



EU forest carbon sink decline as seen by Earth observation and national inventories

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Abstract. The declining European forest carbon uptake in recent years is challenging the capacity of European forests to remain carbon sinks, while the European Union's climate policy relies on this large natural carbon sink to meet its climate targets. The decreased forest carbon sink is thought to be caused by a combination of increased harvest, severe droughts, bark beetle infestations, tree mortality, and slow-down in tree growth causing reduced CO₂ uptake. Yet several knowledge gaps remain, importantly a lack of a reconciliation and country-scale quantitative comparison of carbon losses from recent forest disturbances. In the past years, several estimates of forest C fluxes and losses over Europe based on remote sensing have been developed, complementing national greenhouse gas inventory (NGHGI) information. However, an in-depth intercomparison between these various approaches is needed to derive common best estimates of recent C losses, as well as define mutual benefits and individual weaknesses of the different data streams.

Here we investigate the recent changes in the European forest carbon sink by combining new high-resolution Earth Observation (EO)-based estimates of forest aboveground biomass carbon (AGC), forest disturbance and recovery, EO-based bookkeeping models, atmospheric CO₂ inversions, and NGHGI approaches. We find that all datasets agree on a reduction of forest C uptake in 2020-2023 by 17-27% compared to the average of 1990-2019 (-135 to -233 TgC/yr), with a remaining forest C sink in 2020-2023 in the range of -100 to -193 TgC/yr. Central and boreal European forest C sink losses contribute most substantially to the observed reduction of the net forest C sink over Europe. This increase in C losses is more strongly



driven by effects of natural disturbance than increased harvest, where natural disturbance C losses increased 2.6-fold in central and 1.4-fold in boreal Europe in 2020-23 compared to 2010-2019. EO data at high resolution detect disturbances at lower or higher magnitude to forest C losses reported in NGHGI. Depending on resolution of the satellite product and disturbance detection approach, C losses from small-scale disturbances and management may be better detected, as higher spatial resolution allows capturing small scale heterogeneity.

Despite overall agreement of different data streams, we find discrepancies of 2–3-fold difference in AGC and carbon losses estimated for many countries between NGHGIs and EO-based datasets. We highlight regional differences across the continent and discuss advantages and challenges of the complementary data streams, with a focus on how high resolution EO and NGHGIs can benefit each other.

1 Introduction

The European Union (EU) relies on sustained carbon uptake by natural and managed forests in order to meet climate mitigation goals, but recent years have seen a stark decrease of this natural forest carbon sink (Korosuo et al. 2023, Migliavacca et al. 2025). As part of the European Green Deal (EU Regulation 2023/839), the EU aims for a carbon sink of -310 MtCO₂eq (-84 MtC yr⁻¹) by 2030 in the land use, land-use change and forestry (LULUCF) sector, corresponding to a -392 MtCO₂eq (-107 MtC yr⁻¹) commitment from forests (Ritter et al., 2026). Yet, based on bottom-up estimates from the EU LULUCF inventory, the forest C has declined by 27% from -457 Mt CO₂e yr⁻¹ (-125 MtC yr⁻¹) on average in 2010-2014 to -332 Mt CO₂e yr⁻¹ (-90 MtC yr⁻¹) in 2020-2022 (Migliavacca et al., 2025), with a 39% reduction projected for 2030 compared to 2010 (Ritter et al., 2026). Despite the wealth of data available for Europe compared to other regions, the EU carbon budget still suffers from large uncertainties. Specifically the forest C budget and recent trends in forest C losses are not sufficiently quantified and synthesized across diverging data streams.

The European forest carbon balance is influenced both by: anthropogenic factors such as management, and natural processes such as extreme events and disturbances, as well as their interactions. Anthropogenic canopy openings account for a dominant 86% of disturbed forest area over Europe in the 1986-2020 period, and have increased by 24% in 2001-2020 (Seidl & Senf, 2024). Simultaneously, European forests are ageing on average (Besnard et al., 2025), which is generally considered to result in a lower net carbon uptake (Nabuurs et al., 2013, Besnard et al., 2021). The recent decrease in net carbon sink is also likely strongly related to increased heat and drought stress over the European continent, which is partly driven by anthropogenic climate change (Dunkl et al. 2026). Drought and heat stress on the one hand reduce plant productivity (Ciais et al., 2005; Bastos et al., 2020, van der Woude et al., 2023) and, on the other hand, increase natural disturbances such as fires and insect outbreaks, amplifying carbon loss (Forzieri et al., 2021; Patacca et al., 2023, Seidl & Senf, 2024). In the light of the overlapping pressures from natural and anthropogenic disturbances on EU carbon sequestration, quantifying each term of the budget and determining their causes is crucial. Such information allows for better assessing the threat to the natural



carbon sink posed by climate-driven disturbances, as well as opportunities to mitigate those risks by anthropogenic
70 interventions that can be more readily acted upon by policy changes than natural ones (EUCRA 2024; Migliavacca et al.
2025).

Different data streams are available to assess global to national carbon budgets, including forest C fluxes and stocks (Ciais et
al., 2022; Poulter et al. 2022, Canadell 2025). At national scales, carbon stock changes over managed land are reported by
75 national greenhouse gas inventories (NGHGs) to the UNFCCC, as part of the Measurement, Reporting and Verification
(MRV) system, and the Paris Agreement's Enhanced Transparency Framework (ETF). These reports are prepared annually
by each country and compiled from upscaled forest plot measurements and standardized emission and trade reporting from
industry and other sectors. NGHGs also compile estimates of biomass carbon lost to fires or diverted into harvested wood
products. NGHGs are important sources of forest C flux estimates, but inventories have long revisit times, so that NGHGs
80 incorporate changes in the forest C sink with delays of one or several years (e.g. German National Inventory Document,
2026). Especially with regard to forest biomass losses, data streams additional to inventories, such as EO-based products, are
key to quantify the evolution of the forest carbon sink accurately with lower latency. At continental to sub-continental scales,
top-down estimates of net carbon fluxes can be derived from atmospheric inversions, but uncertainty increases at national
scales (Byrne et al., 2023). Satellite-based Earth Observation (EO) products provide the opportunity to bridge carbon
85 budgets estimated by different methods and at different scales through biomass carbon monitoring at global scale with
moderate to high resolution (Crisp et al., 2022; Frappart et al., 2020, Liu et al., 2023). Site-scale measurements and reference
plots to determine biomass increments offer additional ground-based information on C stocks and fluxes (REF). Each of
these data streams captures different parts of the carbon balance, rendering them inherently difficult to compare (Winkler et
al., 2023, Chevallier et al., 2021).

90 Quantifying carbon fluxes in the EU is complicated by diverging estimates derived from different data sources (Winkler et
al., 2023, Lauerwald et al., 2024), high spatial heterogeneity (Lauerwald et al., 2024), and large uncertainties remaining e. g.
about the contribution of the LULUCF sector (Bastos et al., 2022). As a consequence of these discrepancies, average
estimates and trends in the EU carbon budgets still contain considerable uncertainty (Lauerwald et al., 2024, O'Sullivan et
95 al., 2024, Winkler et al., 2023, Petrescu et al., 2021). The aforementioned studies employ atmospheric inversions, national
forest statistics and NGHGs, process-based ecosystem and bookkeeping models, as well as low-resolution observation-
driven data products. Critically, a direct assessment of forest disturbances and associated biomass losses from EO in relation
to these other data streams is lacking (Migliavacca et al. 2025). This study aims to close the gap by assessing forest carbon
losses at European level directly from novel high-resolution EO-based datasets on forest disturbance and C losses as
100 independent proxy in relation to other top-down and bottom-up estimates of EU C losses.



Emerging high-resolution Earth Observation (EO) products now offer leverage for improving regional estimates of forest carbon losses and their attribution in the European carbon budget by providing more detailed information on forest stocks and fluxes. Because most forested landscapes in the European region are fragmented and often managed, coarse resolution datasets may miss smaller-scale disturbances and cannot fully capture spatially explicit information on forest carbon stock changes, their spatial extent and intensity. Recent developments with high-resolution EO data include mapping of single trees inside and outside forests and derived aboveground biomass (AGB) estimates over Europe at 30m resolution (Liu et al., 2023), as well as mapping of standing deadwood and tree cover change at 10m resolution using Sentinel-2 data with machine learning trained with thousands of crowd-sourced drone dataset from the deadtrees.earth platform (Mosig et al. 2026a, Mosig et al. 2026b). Long-term datasets with high resolution, such as the Landsat-based European Forest Disturbance Atlas (EFDA) maps disturbance year (Viana-Soto et al., 2025), agent and severity over Europe at 30m resolution, allow to derive AGB losses with attribution to disturbance agents over multiple decades (Kowalski et al., 2026). Based on these datasets, bookkeeping model estimates of annual forest biomass gains and losses now also reflect biomass dynamics at higher spatial resolution (Ritter et al., 2026, Xu et al., in preparation). To leverage the added value of these new data streams for existing methodologies, they need to be compared with existing knowledge, particularly with NGHGIs.

In this study in the context of the REgional Carbon Cycle Assessment and Processes Phase 2 (RECCAP2) related ESA project RECCAP2-Climate Space, we investigate how new high-resolution EO datasets on forest aboveground biomass (Liu et al., 2023), high-resolution forest disturbances and carbon losses (Kowalski et al., 2026, Mosig et al. 2026b), and gains and losses estimated from bookkeeping (BK) models (Ritter et al., 2026, Xu et al., in prep) capture biomass carbon changes in European forests, and how they compare to the net C sink estimated by atmospheric inversions and recent biomass losses allocated and reported in NGHGI inventories. We identify hotspots of biomass decline since 2010 and the underlying causes at both European and regional scale. Finally, by comparing different datasets, we quantify uncertainties and identify possible reasons for discrepancies.



Methods

Data

130 The datasets used in this project are summarized in Table 1 and Fig. 1 for overview, and further details follow below.

Table 1 - Overview of datasets used in this study with their main characteristics.

Dataset	Abbreviation	Data source	Resolution	Timespan	Version	Reference
UNFCCC National GHG Inventories	UNFCCC NGHGI	Inventory	country level (see Sup. Table S4 for details)	1990 - 2024	v2026	https://unfccc.int/ghg-inventories-annex-i-parties/2026
European Forest Disturbance Atlas	EFDA	Earth Observation	up to 30m (here 0.25°)	1985 - 2023	v2.1.1	Viana-Soto and Senf, 2025
ESA CCI Biomass	ESA CCI AGB	Earth Observation	Up to 100m (here 10km)	2007-2012, 2015-2024	v7.0	Santoro et al., 2021; https://catalogue.ceda.ac.uk/uuid/6429d1aaf61e43b9b414e4a5a7f8b903/
Aboveground Biomass	Liu23 AGB	Earth Observation	30m	2018 - 2023	v1	Liu et al., 2023
Aboveground Biomass Loss	Kowalski26	Earth Observation	20x20km grid cells	1985 - 2023	v1	Kowalski et al., 2026
Bookkeeping model	Ritter26 BK	Earth Observation + bookkeeping	18km	2010-2030	-	Ritter et al., 2026
Bookkeeping model based biomass gains and losses	Xu26 BK	Earth Observation + bookkeeping	0.5°	1985 - 2023	v2	Xu et al., in preparation
Global Inversions	Wang25	Inversion	1°	2011 - 2020	-	Wang et al. 2025
Global inversions	GCP2025	Inversion	1°	1976 - 2024	GCP2025_inversions_1x1_version1_0_20251031	https://meta.icos-cp.eu/objects/6gR_MW23fL2KEI860UX_TGoO
deadtrees.earth	deadtrees.earth	Earth Observation	10m	2017-2024	v5	Mosig et al. 2026a, Mosig et al. 2026b



PlanetScope AGB density map

- 135 This high-resolution biomass map over Europe maps AGB at high resolution of 30m based on satellite data from Planet Labs (hereafter Liu23 AGB, Liu et al., 2023). Five years of data are available, from which a higher-confidence composite map is calculated. Due to the high spatial resolution of the PlanetScope input data (3m), more subtle biomass losses such as forest thinning may be detectable from this dataset.

European Forest Disturbance Atlas and Kolwalski26 AGB loss map

- 140 The European Forest Disturbance Atlas (EFDA) is a Landsat-based dataset of forest disturbances over Europe (Viana-Soto and Senf, 2025), available for all years since 1985. The EFDA includes classification of disturbance agents into natural disturbance and harvest. This dataset is used here to assess forest carbon losses, as well as attribution of these losses to the agents of natural and anthropogenic drivers (Viana-Soto and Senf, 2025). AGB losses (hereafter Kowalski26), were derived from space-for-time substitution combining the EFDA and the AGB density map from 2019 (Kowalski et al., 2026, Liu et al., 2023 <https://zenodo.org/records/8154445>).
- 145

ESA CCI Biomass

- The ESA Climate Change Initiative (CCI) Biomass product provides global maps of forest above-ground biomass (AGB; Mg ha^{-1}) at a native spatial resolution of 100 m, quantifying the oven-dry mass of living woody vegetation excluding stumps and roots (Santoro et al., 2021). The dataset is combined from multi-sensor Earth observation data, and biomass estimates are generated using retrieval algorithms that combine radar backscatter with forest structural information to produce spatially consistent AGB estimates across global forest biomes. The most recent release (v7) used in this study provides annual AGB estimates for 2005-2012 and 2015-2024 (Santoro et al., 2026). The dataset was masked with the EFDA forest mask for comparability. Net biomass change was computed as pixel-wise differences between subsequent years, where a data point for a given year corresponds to the difference from the previous year to that year.
- 150

155 deadtrees.earth

- The deadtrees.earth product estimates tree cover and standing deadwood cover as percentages of each 10 m Sentinel-2 pixel using deep-learning transformer models (Mosig et al. 2026a) trained and validated on thousands of drone orthophotos crowdsourced worldwide (Mosig et al., 2026b). We combined the annual maps with ESA CCI aboveground biomass (v7.0, Santoro and Cartus 2026) at 100 m resolution to estimate biomass associated with canopy loss and standing dead trees.
- 160 Canopy loss was calculated as the positive year-to-year decrease in tree cover relative to previous-year tree cover. To suppress background variability, we applied a two-sigma threshold derived from the median absolute deviation (MAD) of interannual tree-cover differences in the maps, pooled over all years. Tree-cover decreases were retained where they exceeded a threshold that depends on previous-year tree cover (7.0 to 14.0 percentage points across five cover classes, 10.7



on average). Standing deadwood cover was retained where it exceeded 30.1% of pixel area before normalization, a threshold
 165 derived from the MAD of interannual differences in standing deadwood cover. The filtered fractions were averaged to 100
 m, aligned with the ESA CCI grid, and multiplied by AGB density from two years before the mapped year. This calculation
 assumes that affected canopy fractions are proportional to affected biomass fractions. The resulting estimates (Mg ha^{-1}) were
 aggregated using area-weighted means on a 10 km equal-area grid and reprojected to geographic coordinates for delivery.

Spatially-explicit bottom-up C gain-loss model

170 The spatially-explicit bookkeeping model (Xu26 BK) uses a forest carbon bookkeeping model to reconstruct forest carbon
 dynamics by integrating disturbance history, biomass maps, forest age information, national harvest statistics, and spatially
 explicit recovery trajectories through several EO-based input datasets, including the Kowalski26 AGB loss and Liu23 AGB
 map (Xu et al., in preparation). It estimates both C gains and losses from satellite-based disturbance and biomass
 information, while supplementing Landsat-detected harvest clearcuts with non-detected thinning losses constrained by
 175 national harvest volumes. Post-disturbance regrowth is represented using Chapman–Richards growth curves derived from
 satellite observations at 0.5° resolution to capture regional variation in recovery rates and biomass potential. The Xu26
 model is used in this report to compare forest C gains and losses with the Kowalski26 AGB loss data and NGHGs.

Ritter26 bookkeeping model

The Data-Driven Carbon Model (DDCM v1.2) bookkeeping model used by Ritter et al. (2026) combines remote sensing and
 180 inventory datasets to quantify forest carbon dynamics across Europe. Above-ground biomass carbon (AGC) was derived
 from PlanetScope-based biomass map (REF), bias-corrected using regional National Forest Inventory (NFI) data. Forest
 disturbance information was obtained from Landsat-based forest cover loss maps (REF). National trends in forest area and
 forest carbon sinks were derived from UNFCCC reports for 2010–2021. These datasets were integrated within DDCM to
 simulate annual biomass carbon stocks at 18 km spatial resolution, enabling spatially explicit assessments of forest carbon
 185 sink trajectories and disturbance impacts across Europe through 2030.

UNFCCC National Inventory Data (NGHGs)

National greenhouse gas inventories (NGHGs) track bottom-up estimates of countries' GHG emissions and removals
 (UNFCCC, 2025). NGHGs are available for all countries based on annual reports to the UNFCCC, and selected here for 32
 European countries (see Methods - Study Area). NGHGs are relevant as the official means for tracking progress towards
 190 policy greenhouse gas emission reduction targets. Under the Land Use, Land Use Change and Forestry (LULUCF) sector
 they contain reporting of annual carbon stock change of forest living biomass (in terms of gross gains and losses, or net
 variation, mostly derived from National Forest Inventories (NFIs)), dead organic matter and soil pools, as well as variations
 of the harvested wood products (HWP) pool. Furthermore, they contain detailed information on the approaches used and
 methods applied by each country in the EU, including implied emission factors and biomass-to-carbon conversion. Some



195 NGHIs may also track sources of uncertainty or variables that can explain reasons for disagreement with other datasets. They are used here as independent estimates for country-level carbon sinks and sources, and considered “ground truth”, although it should be noted that these data also contain considerable uncertainties, as well as methodological differences between countries that complicate comparisons. Although NFIs are recognized as an official reference data for forest biomass, they are often reported as aggregated regional averages and are conducted at country-specific intervals, typically
 200 every 5–10 years, requiring annual estimates to be interpolated between inventory years. Moreover, countries can apply different national forest definitions and associated thresholds for the NFIs.

NGHGI data was extracted from the common reporting format reports (CRF) of all 33 countries available in Europe (<https://unfccc.int/ghg-inventories-annex-i-parties/2026>). For estimation of the net C sink, we extracted Table 4a, using the
 205 following components for total forest land: “Carbon stock change in living biomass - Net Changes”, “Net carbon stock change in dead wood”, “Net carbon stock change in litter”, “Net carbon stock change in mineral soils” and “Net carbon stock change in organic soils”. All components were summed and averages calculated across years and countries as indicated. For estimation of C losses and gains, we extracted the columns “Carbon stock change in living biomass - Gains” and “Carbon stock change in living biomass - Losses” where available. To calculate fluxes per area, we extracted the components “Area of mineral soil” and “Area of organic soil” and summed them to obtain total area. We corrected the area reported for France
 210 to exclude its overseas territories.

Atmospheric inversions

Atmospheric inversions offer a top-down perspective on atmospheric carbon fluxes based on atmospheric records and satellite observations (Ciais et al., 2022). They provide an independent constraint to the other datasets used here, as they are
 215 derived from different data and with different methods. Inversions estimate the net C flux over land and sea, and hence do not separate gains and losses, nor do they explicitly estimate the biomass C flux. Corrections on carbon fluxes resulting from fossil fuel emissions and other factors have to be applied before direct comparison to land carbon fluxes or forest fluxes. The data used here was produced by Wang et al. (2025), based on five global inversions from the Global Carbon Budget 2022, which are all based on ground-based CO₂ observations (hereafter Wang25). These inversions were corrected for lateral
 220 fluxes not leading to carbon storage (Wang et al., 2025). We also include the updated Global Carbon Project 2025 inversions (hereafter GCP2025), applying the accompanying correction for inland water CO₂ fluxes (Friedlingstein et al., 2026).

Atmospheric inversions were weighted by managed forest area per pixel to account for managed forested land only, and provide information about the net forest carbon flux comparable to the NGHGI estimates representing bottom-up estimated
 225 net C flux of forests, here aggregating biomass and soil fluxes.

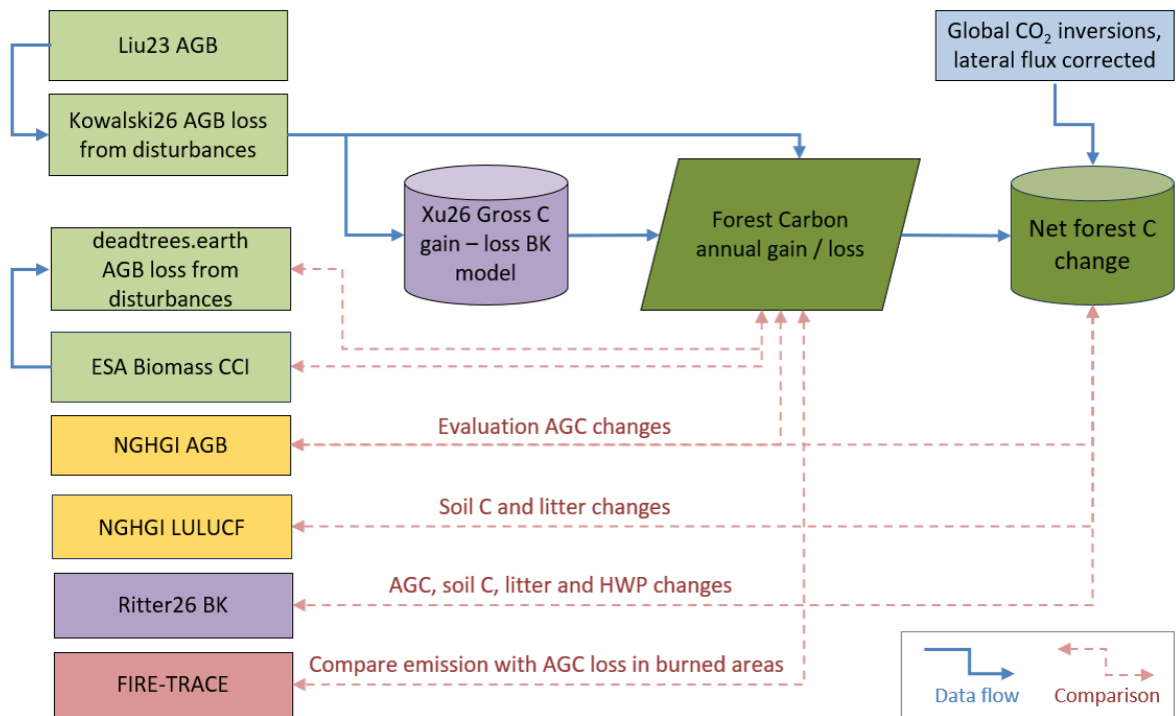


Wildfire data & modelling

Forest fires significantly contribute to carbon losses, especially in fire-prone countries in Europe, and their quantification varies considerably across NGHGs. Methodological approaches differ: some countries apply fixed or species- and fire intensity-specific combustion factors, while others assume complete loss of pre-existing biomass during fire events (Chiriacò et al., 2013; Aquino et al., 2026). Nevertheless, all approaches rely on NFIs biomass stock data collected at country-specific inventory years and subsequently interpolated to derive annual estimates, with additional differences arising from country-specific forest definitions and associated thresholds.

Consequently, fire-induced forest carbon loss estimates reported in NGHGs can diverge significantly from those derived using EO-based products. In this study, we integrate the Liu23 AGB annual satellite-derived biomass data at 30 m of spatial resolution into the FIRE-TRACE (Forest fIRE framEwork for Tier3 Reporting and Accounting of Country-level Emissions) model developed for Italy by CMCC (Aquino et al., 2026), particularly by improving the estimation of available biomass for burning. Using the FIRE-TRACE model (Aquino et al., 2026) we calculated GHGs (CO₂ and non-CO₂) directly released from fires, where the actual fraction of biomass that is lost during a fire event is calculated as a spatially-dependent value directly related to satellite-measured burn severity, using a country-specific model of combustion completeness (Aquino et al., 2026). GHG emissions were estimated for 2018-2023 in Italy, and benchmarked against FIRE-TRACE model simulations based on forest biomass retrieved from the Italian National Forest Census (INFC), which correspond the the data used in the official Italian NGHGI, and from ESA CCI Biomass data. In all simulations, total burned area was derived from EFFIS Burned Area product (<https://forest-fire.emergency.copernicus.eu/applications/data-and-services>).

Wildfire emissions were estimated for CO₂, CH₄, N₂O, CO, NO_x and PM_{2.5} using the respective emission factors from IPCC 2019. For the calculation of GHG (CO₂e) emissions, only CO₂, CH₄ and N₂O were included, with CH₄ and N₂O converted to CO₂e using 100-year global warming potentials (GWP100), applying factors of 28 and 273, respectively (IPCC, 2023).



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Figure 1: Conceptual flow chart of data integration. AGB: Aboveground biomass, BK: bookkeeping, LULUCF: Land use, land use change and forestry.



Methods

Study area

255 The region of interest covers the bounding box of the RECCAP2 European region (see also Fig. 2) and reaches across the continental areas of the 32 countries for which all datasets were available: Austria (AUS), Belarus (BLR), Belgium (BEL), Bulgaria (BGR), Croatia (HRV), Czech Republic (CZE), Denmark (DNK), Estonia (EST), Finland (FIN), France (FRA), Germany (GER), Greece (GRC), Hungary (HUN), Ireland (IRL), Italy (ITA), Latvia (LVA), Lithuania (LTU), Luxemburg (LUX), Netherlands (NLD), Norway (NOR), Poland (POL), Portugal (PRT), Romania (ROU), Serbia (SRB), Slovakia (SVK), Slovenia (SVN), Spain (ESP), Sweden (SWE), Switzerland (CHE), Ukraine (UKR) and United Kingdom (GBR),
 260 (SVK), Slovenia (SVN), Spain (ESP), Sweden (SWE), Switzerland (CHE), Ukraine (UKR) and United Kingdom (GBR), excluding their overseas territories (Lauerwald et al., 2024). In contrast to the full RECCAP2 European region, Cyprus, Faroe Islands, Greenland, Iceland, Malta, and San Marino are not covered in the disturbance datasets, and for the 7 following countries not all datasets were available and they were therefore excluded from the regional analysis: Albania (ALB), Andorra (AND), Bosnia and Herzegovina (BIH), Liechtenstein (LIE), North-Macedonia (MKD), Moldova (MDA),
 265 Montenegro (MNE). For analyses concerning forest C losses, additional countries were excluded which do not separately report C gains and losses in their NGHGs: Belgium, Bulgaria, Hungary, Germany, Greece, Malta, Moldova, Spain and Poland.

Biomass Unit Conversions

Some datasets provided biomass values, while others provided carbon equivalents. As a first step, biomass values were
 270 converted to carbon equivalent to bring all data to the same units, multiplying values referring to CO₂ equivalents (CO₂e) by the factor 12/44 to obtain the corresponding value for C. For datasets of above-ground biomass (AGB), i. e. ESA CCI biomass, Kolwaski26, and deadtree.earth, values were converted to aboveground carbon (AGC) equivalents using a conversion factor of 0.47 (IPCC, 2006, Table 4.3). The UNFCCC NGHGI datasets additionally report gains and losses in living biomass as a total of above- and below-ground living biomass. Therefore, we converted biomass to AGB following
 275 the IPCC guidelines (IPCC, 2006, Section 4.2.1.4), by applying a ratio of below-ground biomass to above-ground biomass (R, also: root-to-shoot ratio) via the formula:

$$AGB = \frac{biomass}{(1 + R)} \quad (1)$$

We derived national R factors according to Ritter et al. (2026), by extracting and dividing “Carbon in belowground biomass”
 280 and “Carbon in aboveground biomass” values for each country from the Food and Agriculture Organization’s Global Forest Resources Assessment 2025 (FAO-FRA2025, <https://fra-data.fao.org/assessments/fra/2025/EU/sections/carbonStock>, accessed 4.8.2026). We calculated R values for all available census dates (1990, 2000, 2010, 2015, 2020, and 2025) covering the full time period assessed in this study, and derived an average R factor per country over time.



285 All datasets were converted to a common unit of Tg carbon per year (TgC/yr), with negative values representing a carbon sink and positive values representing a carbon source.

Data processing

For spatial aggregation, all datasets were aggregated to country level. Country-specific masks were generated by clipping the original raster masks using polygon shapefiles (20 m spatial resolution) downloaded from Eurostat's GISCO data distribution services (<https://ec.europa.eu/eurostat/web/gisco/geodata/administrative-units/countries>). Datasets were aggregated to annual country-level values at their original spatial resolutions (Inversions: 1° lat/lon, Kowalski26: 0.25° lat/lon, Bookkeeping gain-loss model: 0.5° lat/lon). This aggregation was conducted by summation over the land area, using the country-specific masks. For the Kowalski26 dataset, values were given in the unit of tons/gridcell. Therefore, they were integrated over the area to unit TgC.

295 For continental and regional scale analyses, country-level data were summed to annual region-level values. Regional masks for five subregions of the EU were created according to Sup. Table S1 (see also Fig. 2). For the data coverage comparison (Sup. Fig. S1), all datasets were brought to the lowest common resolution of 0.25° lat/lon. We quantified the spatial overlap of the datasets, and their spatial coverage on each investigated country (Sup. Fig. S1), since differences in spatial coverage between datasets can induce discrepancies between country-level budgets. Inventories with country-level data are by definition present (1) or absent (0) in a given country. Data coverage of the EO datasets is generally close to or above 90% across countries, with exceptions for Wang25 inversions and Kowalski26 ABG loss over Denmark, Greece, Ireland, Italy, Moldova, Netherlands, Norway, Ukraine, and the United Kingdom where values can reach below 50%. The Kowalski26 AGB loss dataset excludes grid cells with less than 10% forest cover to make sure that estimates are robust, which concerns larger areas in some of these countries. Hence for most data comparisons this data mismatch should not have a large effect to compare with other forest estimates, but needs to be considered especially in the latter cases and if fluxes additional to forests are concerned.

Concerning temporal aggregation, all datasets were provided in yearly resolution. Average values were calculated over time either for the full temporal coverage of 1990-2023, or for shorter time periods of interest. Specifically in order to investigate longer-term changes, time series were split into decadal time windows of 1990-1999, 2000-2009, 2010-2019, and 2020-2025. To investigate trends, time series were split into two periods before and after 2010. Linear trends based on Ordinary Least Squares (OLS) regression were calculated for time series in predefined temporal windows.



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Results & Discussion

Agreement on declining European net forest carbon sink across datasets

To assess the net biomass carbon sink trajectory of forests over Europe from 1990 to 2023, we compared available net forest biomass flux estimates from the NGHGs with atmospheric inversions weighted by managed forest area for comparability (Fig. 2). For the common time horizon (1990-2023), all datasets indicate on average a net carbon sink over Europe, in line with previous reports (Lauerwald et al., 2024, Korusuo et al., 2023, Migliavacca et al., 2025). A decline in the net C sink is found especially since 2010, although with large spread in the inversion ensembles and high interannual variability (IAV) (Sup. Fig. S2). In the following, we analyse decadal averages for more robust comparison (Fig. 2).

The net C sink over Europe in living aboveground biomass (AGC) declined by an average 27% from -136 TgC/yr in 1990-2019 to -100 TgC/yr in the period 2020-2023 (Fig. 2) according to total net forest C fluxes from NGHGs. According to the Xu26 BK model, the net C sink in AGC declined by 49% (-79 to -40 TgC/yr). A marked reduction in forest biomass C sink is also observed by the Ritter26 BK model indicating a 17% decrease (-233 to -192 TgC/yr), which includes estimates of deadwood, litter and solid carbon pools, as well as harvested wood products counting towards the net C sink. According to in-situ based GCB2025 CO₂ inversions, net C uptake declined by an average of 20% from 1990-2019 (-28±42 TgC/yr) to the period 2020-2023 (-23±56 TgC/yr, Fig. 2), compared to 23% decline indicated by satellite-based inversions (-139±74 TgC/yr to -106±82 TgC/yr). These reductions are already in a comparable order of magnitude to the 39% sink decline projected for 2030 by Ritter et al. (2026).

Focusing on the regional distribution of recent changes of 2020-2023, the most pronounced decrease in the forest net C sink over time is found in boreal and central Europe (Fig. 2). These reductions are observed in NGHGs and inversions alike, albeit of different magnitudes: Central European forest net C uptake decreased by 63% from an average -36 TgC/yr in 1990-2019 (see Fig. 2 for decadal variability) to an average -13 TgC/yr in 2020-2023 according to NGHGI net AGC records, by 55% according to Xu26 (-17 to -8 TgC/yr) and by 23% (-50 to -39 TgC/yr) according to the Ritter26 bookkeeping model (Ritter et al., 2026). Inversions indicate a 35% (In-situ) and 20% (satellite) decline in overall net C uptake in 2020-2023 compared to the long-term average in 1990-2019. For boreal Europe, NGHGs indicate 40% (-30 to -18 TgC/yr) reduction of the average forest C sink, and Ritter2026 BK indicates a 25% reduction (-43 to -33 TgC/yr) of the forest C sink in 2020-2023 compared to 1990-2019. The Xu26 BK model suggests a reduction of -140%, turning the live AGC flux from a sink of -9 TgC/yr into a source of 4 TgC/yr. Inversions in boreal Europe on the contrary indicate a reduction of net forest C uptake by 1% (satellite, -41 to -40 TgC/yr) and an increase of 53% (in situ, -10 to -15 TgC/yr).



Central and boreal European forest C sink changes hence contribute most substantially to the observed reduced net forest C sink over Europe. Other European regions show a smaller decline of the forest C sink, with no change in Atlantic and 7% in Continental Europe, while the Mediterranean forest C sink increased by 6% in 2020-2023 compared to 1990-2019 according to NGHGs. These nevertheless contribute to the overall 27% forest C sink decrease over Europe estimated by NGHGs.

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To estimate the trends of forest C uptake, we compare longer-term trends of atmospheric inversions and the forest carbon sink before and after 2010 (1990-2009 vs 2010-2023, Sup. Fig. S2, Sup. Table S2). In the period of 1990-2010, trends in inversions, NGHGs and BK models all showed small negative trends indicating a strengthening of the forest C sink between -0.3 to -2.1 TgC/yr over Europe. After 2010, all long-running datasets show positive (weakening) trends between 0.9 to 4.9 TgC/yr. The strongest difference is observed in NGHGs, which indicate a negative 15-fold reduction in the rate of net forest C uptake from -0.3 to 4.5 TgC/yr for the whole study area. The Xu26 BK model indicated a reversal and 3-fold higher rate of loss in 2010-2023 compared to 1990-2010 (from -1.5 TgC/yr increase to 4.9 TgC/yr decrease). In-situ inversions indicate smaller losses in the order of magnitude of 45% of the previous gains since 2010 (-2.1 to 1.0 TgC/yr). ESA CCI biomass data was included in the analysis for comparison (Sup. Fig. S2), but cannot be compared with other datasets directly due to the shorter time periods available (Sup. Fig. S2).

360

The large difference in magnitude between in-situ and satellite inversions must be noted, producing different estimates of C sink trajectories in this analysis. While both data streams agree on a decreasing net C sink over Europe since 2010, satellite inversion estimates of net C fluxes are more than twice as high in magnitude than those calculated from in-situ inversions. Satellite inversions also match better in magnitude with NGHG and BK estimates of the net forest C sink. This might be because satellite based inversions better resolve spatial gradients in atmospheric concentration over the continent, therefore better quantifying source and sink hotspots (Lauerwald et al., 2024).

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The datasets in this comparison capture different terms of the net C sink, explaining partially their different magnitudes: While inversions see a net atmospheric signal of C uptake or release, the NGHG derived from the forest land category (4A) represent changes in the living forest biomass pool, deadwood, litter, and soil carbon pools. Ritter26 also count harvested wood products (HWP) towards the net sink, which leads to a larger estimated net C sink compared to other datasets analysed (Fig. 2), while Xu26 quantify only living AGC. In the IPCC methods used for NGHGs, harvested wood is accounted for within biomass losses from forests, but also counts as a carbon input term in calculations of stock variations of the HWP pool, as it represents (near-term) C sequestration rather than CO₂ emissions. HWP information could be integrated in the net forest C sink to remove the sequestered C in wood products from harvest reported as biomass loss from NGHGs.

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These analyses indicate that the EU forest sink losses have increased since 2010, and more strongly so in the period 2020-2023 by 17-27% compared to previous decades, and given the longer-term trends since 2010, the net forest C sink is



380 decreasing at a 15-fold faster rate than it has been increasing prior to 2010 according to NGHGs. Compared to the net C
sink 1990-2019 at -135 to -233 TgC/yr, the remaining forest C sink in 2020-2023 lies in the range of -100 to -193 TgC/yr
depending on estimate and component fluxes considered. Boreal and central European regions show the largest recent
reduction in net carbon uptake, and thus the highest risk for turning into a carbon source in the near future. In the next
section, we highlight regional carbon gains and losses over Europe to assess the drivers of reduced forest C uptake.

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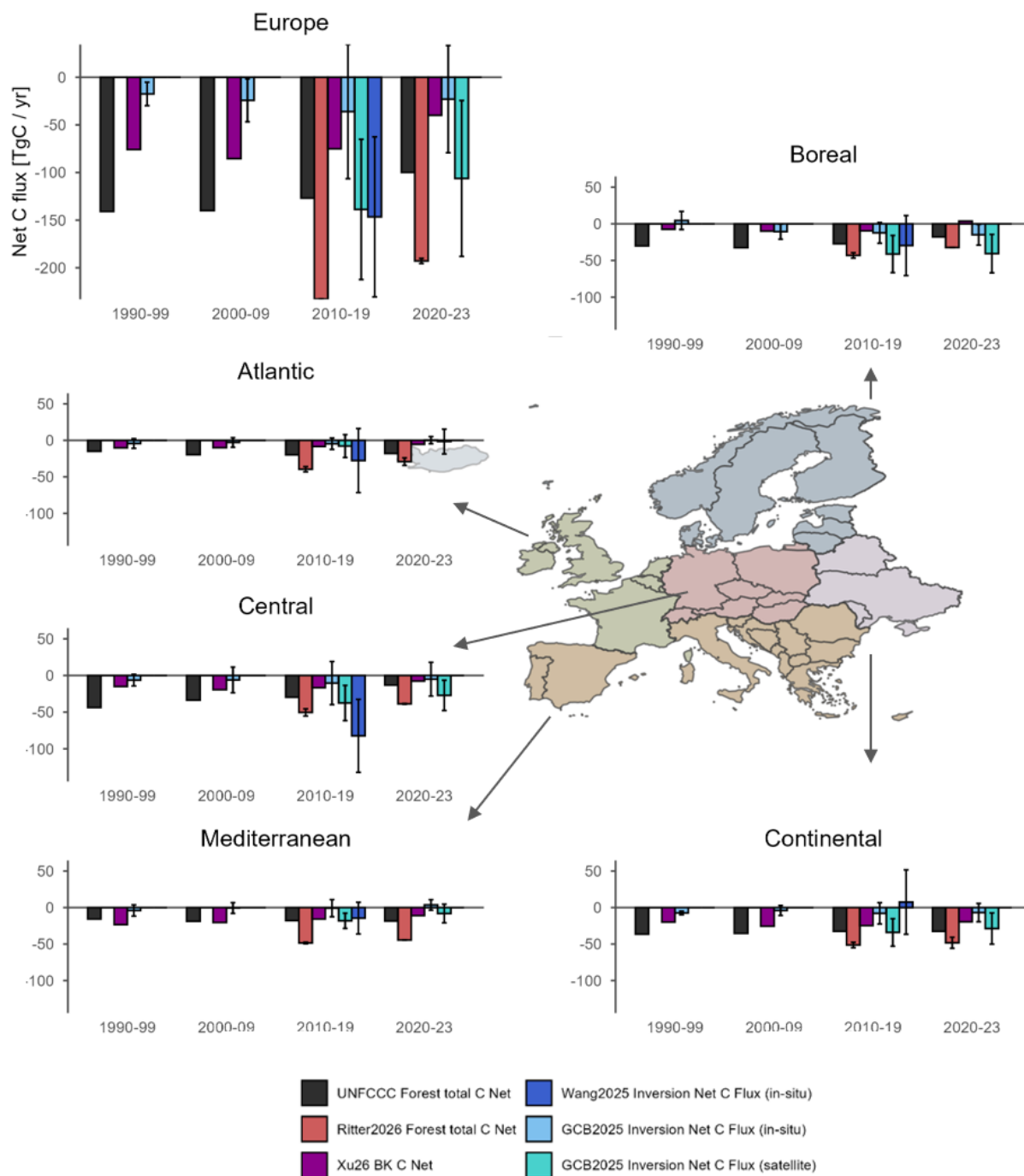


Figure 2: Temporal evolution of net carbon fluxes for Europe and its subregions over the available time periods. Positive values represent a carbon sink from atmosphere to land, and negative values represent a carbon sink.



Regional Forest Carbon Losses

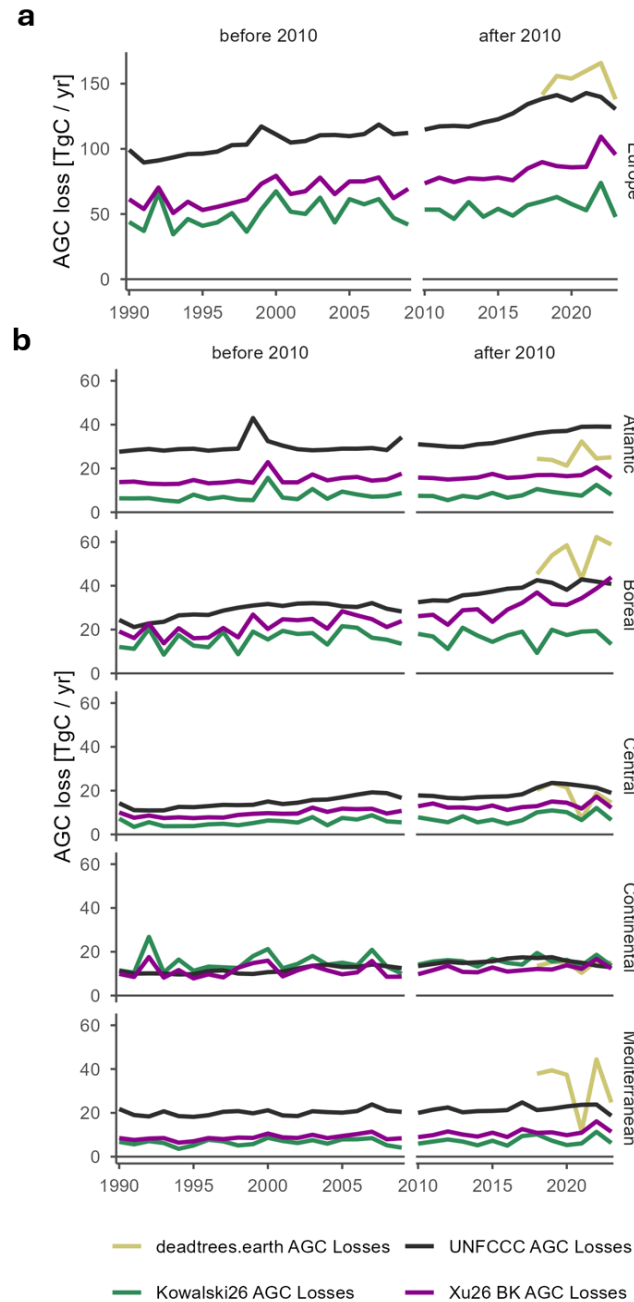
The reduced net C sink shown in the previous section is mostly related to strong reported losses in the EU forest C sink, especially of aboveground carbon (AGC), which can also be quantified by satellite data. We investigate these changes further based on the high-resolution EO datasets from Kowalski26 AGC loss data, the Xu26 satellite-based bookkeeping model, and deadtrees.earth AGC losses, to complement NGHGI assessments (Fig. 3, Sup. Table S3). Several countries for which no distinction of gains and losses is recorded in NGHGIs had to be removed from this analysis (see Methods), including Germany with some of the largest recent losses in central Europe, so that the portrayed regional losses cannot be seen as representative for the whole continent. Both EO and NGHGI AGC loss estimates are of similar orders of magnitude, but can differ by a factor of 2-3 (Fig. 3). A larger interannual variability (IAV) is visible in EO-based datasets than NGHGIs, but several large events are captured in all long-running data streams, especially large storms with considerable recorded damage: Cyclone Lothar in 1999 and Cyclone Klaus in 2009 in the Atlantic region, as well as Storm Kyrill in 2007 in Central and Boreal Europe (Fig. 3b). While losses from Cyclone Klaus in January 2009 are captured correctly in 2009 in all datasets, satellite-based estimates report the losses by Cyclone Lothar in December 1999 with a one-year delay due to the annual time scale introducing uncertainties in the change detection algorithms applied for disturbance mapping (i.e. the change of winter 1999 is “seen” in 2000, Viana-Soto and Senf, 2025, Eifler et al. 2026).

To assess changes over time while accounting for interannual variability, we again separate the available time series into two multi-decadal time windows before and after the year 2010 (1990-2009 vs 2010-2023). For Europe, AGC loss trends are observed to increase about 1.7-fold (1.2 to 2.1-fold) after 2010 according to NGHGI reports (from 1.2 to 2.2 TgC/yr), Kowalski26 data (from 0.6 to 0.7 TgC/yr) and Xu26 BK data (0.9 to 2.0 TgC/yr). In accordance with boreal and central Europe showing the strongest declines of net carbon uptake in recent years (Fig. 2), the high resolution AGC losses from EO also highlight changes in the same regions in both datasets with similar or higher estimates than NGHGIs, as well as in the Atlantic region. In central Europe, NGHGI and EO-based datasets agree on increased AGC losses since 2010, with a 1.2-fold increase seen by NGHGIs (0.38 to 0.44 TgC/yr) and a 1.8-fold increase seen by Kowalski26 (0.13 to 0.23 TgC/yr), while Xu26 estimate a 0.6-fold decreasing loss rate (0.19 to 0.12 TgC/yr) from before to after 2010 (Fig. 3b, Sup. Table S3). For Atlantic Europe, NGHGIs indicate 7.9-fold increased AGC losses (0.10 to 0.83 TgC/yr), while for Boreal Europe especially NGHGIs see a 1.7-fold increase (0.44 to 0.77 TgC/yr) in biomass C losses over forests. Some countries with large losses (Belgium, Bulgaria, Hungary, Germany, Greece, Malta, Moldova, Spain, Sweden, and Poland) had to be removed from the analysis because NGHGIs do not separate gains and losses, therefore major C losses in central Europe are underrepresented. Considering forest C losses for all countries available from EO datasets, larger losses are found (Sup. Fig. S3). This exemplifies the limitations of NGHGIs in providing the data necessary for comprehensive assessment of biomass loss trajectories across the EU.



Although all approaches agree on the sign of trends, differences in magnitude become apparent, highlighting the difficulty in
425 deriving consistent numbers on forest AGC loss across data streams. In general, NGHGIs estimate the largest losses on a
European scale, followed by Xu26, and the lowest losses estimated by Kowalski26. Regionally, NGHGIs estimate larger in
all regions except continental Europe, where all estimates are similar and spikes in losses are more pronounced in EO-based
products. These differences are in part due to different methods and measurement techniques, and sensitivities to different
biomass fluxes (Kowalski et al., 2026, Xu et al, in preparation). Factors leading to underestimation of NGHGI data relative
430 to remote sensing include the forest definition thresholds of NGHGIs which do not consider smaller forested areas included
in EO estimates. Factors leading to higher values reported in NGHGI data relative to remote sensing most importantly
include the fact that NGHGIs also report losses from small-scale, sub-canopy disturbances and management such as
selective logging, forest thinning and felling, often sub-canopy, which cannot be fully captured by satellites especially at
lower resolution (Schwartz et al., 2026). Specifically, the forest disturbance dataset by Viana-Soto and Senf (2025) mostly
435 targets stand replacing disturbances with a minimum mapping unit of 0.27 ha, therefore potentially missing more subtle
disturbance events. The deadtrees.earth dataset built on upscaling drone-based imagery upscaled with 10m Sentinel-2 data
also detects small-scale disturbances down to 0.01 ha (Mosig et al. 2026b) and thus captures higher rates of AGC loss over
Europe than the other EO-based datasets, and sometimes even higher than NGHGIs, especially in boreal Europe.

440 The magnitude of disturbance-induced AGC losses also differs between datasets due to fundamental methodological
differences. The Xu26 bookkeeping framework includes non-detected thinning losses constrained by national harvest
volumes beyond Landsat-detected tree cover loss included in Kowalski26 and thus estimates higher losses that tend to be
closer to national inventory estimates than the two independent EO datasets. Xu26 apply space-for-time substitution to
constrain post-disturbance recovery. The bookkeeping model operates annually at 30 m resolution, while post-disturbance
445 gains at each 30 m pixel follow biomass recovery curves parameterized at a coarser 50 km spatial resolution. Because the Xu
et al. (2026) bookkeeping model explicitly accounts for biomass recovery and disturbance recurrence, the biomass available
to be lost depends on prior disturbance history. In areas affected by repeated disturbances, incomplete recovery results in
lower pre-disturbance biomass and therefore lower loss per event compared to fixed severity estimates derived from mature
stands. In contrast, Kowalski et al. (2026) estimate loss severity from remote sensing alone, using a space-for-time
450 substitution anchored to the 2019 Liu23 AGB map and apply a fixed loss density at a spatial resolution of 20 km. These
differences in the representation of biomass dynamics contribute to discrepancies in the magnitude and spatial distribution of
gross carbon losses between the two approaches.



455 **Figure 3: Time series of forest aboveground carbon losses from different estimates** for a) Europe and b) three most affected European regions, comparing the temporal windows 1990-2009 and 2010-2023. Positive values represent aboveground carbon losses. Dotted lines show linear trends for each time period. AGC: Aboveground carbon. See Sup. Table T2 for corresponding numbers. This analysis is based on 23 countries, excluding Belgium, Bulgaria, Hungary, Germany, Greece, Malta, Moldova, Spain, Sweden, and Poland due to missing NGHGI gross C loss data. See Sup. Fig.3 for comparison of EO-based estimates of all countries.



460 Attribution of forest carbon losses to natural drivers and anthropogenic harvest

The distinction into natural disturbance and harvest from the EFDA allows attribution of detected tree cover loss to causal agents across the European regions. Of the AGC loss in Europe, 72% is attributable to harvest in 2020-23 (Fig. 4) with increasing losses observed over time (54 TgC/yr in 1990-99 vs. 67 TgC/yr in 2020-23). Accordingly, natural disturbances in Europe make up 28% AGC loss in 2020-23. A recent intensification of harvest is estimated especially in the southern boreal regions (Sup. Fig. S4), consistent with Ahlström et al. (2022). While harvest over Europe has increased only 2% in 2020-23 compared to 2010-19, natural disturbances have increased by 80% in the same time frame (from 14 to 25 TgC/yr), concordant with increasing natural disturbances observed during consecutive drought years of 2018 and 2019 and follow-on bark beetle infestations in many European forests, such as in Germany and the Czech Republic (Hlázny et al., 2021, BMLEH, 2025). The increased natural disturbances dominating European timber losses until 2020 have been attributed to higher biotic disturbance, while abiotic disturbances decreased over time (Patacca et al, 2022).

Aggregated by region, the largest harvest losses in 2020-23 occurred in Boreal and Central Europe (29 TgC/yr and 16 TgC/yr), while largest natural losses occurred in Central and Mediterranean Europe (13 TgC/yr and 4 TgC/yr). Harvest losses have on average slightly increased since 2020 mostly in Boreal and Central Europe (Fig. 4). Natural losses show a 2.5-fold increase for Central Europe in 2020-23 compared to the 2010-19 average (Fig. 4), a 1.5-fold increase for Atlantic and Boreal Europe, as well as a more moderate 1.2-fold increase for the Mediterranean and little change for Continental Europe. These together dominate the recent 1.8-fold increase in AGC loss over Europe. To investigate these losses further, we compare EO-informed data sources to those recorded in NGHGI inventories at country level in the next section.

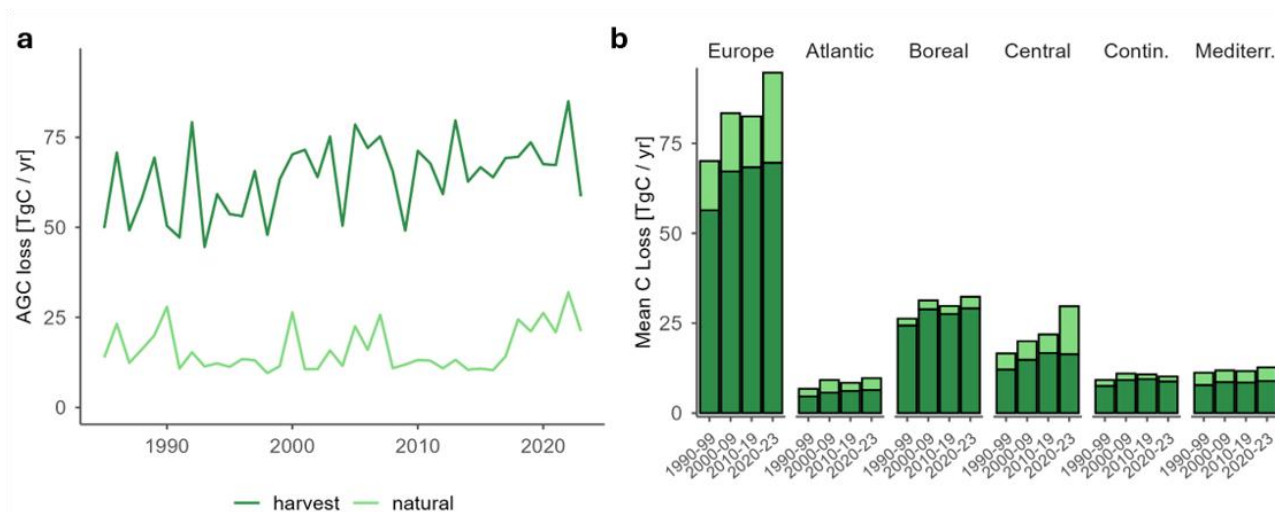


Figure 4: Distinction between natural and harvest-related biomass losses for a) Europe over time and b) averages over Europe and European regions in decadal time windows between 1990-2023 derived from Kowalski26 AGB loss data. Positive values represent carbon losses. AGC: Aboveground carbon.

Country-level gains and losses

Considering increased forest carbon losses over the past decades per country, we compare the estimated aboveground carbon losses based on NGHGs against high-resolution Kowalski26 AGC loss data to assess whether EO-based datasets detect disturbances comparable to NGHGs (Fig. 5). For many countries, both NGHGI data and Kowalski26 AGC loss estimates show similar average biomass carbon loss estimates ($r^2=0.57$, Sup Fig. S5-6). However, some countries diverge from this pattern or show apparent differences over time. For example, in France or the United Kingdom, the EO-based datasets do not fully capture recent losses (Fig. 5a, Fig. 6). The same is found, to a smaller extent, in Austria, Ireland, and Norway (Sup. Fig. S7). Kowalski26 and Xu26 show larger losses in some countries like Belarus, Croatia, Denmark, and Estonia (Sup. Figure S7). Of these countries, Italy, Ireland, Norway and the United Kingdom show lower data coverage fractions (0.44-0.79) in EO data (see Supplementary Information, Sup. Fig. S1) or low forest cover, which could partly explain this disagreement with NGHGI records. Meanwhile France and Finland show a high data coverage fraction (>0.95) in all datasets, so that discrepancies should have a different cause.

In the period 2010-2023, for most countries, NGHGI estimates are larger or similar than EO-based AGC loss estimates (Fig. 5a). Absolute differences are larger in larger countries, with Finland (14.0 TgC/yr), France (13.8 TgC/yr), Italy (9.4 TgC/yr), and the UK (8.9 TgC/yr) showing the largest difference of NGHGs compared to Kowalski26 (Fig. 5a, Sup. Fig. S8). This result may first of all represent the effect of total area over which losses can occur, which increases with country size and forested area. The two datasets also show differences in the underlying area considered as forest (Sup. Fig. S9), with larger forest areas in EFDA observed especially in Finland, Italy, Norway, Poland, Romania and Sweden, which can be a large



contributing factor to the differences in estimated totals in these countries. If C losses are calculated per forested area (Fig. 5b), both datasets agree well for France, Finland, Croatia, Denmark, and others (Sup Fig. S8), while the UK, Ireland, and Italy show the largest positive differences also here (UNFCCC showing higher values than Kowalski26). These differences thus also propagate into diverging national totals, and may be partly due to the reasons discussed in previous sections, i. e. NGHGs can record carbon losses from small-scale disturbances and selective logging, which are harder to capture for spatially coarser resolved satellite products than clear-cut disturbances. Clearcuts, which are more easily detected by EO, e. g. make up the minority of total harvest in central Europe: In France, for example, 72% of disturbances are at sub-100 m² scale and not detectable by products with 10–30m resolution (Schwartz et al., 2026). We selected four countries as case studies, two with large absolute deviations, France, Finland, as well as two with well matching estimates, Czech Republic and Estonia, for detailed analysis below.

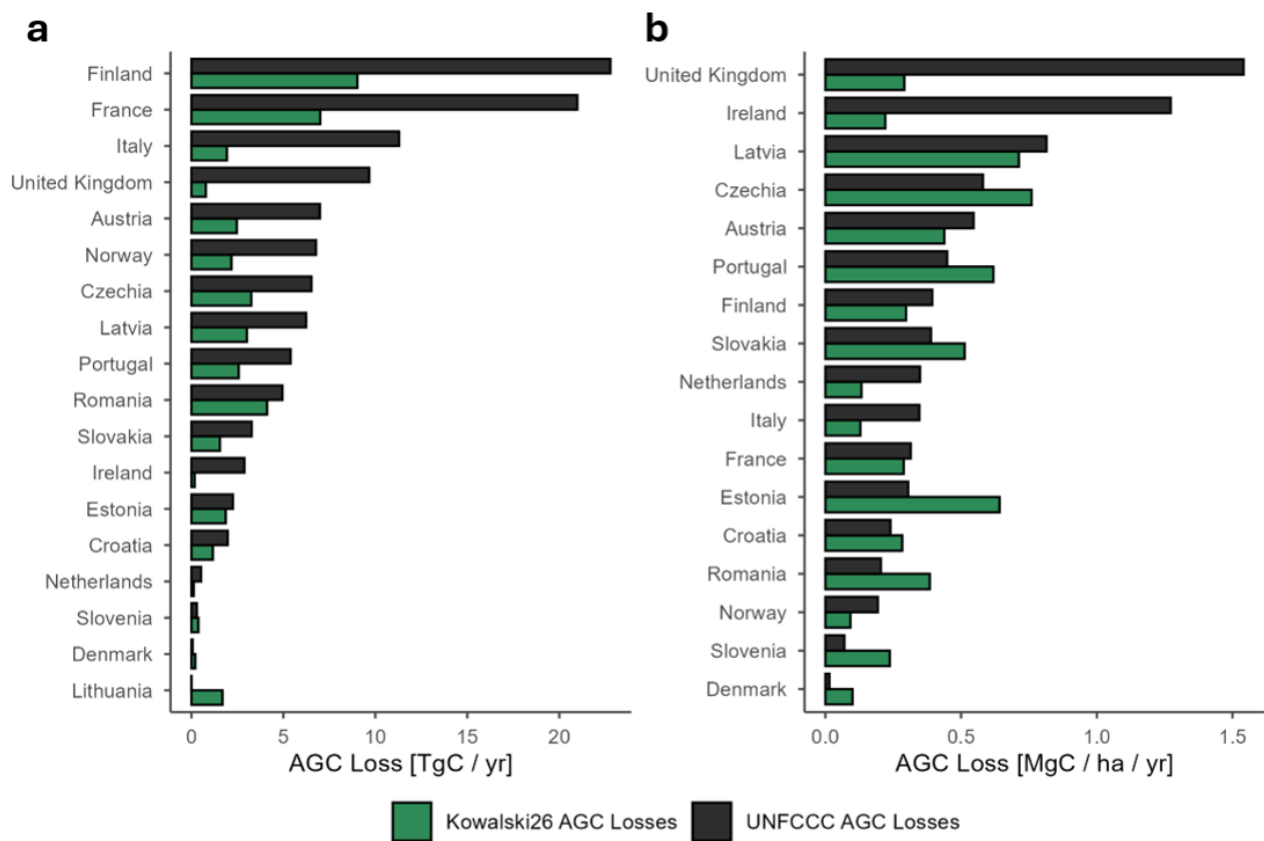
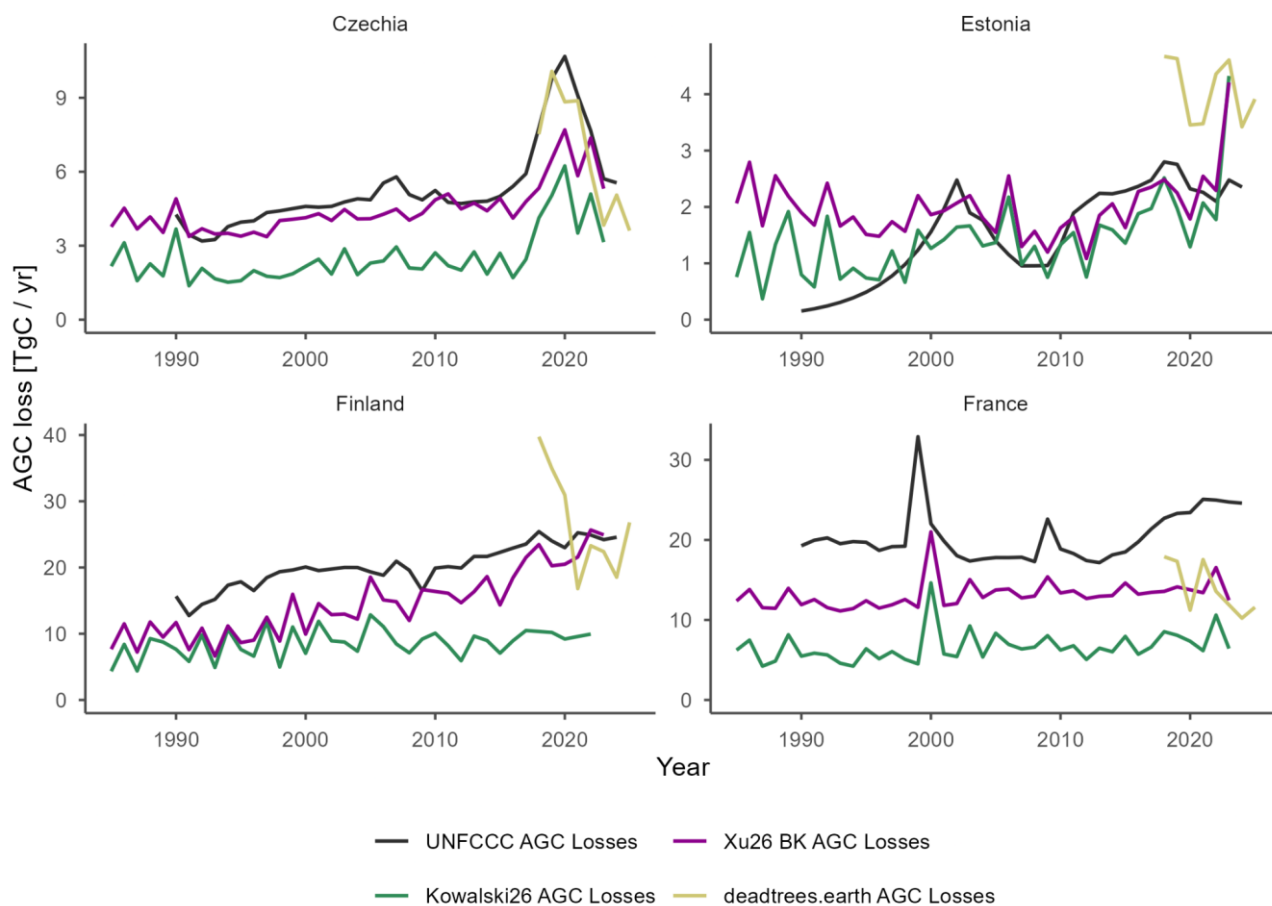


Figure 5: Aboveground Carbon losses in European countries a) Mean annual AGC losses for European countries reporting losses in their NGHGs, showing estimates from NGHGs (UNFCCC AGB Losses) and Kowalski26 AGB Losses between 2010-2023, sorted from highest to lowest NGHGI estimate, and b) corresponding mean annual AGC losses per hectare forested land. Countries reporting only the net forest C sink and no separate gains and losses are excluded from the analysis. AGC: Aboveground carbon.



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The timeseries of the data from the four selected countries suggests moderate agreement in temporal dynamics between loss estimates over the common time period, while the overall magnitude of estimates differ (Fig. 6, Sup. Fig. S10). Data sources for the Czech Republic agree on the temporal evolution of the signal with a recent maximum in C losses, but an offset between NGHGI and EO-informed estimates with average losses of 3.3 TgC/yr estimated by Kowalski26 and 6.5 TgC/yr by NGHGIs for 2010-2023. For Estonia, all datasets show good agreement in their mean (1.9 vs 2.3 TgC/yr in Kowalski26 and NGHGIs, respectively in 2010-2023), as well as their year-to-year variability especially from the 2000s onwards. For disturbances after 2020, all EO-based datasets also predict higher losses than NGHGIs in Estonia (Fig. 6). For France, large events of biomass losses from Cyclone Lothar in 1999 and Cyclone Klaus in 2009 are well captured in all data sources, although with temporal shifts in 1999, while the recent (2010-2023) decline in the NGHGI forest carbon sink is different in magnitude in Kowalski26 (7.0 TgC/yr) and NGHGIs (21.0 TgC/yr). For Finland, a much larger interannual variability is recorded in EO-based estimates, while losses indicated in NGHGIs are captured to different degrees by the three EO datasets (Fig. 6). Differences in magnitude of carbon gains between datasets are even more pronounced for these countries (Sup. Fig. S10). One reason for these discrepancies could lie in the different forest definitions adopted by countries in their NGHGIs. For example, France and Italy adopt the FAO definition, which requires a minimum area of 0.5ha, while Finland considers 0.25ha and Ireland 0.1ha thresholds. These differences in thresholds can lead to variations in the total area classified as forest and, consequently, in reported gains and losses. Including smaller forested areas would increase total NGHGI estimates, potentially reducing the gaps between NGHGI and EO-based estimates with minimum mapping units of 0.27ha (Kowalski26) to 0.01ha (deadtrees.earth). Estimates of forest C losses per ha forest show country-specific differences between Kowalski26 estimates than NGHGI data (Fig. 5b), pointing to additional factors of difference depending on individual national NGHGI specifications. These four examples represent different cases of data mismatch warranting further analysis and exemplifying the difficulty of data reconciliation.



545 **Figure 6: Time series of forest aboveground carbon losses for four selected European countries with high data discrepancies.**
 Positive values represent carbon losses. Plots for all countries can be found in Sup. Fig. S7. AGC: Aboveground biomass carbon.



Wildfire impacts - Case study in Italy

Forest fires are a major source of forest carbon loss in fire-prone parts of Europe, yet marked differences are observed when comparing NGHGI with EO-based estimates. Here we show results of a comparison of fire-related forest carbon losses reported by the Italian NGHGI, estimated with the FIRE-TRACE model based on Italian National Forest Inventory (INFC) data, with estimates derived from Liu23 high-resolution AGC and ESA Biomass CCI data. The total available biomass at the time of the fire in the burned area for Liu23 and ESA CCI are very similar (Fig. 7, left) while both datasets show consistently different values to the INFC inventory forest biomass (equal to Italian UNFCCC NGHGI numbers). This translates into a difference of 7% in GHG emissions between Liu23 and ESA CCI in 2019 and more than 45% of difference in the estimation of the GHG emissions for Liu23 and ESA CCI when compared to the inventory (Fig. 7, right). These differences may be due to the definition of forest type used in the INFC dataset to estimate GHG emission: In fact, INFC only reports AGC estimates for “high forests”, which generally consist of mature trees of considerable height and with a closed canopy, in contrast to coppice (low) forests. Hence, forest management should be considered in the definition of emission factors applied in the FIRE-TRACE model. Another difference between AGC satellite data and INFC data is the fact that the INFC dataset is not spatially explicit: INFC census provides average AGC values per Italian region rather than spatially explicit maps as it is the case for the satellite-derived data. Therefore, INFC does not account for annual forest sub-regional variability, due, for example, to forest disturbance events, assuming that forest biomass is always at the highest possible value. Recovery from previous fires in 2018-2022 is not included in these estimates, while earlier recovery may be included if seen by the underlying CORINE land cover product of 20218. An overestimation of fire emissions derived in the NGHGI data, based on INFC forest census data, is therefore likely. Another important source of uncertainty can be due to the temporal mismatch between ESA CCI epochs and the census date, although the estimates agree well in the temporal variability for the studied period.

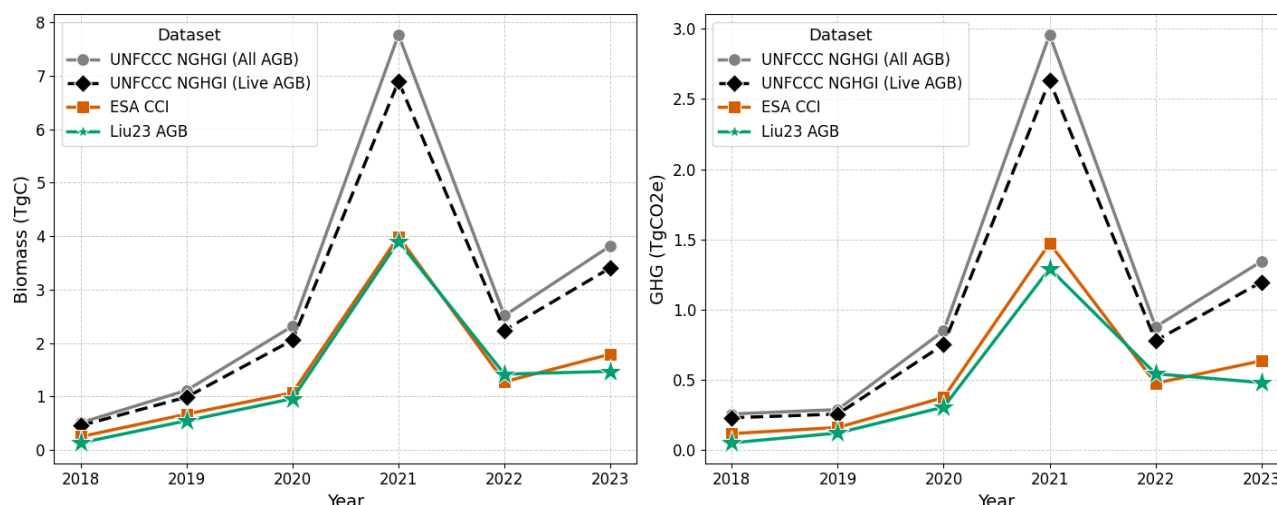


Figure 7: Comparisons between pre-fire forest biomass (left) and GHG emissions (right) derived from: the UNFCCC National Greenhouse Gas Inventory for Italy (UNFCCC NGHGI), considering all AGC components (grey) and live AGC components only (black); FIRE-TRACE model outputs using as input ESA CCI biomass (red); and Liu23 AGC (green).

Regarding wildfire C loss quantification in NGHGIs and comparison to EO, incomplete distinction of fire emissions in the reporting must be considered. NGHGIs separately report C losses from forest wildfires, with detailed descriptions of methods applied by each country reported in the National Inventory Document. In this reporting, carbon is lost as a result of combustion (biomass multiplied by a combustion factor). However, many more losses can be fire induced, such as dead trees that are still standing or removals following the fires. Combustion completeness considers potential decays or post-fire tree mortality, like removal of tree-trunks after fire to avoid plagues. These are usually included in the "conventional" biomass C losses. While the details may differ between countries, the values in NGHGIs on wildfires is thus only a fraction of the whole picture, and a full quantification of wildfire C losses would require a more in-depth estimation of combustion completeness and post-fire fluxes.

Discrepancies between Earth Observation and National inventory approaches

Discrepancies between NGHGIs and EO-based datasets as described above can stem from differences in measurement techniques and modeling assumptions. Here we discuss the most relevant sources of uncertainty affecting estimates by different approaches: differences in forest definitions and methodology, as well as uncertainties and detection thresholds in NGHGI and EO data.



One main source of difference between EO and NGHGI data is the definition of which land is included as forest. Technical reasons such as forest definition thresholds, as well as qualitative aspects or emission factors may play a role in the observed country-specific differences of relative over- or underestimation. For example, forest definitions may differ in the treatment of forest land without tree cover and may include additional qualitative criteria, such as the inclusion or exclusion of forest roads, temporarily unstocked areas, arboriculture, nurseries, willow crops, and other specific land categories (Sup. Table S4). The implementation of country-specific forest definitions is considered important to adequately capture the diversity of forest ecosystems and management practices across Europe within national GHG inventories (EEA, 2026). However, these differences inevitably introduce some degree of methodological heterogeneity and may result in incomplete alignment and comparability across countries and with EO-derived information. The areas defined as forest show larger or smaller differences between EO-based datasets and NGHGIs, depending on the country (Sup. Fig S9). Spatially explicit forest maps underlying NGHGIs are often not publicly available, hampering data harmonization and uncertainty assessments.

Another factor of influence are methodology and data updates in NGHGIs. NGHGIs are updated each year including retrospective updates due to e. g. temporally delayed addition of fluxes or stepwise integration of new data with long revisit cycles, such as forest inventory updates. When comparing different revisions of NGHGIs from 2023 to 2026 (Fig. 8), we find that these updates can amount to considerable differences, reaching up to ~10 TgC/yr (or about 30% of the mean sink) between consecutive versions in central and Atlantic Europe. Inventory estimates between versions are rather consistent for Boreal and continental Europe, while differences exist for the most recent years especially in Mediterranean, Atlantic and Central Europe (Fig. 8). These differences develop in a consistent direction of increased sink strength estimation for Mediterranean and Atlantic Europe in later inventory versions, while the UNFCCC inventory v28 of 2025 indicated Central Europe reaching a net zero forest carbon balance in 2020, with an almost 20 Tg/yr difference to v27, which was corrected back to -10 TgC/yr in the most recent v30. When assessing changes in forest C fluxes, this uncertainty in the last 5-10 years of NGHGI records must be considered. The occurrence of more frequent and impactful climate extremes may exacerbate these versioning differences in the latest years of NGHGIs, if affected plots are sampled irregularly and time delays in forest management, such as deadwood clearing, become inevitable due to larger affected areas. Furthermore, in NGHGIs, some countries remove interannual variability not related to direct anthropogenic disturbance or management (Kurz et al., 2018), which renders them less comparable to EO datasets where often no distinction between natural and anthropogenic disturbance can be made. These uncertainties further challenge the timeliness and reliability of NGHGIs for informing policy, and highlight the potential added value of EO-based estimates in supporting decision making.

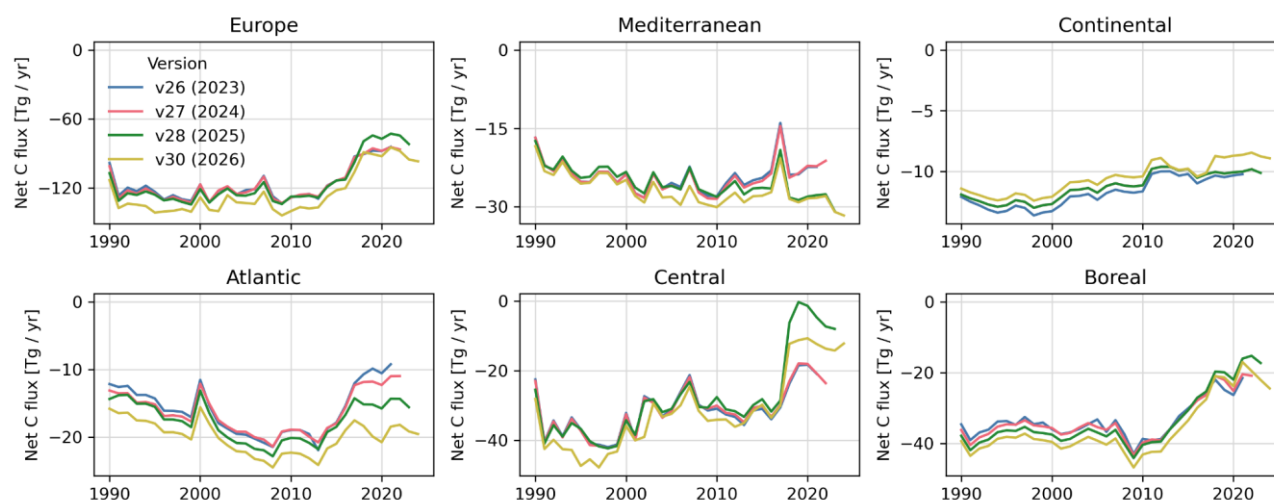


Figure 8: Comparison between different versions of UNFCCC NGHGI released between 2023-2026 for Europe and European regions. Differences between versions stem from stepwise integration of new data with long revisit cycles such as forest inventory updates, as well as fluxes recorded with temporal delay and methodological updates. Negative values indicate a carbon sink from atmosphere to land.

Regarding estimates of forest carbon losses, NGHIs mostly show higher losses than all EO-based estimates in this analysis, with country-specific magnitude. This is due to the fact that NGHIs record forest C losses beyond what EO can assess, such as thinning and felling related wood removals that are not visible to satellites either at the given resolution, or generally if these changes happen below the canopy. However, in some cases, NGHGI losses are underestimated due to various reasons, including differences in the underlying forest area considered (discussed above), as well as some forest C losses reported in other LULUCF categories. For example, when a forest transitions to another land use category such as grassland or cropland, the C losses from the deforestation are accounted for in the new land use category in the NGHGI. In EO-based products in contrast, such deforestation would generally be recorded as a forest C loss. The effect of land use change is thus not fully represented here and may increase NGHGI estimates when fully accounted for. Forest C losses reported in NGHIs may also face time lags or imprecisions in recording (discussed above), and the spatially and temporally sparse measurements of inventory plots may not fully capture forest disturbances and related carbon losses. While this highlights that EO and NGHIs still face limited comparability, especially in small scale and non-stand replacing disturbance detection, the added value of spatially explicit information on disturbance time, severity and type, extractable from EO datasets, should be integrated into NGHGI practices to improve estimates of forest carbon losses.

Uncertainties in the EO data streams mainly stem from underlying uncertainties in i) forest area (discussed above) and ii) in biomass maps (Santoro and Cartus, 2026, Liu et al., 2023), iii) tree cover loss maps, including in the original remote-sensing signal and the change detection algorithms, as well as iv) the approach used to estimate losses and gains. Uncertainties in the



underlying biomass maps (ii), e.g. as provided by ESA Biomass CCI, and in tree cover loss area can be propagated in the models used to estimate AGC losses and gains (see Kowalski et al. 2026). Regarding data coverage (iii), some countries in our comparison show lower data coverage in the EO-based Kowalski26 AGC estimates, likely due to differences in the exact forest area extent and inclusion of different ecoregions (Sup. Fig. S1). This affects the AGC loss estimation, so that a direct comparison to NGHGs is inevitably biased and would need to be scaled by data cover fraction, or ideally masked for regions of overlapping data coverage, if spatially explicit NGHGI information were available. A considerable uncertainty in disturbance AGC loss/gain estimates arises from detecting tree cover loss (iii), particularly mapping tree cover loss and increases in standing deadwood at different spatial scales (Schiefer et al. 2025, Cheng et al. 2024, Schwarz et al. 2026). Landsat-based maps may miss small or low-severity disturbances and only partly capture biomass removal from thinning and selective logging. Conversely deadtrees.earth shows very high losses in some countries especially in 2018 that should be tested for plausibility (Sup. Fig. S3). The deadtrees.earth product attempts to map both tree cover loss and standing deadwood as continuous cover fraction (Mosig et al., 2026a, Mosig et al., 2026b), but only tree cover loss was considered here for assessing related AGC loss, since incorporating standing deadwood would require a better understanding of its subsequent dynamics. Particularly, mortality followed by salvage logging, clear-cutting or selective removal can generate successive signals affecting the same trees, creating a risk of double counting if these signals are independently converted into losses of living biomass. Concurrent canopy recovery further complicates their interpretation. Resolving these trajectories and evaluating them against field observations of biomass removal and standing dead biomass is therefore essential for consistent biomass accounting (Migliavacca et al. 2026). The Xu26 model partly compensates for unmapped harvest losses using national harvest-volume statistics, but uncertainties and spatial or temporal mismatches among biomass, forest age, rotation, and gridded growth-curve data can further propagate into estimates of gross carbon gains and losses. For the Xu26 bookkeeping model, uncertainties arise from both disturbance detection, the integration of multiple data sources and the uncertainty in the recovery curves.

Regarding the comparison of EO and NGHGI data, EO-based datasets generally estimate lower forest C losses than NGHGs, likely related to the capacity of NGHGs to account for changes in specific components of the aboveground biomass pool, such as those resulting from thinning or selective felling, particularly within the sub-canopy layer that may not be readily detectable from satellite observations, as well as to the resolution-dependent capability of EO-based datasets to capture small-scale losses. In cases where EO-based datasets estimate lower losses than NGHGs, such as in United Kingdom, Italy, or Ireland, this may be related to the fact that the EFDA and Kowalski26 primarily record larger and stand-replacing disturbances based on Landsat imagery, but do not fully capture forest management such as thinning or non-stand-replacing disturbances. The Sentinel-2 based deadtrees.earth dataset estimates larger losses than NGHGs and Kowalski26 in some regions, indicating that higher resolution EO data, in combination with training on drone imagery as reference, can capture more subtle tree cover losses (Mosig et al. 2026b, Schwarz et al. 2026). Larger interannual variability of the deadtrees.earth product may stem from more tree cover loss signals captured, but may also be influenced by the difficulty of



reliably detecting small-scale disturbances, and thus requires further analysis. The long-running timeseries of Kowalski26
680 hold additional value for monitoring temporal dynamics and changing trends, especially with regard to national inventory
applications which ideally require datasets to be available from the 1990s. High-resolution maps may be further exploited to
add sensitivity for detection of non-stand replacing biomass losses. While the static 30 m Liu23 AGB map was integrated as
an input dataset to estimate Kowalski26 AGB losses, annual 3 m canopy height, canopy cover and derived AGB change
maps have since been produced across the EU for 2018–2023, including an overall uncertainty assessment (Liu et al., 2025,
685 preprint). However, part of the year-to-year change signal in the current version stems from inconsistencies in the
PlanetScope input imagery (e.g. varying image quality between years). An improved compositing approach for PlanetScope
mosaics is being implemented, which is expected to yield more temporally stable annual change maps for integration in
future EO–NGHGI comparisons. (Liu et al., 2025). In cases where EO-based datasets record higher losses than NGHGIs
inventory model assumptions, temporal lags in deadwood processing and recording of census data may also play a major
690 role for C loss estimates from living biomass, as countries can estimate C loss from this pool from mortality (trees switching
from living biomass to dead biomass, sometimes still standing). Especially in these cases, EO-based datasets offer the
opportunity to estimate the concurrent forest C sink more accurately and with higher temporal consistency at low latency
(Schiefer et al. 2025, Mosig et al. 2026b). We note, however, that no approach outperforms the others: increased
spatiotemporal data coverage and detection of tree cover loss, including both harvest and natural disturbance, allow to map
695 forest C loss more comprehensively with EO-based products, while NGHGIs can capture additional components invisible to
EO. AGC losses estimated by EO-based datasets in this study can be expected to lie on the conservative side given the
detection limit posed by the resolution of the remote sensing products, but they can complement NGHGIs in providing
independent spatially and temporally continuous estimates of aboveground components. With increased resolution of EO
products, alongside growing algorithmic complexity and the rise of drone-based ground truthing data, EO-derived datasets
700 may in the near future be able to even better inform NGHGIs on small scale effects such as disturbance and degradation.

In summary, NGHGIs comprehensively record components of forest C fluxes beyond what EO-based methods can assess,
although with temporal delay and considerable uncertainty especially in the latest years on record introduced by sparse
temporal and spatial sampling. Earth observation provides timely, spatially explicit information at high spatial and temporal
705 resolution complementary to NGHGIs, with resolution-dependent sensitivity to detecting also smaller-scale disturbances in
heterogeneous landscapes. While inherently limited to capturing fluxes derived from visible changes of the land surface,
increased spatial and temporal coverage and disturbance quantification go far beyond plot-based inventory approaches. Both
approaches should be used in tandem, together with atmospheric inversions, to complement shortcomings and reduce
uncertainties. Further work is necessary to best integrate these datasets and arrive at more certain combined estimates,
710 discussed below.



Recommendations and Outlook for ways ahead in EO-NGHGI cross fertilization

715 In this analysis, we show that high-resolution EO datasets can provide valuable information on spatial patterns and temporal trajectories of biomass C change that can complement NGHGIs, which strongly rely on sparse spatial and temporal plot-scale forest inventory measurements. We also show that EO-based attribution of forest disturbance helps to separate anthropogenic and natural drivers of forest C losses.

720 Opportunities arise for more comprehensive EO-based detection of forest disturbances, degradation, and biomass change, or balancing data for under-sampled types of forest, land use, and disturbance regime in plot-based inventory estimates (Bastos et al., 2022). EO-based approaches and models can benefit from NGHGI data as reference to assess how well GHG fluxes are captured in these approaches, while accounting for uncertainties within the NGHGI data itself. NGHGIs can benefit from EO-based datasets especially in characterization of AGB losses between different pools, as well as distinguishing fluxes attributable to natural and anthropogenic causes in a spatially- and temporally-consistent manner. New EU regulations (EU 725 2018/841) require countries to follow their deadwood pool, but high methodological heterogeneity exists between countries. Novel EO-based datasets can advance the typology and estimation of carbon loss pools: NGHGIs have to capture living biomass variations (with possible distinction between gains and losses), and deadwood stock variations, but the distinction of the fluxes between carbon pool is not always accessible from NFI data. For instance, the distinction between natural mortality and harvest within biomass losses is complex. The amount of standing deadwood and its transition to harvest and 730 then product pools is not well constrained. High-resolution datasets such as Kowalski26 or deadtrees.earth can inform NGHGIs about such transitions and improve the quantification of different types of transitions between live biomass and dead biomass pools. Accounting for harvest and natural disturbances separately can also be facilitated with EO-based datasets, such as the EFDA and resulting biomass losses estimated by Kowlaski et al (2026).

735 To maximize mutual benefit and allow easier evaluation of uncertainties in both directions, we recommend the following steps to further comparability between Earth observation and national inventories:

For comparability, EO-based assessments may consider to routinely align not only along natural categories such as biomes, but additionally; along categories relevant to NGHGIs, such as aggregated statistics over national boundaries, NUTS2 or 740 NUTS3 regions for finer than national resolution, or land use and land use change categories harmonized with NGHGI practices and definitions. Not all inventory agencies routinely work with gridded, spatially explicit data. Hence providing readily aggregated statistics or tools to do so, such as the RECCAP-Viewer (<https://reccap2.viewer.brockmann-consult.de/>), could greatly enhance the accessibility of mutually beneficial information.



- 745 Spatially explicit information provided by inventory agencies whenever possible would be very valuable for the comparison to EO datasets, such as information on managed and unmanaged areas considered in NGHGs, land cover masks to assess e.g. forested areas, as well as inventory-based biomass estimates to calibrate EO datasets. With new UNFCCC regulations to move NGHGs towards Tier2 and Tier3 methodology upcoming for the 2028 and 2030 submissions, the added spatially explicit and high resolution data should be made available to the research community wherever possible. This should include
- 750 availability of the forest or land use masks used for better comparability with EO-based estimates.
1. Explicitly reporting carbon gains and losses, as well as component fluxes in NGHGs which are currently aggregated for reporting, such as above- and belowground biomass, would allow more direct and accurate comparison with EO-based estimates, which currently require back calculation of component fluxes with approximation methods. Detailed national Forest inventory data on above and below-ground C stocks, along with
755 their spatial information, would allow for improved comparison with and refinement of EO-based products. Unfortunately, such data is not publicly available for all countries in the EU. The more components that can be reported in a programmatically accessible tabular format and following FAIR principles, the easier comparison and cross-fertilization with EO data can be.
 - 760 2. Increased detail in the reporting of fluxes that contribute to interannual variability such as wildfire- or disturbance-related fluxes, and their treatment (removal, consideration of recovery, etc), and of other aspects that contribute to temporal uncertainties (e.g. plot revisit periods) would allow for better comparability and better constraining the uncertainty in the last few years of each inventory update. Here, EO can be of high value by providing spatially-consistent coverage with low latency updates.
 - 765 3. Harvest typology is challenging to estimate for NGHGs, and not always accessible from NFI data. Novel EO-based datasets can advance the typology and estimation of deadwood stock variations, e.g. the distinction between natural mortality and harvest, or the amount of standing deadwood and its transition to harvest, and improve the quantification of different types of transitions between live biomass and dead biomass pools.
 - 770 4. Treatment of harvest and deadwood pools requires consideration between EO-based products and NGHGs. In EO-based datasets, harvest and tree death are considered a net loss, as well as for NGHGI forest living biomass pools. For the net forest C sink however, in NGHGs, they can be counted towards the net C sink as sequestered C in the form of harvested wood products (HWP), as well as deadwood biomass pools. Information on HWP and deadwood are available in inventories, but not all component fluxes beyond harvested roundwood are made public, complicating the translation between NGHGI fluxes and EO data.
 - 775 5. NGHGs provide an important basis for policy decisions, but face issues of timeliness since they are published with a two year time lag. If delayed accounting from extreme event impacts increases due to higher impacts and thus larger burden on authorities and foresters, the resulting uncertainties in the quantification of recent years' budgets



may further reduce the near-term reliability of NGHGs. Better constraining the effects of climate IAV and extremes on GHG inventories is essential for near future policy decisions.

6. NGHGs require long-term methodological stability and datasets available since 1990 with yearly updates for a meaningful integration of EO data. It is therefore necessary to move from one-time pilot studies to sustaining consistent, regularly updated data pipelines to effectively provide EO information to inventory agencies.

Next steps should focus on integrating further novel EO-based datasets produced over Europe, as well as more detailed information available for inversions and inventories. This will allow a fairer comparison of different estimates, notably (i) employing novel datasets of inland water CO₂ fluxes to correct inversions, which account for currently underrepresented year-to-year variability from water bodies and distinguish these from the variability of vegetation fluxes (Lauerwald et al., 2023, Zhang et al. 2022); (ii) including NGHGI information on deadwood and harvested wood products (HWP) to count towards the net forest C sink, and vice versa using deadwood and harvest losses estimated by the EO-based datasets to inform NGHGs. Future work on product intercomparison should include pre-operational evaluation and intercomparison of country-level NGHGs reporting, bottom-up and top-down approaches to provide systematic assessments of the consistency and uncertainty between these data streams.

Conclusion

This study provides an evaluation and intercomparison for reconciling bottom-up and top-down estimates of the European forest C sink, harmonising high-resolution Earth Observation (EO) based datasets, atmospheric inversions, and national greenhouse gas inventories (NGHGs).

Recent losses in the European forest carbon sink are captured by both EO-based datasets and NGHGs, as well as atmospheric inversions. Estimates from different approaches vary in magnitude of averages and trends, in line with previous studies (Lauerwald et al., 2024, O'Sullivan et al., 2024, Winkler et al., 2023). All datasets agree on a decreasing European net forest carbon sink since 2010, with a pronounced reduction in 2020-2023. In line with this decreased net sink, the forest carbon balance as quantified by both NGHGs and EO-based datasets shows increased forest carbon losses since 2010 in general, as well as the acceleration of these losses by up 1.7-fold in 2020-2023 compared to 2010-2019 in Europe. The high-resolution EO-based datasets assessed in this study indicate higher aboveground forest carbon losses than estimated by NGHGs in most countries. Large discrepancies between estimates from EO and NGHGs are observed notably in Ireland, the United Kingdom, and the Czech Republic. Regarding net changes, atmospheric inversions, in spite of their coarser resolution, show regional patterns in net carbon flux trends that are generally consistent with NGHGs, and thus found to provide valuable independent information to those of bottom-up estimates, but considerable differences in the estimated sink strength remain.



Code and data availability

The majority of datasets used in this study are publicly available online: UNFCCC National GHG Inventories submission of 2026 from <https://unfccc.int/ghg-inventories-annex-i-parties/2026>, European Forest Disturbance Atlas from Viana-Soto and Senf, 2025, ESA CCI Biomass from <https://catalogue.ceda.ac.uk/uuid/6429d1aafe1e43b9b414e4a5a7f8b903/>, Liu23
815 Aboveground Biomass from <https://doi.org/10.5281/zenodo.8154445>, Kowalski26 Aboveground Biomass Loss from <https://doi.org/10.5281/zenodo.20314920>, Ritter26 BK from <https://doi.org/10.5281/zenodo.20203371>, GCP2025 Global inversions from https://meta.icos-cp.eu/objects/6gR_MW23fL2KEI860UX_TGoO, and deadtrees.earth from Mosig et al. 2026a, Mosig et al. 2026b. Code and data products used in this study will be made available upon publication of the manuscript.

820 Author contributions

AB and NL conceptualized the study. Methodology was developed by AB, NL, and LM. Software was developed by NL, LM, CA, JM, and CM. Validation was performed by NL, LM, CA, MVC, MJ, KK, and CM. Formal Analysis was carried out by NL, LM, CA, MVC, and MJ. Investigation was carried out by NL, LM, CA, and MVC. Data Curation was performed by NL, LM, CA, MVC, MJ, MF, SL, AVS, KK, YX, and YY. The original draft was written by NL, AB, LM, MBa, MVC,
825 and MJ, reviewed and edited by all authors. Visualization was performed by LM, NL, and CA. Supervision was carried out by AB, NL, MBa, MBr, PC, EC, RF, TK, PR, and CS. The project was administered by NL, AB, and PC. Funding was acquired by MBa, MJ, MBr, PC, EC, RF, TK, PR, CS, and AB.

Competing interests

The authors declare no competing interests.

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