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For the first three months, we provide the three following scientific highlights, all related to the **importance of forest disturbances in the carbon balance of European and northern forests**. On the one hand, the existence of recurrent disturbances causes a permanent rejuvenation of forests and induces a regrowth sink in the long term. This means that an area with more young forests will take up more carbon than the same area covered by old forests, even though the carbon stock in the young forest area is less than the one of the old forest area. Global models ignoring disturbances thus underestimate carbon sinks in northern forests as shown by (O'Sullivan et al. 2024). At face value, a sudden intensification of climate induced disturbances, such as observed in European forests over the last decade, précipitates carbon losses which are not compensated quickly by regrowth. In that case, forests lose carbon and their sink decreases during a transient period, before increasing again in the long term if disturbances stabilize to a new level after rejuvenation of the forests. The second study by Ritter el. (2024, in revision) uses the CCI Biomass maps and an existing disturbance dataset from Landsat to **attribute the recent decline of the European sink to rising disturbances, with a grim projection that if past trends of disturbances continue, the EU countries will fall short of their GHG neutrality commitment to store 400 MtCO2 per year in the forest sector**. These results rely on the best available reconstruction of disturbances from Landsat so far. In the third study (Viana-Soto & Senf 2024, in review) a **new dataset of forest disturbances is presented, showing for the first time disturbance agents and multiple events in the same location, opening a new window for carbon cycle research** in Europe.

The key role of forest disturbance in reconciling estimates of the northern carbon sink (UEXE)

Forests play a pivotal role in the global carbon cycle, acting as significant carbon sinks. However, discrepancies exist between estimates from dynamic global vegetation models (DGVMs) and atmospheric inversion methods regarding the magnitude and distribution of this sink. A key factor contributing to these discrepancies is the impact of forest disturbances—such as fires, logging, and land-use changes—on carbon fluxes. In this study, we utilise EO data on forest disturbances and biomass to assess how disturbances and regrowth influence carbon emissions and sequestration. By incorporating disturbance-related carbon losses into our calculations, we can reconcile differences between DGVM outputs and inversion-based estimates of the land carbon sink (Figure 1). Our findings reveal that accounting for forest disturbances significantly improves the alignment between model-based and observation-based estimates of the global land carbon sink. This underscores the necessity of including disturbance dynamics in carbon cycle assessments to enhance the accuracy of global carbon budget evaluations. These results have important implications for climate policy and forest management strategies. Recognising the substantial impact of forest disturbances on carbon fluxes is crucial for developing effective mitigation and adaptation measures in response to climate change.
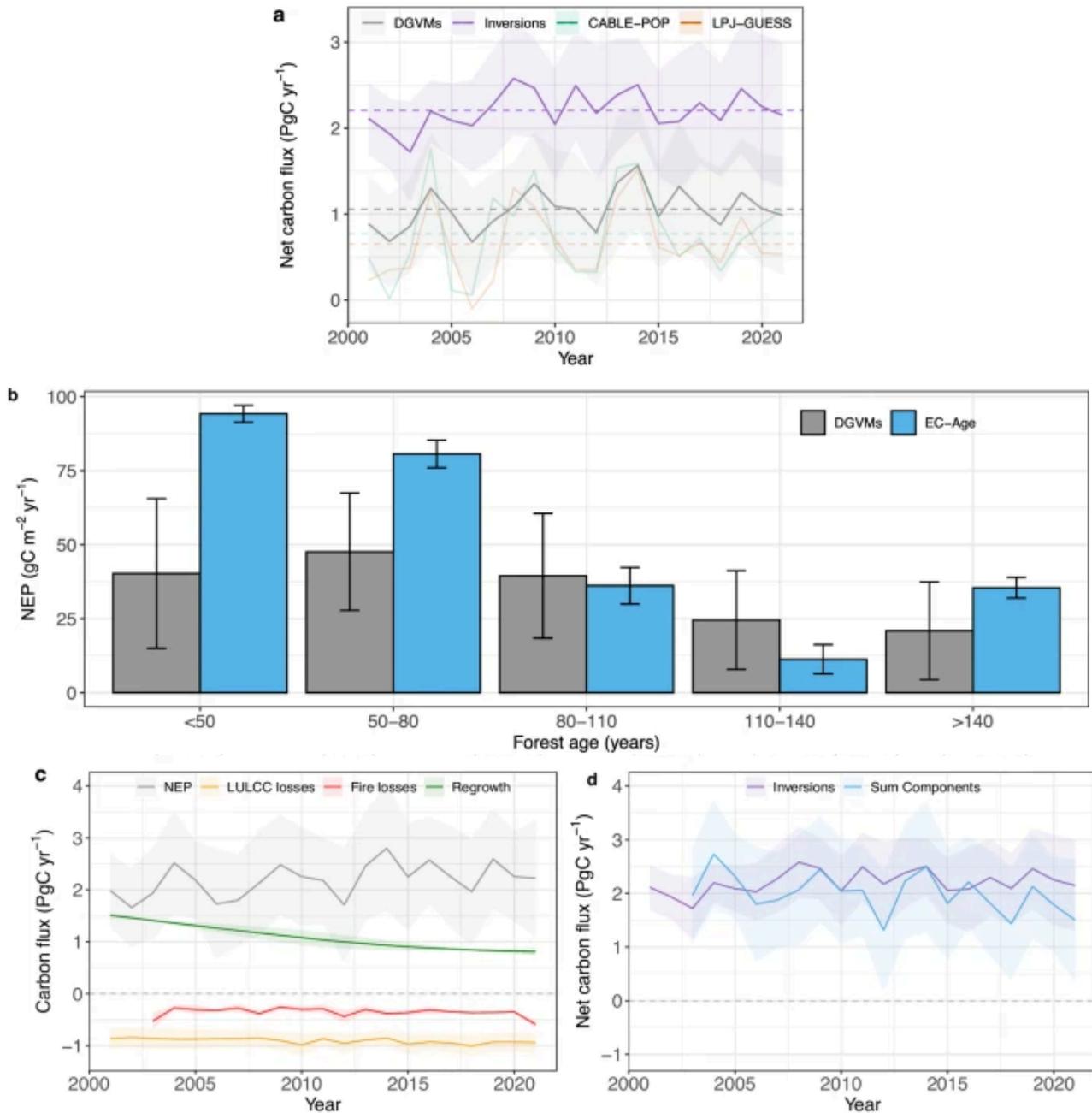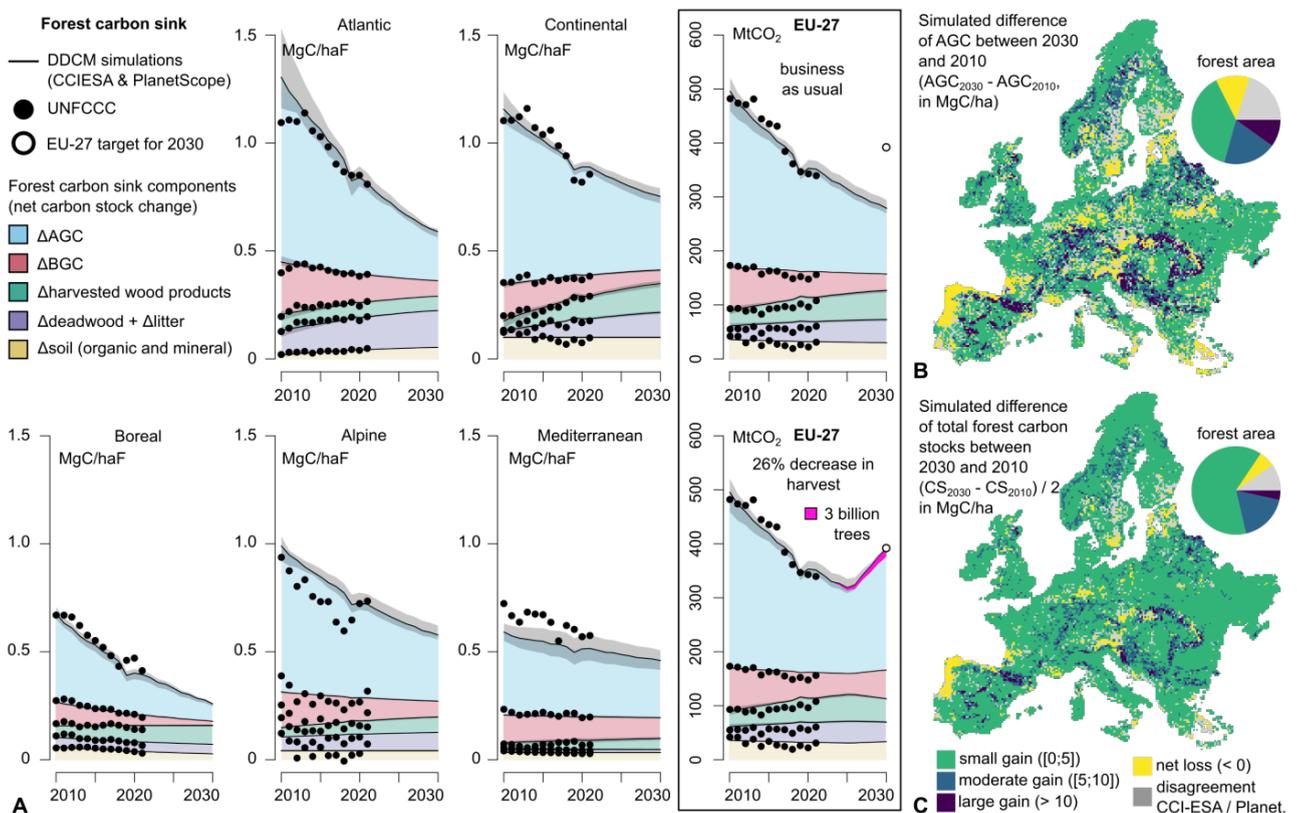
Figure 1 (Adapted from O'Sullivan et al. 2024). Large discrepancy in northern carbon sink between bottom-up and top-down estimates can be explained by disturbance processes. a) Mean net carbon flux for North America, Europe, Russia, and China combined for dynamic global vegetation models (DGVMs) (grey), atmospheric inversions (purple), and the two demography-enabled DGVMs; CABLE-POP (green) and LPJ-GUESS (orange). Positive values are a net uptake by land. Dashed lines show mean values over the study period and shading represents 1σ model spread. b) Net ecosystem production (NEP) estimates from DGVMs (grey) and upscaled eddy covariance data (EC-Age), which has been adjusted for tree age (blue). The NEP fluxes are partitioned into forest age classes. Here we show gridbox mean NEP for the DGVMs, which includes non-forest fluxes. However, in general, forest NEP has a dominant control on gridbox NEP in the regions considered in this study. Annual mean carbon fluxes for c) the four component fluxes; NEP (fire-enabled DGVMs only), Regrowth, LULCC losses, and fire losses (positive values mean flux from atmosphere to land),

and d) the sum of the four components (blue), and the net land sink as estimated by the inversions (purple). Shading in all panels represents 1σ uncertainty across the models or inversion datasets, respectively.

An alarming decline of the European forest carbon sink (LSCE/CUPH)

This study is currently under review in *Science* (as of November 2024). We developed a spatially explicit model at 18 km resolution that estimates the net carbon sink of forests based on five components: net carbon stock changes in aboveground biomass, belowground biomass, harvested wood products, soils, and finally deadwood (and litter). The model input is the CCI-ESA biomass (2017-2021, v5) and a disturbance map that is Landsat based (1985-2020). This model has been constrained to align with the UNFCCC data (33 country reports) across the recent historical period (2010-2021), and it projects the European carbon sink from 2022 to 2030. The following processes have been implemented in this model at 18 km: forest growth (local recovery curves), long-term trends in disturbances (anthropogenic & natural disturbances, Landsat data) and carbon transfer from the different sink components. Our results show that the carbon sink of the forests in the EU-27 is decreasing at an alarming rate, and by 2030 it will be 30% lower than previously expected by the EU-27 (Figure 2). By partitioning harvests and natural disturbances at 18 km based on a constant ratio, we assessed that a reduction of 26% in the harvest rates from 2025 to 2030 will be necessary for the EU-27 to reach their 2030 target (in addition to their pledge to plant 3 billion trees by 2030). Additionally, because our model is spatially explicit, we demonstrated that 12% of European forests are consistently losing above ground biomass each year. These forests are mainly located in Portugal, Slovenia, Southern France, Austria, Czechia, Estonia, Latvia, Northern Ukraine, Northern Germany, the Eastern Alps, and large parts of Scandinavia.

Figure. 2. Spatial and temporal changes in the carbon sink of European forests. (A) Forest sink for five biogeographical regions and the EU-27 under two management scenarios: business as usual and a 26% harvest reduction with 3 billion trees planted by 2030 (their total forest sink is in pink). The EU-27 forest sink target is estimated at 392 MtCO$_2$eq (average for 2016-2018). The black-shaded area shows variability from using PlanetScope or CCI-ESA maps with country- or region-specific parameterization. (B) Simulated difference in AGC between 2030 and 2010. (C) Simulated difference in total forest carbon stocks (AGC, BGC, HWP, soils, deadwood, and litter) between 2030 and 2010 (values are divided by two to match the legend). Inconsistencies between CCI-ESA and PlanetScope are shown in gray (when one predicts a carbon source and the other a carbon sink).

New map of forest disturbances over Europe (TUM)

The newly developed European Forest Disturbance Atlas (EFDA, v2.1.1) (Viana-Soto & Senf 2024, *in review*), provides spatially explicit information on forest disturbances since 1985 at 30-m resolution, constituting the longest remote sensing based disturbance product available at continental scale today. Based on a consistent Landsat data cube, a classification-based approach was developed to detect forest disturbances annually (1985-2023). The dataset goes beyond existing products in several important ways. Compared to previous assessments, we reduced omission errors considerably (22.5%) while maintaining low commission errors (17.3%). Second, annual disturbance mapping enables to capture multiple disturbance events, providing direct information on disturbance frequencies (e.g. recurrent fires or multiple harvest in short rotation plantation systems). Further, we identified the most likely agent of disturbances (bark beetle, withrow, fire and harvest) for the annual disturbance maps (Seidl & Senf, 2024). Based on the annual estimates, we quantified a total forest disturbed area of 439,000 km2 (22% of the total forest area) that increases to 610,000 km2 when accounting for multiple disturbance events. Planned disturbances caused by human land use (harvest) caused 79.2% of the total disturbed area and the natural agents were responsible for 20.8% of the disturbances found (12% from wind and bark beetle outbreaks and 8.8% from wildfires).

Combining disturbance information from the EFDA with recent state-of-the-art biomass products from GEDI (Dubayah et al. 2022), Planet (Liu et al. 2023), and ESA CCI (Santoro & Cartus, 2024) enabled us to empirically quantify the aboveground biomass lost due to forest disturbances across Europe. In a space-for-time substitution approach, we estimated disturbance severity as the difference between pre- and post-disturbance AGBD and quantified total biomass loss from 1985 to 2023. Disturbance severity from the three products agreed well, with the best agreement between GEDI- and Planet-based estimates. Preliminary results showed that the total biomass loss during forest disturbances amounted to 4.5-6.6 Pg AGB (or 2.25-3.3 Pg C) indicating substantial impacts of forest disturbances on the European carbon sink. A manuscript presenting this work is currently in preparation for submission.
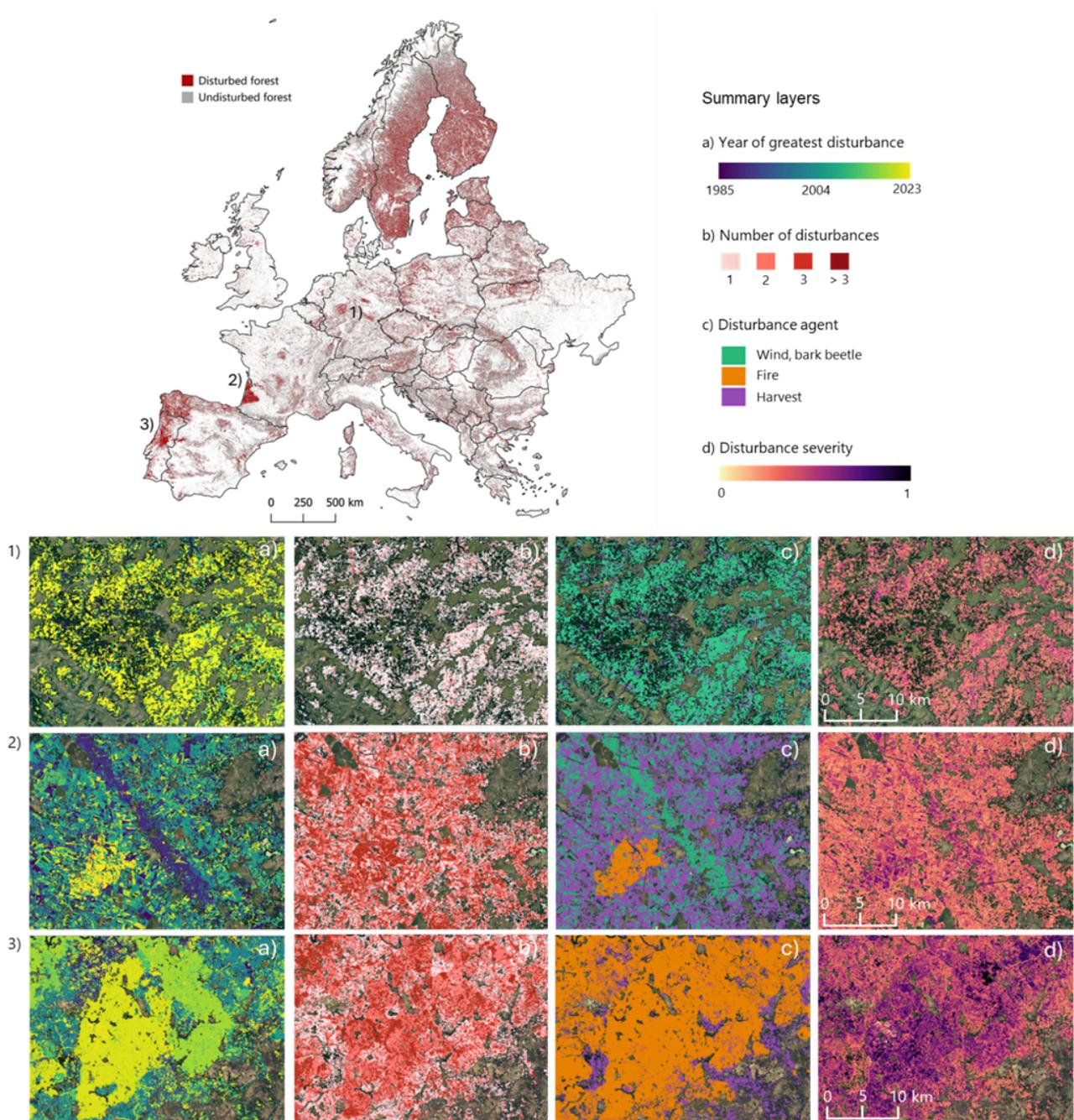
Figure 3. Forest disturbances in selected locations in European forests from the new map produced by TUM as part of CS-RECCAP2 (1985-2023). Details show (a) bark beetle outbreaks in central Germany; (b) a combination of a windstorm event and a recent fire in a managed forest plantation in Gascony (France); and (c) recurrent fire disturbances in central Portugal. From Viana-Soto and Senf, https://doi.org/10.5194/essd-2024-361, in review, 2024.

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