



Supplement of

Natural disturbances from bark beetle outbreaks and windthrow increasingly affect Europe's most mature and carbon-rich forests

Simon Besnard et al.

Correspondence to: Simon Besnard (simon.besnard@gfz.de)

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1 S1. Additional results

2 **Table S1: Total disturbed area by disturbance type, age class, and period.** Total forest area
 3 disturbed (in million hectares, Mha) by harvest and natural disturbances across Europe,
 4 disaggregated by age class (1-60 and >60 years old) and period. The periods 2011-2016 and 2017-
 5 2023 reflect early and recent disturbance phases, respectively. Only 100 m pixels with at least 30%
 6 forest cover were retained, and among those, only pixels where at least 50% of the forested area
 7 was disturbed by a specific agent were considered.

	2011-2016		2017-2023	
	1-60 years	>60 years	1-60 years	>60 years
Natural disturbance	0.35	0.38	0.56	1.06
Harvest	2.57	2.36	2.91	3.84

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9 **Table S2: Total disturbed area by disturbance type, genus group, and period.** Total forest area
 10 disturbed (in million hectares, Mha) by harvest and natural disturbances across Europe,
 11 disaggregated by genus group and period. Genus groups include Spruce, Other needleleaf (e.g.,
 12 Pinus, Larix, and other needleleaf), and Broadleaf (e.g., Fagus, Quercus, and other broadleaf). The
 13 periods 2011-2016 and 2017-2023 reflect early and recent disturbance phases, respectively. Only
 14 100 m pixels with at least 30% forest cover were retained, and among those, only pixels where at
 15 least 50% of the forested area was disturbed by a specific agent were considered.

	2011-2016			2017-2023		
	Spruce	Other needleleaf	Broadleaf	Spruce	Other needleleaf	Broadleaf
Natural disturbance	0.07	0.26	0.30	0.46	0.53	0.46
Harvest	0.28	1.85	2.2	0.90	2.8	2.4

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Table S3. Frequency of stand-replacing disturbance events per pixel across European forests (2011-2023). Fractions are expressed as a percentage of pixels disturbed by the respective agent at least once during 2011-2023. A stand-replacing event is defined as a disturbance fraction $\geq 50\%$ of the forested area within a 100 m pixel in a given year.

Disturbance type	Total disturbed pixels	Disturbed exactly once	Disturbed 2+ times	Repeat fraction (%)
Natural disturbance	5,381,654	5,225,132 (97.09%)	156,522	2.91%
Harvest	30,322,484	27,946,895 (92.17%)	2,375,589	7.83%

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Table S4. Number of 100 km hexagonal grid cells retained per disturbance type and analysis period.

Disturbance type	Period	Hexagons retained (n)
Natural disturbance	2011-2016	683
Natural disturbance	2017-2023	753
Harvest	2011-2016	1093
Harvest	2017-2023	1102

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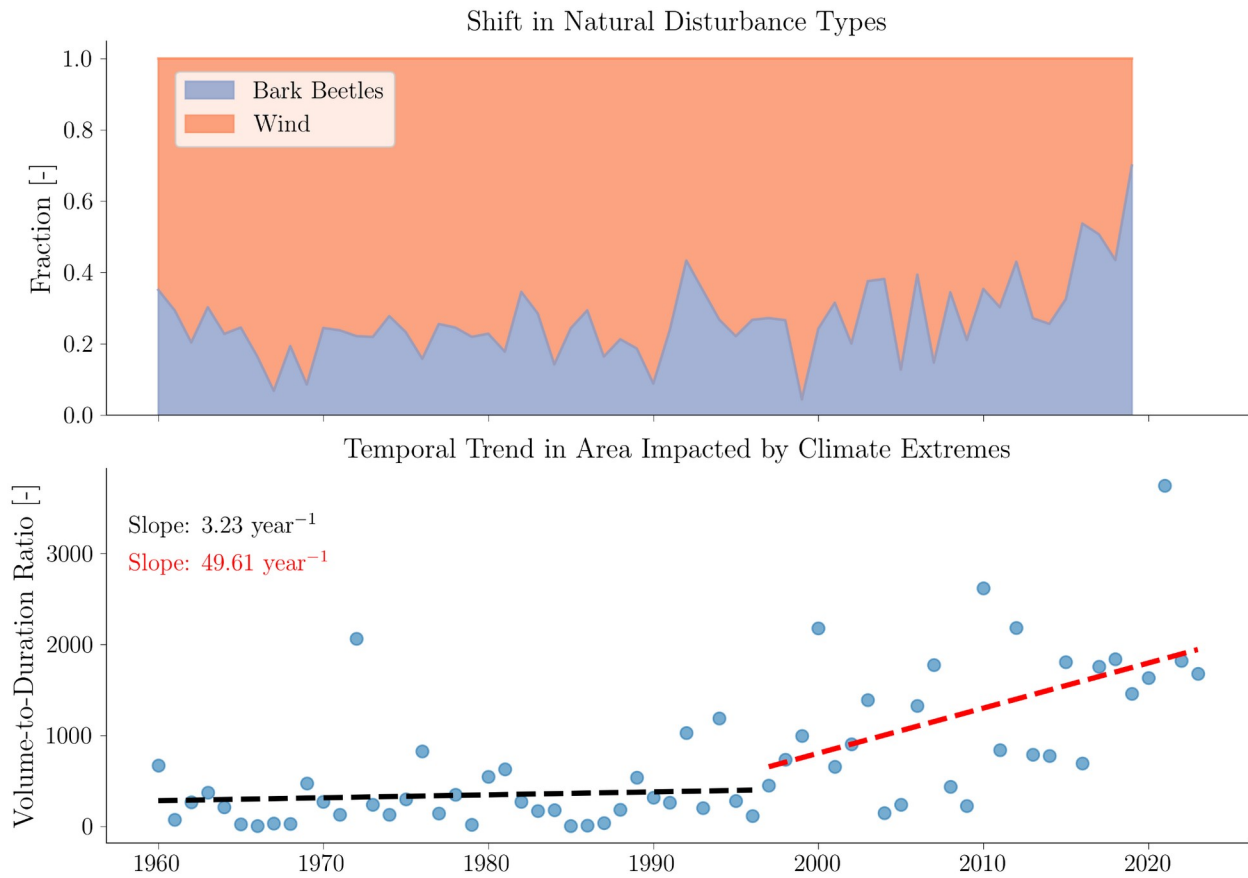
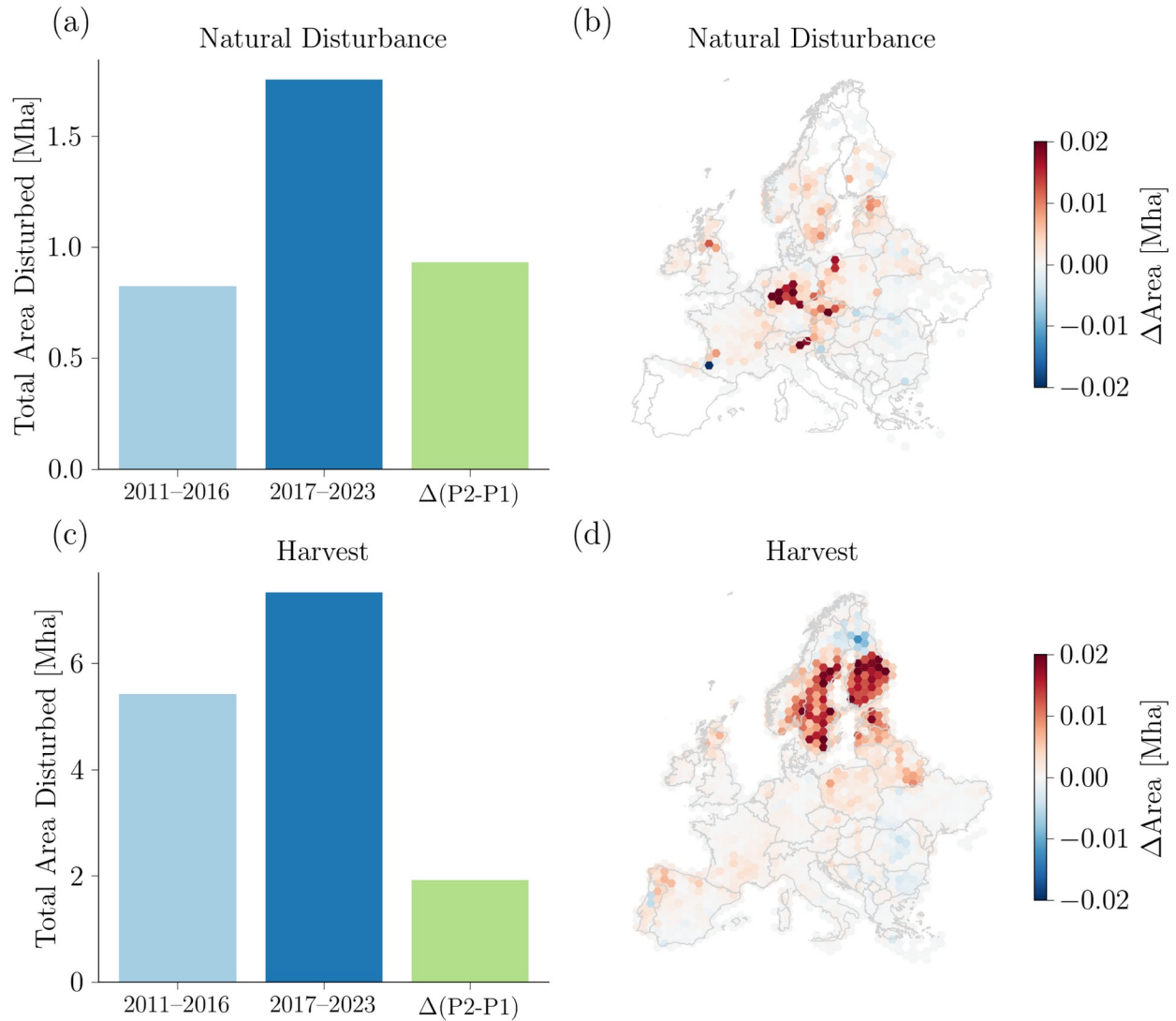
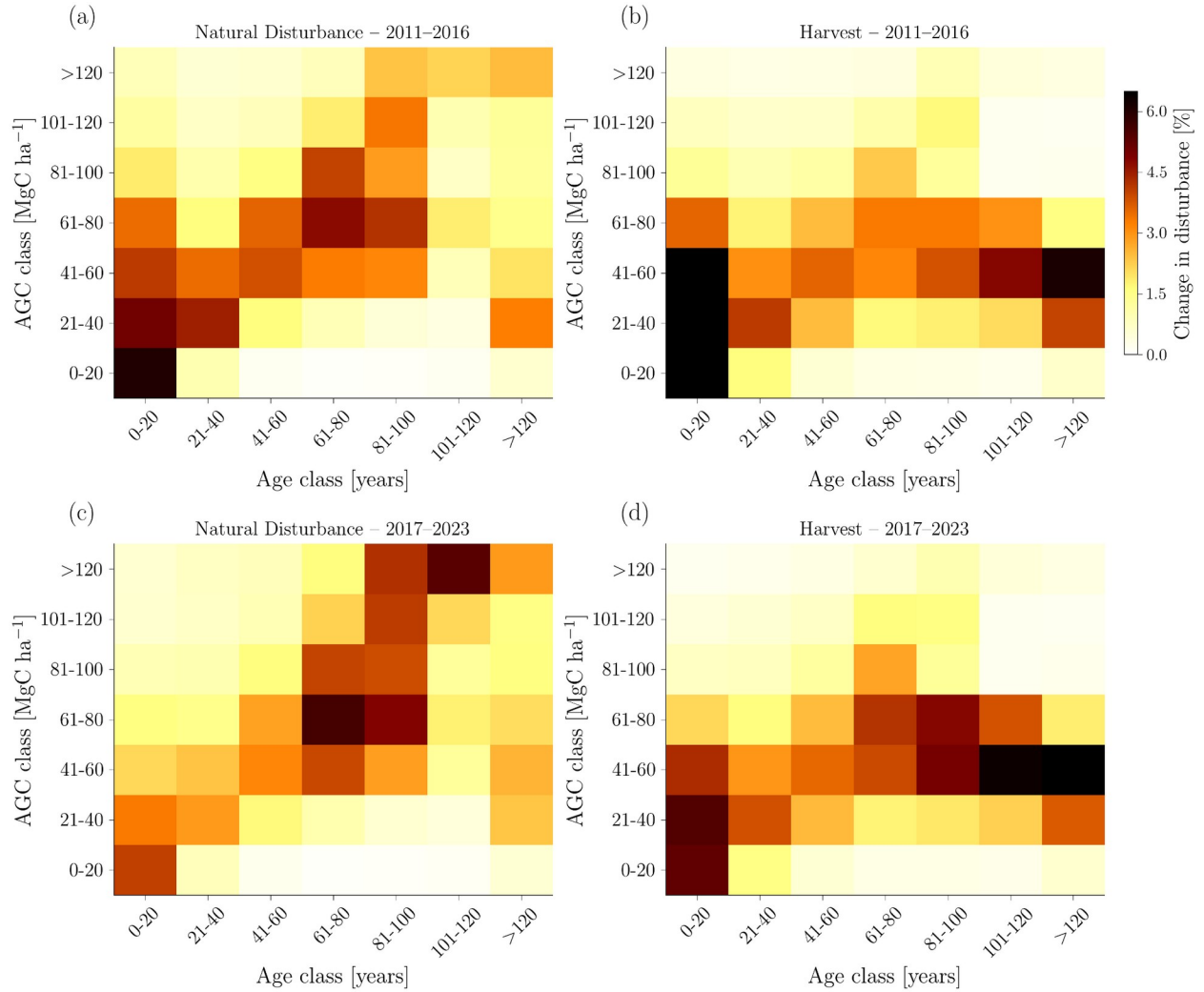


Figure S1: Shifting disturbance agents and climate extremes in European forests. (a) Relative contribution of wind and bark beetle damage to total natural disturbance volume in European forests from 1960 to 2023, based on national inventory records⁶. (b) Total annual area impacted by compound climate extremes (heat and drought) across Europe from 1960 to 2023 derived from the Dheed database⁸.



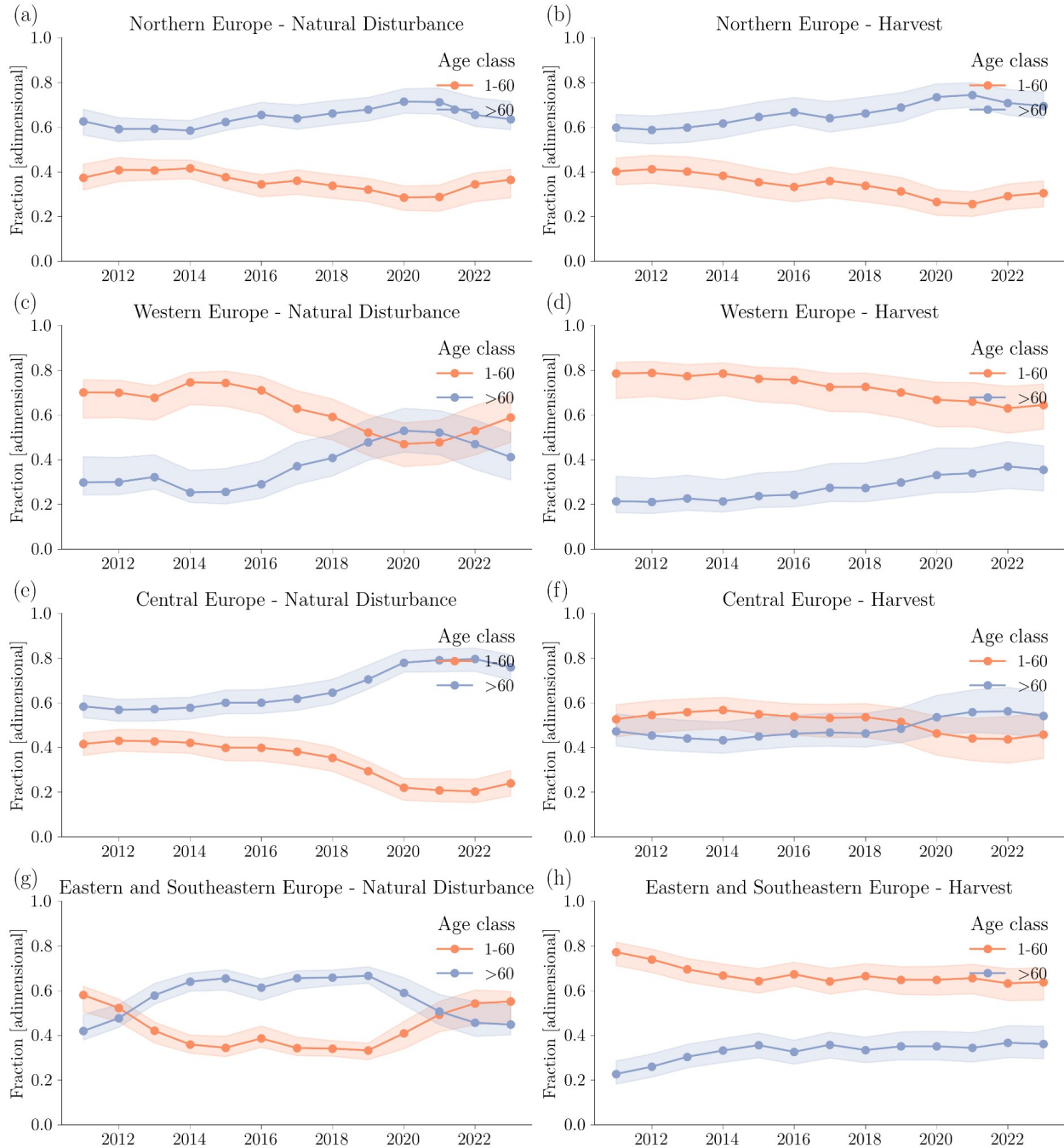
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38 **Figure S2: Changes in forest disturbance area across Europe between 2011-2016 and**
 39 **2017-2023.** (a) Total area affected by natural disturbances (wind and bark beetle) during early
 40 (2011-2016) and late (2017-2023) periods, along with the absolute change in disturbed area. (b)
 41 Spatial distribution of the shift in natural disturbance area across 100km diameter hexagons.
 42 Positive values indicate an expansion of natural disturbances, particularly in Northern and Central
 43 Europe. (c) Total area affected by harvest during the early and late periods, and the corresponding
 44 absolute change. (d) Spatial distribution of the change in harvested area. Only 100 m pixels with at
 45 least 30% forest cover were retained, and among those, only pixels where at least 50% of the
 46 forested area was disturbed by a specific agent in a given year were considered. Hexagons
 47 represent aggregated changes in the disturbed area expressed in Mha. Each hexagon has a diameter
 48 of 100 km.



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50 **Figure S3: Structural profile of disturbed forests by disturbance type.** Fraction of disturbed
 51 forests by aboveground carbon (AGC) class (MgC ha⁻¹) and age class (years) for natural
 52 disturbances and harvest across Europe (2011-2016). (c-d) Same as (a-b), but for 2017-2023. Only
 53 100m pixels with at least 30% forest cover were retained, and among those, only pixels where at
 54 least 50% of the forested area was disturbed by a specific agent in a given year were considered.

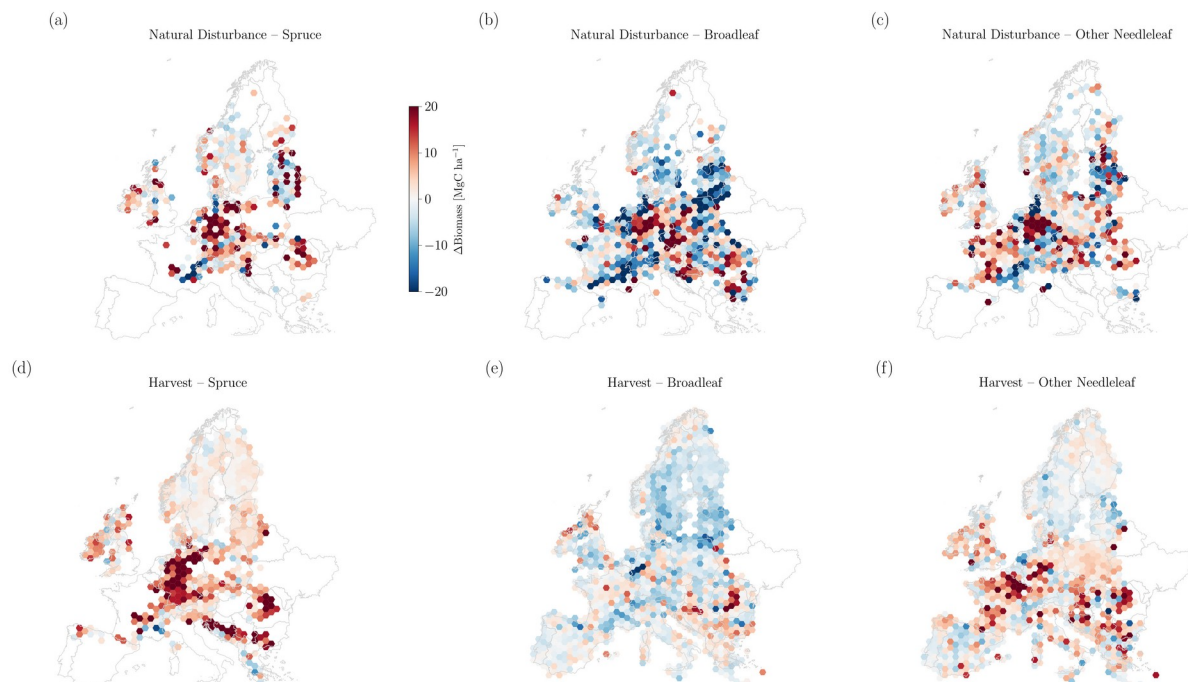


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56 **Figure S4: Temporal trends in the fraction of forest disturbances across age classes for**
 57 **harvest and natural disturbances (2011-2023), shown at the regional scale.** Panels display the
 58 annual fraction of disturbed pixels by age class for each disturbance type across four regions:
 59 Northern Europe (Finland, Sweden, Norway, Denmark, Estonia, Latvia, Lithuania), Central
 60 Europe (Germany, Switzerland, Austria, Czechia, Poland), Western Europe (United Kingdom,
 61 Ireland, France, Belgium, Netherlands, Luxembourg), and Eastern & Southeastern Europe
 62 (Hungary, Slovakia, Slovenia, Ukraine, Turkey, Croatia, Bosnia and Herzegovina, Serbia,
 63 Montenegro, Kosovo, Albania, North Macedonia, Moldova, Bulgaria, Romania). Shaded ribbons
 64 represent the 95% quantile range across the 20-member forest age ensemble, and lines show the

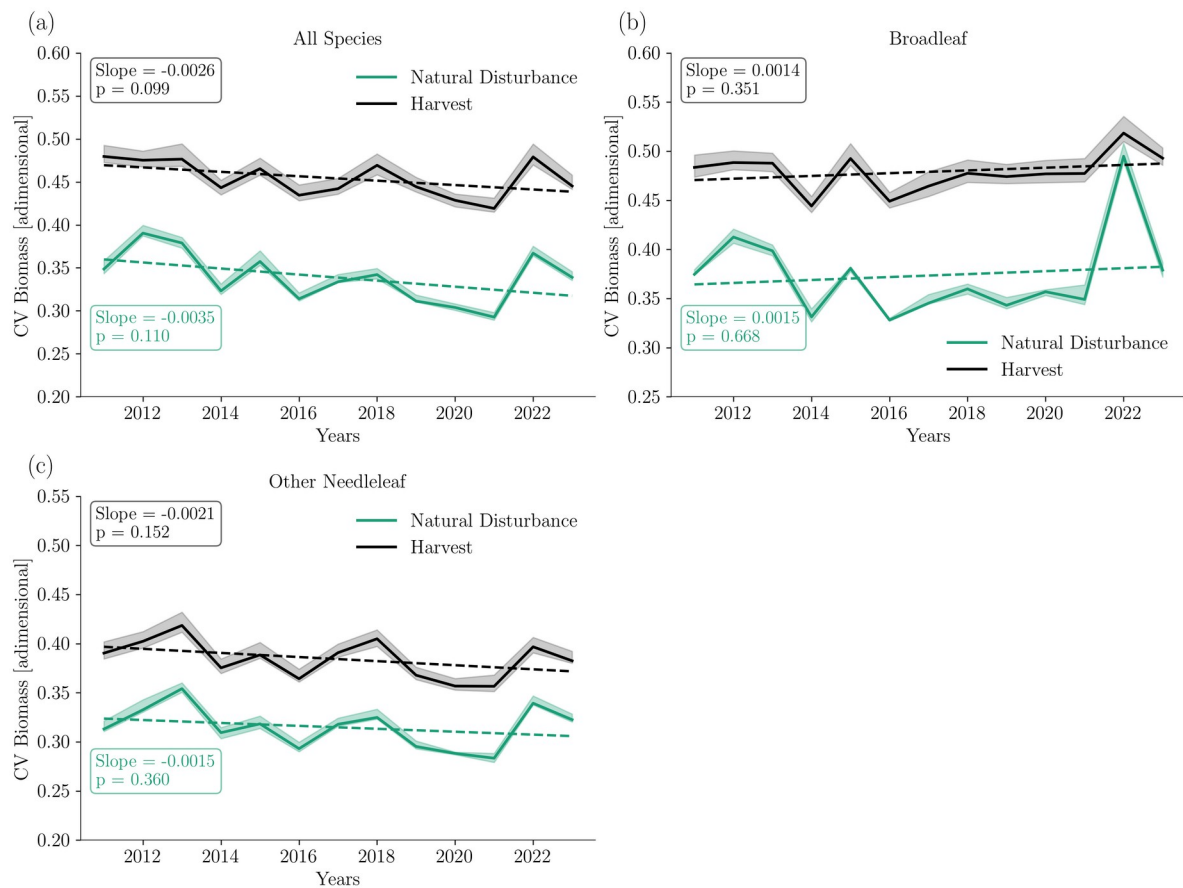
65 median trajectory. Only 100 m pixels with at least 30% forest cover were retained, and among
 66 those, only pixels where at least 50% of the forested area was disturbed by a specific agent in a
 67 given year were considered.

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70 **Figure S5: Changes in biomass loss by genus and disturbance type.** Changes in average
 71 biomass loss ($\Delta\text{biomass}$ in MgC ha^{-1}) between 2011-2016 and 2017-2023 across Europe, separated
 72 by disturbance type (natural disturbances vs. harvest) and dominant genus (spruce, broadleaf, other
 73 needleleaf). Each hexagon represents the spatially aggregated difference in biomass of affected
 74 forest areas between the two periods. Negative values (blue) indicate a relative decrease in biomass
 75 between the two periods, while positive values (red) reflect an increase. Only 100 m pixels with at
 76 least 30% forest cover were retained, and among those, only pixels where at least 50% of the
 77 forested area was disturbed by a specific agent in a given year were considered. Each hexagon has a
 78 diameter of 100 km.

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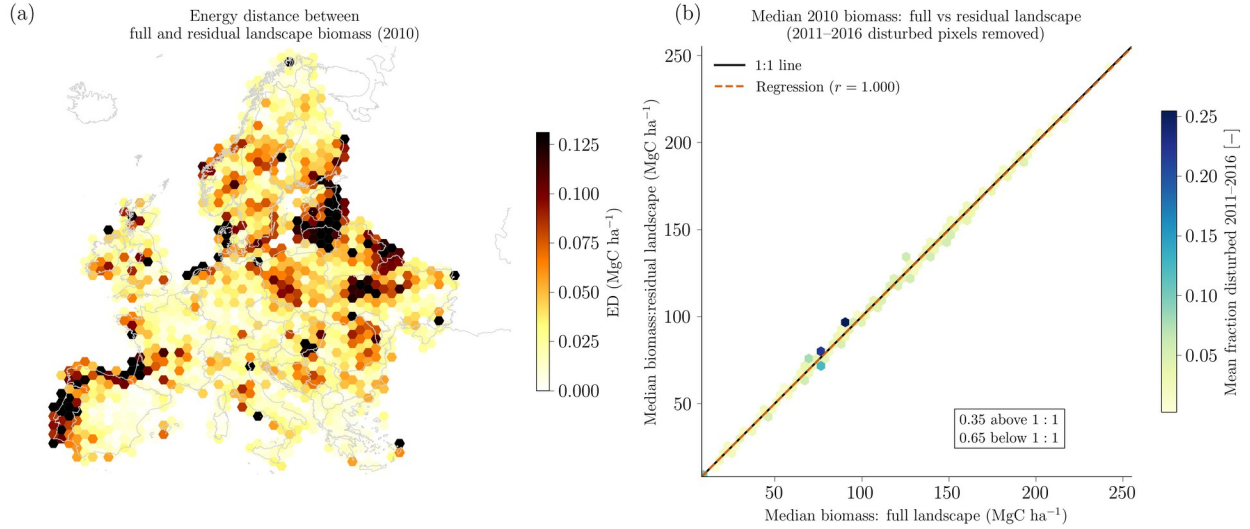
81 **Figure S6: Temporal trends in structural heterogeneity (CV of biomass) by genus type.**
82 Coefficient of variation (CV) in pre-disturbance biomass (2010 baseline) for stands affected by
83 natural disturbances (green) and harvest (black) between 2011 and 2023, partitioned by genus
84 group: (a) all species, (b) broadleaf, and (c) other needleleaf. Lines represent the annual median CV
85 across hexagons; shaded ribbons indicate the 5th to 95th percentile range across biomass members.

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90 **Figure S7:** Persistence of the background landscape biomass distribution after removing 2011-
 91 2016 disturbed pixels. (a) Spatial distribution of energy distance (ED) between the biomass
 92 distribution of the full forested landscape and the residual landscape obtained by removing pixels
 93 disturbed by any agent during 2011-2016, computed for each 100 km hexagon using fixed 2010
 94 ESA CCI v6.0 biomass estimates. Low ED values indicate that the early disturbance wave did not
 95 meaningfully alter the biomass composition of the remaining host landscape. (b) Scatter plot of
 96 median 2010 biomass in the full landscape (x-axis) versus the residual landscape (y-axis) per
 97 hexagon, coloured by the mean fraction of forested area disturbed during 2011-2016. The black
 98 line shows the 1:1 reference; the orange dashed line shows the ordinary least-squares regression (r
 99 $= 1.000$). Only hexagons with at least 50 valid forested pixels are shown.