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Integrated analysis of harvest statistics provided by remote sensing, national forest inventories and administrative survey systems: An example from Italy

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ABSTRACT

Forests are a key element for reaching the EU climate neutrality targets, but natural disturbances, climate change and human activities, make it urgent to set up a continuous monitoring system of the main parameters affecting forest ecosystems. A key parameter is the annual felling: the volume of trees felled during a given reference period.

We combine National Forest Inventory data, based on direct field measurements, with yearly time series data derived by remote sensing, to assess the amount of fellings carried out in Italy between 2000 and 2023. Italy was selected as a representative case study as harvest statistics are missing or partially inconsistent, which is also the case for other European countries.

We highlighted that no data source, considered individually, can provide a comprehensive estimate of the harvest level and its evolution in time.

Between 2000 and 2023, total fellings ranged from a peak of 16.5 million m^3 in 2006 to a low of 10.4 million m^3 in 2014.

A near real-time assessment of the harvest level, such as estimated within our study, is increasingly important to quantify the impact of human activities on forest ecosystems. According to our results, the fellings rate, i.e. the ratio between fellings and increment, was about 0.38 within the latest years. Nevertheless, considering the uncertainty of all input data, the total fellings ranged by about ± 50 %, and the corresponding fellings rate could be significantly larger. From this arises the urgent need to set up a continuous monitoring system, integrating National Forest Inventory surveys and remote sensing data reliably, not only in Italy, but across the EU.

1. Introduction

As stated by the New European Forest Strategy, strategic forest planning must be based on reliable monitoring and data (European Commission, 2021). In the case of forests, one of the key variables affecting the system are annual fellings, i.e. the average annual standing volume of all trees, living or dead, that are felled during a given reference period (UNECE/FAO 2000). When related to the net annual increment (NAI), the total amount of fellings is a key parameter to quantify the sustainability of forest management (Avitabile et al., 2023), determining also the short to medium-term evolution of the forest carbon sink (Pilli et al., 2016), such as other socio-economic and ecosystem services provided by the forests (Mansuy et al., 2024; Jonsson, 2024). In most cases, in Europe, at least 85–90 % of felled trees are removed from forests and used as industrial roundwood and fuelwood material (Pilli and Grassi, 2021).

At local scale, fellings can be easily determined through direct field measurements carried out on felled trees or using Airborne Laser

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Scanning technologies (Gülci et al., 2023). At regional and national scale, annual fellings are generally estimated through indirect statistical surveys. When available, annual statistical surveys based on data provided by forest management plans can be collected and integrated with data provided by forest authorities and by the industrial sector. This provides a continuous and detailed monitoring system of fellings (e.g., Swedish Forest Agency, 2025), which can be further refined with direct field measurements collected from National Forest Inventories (NFI, Vidal et al., 2016). Although NFI are available for most European countries, they do not provide the needed continuous monitoring system of annual fellings on their own, as the NFI survey cycles span multiple years. To fill this (temporal) gap, various approaches to estimate the amount of fellings from remote sensing, both at national and subnational scale, were tested recently (e.g., Ceccherini et al., 2020, Fassnacht et al., 2024). Despite an increased temporal coverage and availability of remote sensing data as well as enhanced assessment tools, remote sensing techniques primarily detect the area affected by changes, such as from large-scale felling activities, but also from natural disturbances and land use change, i.e. deforestation (Viana-Soto and Senf, 2025). However, attributing this areal change to one source, e.g. fellings or natural disturbance, remains very challenging with remote sensing. Following this, there is a high level of uncertainty when using area change as detected by remote sensing as a proxy to determine the volume of felled trees. Hence, remote sensing alone does not provide the means to estimate the total volume of felled trees at high temporal resolution, neither at local nor at large scale, but needs to be integrated with other data sources (Ceccherini et al., 2022).

Although in EU-27 at least 57 % of the forest area is covered by long-term forest management plans (FAO, 2020), detailed data series on the annual fellings, or just on annual removals (i.e., the fraction of fellings removed from forests), are sometimes missing, incomplete, and in most cases, not fully comparable among EU member states (Camia et al., 2018; Päivinen et al., 2022). In some countries, with long-established forest monitoring systems, detailed information on annual removals is already available at both national and regional (NUT2) levels. This is, for example, the case of some central and northern European countries (Czech Statistical Office, 2024; Swedish National Forest Inventory, 2024). In other cases, however, harvest statistics are partially missing or, if available, underestimated (Camia et al., 2018; Pilli and Grassi, 2021) and, in most cases, not reporting the most recent evolution of the harvest rate, which is essential to monitor the ongoing development of the forest carbon sink (Korosuo et al., 2023). An overview of roundwood removals reported by FAOSTAT (2025) for the EU-27 highlights that at least five EU member states report a partially constant data series for the period 2000–2023, either for total roundwood or fuelwood. Similar patterns, including data gaps, are also evident in data reported by EUROSTAT and by the State of Europe's Forests (SoEF) (Pilli et al., 2023). In these cases, if properly integrated with direct field measurements, remote sensing data can partially supply the lack of data collected at the national level.

This may be the case of Italy, where, until 2012, national statistics on annual removals, based on data collected at the regional level, were made available from the National Italian Statistical Institute (ISTAT, 2015; Pettenella, 2024). Since 2013, increasing gaps in data provided by single administrative regions made this data series quite uncertain, breaking off the publication in 2015. Meanwhile, two National Forest Inventories, formally attributed to 2005 and 2015 (Gasparini and Tabacchi, 2011; Gasparini et al., 2022), provided some direct estimates on the annual amount of fellings attributed to single regions, and the overall country. Italy, where forests and other wooded land cover about 37 % of the area (Gasparini et al., 2022), has transitioned from having some data series, albeit underestimated, that reported interannual variations in harvest levels at both national and regional scales, to a complete lack of data since 2015 onward. In the meantime, exceptional events, such as windstorms and insect outbreaks, made it more urgent to establish a consistent national monitoring system (Pettenella et al., 2021). Recent initiatives, based on the use of remote sensing data, collected both at the national (Chirici et al., 2019; Francini and Chirici, 2022; Chirici et al., 2011) and supranational level (Viana-Soto and Senf, 2025), and on a bottom-up, participative voluntary process (Pecchi et al., 2024), are trying to fill these gaps. Nevertheless, they can hardly fill the historical gap due to the lack of information within previous years, and they need a running system moving forward.

Taking these premises into account, with this study we aim to address the following questions. (i) How accurately can annual felling in Italy be estimated at national and regional levels, through a multi-layered integration of field measurements, statistical surveys, and remote sensing data? (ii) To what extent does this integrated approach improve the consistency and completeness of historical harvest statistics (from 2000 onward) in line with the objectives of the New EU Forest Strategy (European Commission, 2021)?

This approach can also serve as a useful case study for other European countries, not only for integrating missing or incomplete harvest statistics, but also for providing a preliminary, near real-time estimate of ongoing forest harvest dynamics.

2. Material and methods

2.1. Comparison between available data sources

Firstly, all the available data sources for Italy were critically revised. Fig. 1 presents a comparison of annual removals as reported by ISTAT (2015), FAOSTAT (2025), EUROSTAT, (2025), and State of Europe's Forests (SoEF, Forest Europe, 2020), alongside the total amount of fellings −including bark and logging residues − estimated by NFI 2005 and 2015, as well as those inferred from the 2018 Italian National Inventory Report (NIR, Italy, 2018).

The lowest harvest level of about 7.5 million m^3 yr^{-1} between 2001 and 2012 is reported by ISTAT. This is in line with various studies, which highlighted that statistical surveys provided by the National Italian Statistical Institute largely underestimate harvest levels, neglecting the amount of wood used for fuelwood (Pra & Pettenella, 2016; Marongiu & Gismondi, 2018). The decreasing removals reported by ISTAT between 2013 and 2015 are mostly due to the lack of data provided by individual regions. SoEF data are well aligned with ISTAT, at least for 2010. The FAOSTAT data series, based on values reported by the country and further refined by FAO, reports an average annual amount of removals equal to 12.2 million m^3 yr^{-1} until 2012. This value, 1.6 times larger than the average estimate provided by ISTAT within the same period, is probably inferred by applying constant correction factors to the original data series made available by ISTAT and further scaled to regional level. The same approach was applied by the Italian NIR (Italy, 2018). Between 2013 and 2018, FAOSTAT did not report any interannual variation, suggesting that no update was made available by national statistics until 2019. Salvage logging activities were carried out after a windstorm that occurred in autumn 2018 (hereafter named Vaia), which led to an abrupt increase in total removals reported by FAOSTAT in 2019. This diverse picture is complemented by removals reported by EUROSTAT, which are mostly at an intermediate level between FAOSTAT and ISTAT, except for an abrupt annual increase reported for 2013 and 2019 after the Vaia windstorm.

The data reported by the two NFI also include logging residues, therefore they refer to total fellings, and they are conventionally attributed to the years 2005 and 2015. The total amount of fellings reported by NFI 2005 equalling to 13.8 million m^3 is larger than the total removals reported by FAOSTAT, which excludes logging residues and bark fraction. On the other hand, total removals reported by FAOSTAT in 2015 are considerably larger than the total fellings estimated by NFI 2015, equal to 9.5 million m^3. Until 2018, Italy's National Inventory Report (NIR) used a dataset of national timber harvesting estimates, which were based on ISTAT statistics that had been regionally adjusted to match the 2005 National Forest Inventory totals. These numbers were consistent with both NFI data and ISTAT trends up until 2015.

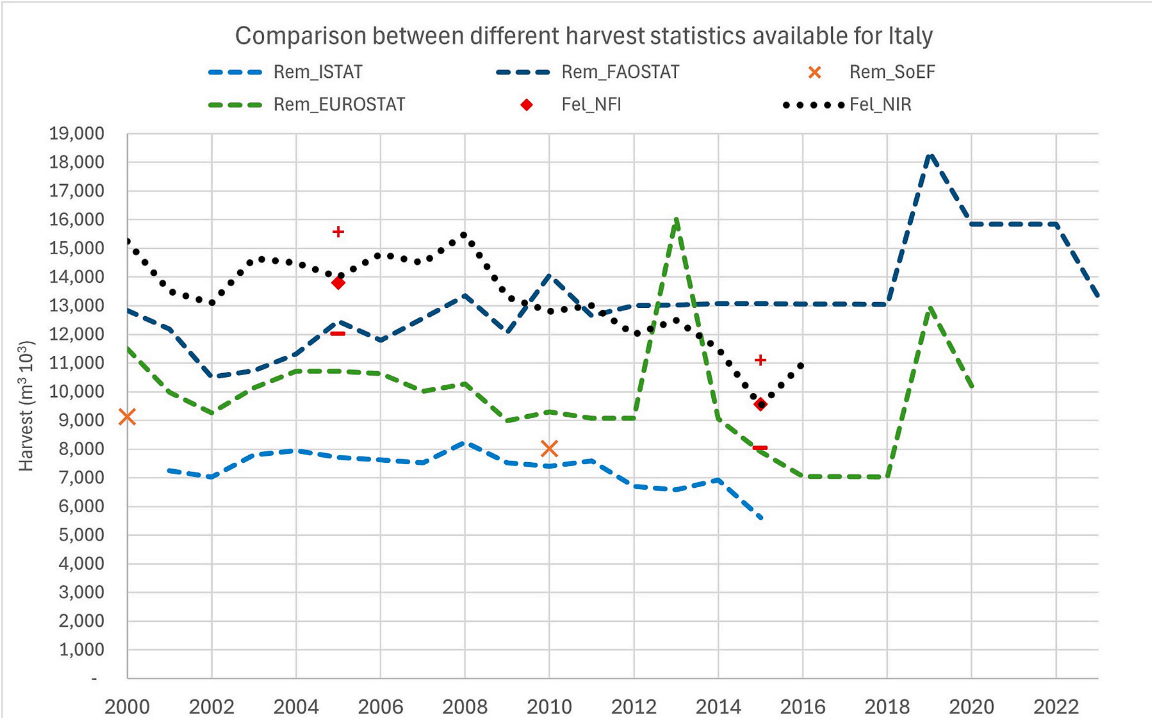

Fig. 1. Comparison between total removals reported by ISTAT (until 2015), FAOSTAT, EUROSTAT and State of Europe's Forests (SoEF, 2020) and total felling (including logging residues) reported by NFI (NFI 2005 and 2015) and by the Italian National Inventory Report (NIR, 2018). NFI also reports the percentage standard error associated to each record, reported on the figure as red + and – markers. Data is reported in thousands of m^3, over (o.b.) or under bark (u.b.), depending on data sources. Rem_stands for removal and Fel_for fellings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Input data selection

Based on the previous assessment, we selected the following input data to be used for our analysis:

1. Amount of fellings reported by the Italian NFI 2005 and 2015, further scaled at NUTS2 level (see Fig. 1A, Supplementary Material), including the corresponding confidence interval reported by NFI for each region (Gasparini and Tabacchi, 2011; Gasparini et al., 2022). These values, which represent the only data source based on direct, standardized, field measurements, are conventionally attributed to the amount of harvest that occurred during the 12 months before the field detection period (Gasparini et al., 2022). For this reason, we also considered, as ancillary information, the date associated with each field plot measurement carried out at the regional level by NFI 2005 and 2015 (Chirici & D'Amico, *pers. comm.*).
2. Data reported by the European Forest Disturbance Atlas (EFDA). The EFDA is a remote sensing-based disturbance dataset, indicating pixel-based identified forest disturbances by their disturbance year (1985–2023) and disturbance agents, such as fires, windstorms and bark beetle infestation, harvest activities, and areas affected by multiple disturbance agents. A forest land use mask was applied that broadly follows the FAO definition. Additionally, a minimum mapping unit (MMU) consisting of 6 Landsat pixels (0.54 ha) was applied for the forest mask (Viana-Soto and Senf, 2025).
3. Ancillary information, including: (i) the area affected by fires, as reported both by EFDA (at the national and regional level) and by the European Forest Fire Information System (EFFIS, 2024), (ii) the area and volume affected by the recent windstorm that occurred in northern Italy in October 2018 (see Fig. 1A, Supplementary Material), as reported by various data sources, including both specific studies based on remote sensing data (Chirici et al., 2019) and data collected at the regional level (AA. VV., 2020; Cozzarini, 2018; Provincia Autonoma di Bolzano, 2018, Celona et al., 2023), (iii) harvest statistics collected at regional level, when publicly available and reporting a continuous time series (e.g., Celona et al., 2023).
4. Historical harvest statistics provided by the National Italian Statistical Institute, for the period 2000–2015, based on data collected at the regional level, were used for validating our results. This database (only partially accessible online, but already used in previous studies, e.g., Pilli et al., 2013) reports the annual removals, scaled at the regional level, further distinguished between timber (i.e. industrial round wood) and wood used for energy.

2.3. Data integration

The analysis is based on the integration of NFI and remote sensing data, identifying their individual and combined strengths for various assessment periods and administrative units, primarily NUTS2 level (see Appendix A, Supplementary Material). Before combining NFI data and EFDA time series, we assessed the consistency of both input datasets, to identify possible outliers.

2.3.1. Data preprocessing

As stressed by Viana-Soto & Senf (2025), the agent attribution provided by EFDA should be taken with caution as reliable estimates of disturbance agent map accuracies are missing. This is quite crucial for the following analysis, since we aim to use the area classified as "harvest" by EFDA as a proxy to infer the amount of fellings. Moreover, in their study, the authors emphasize that the quantification of disturbances and trends should rely on "manually interpreted sample" techniques or on models that account for the varying accuracy of these data over time. Based on that, we checked and preprocessed the EFDA dataset through the following steps (see Fig. 2 and Supplementary Material, sheet '*EFDA_data_check*' for further details):

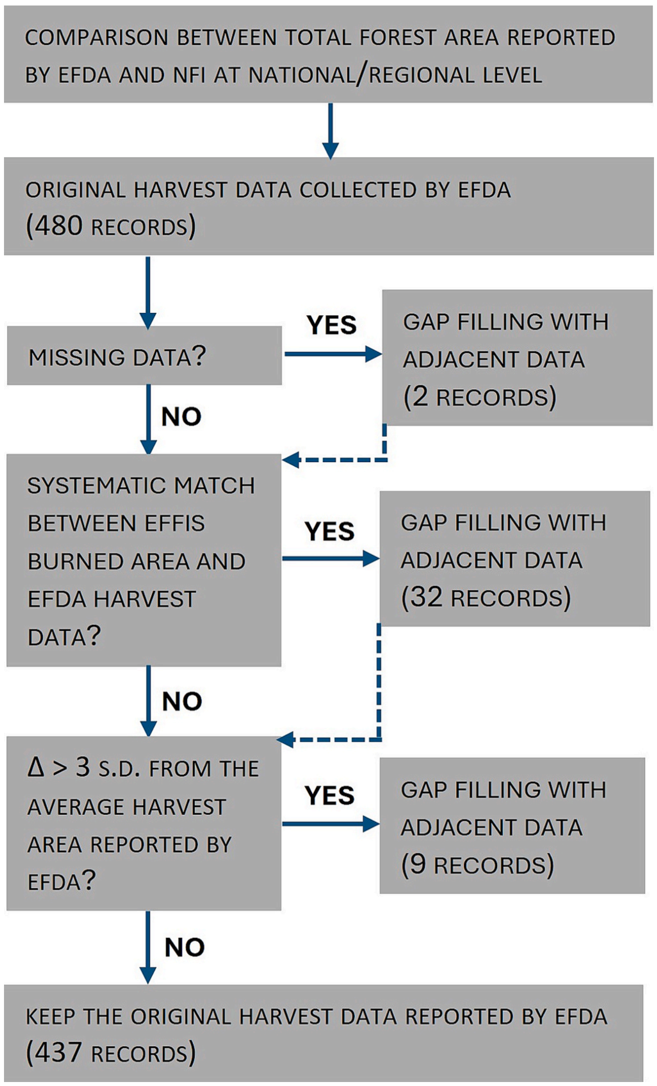

Fig. 2. Preliminary check and corrections applied to original harvest data collected by EFDA.

1. We preliminarily compared the total forest area considered by EFDA with the one reported by NFI 2015, to assess the reciprocal consistencies between the two main input datasets used within this study.
2. We identified two single years (both in the same region), with missing EFDA disturbance records. To address these gaps, we implemented a gap-filling method using the averages from adjacent years.
3. A systematic comparison was carried out between the relative area assigned to harvest and wildfires by EFDA with the area affected by fire as reported by EFFIS for each region. This analysis identified 32 records where both the EFFIS data and the harvest-EFDA data series report a peak in disturbance dynamics. However, these peaks generally do not correspond with similar trends in the fire data reported by EFDA. In some cases, EFDA reports a peak on the area affected by fire with a delay of 1 year (Viana-Soto & Senf, 2025). For these values, which represent 6.6 % of total records considered by our analysis (i.e., 20 administrative regions * 24 years), the value reported by EFDA as "harvest" was replaced by the average from the adjacent years. Since there is no salvage logging generally applied after fire events in Italy, we can assume that the area affected by wildfires was erroneously assigned to "harvest" within the EFDA database.
4. Following the corrections reported in points (2) and (3), we performed an overall analysis of the final values reported by EFDA, for each region, to identify other observations affected by possible detection errors. For this, annual records with a difference greater than 3 standard deviations from the average area disturbed by harvest activities at regional level were considered to be outliers and excluded from the subsequent analyses. At this stage, we identified nine additional records that were replaced with the average of adjacent data points.

Before using NFI data we performed (i) a reciprocal comparison between NFI 2005 and 2015 data at regional level and (ii) an accuracy assessment of the NFI reference year, to correctly attribute the amount of fellings reported by NFI to the corresponding period. To assess the quality of NFI data, we applied the following criteria:

1. When the amount of fellings reported by NFI for a NUTS2 region was null, then we excluded this data series from the following data integration. This is the case for the Val d'Aosta region, reported by NFI 2005.
2. If the difference between the amount of fellings reported by the two NFIs is larger than 80 % for a region, then the NFI reporting the lower amount of fellings was excluded by the following data integration. This is the case for 3 records reported by NFI 2015 and 1 record reported by NFI 2005. All details are reported in Supplementary Material (sheet '*Data_analysis*').

The date recorded for each NFI field plot (see Fig. 1B, Supplementary Material) shows that the amount of fellings reported by NFI 2005 (F_{2005}) was derived from field measurements carried out between May 2004 and July 2005 (at least for the field plots reporting harvest activities). This data indicates the volume of fellings that took place within a 12-months period. In some cases, this period may extend up to 24 months before the survey date, due to challenges in determining whether harvesting occurred before or after the 12-month threshold during the field survey. Similarly to the NFI 2005 data, NFI 2015 data is derived from ground measurements collected in various years (Fig. 1B), with most of the surveys reporting harvest activities carried out between 2018 and autumn 2019 (Gasparini et al., 2022). In this case, however, survey years vary across the regions.

2.3.2. *Data integration*

As shown in Fig. 3 (Step 1), while EFDA provides a long data time series, the NFI data report total fellings for two points in time. Based on our preliminary assessment of the actual survey dates, data reported by NFI 2005 was assigned to 2004, and NFI 2015 was assigned to 2018.

Combining both data sets allows us to, on the one hand, work with ground data and, on the other hand, take advantage of a long, consistent, and yearly time series. Data reported by NFI 2005 can be associated with the average area (A_{NFI}) affected by harvest disturbances reported by EFDA within the period 2003 – 2005. Therefore, for each region i, A^i is given by:

$$A^i_{NFI} = A^i_{03} * w^i_{03} + A^i_{04} * w^i_{04} + A^i_{05} * w^i_{05} \quad (1)$$

With this equation, the disturbed area associated with each year y, as reported by EFDA, was scaled using a weighting factor w^i_y (see for example Tomppo et al., 2008) inferred from the number (N) of field plots reporting harvest data for each region and year:

$$w^i_y = \frac{0.5 * N^i_y + 0.5 * N^i_{y-1}}{\sum^i_{03-05} N^i_y} \quad (2)$$

The number of field plots reporting harvest data was directly inferred from the original data collected from NFI field measurements (see Fig. 1B, Supplementary Material). Similarly to the NFI 2005 data, NFI

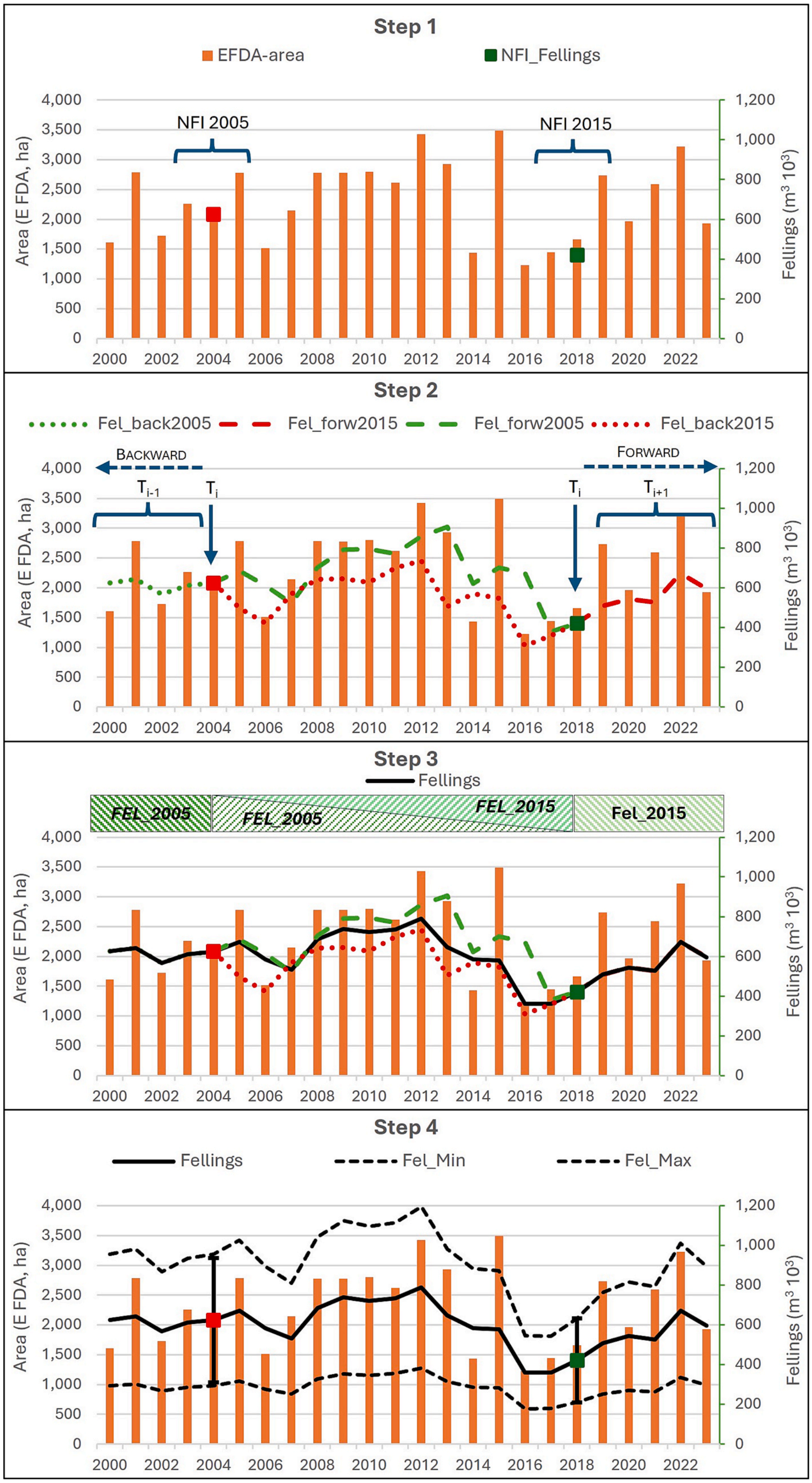

Fig. 3. The following panels report an example of the main steps implemented, at regional level, by our methodological framework: Step 1: temporal evolution of the area affected by harvest according to EFDA (reported on the left axis) and total fellings (reported on the right axis) estimated by NFI 2005, assigned to 2004, and NFI 2015, assigned to 2018; Step 2: calibration of EFDA data series against NFI data; Step 3: final fellings derived by Fel_back_2005, Fel_forw_2015 and by combining Fel_forw_2005 with Fel_back_2015 with scaling weighting factors; Step 4: maximum and minimum amount of fellings as derived by NFI error intervals.

2015 data is associated with the area affected by the disturbance events reported by EFDA within the period 2017–2019.

If properly calibrated with NFI data reporting the total fellings (F_i) that occurred within a certain period (Ti), the relative difference between the area affected by disturbance events in EFDA within the period Ti, and the following or preceding periods (T_{i+1} or T_{i-1}) can be used to estimate the evolution of Fi within a certain time period (Fig. 3, Step 2). A prerequisite is that the share of different silvicultural practices determining the total fellings, i.e., thinning, final cuts, selective logging and any other activities applied within a certain region, is stable over time, as EFDA cannot pick up thinning or selective logging (Viana-Soto and Senf, 2025). The further the assessment period is from T_i, the higher is the probability that silvicultural practices have changed, increasing the uncertainty of the final results. Given the availability of two NFIs documenting total fellings for 2004 and 2018, the data series can be divided to determine the relative variation in fellings by applying each NFI within a forward or backward calibration framework (see the example of Fig. 3, Step 2). For the years before 2004, we used a backward approach to estimate the fellings, starting from the amount of fellings reported by NFI 2005 (F^i_{2005}). We derived the ratio (D_{yy}) between the area affected by disturbance events within the previous periods 2003 – 2004, 2002 – 2003, 2001—2002, and 2000 – 2001, and A^i_{NFI}:

$$D^i_{yy} = \frac{(D^i_y + D^i_{y+1})/2}{A^i_{NFI}} \tag{3}$$

This ratio represents the relative variation of the forest area affected by disturbance events within each period and the NFI detection period. For each region, the amount of fellings associated to each year (Fy) is then assessed by multiplying the relative variation of the area affected by disturbance events within each biannual period, with the amount of fellings reported by NFI data:

$$F^i_y = F^i_{2005} {}^* D^i_{yy} \tag{4}$$

This data series is defined as Fel_back_{2005}. In the same way, using a forward approach, starting from F^i_{2005} we estimated the fellings from 2005 onward, until 2017. We derived the average area affected by disturbance events within the following periods, 2004 – 2005, 2005 – 2006, and so on until 2016 – 2017, determining the corresponding amount of fellings using Eqs. (3) and (4). This data series is defined as Fel_forw_{2005}.

By using the NFI 2015 and same backward approach applied for NFI 2005, we inferred the amount of fellings within the period 2005 –2017 (this data series is defined as Fel_back_{2015}), and the period 2019 – 2023, using a forward approach (Fel_forw_{2015}), with the value associated to 2023, inferred only from remote sensing data attributed to 2023.

For Trentino-Alto Adige and Veneto, the two regions mostly affected by the Vaia windstorm in October 2018 (see Table 1E, Supplementary Material), we diverted slightly from the previously outlined workflow. When calibrating the data series with NFI 2015 data, we included, for the years 2019, 2020 and 2021, the area classified as "Mixed" disturbance event, together with the area affected by "Harvest", as defined by EFDA. In this way, we accounted for the additional removals due to salvage logging that occurred in these regions after the windstorm.

For 2004 and 2018, each region was assigned the amount of fellings reported by NFI 2005 and 2015, respectively, provided these values were not excluded from the analysis based on the previous assessment (see Fig. 3, Step 3). For the other years, we estimated the annual amount of fellings by selecting the most suitable data series, between Fel_back_{2005}, Fel_forw_{2005}, Fel_back_{2015}, and Fel_forw_{2015}. We selected the values estimated by the data series Fel_back_{2005} for the period 2000–2004 and the values estimated by the data series Fel_forw_{2015} for the period 2019 – 2023. Between 2005 and 2017, we combined the two data series Fel_forw_{2005} and Fel_back_{2015}. In theory, the two data series should provide similar values, however, since felling activities varied within such a long period of time, and both NFI surveys were conducted within a relatively large time interval (2–4 years), for each region i and year y, we combined the amount of fellings provided by the two data series applying decreasing correction factors (cf_{2005}) for Fel_forw_{2005} and increasing correction factors (cf_{2015}) for Fel_back_{2015} (see Appendix C, Supplementary Material for further details). Using these correction factors we estimated the amount of fellings attributed to each region (Fel^i_y) between 2005 and 2017, as:

$$Fel^i_y = \frac{cf^y_{2005} {}^* Fel\_forw^i_{2005} + cf^y_{2015} {}^* Fel\_back_{2015}}{14} \tag{5}$$

Within the two regions (Basilicata and Val d'Aosta) where NFI 2005 original data was not consistent with other data sources, all the data series before 2018 (including the year 2004) were directly inferred from Fel_back_{2015}, prolonged until 2000, without using equation (5). Similarly, within the three regions (Lombardia, Molise, Puglia) where NFI 2015 original data was not consistent, all the data series after 2004 (including the year 2018) were directly inferred from Fel_forw_{2005}, prolonged until 2023. The final amount of fellings at the national level was estimated as the sum of fellings assigned to each region.

Using the standard error reported by NFI data (see Appendix D, Supplemenatry Material), we determined the minimum and maximum amount of fellings associated with each region from NFI 2005 and 2015 (Fig. 3, Step 4). Based on these values, we used the same approach described above to estimate the minimum and maximum amount of fellings at the regional and national level (see Supplementary Material for further details).

2.3.3. Data validation

Validating our findings using fully independent and reliable data for Italy presents significant challenges. As NFI data was directly used to calibrate the remote sensing data, our results cannot be considered independent from NFI. Consequently, the estimated amount of fellings for 2004 and 2018 mostly coincides with the amount of fellings reported by NFI at regional and country-level. Otherwise, a third NFI data series, which could be used to independently validate our results within the period 2000–2023, is not available.

Reviewing the various data sources available at the national level, we identified the historical data series reported by ISTAT as the sole source to validate the amount of fellings estimated by our study. Other data sources collected by single administrative regions (Friuli Venezia-Giulia, 2024, since 2000, and Lombardia, since 2007) served as supplementary information (see Supplementary Material).

The ISTAT data series, which was collected until 2015, is generally considered reliable up to 2012, with the subsequent years showing data gaps in the reporting. As reported by literature, the original ISTAT data series cannot be directly compared to data reported by NFI, because they refer to the amount of removals, i.e. excluding logging residues, and hence largely underestimated fellings (Pra & Pettenella, 2016; Marongiu & Gismondi, 2018). Taking into account that NFI 2005 data is mostly referred to the period 2003 – 2005, and following the same approach used by the National Inventory Report of Italy (Italy, 2018) and by previous studies (Pilli et al., 2013), we estimated, for each region i, a correction factor (CF_{ISTAT}) that was applied to the average amount of removals reported by ISTAT for the period 2003–2005 ($ISTAT^i_{03-05}$), with CF_{ISTAT} calculated as:

$$CF^i_{ISTAT} = \frac{ISTAT^i_{03} {}^* w^i_{03} + ISTAT^i_{04} {}^* w^i_{04} + ISTAT^i_{05} {}^* w^i_{05}}{NFI^i_{2005}} \tag{6}$$

where w^i_y is the same weighting factor, applied to calibrate NFI data in Eq. (1), based on the number of NFI field plots reporting harvest activity. We used this average correction factor to estimate, for each region, the share of unaccounted removals, mostly used for fuelwood, not reported by ISTAT. We considered the correction factor to be constant and applied it, for each region, to the entire time series reported by ISTAT between 2000 and 2012. In a few cases, where CF_{ISTAT} was < 1 (i.e. $NFI^{i}_{2005} < ISTAT^{i}_{03-05}$), the correction factor was set to 1.15. Additional information is reported in Appendix D.

We also considered additional information on the amount of fellings provided by salvage logging activities after the windstorm Vaia in 2018, as well as after a minor windstorm that occurred in the Toscana region in 2015 (Chirici et al., 2016). We compared the reported amounts from the literature with our results and with the data reported by EFDA (see Appendix E).

3. Results and discussion

3.1. Total fellings at national and regional level

We estimated that total fellings ranged from a peak of approximately 16.5 million m^3 in 2006 to a low of around 10.4 million m^3 in 2014 between 2000 and 2023 in Italy (Fig. 4).

The value estimated for 2004 (14.0 million m^3) is slightly higher than the corresponding amount of fellings reported by NFI 2005 (13.8 ± 1.8 million m^3), because the NFI data of two regions were excluded from our data integration and replaced with Fel_back_{2015} data. In the same way, the total fellings estimated by our study for 2018, equalling 10.9 million m^3, is 14 % higher than the corresponding amount of fellings reported by NFI 2015 of 9.6 ± 1.5 million m^3. This discrepancy arises from three regions where values derived from the Fel_forw_{2005} data series had to be used, since the NFI 2015 data were inconsistent with other data sources. The larger confidence interval associated with our estimates (about ± 50 % at national level), compared to the one reported by NFI (± 12.9 % and 16.1 %, for NFI 2005 and 2015, respectively), is since in this study total fellings are estimated as the sum of fellings attributed to each region, with their corresponding confidence intervals, directly inferred from NFI data. The overall uncertainty of our assessment is also, indirectly, affected by the relatively long period associated to field measurements (at least with the second NFI) and the possible inclusion of harvesting that occurred prior to the 12-month threshold, during the field surveys.

Interannual variations in total fellings estimated by this study follow the pattern reported by the area affected by harvest from EFDA, both at national and regional level (see Fig. 4 and Fig. 1F, Supplementary Material). Even if preliminarily corrected to factor out the possible additional effect of wildfires and to account for salvage logging after 2019 in regions affected by the Vaia windstorm, we cannot fully exclude that fire events in Mediterranean regions indirectly affected the amount of fellings estimated by our analysis. By comparing fire events reported by EFDA and by EFFIS, we noticed that, in some cases, omission errors are due to a delayed detection of fire disturbance events reported by EFDA (see on Supplementary Material the sheet *EFDA_data_check*). This was also reported by Viana-Soto & Senf (2025). When scaled at the regional level (Fig. 5), the amount of fellings estimated by our study is generally correlated to remote sensing data (with r > 0.50 in 15 out of 20 regions), but, since we applied a bottom-up approach at country-level, the remote sensing data are not directly correlated with the total fellings estimated at the national level.

When comparing the estimations from the data integration approach with the other data sources reported in Fig. 1, we notice that, until 2014, apart from specific inter-annual variations, the overall trend and the absolute magnitude of fellings derived from our estimates are quite aligned with data derived by the Italian NIR (Italy, 2018). However, considering that EUROSTAT and SoEF data only refer to removals, i.e. excluding logging residues, both these data sources seem to be largely underestimating removals and are not consistent with our results. Similarly, since 2008, the amount of removals reported by FAOSTAT is not consistent (i.e., higher) with the amount of fellings inferred in this study. This is very pronounced between 2012 and 2018, when FAOSTAT reports constant values, even higher than the total fellings reported by

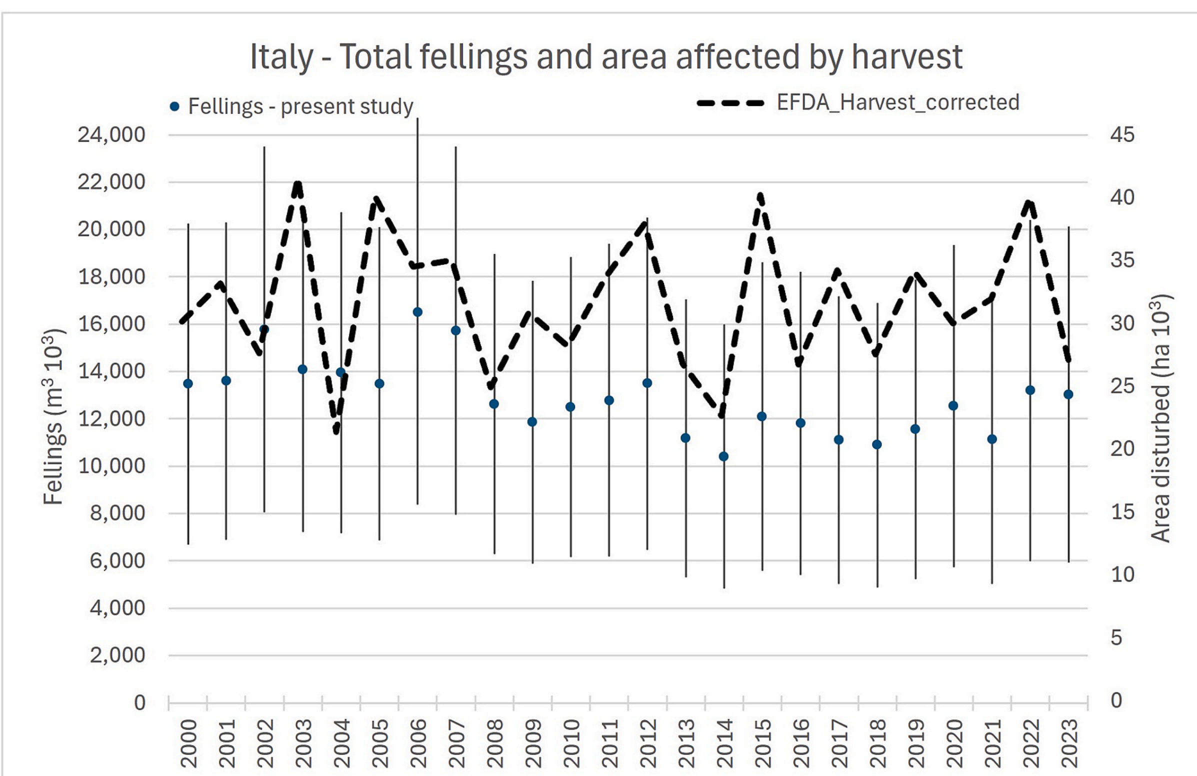

Fig. 4. Total fellings estimated at national level as determined in this study, including the corresponding confidence interval. The figure also reports on the right axis, the total area affected by harvest according to EFDA, as corrected according to our methodological assumptions.

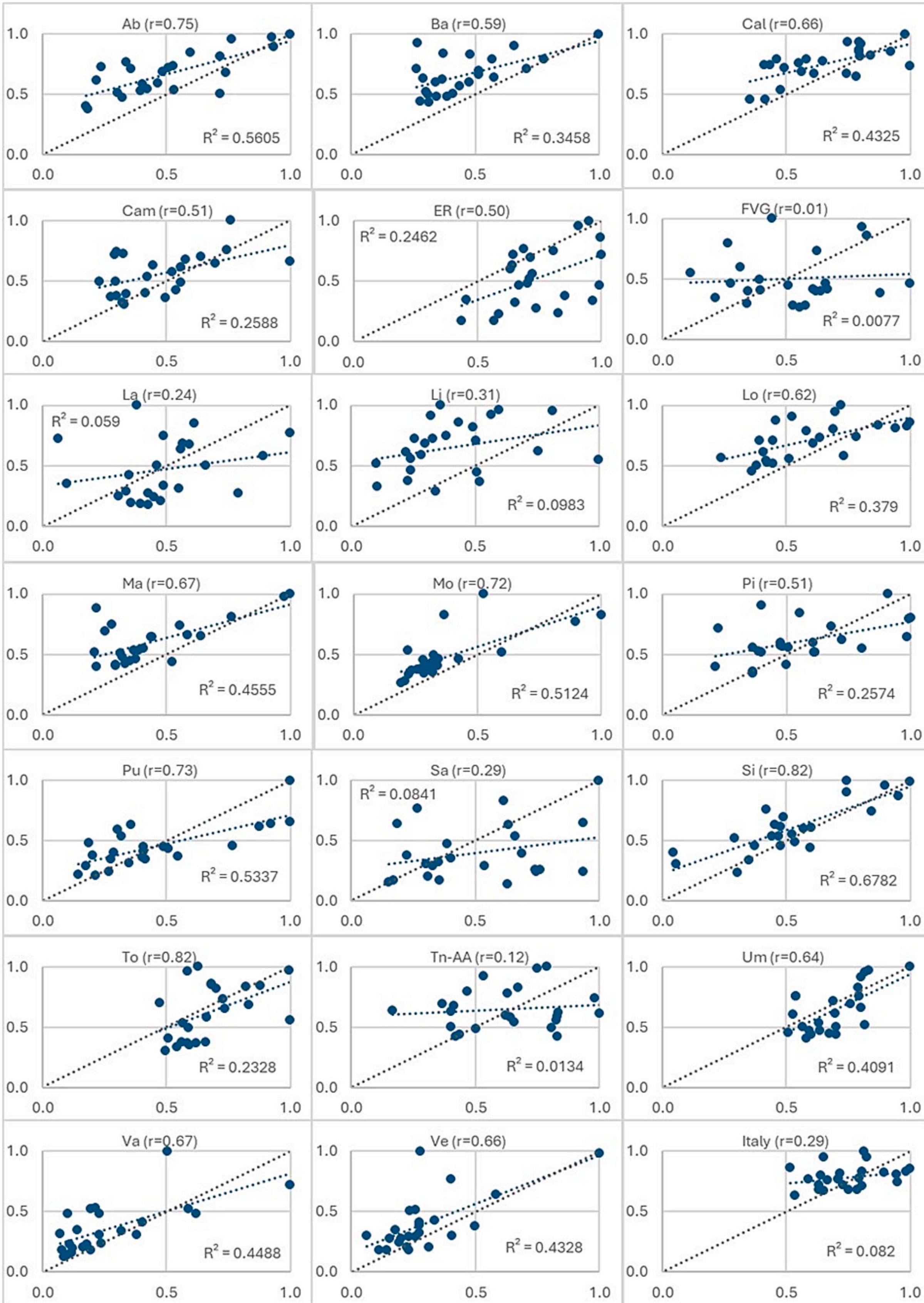

Fig. 5. Amount of fellings estimated by our study (reported on the y-axis) and area reported by EFDA for harvest disturbance events (reported on x-axis and corrected according to our methodological assumptions). Both values were normalized between 0 and 1. Each scatter plot, referring to the single regions and to the entire country, also reports the correlation coefficient (r) between these parameters, the regression coefficient corresponding to the linear regression highlighted in bule and the 1 to 1 regression line in black.

NFI 2015, and even more after 2019, when the absolute amount of removals reported by FAOSTAT increases from 13.0 to 18.3 million m^3, before settling to about 15.8 million m^3 within the following years. This peak is significantly higher than the volume of removals attributed to the Vaia windstorm. According to literature (see Appendix E, Supplementary Material), between 2019 and 2022, approximately 6 million m^3 were removed by salvage logging in the two regions most affected by Vaia. Taking into account that, due to the exceptional impact of the Vaia windstorm in Veneto and Trentino Alto-Adige regions, ordinary management practices were mostly suspended between 2019 and 2021 and replaced by salvage logging activities, we can assume that this amount covered most of the harvest occurring on these two regions after the windstorm. According to our results, the total amount of fellings increasaed from about 10.9 million m^3 in 2018, to 11.6 million m^3 in 2019 (including 3.6 million m^3 from Veneto and Trentino Alto-Adige regions) and to 12.5 in 2020 (including about 4 million m^3 from Veneto and Trentino Alto-Adige regions). At least for the Veneto region, however, we cannot exclude that the amount of fellings estimated by NFI also includes removals due to salvage logging which occurred in spring 2019, after the Vaia windstorm (for this region part of NFI field surveys were conducted in 2019, see Fig. 1E, Supplementary Material). This could affect the estimates reported for the period 2019–2023.

In 2022 and 2023 the estimated total fellings further increased to about 13.0 million m^3, mostly due to additional salvage logging carried out after bark beetle outbreaks occurred within the same area affected by Vaia. Following the few information made available by literature (Battisti, 2024), a consequence of the large amount of dead wood material and favorable climatic conditions since 2020 is that the same regions were also affected by a bark beetle outbreak, mostly concentrated within the period 2021–2023 (Nardi et al., 2022). The overall volume affected by this outbreak was similar to the one affected by Vaia.

The average amount of fellings per unit of forest area within the period 2000 – 2023 is equal to 1.4 $m^3\ ha^{-1}\ yr^{-1}$, with strong interannual variations, especially when scaled at the regional level (see Appendix F). For most of the regions, the average fellings per unit of area is lower than the national one, and it is mostly stable, or even decreasing between 2000 and 2023. The few exceptions include the Veneto region, where salvage logging occurred after the Vaia windstorm considerably increasing the amount of fellings from 2019 onward. This means that, in some cases, tree cover losses reported by remote sensing data are not fully comparable with data collected before 2019. In these cases, only ancillary information collected at the local level can provide an accurate assessment of the amount of fellings.

3.2. Validation and comparison with other data sources

For the period 2000–2012, the estimates are well aligned with data inferred from ISTAT (Fig. 6). The difference between total fellings derived from ISTAT and estimated by this study is on average −1%, with a range between + 21 % and −15 %.

As expected, when scaled at regional level, the estimates show stronger interannual variations and discrepancies from other data sources (see Fig. 7 and Supplementary Material). In some cases, however, data inferred from ISTAT is not consistent with other data series (i.e. in the case of the Basilicata region for 2000 and 2001). Moreover, the ISTAT data used for validating the estimates are not fully independent since ISTAT refers to net removals and the original data were preliminarily corrected.

Despite our efforts to preliminarily harmonize various data sources, inherent differences cannot be neglected. This is quite evident when considering the share of total harvest attributed to each region by the different data sources (Fig. 8). Within the period 2001–2008, we can compare our estimates (i) with NFI 2005 data, (ii) with the data series reported by ISTAT and (iii) with the area affected by harvest disturbance events reported by EFDA, corrected to exclude fire-related effects. While our estimates are generally aligned to NFI data, the share derived by ISTAT, even if preliminarily corrected, and by EFDA, is partially different for most of the Italian regions. Within the following period

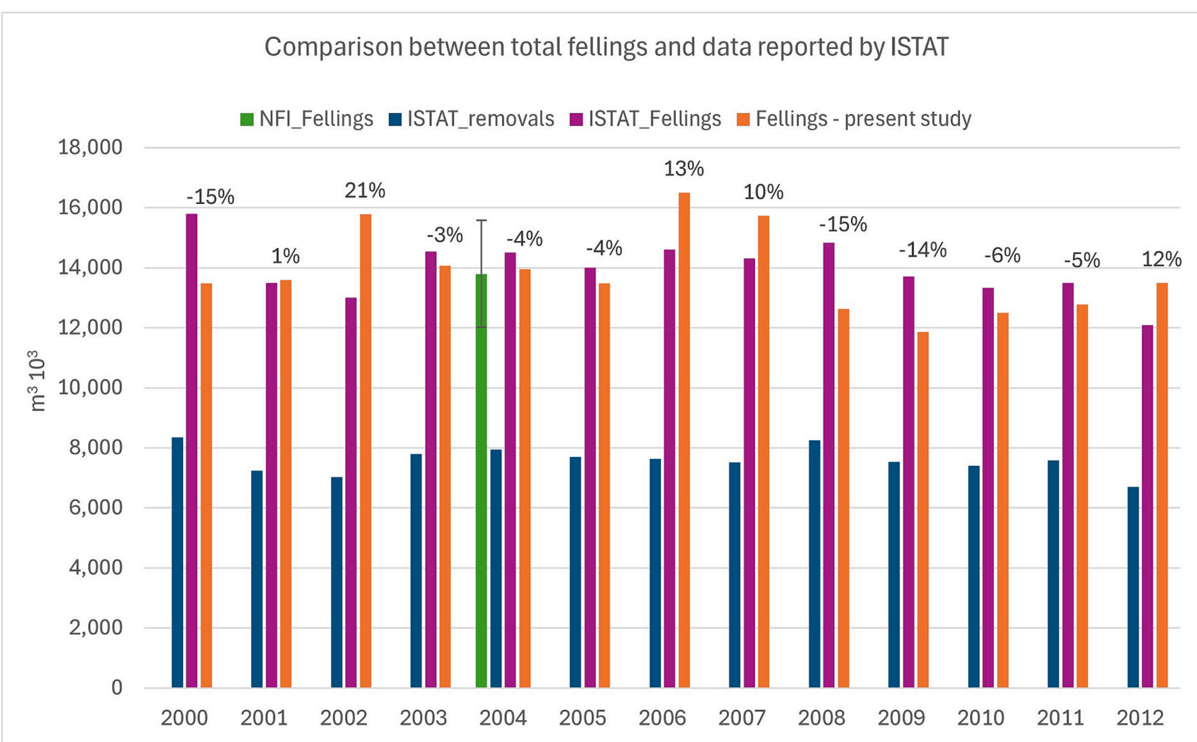

Fig. 6. Total fellings estimated within the present study, compared with (i) the removals reported by original ISTAT data, (ii) the amount of fellings inferred by ISTAT, by applying a regional correction factor, and (iii) the total fellings reported by NFI 2005 data, with the corresponding confidence interval. Upper labels report the percentage difference between current estimates and the amount of fellings inferred from ISTAT.

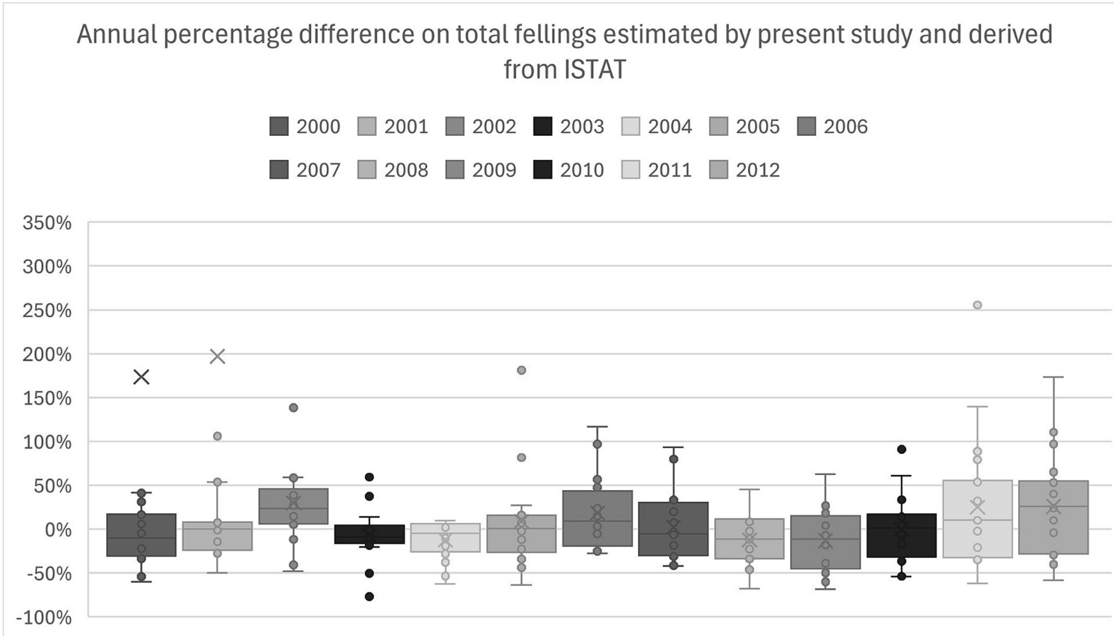

Fig. 7. The boxplot shows the regionally calculated percentage differences between the amount of fellings inferred from ISTAT and estimated by this study for each year. The figure excludes two outliers with a percentage difference > 1000 %, due to inconsistent data reported by ISTAT for Basilicata region.

2016–2020, the share of harvest directly inferred from EFDA in some Mediterranean regions is still overestimated, most likely because of the effects of fire disturbance events. In some cases also the share derived by our estimates diverges from NFI data, where NFI is not consistent with other data sources. This is, for example, the case of the Lombardia region, where, based on ancillary information collected at the regional level, the average amount of harvest, is 1.1 million m^3, in 2016–2020, including removals from poplar plantations, while within the same period NFI data report total fellings (also including plantations) of 0.1 million m^3. We estimated about 1.5 million m^3 within the same period, which is aligned with data reported at the regional level, since it includes logging residues.

The total fellings attributed to the two regions mostly affected by Vaia windstorm, is well aligned with ancillary information on salvage logging reported by literature (see Appendix E, Supplementary Material).

Since the time series was derived from interannual variations reported by EFDA, assessing the consistency of this data with NFI and other data sources available at country-level is important. In theory, both these data sources should assess the total forest area according to the FAO definition, i.e., considering as forest land any area larger than 0.5 ha, that has or will reach tree cover greater than 10 %, and which is primarily not used under urban or agricultural land use (Gasparini et al., 2022; Viana-Soto and Senf, 2025). EFDA shows a very high overall accuracy of 92.5 % of their forest land use mapping, with only a slight tendency to overestimate forest area (Viana-Soto and Senf, 2025). In the case of Italy, the total forest area considered by EFDA, equal to 9,426 kha, is well aligned with the forest area reported by NFI 2015, equal to 9,058 kha. At the regional level, however, the two data sources diverge slightly (see Appendix G). A misalignment of the area classified as forest by NFI and remote sensing data affects the assessment of disturbance events per unit of forest area. In this case, high-resolution forest masks obtained by merging regional forest masks with national forest type maps may have a better consistency with the data reported by NFI (D'Amico et al., 2021; Pecchi et al., 2024). In the same way, particularly for Mediterranean regions, other datasets scaled at local level, can probably perform better results than dataset collected at EU level (Francini et al., 2022; Pecchi et al., 2024).

For a closer look at the area affected by windstorms and bark beetle disturbance events reported by EFDA we focus on 6 administrative regions affected by major windstorms which occurred within the latest years (see Appendix E). By comparing these data with other ancillary information reported in literature it is highlighted that EFDA is well aligned with other data sources in some cases, which mainly focus on the direct impact of the windstorm, excluding bark beetle infestations occurred within the following periods (i.e., for Friuli Venezia-Giulia and Lombardia regions as far as for Alto Adige province). For Trento province, Veneto and Toscana regions (with this last one affected by a windstorm that occurred in 2015), the area estimated by EFDA is generally lower than the area reported in the literature. In some cases, the consistency between various data sources improves considering the area assigned to the "mixed" category by EFDA. Interestingly, within some of these regions, EFDA clearly reports also the impact of additional disturbance events that occurred after 2019 mostly due to bark beetle infestations affecting the same regions. This confirms the capacity of this data source to capture multiple disturbance events, compared with other data made available by literature (Viana-Soto & Senf, 2025).

3.3. Fellings rate and remote sensing data

Subtracting from the Gross Annual Increment reported by NFI data (Gasparini and Tabacchi, 2011, 2022) the Annual Natural Losses, as estimated by literature (Gschwantner et al., 2024), we can derive the NAI associated with NFI 2005 and 2015 (Table 1). Relating these values with the amount of fellings estimated by our study, the felling rates, i.e. the ratio between fellings and NAI, varies between 0.45 and 0.35, within

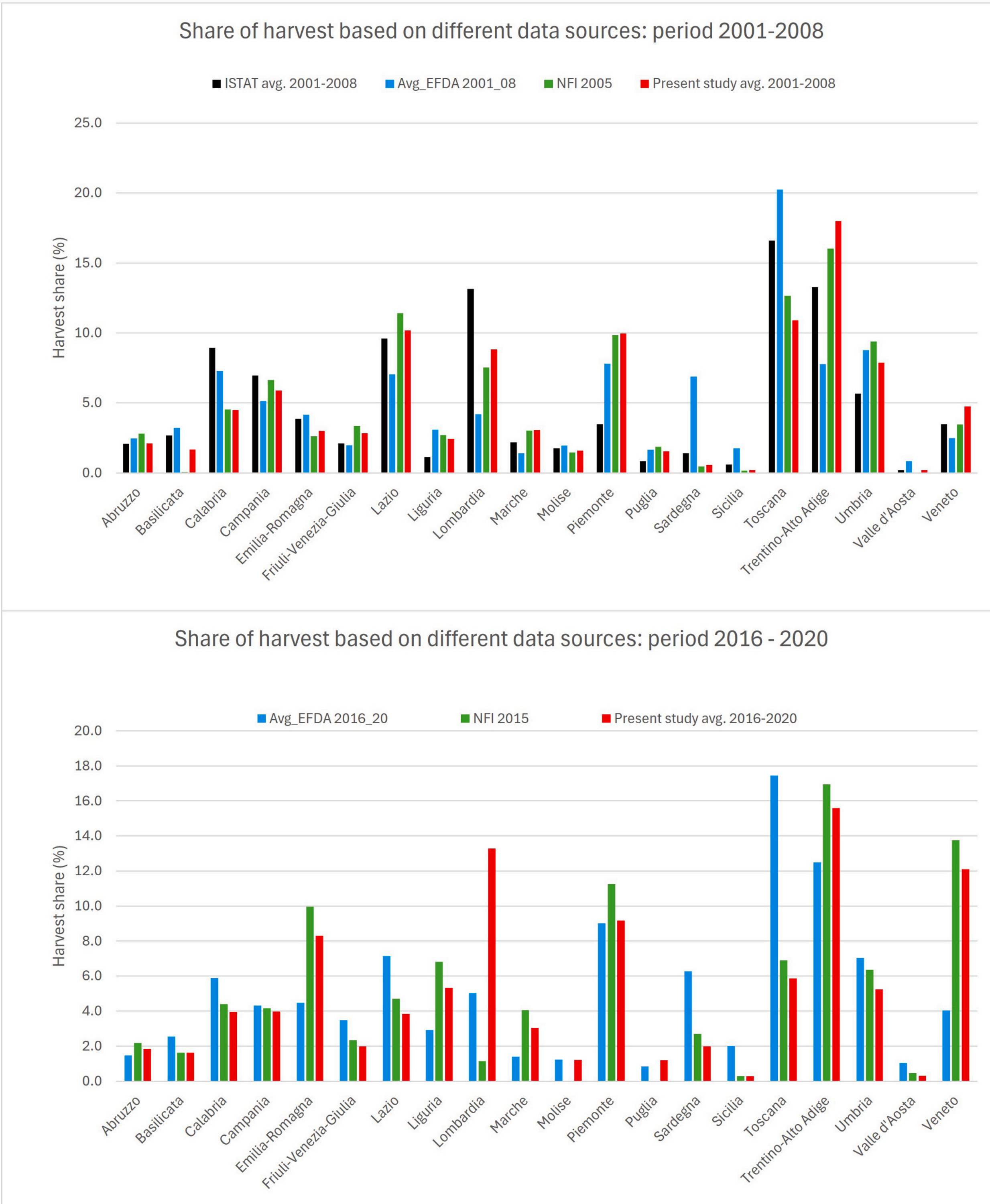

Fig. 8. Comparison between the average share of harvest attributed to each region according to different data sources considered within the present study, within the periods 2001 – 2008 and 2016 – 2020.

Table 1
Main parameters reported by literature and used to estimate the Net Annual Increment and the corresponding fellings rate within the periods 2004 – 2005, 2017 – 2018 and 2021 – 2023. See Supplementary Materials for details.

Period	Unit	2004–2005	2017–2018	2021–2023
Gross Annual Increment (NFI)	m^3 10^3 yr^{-1}	35,872	37,787	
Total forest area (NFI)	ha 10^3	8,759	9,085	≈ 9,174
GAI ha^{-1}	m^3 ha^{-1} yr^{-1}	4.1	4.16	≡ 2016–2018
Annual Natural Losses ≈14 % GAI (inferred from Gschwantner et al., 2024)	m^3 ha^{-1} yr^{-1}	0.57	0.58	
Net Annual Increment	m^3 ha^{-1} yr^{-1}	3.53	3.58	3.58
Fellings (present study)	m^3 10^3 yr^{-1}	14,013 ± 6,815	11,271 ± 6,164	12,452 ± 6,806
Fellings ha^{-1}	m^3 ha^{-1} yr^{-1}	1.60 ± 0.78	1.24 ± 0.68	1.36 ± 0.74
Fellings rate		0.45 ± 0.22	0.35 ± 0.19	0.38 ± 0.21

the period 2004–2005 and 2017–2018, respectively. Assuming as constant the NAI reported from NFI 2015, the fellings rate would increase to about 0.38 within the period 2021–2023. All these values are considerably lower than the fellings rate reported by most of the other European countries (Forest Europe, 2020).

Due to the uncertainty of all input data, however, the total fellings estimated by our study range by about ± 50 % for each period at the national level. This means that also the corresponding fellings rate may be even higher, as suggested by other studies. For example the Wood Resource Balance compiled by the Joint Research Centre of the European Commission (Cazzaniga et al., 2019), based on a compilation of different data sources including data reported by FAOSTAT, highlights that, in the case of Italy, the share of unreported sources, i.e. the gap between wood sources and uses, varies from about 23 % in 2009 (i.e., about 7 million m3) to 73 % in 2017 (i.e., about 24 million m3) as the latest data available. Assuming that part of this gap is due to unaccounted harvest, the amount of fellings, and the corresponding fellings rate, should move towards the higher range reported by our estimates, i.e., 0.67 and 0.59 within the periods 2004–2005 and 2021–2023. In this case, these values would be more consistent with data reported by conterminous countries (Forest Europe, 2020).

It is worth noting that in Italy, such as in other Mediterranean countries, only a fraction of total removals is provided by clear-cut or other silvicultural activities carried out on large forest areas (i.e., on coppices) which can be easily detected by remote sensing (Viana-Soto & Senf, 2025). According to NFI 2015, only 15 % of the total forest area is managed with ordinary (e.g., harvesting at the end of the production cycle) or intensive (typically applied to forest plantations) silvicultural practices, and minimal silvicultural practices (also including, within the NFI definition, clear-cut on coppices where no thinning is done) were detected in 42 % of the total forest area (Gasparini et al., 2022). Nevertheless, if properly calibrated against ground data based on direct field measurements, remote sensing data can be used to infer inter-annual variations that occurred within a certain period. In this case, the prerequisite is that the accuracy of remote sensing data does not vary in time and the relative share of harvest provided by different silvicultural activities (i.e., clear-cut vs. thinnings) is stable within the same period. In our case, by combining different weighting factors and two different data sets, Fel_forw_{2005} and Fel_back_{2015}, based on ground data referring to 2003–2005 and 2017–2019, we partially prevent possible misalignment due to a different accuracy of remote sensing data collected through various sensors and overall variability within such a long time period (Breidenbach et al., 2022; Ceccherini et al., 2022).

Considering the increasing impact of climate change, and of other external drivers, also linked to international political and socio-economic aspects, such as the continuous and very fast changes that we detect on remote sensing technologies (and the consequent accuracy of our data, which is continuously increasing in time), the traditional time horizon applied to forest management assessment, generally scaled against various decades, is quickly reducing. Due to recent bark beetle infestations and windstorms, silvicultural activities were abruptly changed on some Italian regions, such as in various central European countries, and, in the same way, the use of wood residues changed within the latest years. Remote sensing data alone cannot capture all these aspects when used for a multi-year assessment, but they can support a near-real time assessment of the ongoing evolution of harvest activities. Similarly, the yearly harvest activities cannot be easily detected by direct field measurements either, as provided by NFI data

Table 2
Synthesis of the main advantages and disadvantages of the different datasets, as considered within the present study.

Data source	PRO	CONTRA
NFI data	Direct field measurements, essential to properly report on forest status, health and productivity as well as to calibrate RS data. Provide a direct assessment of data uncertainty and a clear definition of background ancillary information (i.e. thresholds, field plots protocol, etc.).	Spare data, referred to single/few years, sometimes not uniformly distributed between different administrative units. In some cases, data is highly uncertain and not representative of harvest activities occurred within the previous 12–24 months. Results can be distorted by exceptional disturbance events and salvage logging occurring during the field plot measurement period.
Remote sensing data	Long time series reporting interannual variations of disturbance events occurred at local/national level, including an assessment of data uncertainty and background ancillary information (i.e. on forest definition). Data can be rescaled at different spatial units and partially distinguished between natural/anthropogenic disturbance events.	Possible misallocation of different disturbance events (e.g wildfires vs harvest). Difficult to account for salvage logging after windstorms or insect outbreaks. On long time periods, RS data cannot be calibrated against direct field measurements, because silvicultural activities (e.g., salvage logging) or the accuracy of RS data (i.e., of various sensors) can vary in time.
Statistical administrative surveys	Indirect assessment of harvest activities, including possible ancillary information on wood removals (i.e., by species, silvicultural treatment, or final use). If properly collected, they can be used to complement/validate other data sources providing useful information both on inter-annual variations and absolute amount of harvest, above all to account for exceptional disturbance events.	If based on data collected at sub-national levels, when scaled up to country level, missing information or different administrative rules may partially invalidate the data. A quality and uncertainty assessment of this data is generally missing, such as a clear definition of the background information (i.e., how these data are collected and thresholds of criteria applied at local level). In some cases, they are only available at the local level, not easily accessible, and with a discontinuous time series.

and administrative surveys systems at the moment. This extends the possible application of our modelling framework even to countries with a more consolidated monitoring system of harvest activities.

4. Conclusions

Combining NFI data, based on direct field measurements, with yearly time series derived by remote sensing data, we assessed the amount of fellings carried out in Italy, at the regional level, between 2000 and 2023.

A preliminary analysis of all available data sources highlighted that none of this data, considered individually, can provide a comprehensive estimate of the relative and absolute amount of harvest, either at the regional or national level and its evolution in time. Each data needs to be critically revised, partially corrected and integrated with other ancillary information, even collected at the regional level. (Table 2). As stressed by Viana-Soto & Senf (2025), when using remote sensing data to quantify the temporal evolution of some disturbance agent (i.e. the harvest), some preprocessing of original input data is always needed. Of course, the criteria applied for preprocessing, to scrutinize the goodness of input data (in our case EFDA and NFI), excluding possible outliers or non-accurate measurements, can also affect the final results.

An in-depth analysis of NFI ground data highlighted that, when scaled at the regional level, some data is not consistent with other information. This can be due to the sampling design, not sufficient to capture a rare phenomenon like harvesting. Moreover, we highlighted that the amount of fellings reported by NFIs cannot be directly attributed to the corresponding NFI year (i.e. 2005 and 2015), but it should be attributed to the periods 2003–2004 and 2017–2019, for NFI 2005 and 2015, respectively. Since remote sensing data are calibrated against NFI data, this has a direct impact on our results.

Assigning our estimates for the corresponding percentage error reported by the original NFI data, we also quantified the possible uncertainty of our results. When upscaled at the national level, this increased to about $\pm$ 50 % uncertainty of the estimates. Even if we did not consider additional errors linked to remote sensing data, we performed a further assessment of this data series, highlighting possible misclassifications of disturbance events, above all within Mediterranean regions, and some inconsistency in the total forest area reported by remote sensing data, when scaled at regional level. This is also in line with the analysis performed on their data by Viana-Soto & Senf (2025). According to our results, the average fellings rate was quite stable in Italy within the study period, and probably below the values reported by other conterminous countries. Nevertheless, as highlighted by previous studies, we stress the uncertainty of all data sources reporting harvest activities and that, when estimating the fellings rate assuming a constant annual increment, we did not account for possible interannual variations due to climatic conditions.

The two main data sources integrated within this approach are available for any (or most) European countries. The European Forest Disturbance Atlas was preferred to other data sources because one of the objectives of this paper, was to use Italy as a case study, without focusing on country-specific remote sensing data, eventually available at national level (i.e. Francini et al., 2022). The data was calibrated with NFI data, which are also available, with different time intervals and country specific definitions, for most European countries. In this sense, we believe that our approach can be easily adapted to most of the other EU member states. The same approach can also provide a near real-time assessment of the national harvest level, which is increasingly important, for all European countries as far as for the European Union, for evaluating the short-term evolution of the forest carbon sink (Korosuo et al., 2023) and quantifying the role of harvesting on the overall impact of human activities on forest ecosystems (Migliavacca et al., 2025).

This study compares various independent datasets, which were not used in conjunction. NFI and remote sensing data (both essential but not sufficient instruments to estimate the impact of human and natural disturbance events), such as administrative surveys conducted at the local level, should be necessary integrated, within a common and continuous monitoring framework. Ongoing initiatives, such as the EU proposal for a regulation on monitoring forest framework (e.g., European Commission, 2023) and the bottom-up, participative voluntary process promoted in Italy by the new National Forest Information System (Pecchi et al., 2024), move towards the same direction.

CRediT authorship contribution statement

Roberto Pilli: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Alexandra Runge:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Gherardo Chirici:** Writing – review & editing. **Elia Vangi:** Writing – review & editing. **Alessio Collalti:** Writing – review & editing. **Martin Herold:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jag.2025.104871.

Data availability

Most of the data are already made available as supplementary material

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