Matters arising

Reply to Wernick, I. K. et al.; Palahí, M. et al.

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REPLYING TO I. K. Wernick et al. *Nature* https://doi.org/10.1038/s41586-021-03293-w (2021)

REPLYING TO M. Palahí et al. *Nature* https://doi.org/10.1038/s41586-021-03292-x (2021)

In the accompanying Comments, Wernick et al.[1] and Palahí et al.[2] provide critical remarks on our Article[3] concerning the increase of forest harvest over Europe using satellite imagery. Here we provide a point-by-point response to these remarks, in particular on the potential effects of the inconsistencies in the time series of the Global Forest Change (GFC) dataset[4], on the potential misattribution of natural disturbances, on the relationship with country statistics and on the effect of our findings on the carbon balance of European Union (EU) forests.

First, Palahí et al.[2] state that our results largely reflect artefacts in the underlying forest cover dataset, because GFC data lacks consistency over time and is therefore not adequate for trend analyses. This is because "The availability of improved Landsat data and more-sensitive change detection models since 2013, with a major enhancement in 2015, influences GFC data consistency" and "the Global Forest Watch website warns about these inconsistencies and advises against using the GFC product for the analysis of temporal trends".

Concerning Landsat data, the most recent changes occurred in 2013 with the availability of Landsat 8 and, therefore, it cannot explain the strong discontinuity in the time series observed in 2016. We note that, although our Article compares 2016–2018 with 2011–2015 (figure 3a in ref. [3]), the comparison of the last three years with 2013–2015 would yield qualitatively similar results, because the major change in harvest rate occurred from 2016 onwards. We also checked for possible differences in Landsat image availability between the two periods 2013–2015 and 2016–2018. As noted in our study, after 2013 there is a complete and frequent cloud-free coverage of Landsat images, with more than seven cloud-free acquisitions per tile every year; according to the authors of the GFC dataset[5], this is sufficient to detect forest loss. Furthermore, a statistical t-test between the total number of cloud-free Landsat images at tile level (Fig. 1b) shows that the number of satellite acquisitions did not change significantly between 2013 and 2018.

Concerning the change detection models, in the technical note to version 1.7 of the Global Forest Change data[6] a change in algorithm is reported only in 2011, and there is no information about following updates. Similarly, in the technical blog of the Global Forest Watch website, under the question "Is the data methodology consistent throughout the time series?" it is clearly stated that "The current tree cover loss data uses one algorithm covering 2001–2010 and another covering 2011–2018"[7]. As a consequence, contrary to the statement of Palahí et al.[2], the technical note to the Global Forest Change data[4] does not warn against the generic use of the GFC product for trend analysis, but only against "the integrated use of version 1.0 2000–2012 data and updated version 1.7 2011–2019". In our Article[3], we followed this recommendation and focused our analysis on the period 2011–2018. In recent years the GFC time series has been extensively used in the scientific literature, to assess the effect of forestry activities as in our Article[3] (for example, at the global level until 2015[8] and until 2019[9], with the time series extended until 2019 for individual countries[10]; and in Norway until 2017[11]) and as the basis for many other analyses (for example, refs. [12,13]). A recent report with high political impact, a Progress Assessment from the New York Declaration on Forests[14], concluded in November 2020 that "gross tree cover loss has increased in all regions" based on the analysis of the GFC time series. None of these publications, including those co-authored by the producers of the GFC dataset, mention an inconsistency of the time series after 2015; to our knowledge, this enhancement to the detection algorithm in 2015 was not reported. The effect of this change on tree cover statistics remains to be seen. Following the arguments of Palahí et al.[2], below we discuss the likelihood of a large influence of this algorithm change on our results.

To demonstrate the temporal inconsistency in our results, Palahí et al.[2] show that similar abrupt increases in GFC forest cover loss after 2015 appear for selected temperate regions of the world, using the Global Forest Watch website (figure 1a of ref. [2]). Although we acknowledge this discontinuity, we note that if it were purely driven by a difference in sensitivity of the algorithm then one would expect a consistent trend everywhere. This is not the case. In our study[3], only a minority of European countries (10 out of 26) show a statistically significant increase of harvest in 2016–2018 compared with the previous five years (extended data figure 6 in ref. [3]), with no apparent correlation with forest types or silvicultural practices. Furthermore, where a more complete dataset is used than the one used by Palahí et al.[2], the Global Forest Watch website shows that the increase in area of GFC tree cover loss due to forestry (large-scale forestry operations occurring within managed forests and tree plantations[7]) in the period 2016–2018 compared with 2011–2015 in large countries of the Northern Hemisphere such as Canada, China, Russia and the United States (+24%, +22%, +3% and +16%, respectively) is on average (+15%) about four times smaller than that reported for the EU (+59%). In the same period, our study indicates an increase in harvested area of +49% because we factored out more natural disturbances than did the Global Forest Watch. This already suggests that the change in algorithm per se is unlikely to explain the majority of the increase in harvested area that was observed in our study.

To assess the argument by Palahí et al.[2] that "detection and identification of selective logging and natural forest disturbances (e.g. wind, fire, and insect outbreaks) has improved markedly", we checked for possible signs of a greater sensitivity of the GFC data to forest loss after 2015. In our Article[3], we had already quantified the harvested area in each country for patches smaller than 0.27 ha, and we found that most of the countries that showed the largest increase in harvest (for example, Sweden, Finland and Poland) have a very limited fraction of clear-cuts in small patches. Here we report the trend of harvested forest area for patches larger than 2 ha (those for which detection is considered more accurate over time) and for patches smaller than 2 ha (those that are likely to be more affected by a change in sensitivity) (Fig. 1a). Our results

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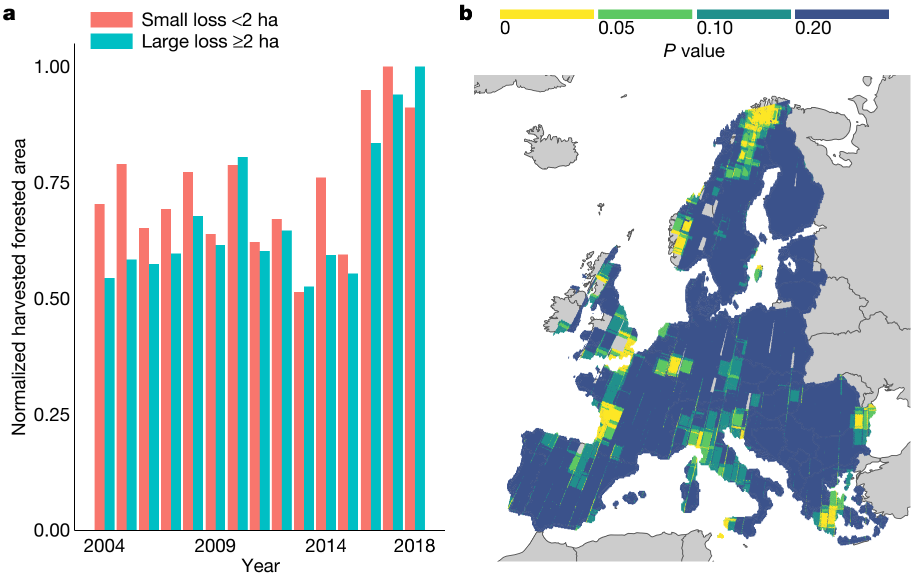

Fig. 1 | Large and small forest-loss patches, and *t*-test on cloud-free observations, for the periods 2013–2015 and 2016–2018. a, Normalized harvested forest areas at the European level between 2004 and 2018, classified by large (≥2 ha) and small (<2 ha) forest loss patches. Comparing the 2016–2018 period with the 2013–2015 period, there is a 59% increase in large patches and a 50% increase in small patches. For further details on harvested forest areas for different classes of patch size, see extended data figure 5 in our original Article[3]. **b**, The results of a *t*-test comparing Landsat 8 cloud-free observations for 2013–2015 and 2016–2018. Yellow (blue) shading indicates areas in which the number of observations changed (did not change) significantly. Using data for 2013–2015 (rather than for 2011–2015 as in ref. [3]) does not qualitatively change the results. Figure generated using Google Earth Engine[34].

show that the harvest rate increases almost equally in the two classes of patch size. Figure 1d in Palahí et al.[2] actually offers further experimental evidence to support our claims. Although a strong discontinuity in the accuracy of the product is evident around 2011–2012—which is expected on the basis of what was reported in the official GFC documentation[6]—no large change is visible in the interval from 2014 to 2017, which covers the two years preceding and following the major change reported in our study[3]. It is questionable whether the minor variations in sensitivity after 2015 shown in figure 1d of Palahí et al.[2] can be the only reason for the large and persistent discontinuity observed in our results, whereas the fourfold change in sensitivity observed around 2011 did not generate any apparent discontinuity in our time series (figure 3a in ref. [3]).

Palahí et al.[2] state that the validation presented in our paper is incomplete, correctly noting that we did not include an evaluation of the omission errors of the GFC data (that is, actual tree cover loss that remains undetected) and that the estimates of area are pixel-based instead of sample-based. They argue that this might especially affect the detection of low-intensity logging, with potential large implications for Sweden and Finland, where a large share of total harvest is derived from thinnings. To address this point, we performed a sample-based analysis to estimate the area of forest change over Sweden and Finland, to assess omission and commission errors, as suggested by Palahí et al.[2]. We performed a visual interpretation of very-high-resolution images from Google Earth and Landsat imagery and we quantified the sample-based area of GFC forest and loss strata for two different periods: 2011–2015 and 2016–2018. Further, we assessed errors of our estimates following standard procedures for accuracy assessment[15]. We applied a stratified random sampling to two strata: stable GFC forest (3,491 points) and GFC loss (1,846 points), using a number of samples per forest area that is substantially higher than those used in similar studies (for example, refs. [8,11,16,17]). Google Earth aerial photographs and very-high-resolution images were used to detect the harvesting, while cross-checks with time series of Landsat NDVI (normalized difference vegetation index) resolved the precise timing of the harvesting operation (Fig. 2d): if a drop in NDVI was observed in the Landsat NDVI time series, the year of disturbance was assigned. To factor out the influence of less-intensive forestry activities (for example, thinning and selective logging), we based the visual interpretation on a majority criterion: harvest was attributed only to 30-m pixels that showed a reduction of tree cover of greater than 50%. In this way, the adjusted areas strictly refer to clear-cuts, because all less-intensive forestry operations are excluded.

Our results show that, in Sweden and Finland, sample-based areas of forest change—which were obtained combining the information in the confusion matrix with the weighted areas for the two forest and loss strata according to ref. [3]—support our observations of an increased harvest rate in clear-cuts during recent years (Fig. 2a, b), although this is less than what was suggested by the pixel-count in the original study[3]. The sample-based area of GFC forest loss is equal to 1,934 ± 136 10^3 ha for the first period (5 years) and 1,568 ± 152 10^3 ha for the second period (3 years), whereas the pixel-based area[3] was equal to 1,906 10^3 ha and 1,761 10^3 ha for the same two periods. The resulting sample-based increase in annual harvested area between the two periods is equal to 35% ± 16% ($P = 0.95$, Fig. 2a), whereas the pixel-based increase was equal to 54%. Note that pixel-based estimates are associated with all detected forestry operations—that is, they also partially consider thinnings and selective logging after 2015—whereas sample-based estimates are specifically restricted to clear-cuts only. We note that the sample-based increase would have been higher if we had used a threshold lower than 50% to characterize loss of tree cover, as in ref. [11].

Ultimately, omission errors were found to be larger in 2011–2015 than in 2016–2018, whereas commission errors were larger in the second period, mostly due to the larger uncertainty in classification before the employment of Landsat 8 in 2013 (Fig. 2c). Each of the 1,846 visually assessed validation points for GFC loss were classified with very-high-resolution imagery into one of the following three classes of tree cover loss: 0–50%, 50–90% and >90%. The results in Fig. 2e show that the frequency of areas with partial change in forest cover did increase during 2016–2018 (from 12% to 21% for the 50–90% class and from 16% to 25% for the 0–50% class). On one hand, these results confirm the increasing sensitivity of GFC to low-intensity logging after 2015 as speculated by Palahí et al.[2], but on the other hand they suggest that this effect can only explain about one-third of the observed increase in harvest trend derived from the pixel-based approach. Although we

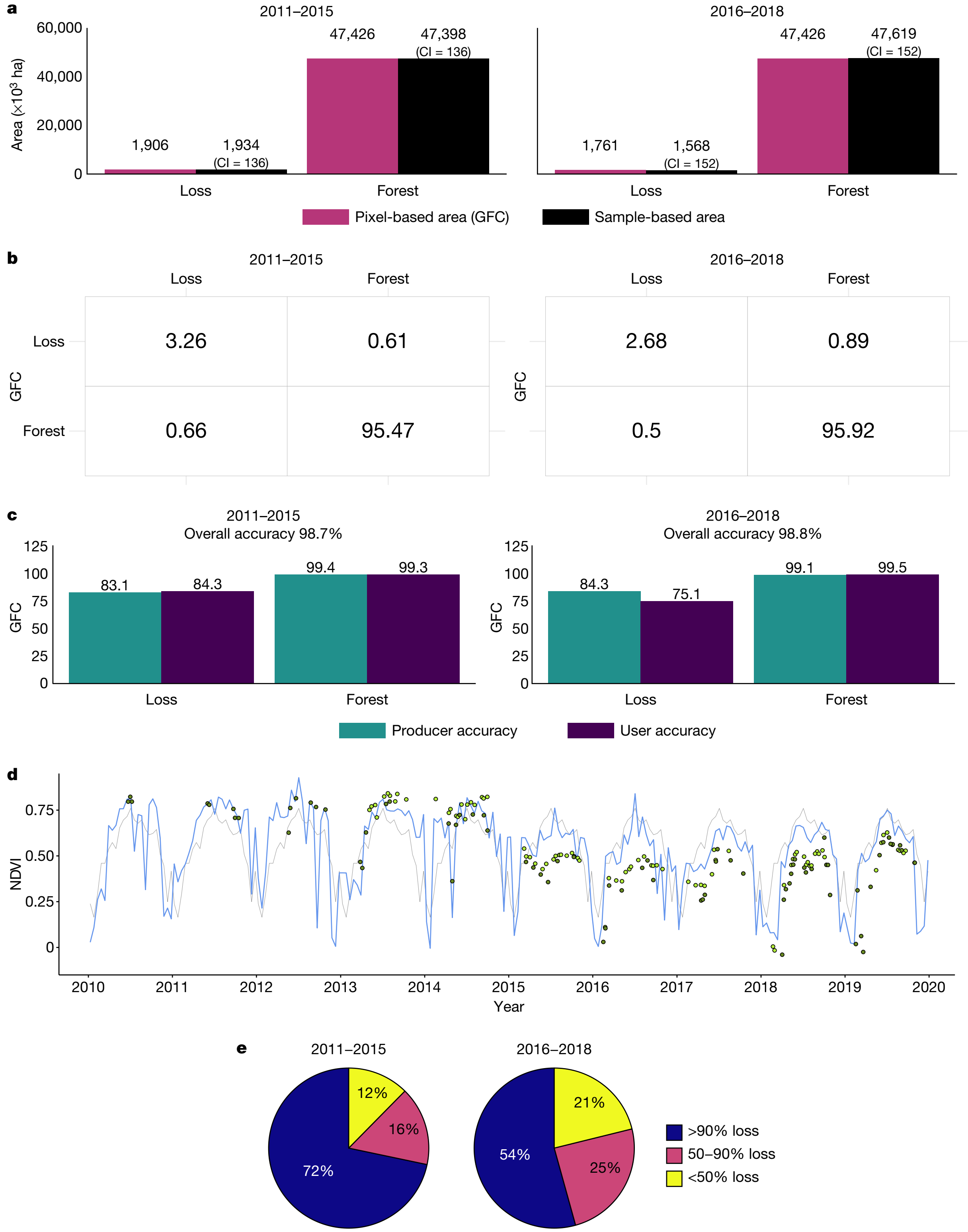

Fig. 2 | Comparison between pixel-based and sample-based estimates of forest change in Sweden and Finland. a, Comparison between the pixel-based GFC data (pink) and sample-based estimates (black) of the areas of forest loss and stable forest, over the periods 2011–2015 and 2016–2018. **b**, Confusion matrix expressed as the estimated area-corrected proportions (%) of forest loss and of stable forest area based on the validation random samples for the periods 2011–2015 and 2016–2018 in Sweden and Finland. **c**, The accuracies relating to the data in **b**. **d**, Example NDVI profile for a validation point that clearly shows the effect of a harvest operation between 2015 and 2016. To quantify the accuracy for the different periods, omissions detected with Google Earth images have been attributed to the year in which they occurred using the time series of NDVI from Landsat and MODIS. Landsat time series (green dots; Landsat 8, light green; Landsat 7, dark green) enable the detection of temporal change information at the pixel level, whereas the MODIS time series (background lines; MYD13, blue; climatology, grey) help to show the phenology of a broader area (250 × 250 m). **e**, The percentage of validation sample points of forest loss, in 2011–2015 and in 2016–2018, in Finland and Sweden that fall in areas with total forest loss (>90%; blue) 50–90% forest loss (pink) and less than 50% forest loss (yellow).

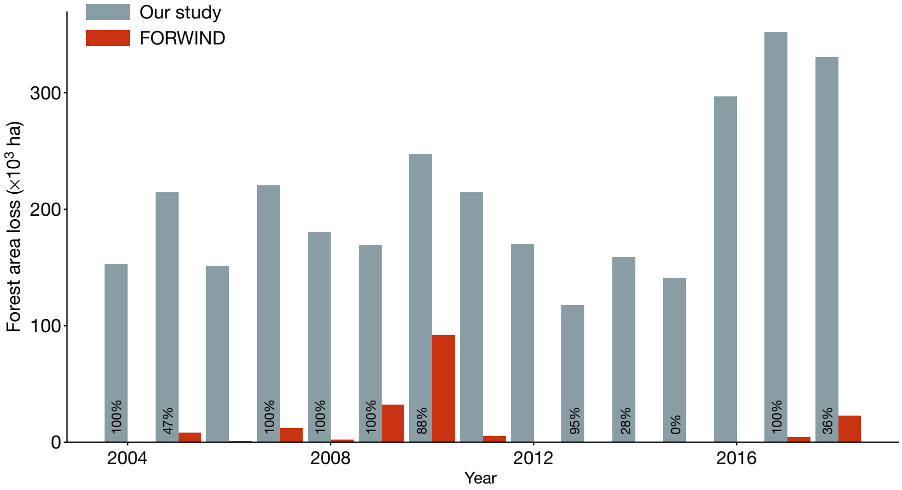

Fig. 3 | Forest loss from 'extreme events' stated in our study and in the FORWIND database. Forest area loss associated with 'extreme events' (mainly windthrows) from our study[3] (grey) and in the FORWIND dataset (red) over time. The labels denote the percentage of windstorm area in the FORWIND data that is also detected by our method. To be more conservative, within each FORWIND polygon we count all the forest losses that occur during the year of the reported windstorm and in the following year, because there might be temporal mismatches between the actual forest loss and the satellite detection. The area stated in the FORWIND dataset is much lower than that detected by our method, which demonstrates that our algorithm is conservative in isolating the harvested forest area. Figure generated using Google Earth Engine[34].

acknowledge the theoretical strengths of sample-based compared with pixel-based estimates of area change, we also stress the large uncertainty of sample-based estimates due to the limited spatial sampling and the difficulties of producing robust estimates of omissions due to the very small area affected by these errors (ref. [18]).

Second, Palahí et al.[2] stress that GlobBiomass is known to be unsuitable for analyses such as our study, due to considerable pixel-level uncertainties. We argue that, even if GlobBiomass may have a substantial uncertainty at the pixel level, the random component of the pixel-level uncertainty is largely reduced by aggregating data over large forest patches—as is the case in our analysis (extended data figure 5 in ref. [3]) and in the production of country statistics. However, we acknowledge that, in areas in which less-intensive forestry activities prevail, the random error component is likely to be higher. Regarding the systematic-error component of the uncertainty, the validation of the GlobBiomass map in Europe—performed using about 42,000 ground plots—showed that this product closely matches the reference data until 150 tonnes per ha and underestimates the biomass density above 200 tonnes per ha (ref. [19]). Because most harvested areas have a biomass density in the range of 100–150 tonnes per ha, our results are only marginally affected by systematic errors in the biomass map.

Third, Palahí et al.[2] argue that natural disturbances such as insects and windstorms were not properly factored out, and in many cases appear as harvest in our study. On the basis of omission errors (that is, areas where an undetected disturbance has occurred) shown in figure 2 of their Comment, Palahí et al.[2] argue that the FORWIND[20] database on wind disturbances in European forests would have provided a basis for more direct attribution. Omission errors are unavoidable, because our attribution was based on a statistical method (detection based on anomalously high harvest level) and not on the direct classification of disturbance patches, due to the lack of appropriate EU-wide observation-driven datasets. However, as was also suggested by Palahí et al.[2], evaluating the accuracy of a map requires accounting for both omission and commission errors (that is, areas in which our statistical approach attributed a natural disturbance that did not occur). On this point, Fig. 3 shows that our attribution of area affected by natural disturbances (defined as 'windthrows' in our original Article[3] but accounting also for major insect outbreaks) is much larger than that reported in the FORWIND database[20], therefore suggesting widespread commission errors. Because commission and omission errors have opposing effects on the overall statistics, they may compensate each other.

We compared the harvested biomass due to natural disturbances from our original study[3] (which was converted to under-bark volumes by assuming a wood density of 0.45, typical for conifers that are mostly affected by these disturbances, and a ratio between under-bark harvest and fellings of 0.7) with salvage-logging statistics that have recently become available for 15 EU countries[21]; these countries represent 82% of the forest harvest reported in EU-level statistics for the period 2011–2018. The annual average salvage logging reported in our original Article[3] is equal to 6.3 Mm^3 (2011–2015) and 31.7 Mm^3 (2016–2018), whereas salvage logging from country reports is equal to 41.7 Mm^3 (2011–2015) and 66.6 Mm^3 (2016–2018). Therefore, although our approach underestimates salvage logging associated with natural disturbances, it correctly captures the trend—that is, the difference in salvage logging between 2011–2015 and 2016–2018 is about 25 Mm^3 yr^{-1} both using our method and using country statistics. This indicates that the underestimation of natural disturbances does not affect the trend in harvested forest area that is reported in our Article[3]. However, comparisons of time series of harvest statistics from salvage logging with remote-sensing retrievals should be made with caution, because of possible time lags (for example, salvage logging may occur a few years after the disturbance takes place) and because of uncertainty in the fraction of timber that is actually collected after the disturbance.

Overall, although we acknowledge that most of the issues raised by Palahí et al.[2] are relevant and worthy of consideration, they do not undermine the value of our study. The temporal inconsistency of GFC data after 2015 did affect the magnitude of our results, but the additional validation exercise for Sweden and Finland—even if not conclusive for the large uncertainties in the estimates—supports our conclusions on the increasing area of clear-cuts. Furthermore, although our approach has limitations in disentangling the planned forest harvest from the effect of natural disturbances such as insects and windstorms, it correctly captured the trend in these disturbances; therefore—in the absence of better data—this approach can be considered an acceptable proxy for the scope of our study. Given the increasing threat posed by these natural disturbances to European forests[22], we agree with Palahí et al.[2] on the need for a collective effort to acquire consistent and spatially explicit data on these events.

While data analysis on natural disturbances progressively improves[23], we think that substantial steps forward regarding the detection and attribution of natural disturbances will become possible only from the analysis of recent EU-wide very-high-resolution spatial data.

Our study[3] indicated the socio-economic context (certainly including the economic recovery after the 2008–2012 crisis, as suggested by Palahí et al.[2]) as a probable main driver of the increase in harvested area not because of a direct causal connection, but because we excluded other potential alternatives. Here we further emphasize the high uncertainty of this attribution, as stated in the original Article[3]. At the same time, it is crucial to understand that our study does not question or undermine the key role of a sustainable forest-based economy towards a carbon-neutral EU, but rather offers a complementary tool to monitor forest resources, therefore supporting the implementation of policies such as the European Bioeconomy Strategy[24], which promotes the sustainable and circular valorization of biological resources within safe ecological boundaries.

In addition, we re-emphasize that the method in our original study[3] mainly detects relatively large-scale (30 × 30 m) forestry operations, whereas less-intensive activities (for example, thinning and selective logging) may have remained largely undetected. This implies that comparisons of our results with national statistics on total harvest should be made with caution, because the forestry activities detected by our method (that is, mainly clear-cuts) do not necessarily represent the largest share of harvest for specific countries, as extensively shown in the original Article[3] (see supplementary table 1 of ref. [3]). This is also evident by the fact that, when our results on biomass in the period 2011–2015 (about 150 $\mathrm{Mt\,yr^{-1}}$ in the EU, figure 3a of ref. [3]) are converted to $\mathrm{m^3}$ (approximately 300 $\mathrm{Mm^3\,yr^{-1}}$), they correspond to only about 50% of the conceptually equivalent data from country statistics (about 600 $\mathrm{Mm^3\,yr^{-1}}$ of fellings including residues and bark, as derived from ref. [25]). For the most recent years this percentage increases, but it is possible that the recent surge in natural disturbances has increased the ratio of forestry activities detected by our method (that is, clear-cuts, also for the purpose of salvage logging) to the undetected less-intensive forestry activities. The direct comparison of country data with annual remote-sensing estimates is further complicated by the fact that, in many countries, harvest statistics are either based on a combination of data sources (including industry reports of wood sourcing) or consist of multi-year rolling averages. We acknowledge the legitimate concerns expressed regarding the discrepancies in trends between our results and individual country statistics (for example, ref. [26]), which probably largely remain even when our results are corrected with a sample-based approach. However, the comparisons shown in our Article (extended data figures 6 and 7 of ref. [3]) should not be interpreted as suggesting that statistics are necessarily incorrect, but are rather aimed at helping to understand general patterns and indicate areas of possible discrepancies that are worthy of further analysis. Although statistics will remain essential for any analyses of forest resources, their robustness varies among countries, and improvements are needed; for example, it is well-documented that reported wood uses are up to 20% higher than wood sources at the EU level[27], and that imports alone cannot explain the gap. We believe that further analysis of the discrepancies noted in our paper may help to increase the confidence in the trend of forest harvest in the EU, and its attribution to specific drivers.

The comment by Wernick et al.[1]. concludes that “there are inconsistencies in the proposal by Ceccherini et al.[3] that sustained increases in the harvested area of EU forests lead to net atmospheric carbon emissions from these forests”.

First, we note that we do not state in our Article[3] that EU forests will turn into a net source of carbon emissions as a result of the harvest increase that we observed in recent years. Our conclusion was that if the high rate of forest harvest observed in our study continues, the post-2020 EU vision of forest-based climate mitigation may be hampered. We used ‘if’ because—contrary to the suggestion of Wernick et al.[1]—we do not make any projection in our study. We stated ‘may’ because, as explained above and in the original Article[3], our method detected mainly clear-cuts, which are not necessarily representative of the total harvest reported in country statistics. Although an increase in total harvest at the EU level would be very likely to lead to a reduction of the carbon sink (equivalent to the ‘additional carbon losses’ mentioned in our Article[3]), this does not suggest that EU forests will necessarily become a net source. The forest biomass sink reflects the difference between forest growth (net increment) on the one hand, and harvest and natural mortality on the other. In the past decades, both growth and harvest in Europe slowly increased[28], leading to an approximately constant sink[29]. Even assuming a sustained slow increase in growth—which is far from certain[28]—a substantial increase in total harvest would lead, in the short term, to a decline of the sink. This is also clearly shown by official projections made by EU countries under a business-as-usual management scenario, in which a projected approximately 17% increase in total harvest for the period 2021–2025 relative to 2000–2009 leads to a corresponding 18% decrease in the forest sink[30]. This effect may be later compensated by a further increase in forest growth, but this rebound typically requires decades. Because reaching the EU climate targets assumes at least conserving (in 2030) or enhancing (in 2050) the current forest sink[31], our results simply warn against the risk of not reaching this assumed sink within this timeframe. The effect of the new sample-based validation on our results, as discussed above, does not substantially alter our previous conclusions.

The inconsistencies noted by Wernick et al.[1] are first that the selection of the two periods for comparison seems to be problematic, because of the global economic expansion in 2016–2018 and because the control period is too short; second, that the effects of fires and windstorms should have been factored out to support our conclusions; and third; that the GFC dataset does not give information on forest density beyond a certain threshold, suggesting that we did not account for the annual incremental growth in the estimate of harvested forest biomass.

On the first point, we did not exclude a possible effect of global markets on the increase of wood demand, which we suggested to be probably the main driver of the observed harvest (but without indicating causal connection, as discussed above). The choice of the control period was to ensure consistency in the GFC product[4], as we also explain above. Extending this period before 2011 would lead to similar conclusions (see figure 3 in ref. [3]), but would introduce the additional uncertainty of the algorithm change documented from 2011 onwards in the GFC dataset.

Second, Wernick et al.[1] note that the effects of fires and windstorm must be factored out. This was done in our original study, as explained in the Article[3]. If the effects of fires and windstorm had not been excluded in the study, the estimates of the recent increase in forest harvested area would have been around 60%, instead of 49%.

On the third point, we stress that biomass density over time was not obtained from the GFC dataset—which indeed does not include these variables—but instead is derived from a combination of a forest biomass dataset (ESA GlobBiomass[32]) and national statistics[33] of growth rate, as reported in the Methods. Therefore, our estimates of harvested biomass explicitly account for the incremental growth.

In conclusion, the comments by Palahí et al.[2] and Wernick et al.[1] gave us the opportunity to assess the effect of the change in the GFC algorithm on our results and to clarify several misunderstandings that led to interpretations of our study that were beyond our original intentions. We believe that these clarifications strengthen the main messages from our study—that is, that Earth observation and big-data analytics are very promising tools for a detailed and spatially explicit monitoring of forest resources (provided that a temporally consistent tree-cover map is available), and that an increase in clear-cut harvest has been observed in recent years in the EU. We are approaching a revolution for the integration of Earth observation in the monitoring of forest resources. The success of this integration, which is essential to the European ambitions on biodiversity conservation and climate-change mitigation, depends not only on the combination of ground surveys with modern satellites—such as the Copernicus Sentinel-1 and Sentinel-2 sensors that have up to 10-m spatial resolution—but also on the continued and effective cooperation among the various scientific communities involved, the national agencies responsible for forest surveys and the European institutions.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this paper.

Data availability

To ensure full reproducibility and transparency of our research, all of the data and the scripts used in our analysis have been made available or can be obtained from the corresponding author upon request. Codes used for this study (Google Earth Engine and R scripts, and data synthesis on the validation for GFC stable forests and loss) are available on GitHub at https://github.com/guidoceccherini/NatureCommentary.

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