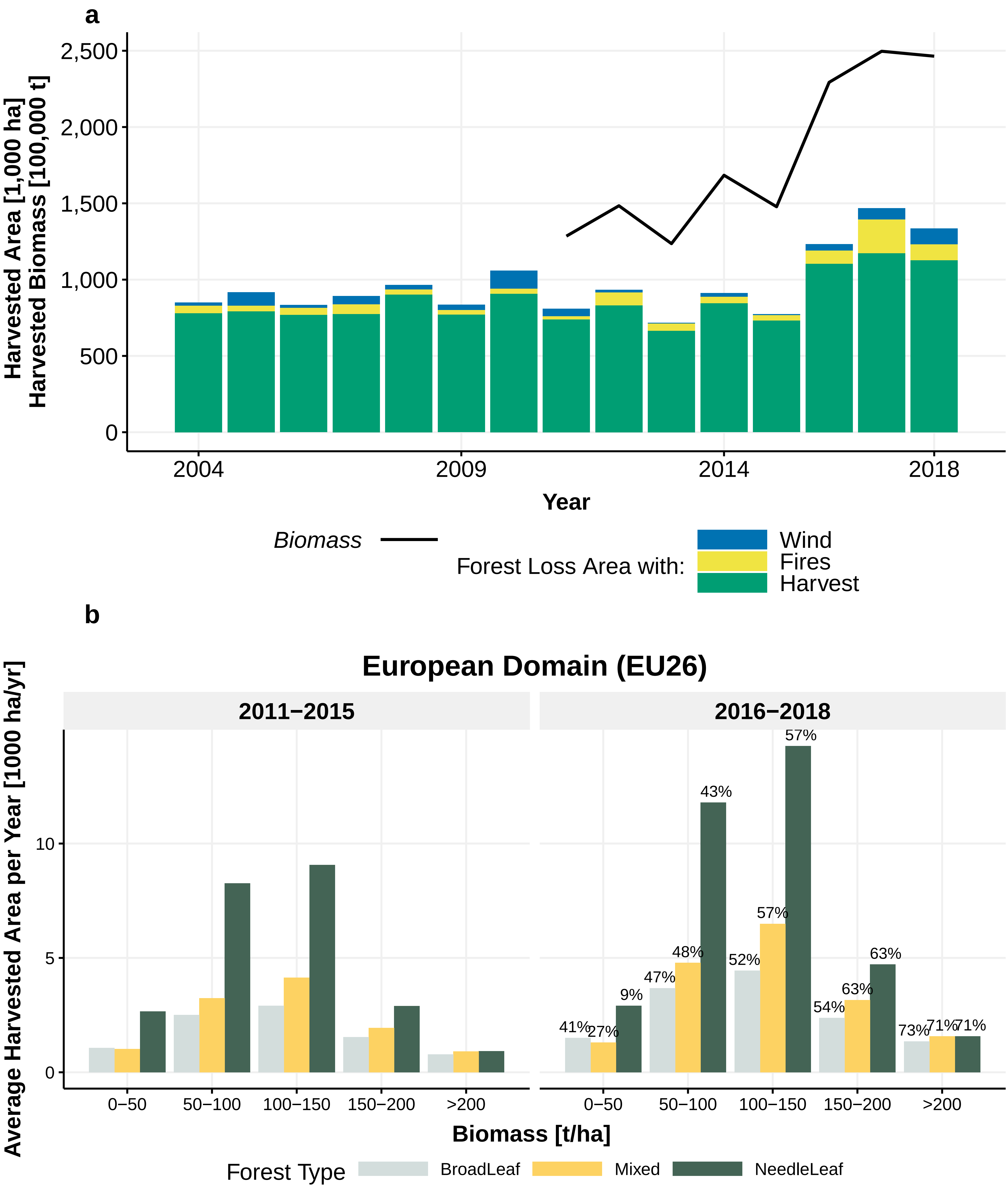
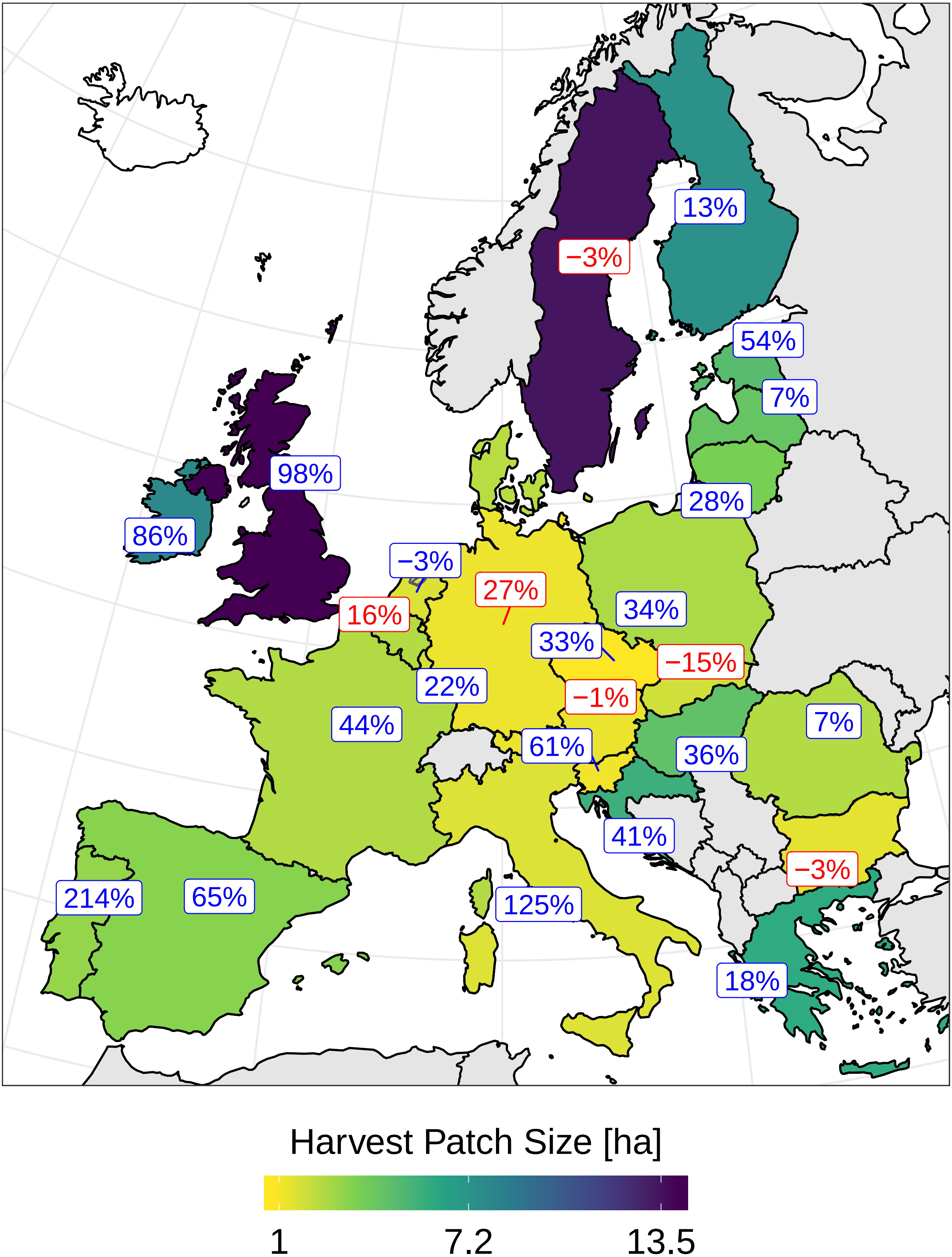

2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Harvested Forest Per Year [%]
0.0
0.5
1.0
1.5
2.0


a
b
54%
36%
85%
32%
44%
−1%
18%
47%
−9%
58%
−7%
−18%
25%
51%
4%
17%
15%
30%
38%
255%
84%
56%
48%
121%
6%
78%
National Contribution to
Harvested Forest 2016−2018 [%]
5
10
15
20
25
Change in Harvested Forest
2016−2018 vs 2004−2015 [%]
−100
0
100
200


a
Harvested Area [1,000 ha]
Harvested Biomass [100,000 t]
2,500
2,000
1,500
1,000
500
0
2004
2009
2014
2018
Year
Biomass
Forest Loss Area with:
Wind
Fires
Harvest
b
European Domain (EU26)
2011−2015
2016−2018
Average Harvested Area per Year [1000 ha/yr]
10
5
0
41%
27%
9%
47%
48%
43%
52%
57%
57%
54%
63%
63%
73%
71%
71%
0−50
50−100
100−150
150−200
>200
Biomass [t/ha]
Forest Type
BroadLeaf
Mixed
NeedleLeaf


13%
−3%
54%
7%
98%
28%
86%
−3%
27%
16%
34%
33%
−15%
22%
−1%
44%
61%
7%
36%
41%
−3%
214%
65%
125%
18%
Harvest Patch Size [ha]
1
7.2
13.5