Response to Referee #1

We thank Referee #1 for their constructive review. Their positive assessment and suggestions have helped us strengthen the manuscript. Below, we address the referee's feedback. Reviewer comments are shown in *italics*, followed by our responses. Line numbers refer to the revised manuscript.

General Comments

Comment 1: *A certain dissatisfaction may arise from the lack of an attempt to explain in more detail the reasons for the change in the characteristics of the stands affected… Was it the result of a change in the disturbance regimes and their vital parameters? Or the result of a change in approach from the forest management side?*

Response: We thank the reviewer for raising this point. We agree that attributing the observed structural shift requires discussion of both changes in disturbance regimes and management responses. We have expanded the relevant section of the Discussion (Section 4) to address this more explicitly.

Our results suggest that the shift is primarily driven by climate-amplified bark beetle dynamics rather than a systematic change in forest management. Several lines of evidence support this: (1) the structural shift is concentrated geographically in Central European spruce forests, coinciding temporally with the 2018-2022 compound drought events; (2) harvest patterns show structural stability between periods (median ED: 0.9 years; stable biomass distributions; <2% change in projected exposure across scenarios), in contrast to the pronounced shift in natural disturbances; and (3) the near-identical temporal CV trajectories of harvested and naturally disturbed spruce stands (Pearson's r = 0.75) are most consistent with salvage logging operations following beetle outbreaks, rather than independent management shifts driving the pattern.

That said, we acknowledge that management choices, including decades of homogeneous spruce planting and, more recently, salvage logging, have helped maintain the structural conditions that amplify susceptibility. We have added the following clarifying passage to Section 4 [L 531-541]:

"*The observed structural shift appears to be primarily driven by climate-amplified bark beetle outbreaks, rather than a systematic change in forest management. Harvest patterns remained structurally similar across periods, with only minor shifts in age and biomass distributions (median ED: 0.9 years). The strong spatial and temporal correspondence between the structural shift in natural disturbances and compound drought events since 2018 points to climate forcing as the* *primary driver. Nevertheless, longstanding management legacies, particularly decades of favouring monospecific spruce planting and increasing growing stocks, have maintained structural conditions that predispose these landscapes to continued outbreak amplification. It is worth noting that the majority of bark beetle-affected stands are subsequently salvage-logged, which explains the tight coupling between natural disturbance and harvest trajectories observed in our data (Pearson's r = 0.75). This coupling reflects a management response to disturbance rather than a driver of structural vulnerability, and is consistent with the structural stability we observe in harvest-related biomass distributions across periods."*

Comment 2: *It would also have been possible to discuss in more detail the consequences from the point of view of the optimal strategy for using forests for climate mitigation. For example, the recently promoted concept of proforestation. Does such a strategy make much sense, given the results of this work?*

Response: We thank the reviewer for this suggestion. The proforestation concept, i.e., withdrawing managed stands from utilisation and allowing them to age under strict protection, raises a question in light of our findings: if older, high-biomass stands are disproportionately vulnerable to climate-driven disturbances, does protecting and ageing stands increase their exposure?

We have added a paragraph in the Discussion to address this directly [L 594-606]:

"These findings have direct implications for proposed strategies to enhance forest carbon storage. For instance, our results raise an important caveat regarding proforestation, the strategy of withdrawing managed stands from harvest and allowing them to age naturally to accumulate carbon. While proforestation can substantially increase carbon stocks in the medium term (Moomaw et al., 2019), our findings reveal a structural vulnerability that can partially counteract its expected carbon benefits: the structural characteristics that proforestation promotes, namely advanced age and greater biomass in early successional phases, are precisely those now associated with disproportionate disturbance susceptibility in Central Europe's spruce-dominated forests. This does not invalidate proforestation as a strategy for increasing forest carbon storage, though. In broadleaf and structurally diverse ecosystems, for instance, the susceptibility we document is substantially lower. However, our findings underscore that the effectiveness of proforestation strategies is strongly species- and region-dependent. In spruce-dominated landscapes, proforestation without concurrent efforts to increase structural and compositional diversity may not fully realise its expected carbon benefits, given the elevated susceptibility to disturbance of ageing, high-biomass stands documented here. Conversely, in broadleaf-dominated or structurally complex

systems with lower susceptibility to disturbance, proforestation remains a promising complement to active management strategies."

Minor Comments

L. 22: Add a space after "area": Corrected.

L. 27: "expose" or "release into the atmosphere"?: We thank the reviewer for this suggestion. After consideration, we have retained "expose" rather than replacing it with "release into the atmosphere." Disturbances transfer carbon from live biomass pools to dead organic matter, from which only a fraction may ultimately reach the atmosphere. Using "release into the atmosphere" would “blur” the distinction between disturbance-related carbon exposure and actual atmospheric emissions, overstating the directness of the flux. The term "expose" is used deliberately and consistently throughout the manuscript to describe carbon stocks that are rendered vulnerable to long-term loss.

L. 38: "climate-sensitive" to "climate-induced" or "climate-driven?": We thank the reviewer for this suggestion. After consideration, we have retained "climate-sensitive" throughout the manuscript. The term is well-established in the disturbance ecology literature and accurately conveys that the frequency and severity of these disturbances are modulated by climate variability, without implying a single-factor direct cause.

L. 53-54: rephrase to avoid repetition of "continue": Revised to: *"These trends are likely to persist as climate change progresses."*

L. 55-56: rephrase storm names with dates: Revised to: *"such as windstorms Vivian and Wiebke (in 1990), Lothar and Martin (in 1999), and Klaus (in 2009)."*

L. 64: "driven primarily by expanding spatial footprints", not clear: Revised to: *"…whether rising disturbance rates reflect a simple increase in the total area affected or a systematic shift toward structurally vulnerable forest cohorts."*

L. 72: "with spatially explicit data on forest age…": Revised as suggested.

L. 85-87: How were 30 m pixels aggregated to 100 m?: We have clarified: *"The reprojected 30 m binary disturbance maps were aggregated to 100 m resolution using average resampling. Within each 100 m pixel (~10,000 m²), we computed the fraction of overlapping 30 m sub-pixels (~9 m² each) classified as disturbed, yielding a continuous disturbance fraction rather than a binary indicator."*

L. 95 (1st): Is "disturbance" appropriate for planned harvesting?: We appreciate this terminological concern. We use "disturbance" in its ecological sense (i.e., loss of the top tree canopy/gap creation), which, in managed systems, encompasses both natural tree death and human tree removal. We explicitly distinguish "natural disturbances" from "harvest" throughout the manuscript and have added a clarifying sentence at first use:

"Fire and mixed disturbances were excluded from this study because our research question specifically concerns the structural consequences of the documented shift from wind-dominated to bark beetle-dominated disturbance regimes. Such a shift unfolds through biotic and abiotic mechanisms distinct from fire dynamics and is geographically concentrated in temperate and boreal forest systems. We focus on two disturbance categories: harvest, representing planned timber removal for wood production or silvicultural reasons, and wind and bark beetle disturbances, representing unplanned canopy loss driven by natural agents but often followed by human management (i.e. salvage logging). We use the term disturbance broadly throughout to encompass both categories, as both human timber removal and natural canopy loss are disturbances with ecological consequences, while maintaining a consistent distinction between natural disturbances and harvest in all analyses and figures." [L 94-102]

L. 95 (2nd): "products" vs. "data": Changed to "forest age and biomass data".

L. 114: Is "20 members" clear enough?: Revised to: *"a 20-member ensemble of forest age maps (GAMIv3.0)"* to clarify what "members" refers to.

L. 116: "forest fraction at 100 m pixel": Revised to: *"forest fraction within each 100 m pixel"*.

L. 124: Repetition of L. 114: Sentence removed; reference to the ensemble is now made by cross-reference only.

L. 128: "indicated"?: Revised to "indicated" as suggested.

L. 134: "independent copies" not clear: Revised to: *"where X' and Y' are additional independent random samples drawn from the same distributions as X and Y, respectively, used to normalise the expected distance."*

L. 143: "member ensembles" unclear: Revised to: *"we summarised uncertainty across all 20 realisations of the forest age ensemble."*

L. 156: "20 biomass members" unclear: Revised to: *"the 20 independent realisations of the ESA CCI biomass ensemble."*

L. 164-167: Repetition: Sentence removed; readers are directed to Section 2.3 for methodological details.

L. 168: "each member of the 20-realisation biomass ensemble" unclear: Revised consistently with our clarification at L. 156.

L. 179-181: Repetition: Removed; cross-reference added to Section 2.3.

L. 232-234: Repetition + belongs in Methods + "higher values"?: The sentence has been moved to the Methods section. "Higher values" have been clarified as: *"higher energy distance values indicate that the age distributions of disturbed forests in the two periods are more dissimilar."*

L. 348: "recent biomass loss scenario": Revised to: *"the recent biomass loss scenario"*.

Fig. 5: "Recent - Early" instead of "Late - Early"?: Corrected to "Recent - Early" for consistency with the terminology used throughout the text.

L. 428-430: Spruce decline even in diverse stands (Brzeziecki et al. 2020): We thank the reviewer for pointing to this study. We have added the following sentence: *"While structural and compositional diversity generally reduces susceptibility, long-term studies demonstrate that spruce decline can also occur in age- and species-diverse stands, suggesting that diversity increases but does not ensure resistance, and that site-level climate stress may outweigh the protective influence of structural diversity under prolonged drought conditions (Brzeziecki et al. (2020))."* [L 547-550]The reference has been added to the bibliography.

L. 443-444: "homogenising effects of salvage logging" unclear: We have clarified: *"Salvage logging following natural disturbances often leads to the establishment of new, even-aged monospecific stands on cleared sites (Sommerfeld et al., 2021), thereby preserving the structural homogeneity associated with high bark beetle susceptibility, even when individual gap creation temporarily increases local heterogeneity."* [L 563-566]

L. 449: High biomass also accumulates in natural beech forests (Schütz 2002): We agree that this is an important nuance. We have revised the sentence to: *"Biomass accumulation occurs across multiple forest types, including naturally developing beech-dominated forests in Europe (Schütz, 2002). In the context of our study, however, biomass accumulation most strongly amplifies disturbance susceptibility in even-aged spruce monocultures, where it combines with structural homogeneity and elevated drought sensitivity."* [L 572-575]The reference has been added.

L. 500-501: "reducing susceptibility in high-risk stands", what does this mean specifically?: We have expanded this to: *"Several measures like increasing species and structural diversity have been proposed to reduce susceptibility in high-risk stands. Targeted interventions promote mixed-species composition, structural thinning reduces stem density and host connectivity, while adopting uneven-aged management in climatically marginal spruce-dominated landscapes and refining harvest and post-disturbance management practices in disturbance-prone regions will further reduce susceptibility (Migliavacca et al., 2025)"* [L 656-659]

Response to Referee #2

We thank Referee #2 for their detailed and constructive review. Their comments have helped us strengthen both the clarity and the framing of the manuscript. We address each point below. Reviewer comments are shown in *italics*, followed by our responses. Line numbers refer to the revised manuscript.

General Comments

Comment 1: *The omission of forest fires is not justified in the manuscript. Fire and droughts are major disturbances in many parts of Europe, particularly in Mediterranean forests, and excluding them effectively removes Mediterranean forests from the analysis… the main messages of the manuscript appear somewhat overstated.*

Response: We appreciate the reviewer's criticism and agree that the study's scope needs more explicit framing. The exclusion of fire is an intended scientific choice driven by our research question/hypothesis, rather than a data limitation. The European Forest Disturbance Atlas v2.1.1 (Viana-Soto and Senf, 2025) provides reliable disturbance mapping across the full range of European forest systems. We excluded fire because our central research question concerns the structural consequences of the documented shift from wind-dominated to bark beetle-dominated disturbance regimes. Including fire would mix ecologically distinct disturbance processes and hide the specific demographic and carbon dynamics we aim to characterise. As such, this decision, which we agree should be stated more explicitly, does not reflect a limitation of the underlying data.

Our spatial coverage is thus not arbitrarily restricted but is determined by where bark beetle and windthrow disturbances actually occur, primarily in Central, Northern, and Eastern Europe. Mediterranean forests are underrepresented not because of a design flaw but because the disturbance agents we study are naturally concentrated outside that region.

That said, we fully agree that the title, abstract, and discussion should more precisely reflect this scope. We have made the following revisions:

- The title has been revised to: *"Natural disturbances from bark beetle outbreaks and windthrow increasingly affect Europe's most mature and carbon-rich forests."*
- The abstract now explicitly states: *"Focusing on bark beetle outbreaks and windthrow, the dominant natural disturbance agents in temperate and boreal European forests, we combine three decades of satellite-derived disturbance maps…"*

- The following sentence has been added to the Methods [L. 94-102]: *"Fire and mixed disturbances were excluded from this study because our research question specifically concerns the structural consequences of the documented shift from wind-dominated to bark beetle-dominated disturbance regimes. Such a shift unfolds through biotic and abiotic mechanisms distinct from fire dynamics and is geographically concentrated in temperate and boreal forest systems. We focus on two disturbance categories: harvest, representing planned timber removal for wood production or silvicultural reasons, and wind and bark beetle disturbances, representing unplanned canopy loss driven by natural agents but often followed by human management (i.e. salvage logging). We use the term disturbance broadly throughout to encompass both categories, as both human timber removal and natural canopy loss are disturbances with ecological consequences, while maintaining a consistent distinction between natural disturbances and harvest in all analyses and figures."*

Comment 2: *The analysis appears to emphasise spruce-specific patterns rather than providing a balanced comparison across taxa. We suggest either broadening the analysis or adjusting the wording to reflect the actual scope.*

Response: We agree that the prominence of spruce in our results requires explicit justification. The emphasis on spruce is not an a priori analytical choice but emerges directly from the data: spruce-dominated forests exhibit by far the strongest and most statistically robust structural shifts between periods (Cohen's d = 1.0 for biomass, d = 1.25 for structural homogeneity), and they account for a disproportionate share of disturbance-related carbon losses relative to their disturbed area (approximately 40% of losses from 30% of area). The genus grouping into spruce, other needleleaf, and broadleaf is justified because the research question specifically concerns whether disturbance selectivity differs between a known high-susceptibility group (spruce) and other forest types, and because finer genus-level comparisons are not statistically supported at the continental scale, given the available sample sizes.

We have revised the manuscript to make this framing more explicit throughout. We have added the following justification at the first introduction of the genus grouping [L. 110-119]: *"Prior to spatial aggregation, these eight classes were reclassified at the native 10 m resolution into three functional groups based on known differences in disturbance susceptibility: spruce (Picea spp.), other needleleaf (Larix spp., Pinus spp., and other conifers), and broadleaf (Fagus spp., Quercus spp., and other broadleaf species). Non-tree pixels were assigned to nodata at this stage and excluded from the subsequent majority filter. Spruce was retained as a distinct group given its documented preferential susceptibility to bark beetle outbreaks and its dominant role in Central European disturbance dynamics. This grouping is analytical and is not intended to provide a balanced comparison across taxa. The reclassified 10 m map was then reprojected to EPSG:4326 and aggregated to 100 m resolution using a mode-based majority filter, assigning each 100 m cell the* *functional group that occurred most frequently among its underlying 10 m pixels. Reclassifying to three functional groups prior to spatial aggregation reduces class fragmentation during the majority filter, producing more robust and stable genus assignments under the projection transformation from EPSG:3035 to EPSG:4326."*

Comment 3: *Because forest age is fixed at its 2010 value, the discrepancy between the assigned age and the true age at the time of disturbance increases over time. Disturbances in 2017-2023 are associated with systematically larger age errors than those in 2011-2016, meaning the two periods are not strictly comparable.*

Response: We respectfully disagree with this interpretation and believe it reflects a misunderstanding of the methodological design, which we may not have sufficiently explained in the manuscript. The use of a fixed 2010 baseline age is not a limitation but an analytical choice designed precisely to ensure comparability between the two periods.

By fixing all pixels to their 2010 age, we hold the landscape composition constant. This means that any difference in the age distribution of disturbed stands between the early (2011-2016) and recent (2017-2023) periods cannot be attributed to natural forest ageing during the study period. It can only reflect an actual change that affects age cohorts. This is explicitly stated in Figure 2c of the manuscript: *"Because all ages are fixed to 2010 values, the differences reflect selection, not regrowth or mortality."*

If we had instead used contemporary age estimates (i.e., allowing age to increase each year), any apparent shift toward older disturbed stands could simply reflect that all forests have aged by 6-12 years over the study period, thereby confounding disturbance selectivity with natural ageing. The 2010 fixed baseline eliminates this confounded effect entirely.

We have expanded the methodological explanation in Section 2.4 [L 153-158] to make this reasoning more explicit: *"All analyses were fixed to the 2010 age estimate regardless of the year of disturbance. This design choice is intentional: by holding the landscape age structure constant, we ensure that differences in the age of disturbed stands between the early (2011-2016) and recent (2017-2023) periods reflect actual changes in disturbance selectivity rather than the confounding effect of natural forest ageing. Any shift toward older disturbed cohorts, therefore, represents an actual change of forest age classes preferentially affected by disturbances, independent of natural stand development."*

Comment 4: *The manuscript should clarify how pixels disturbed in both periods are treated. If a stand is disturbed in 2011 and again in 2020, is it classified as >60 years in both cases, even if the 2011 event was stand-replacing?*

Response: This is a valid clarification point. In our dataset, each disturbed pixel is assigned its 2010 baseline age regardless of when the disturbance occurred within the study period. Pixels disturbed in both periods are treated independently in each period's analysis, each time retaining their 2010 age. We acknowledge that for pixels experiencing a stand-replacing disturbance in the early period, the assigned age in the recent period would no longer reflect the true post-disturbance age. However, the proportion of pixels experiencing two stand-replacing disturbances within a 12-year window was expected to be very small for two reasons. First, natural disturbance return intervals in European forests typically range from decades to centuries (Schelhaas et al., 2003; Seidl et al., 2014), making repeated stand-replacing events within 12 years rare. Second, even in the unlikely case of two successive disturbances, stands regenerating after a stand-replacing event in 2011 would not reach the structural maturity, stem density, or canopy height required to become susceptible to bark beetle attack or windthrow by 2020, given known minimum rotation lengths and stand development trajectories in European forests (Lindegaard et al., 2016; Suvanto et al., 2025). To confirm this empirically, we quantified the fraction of pixels that experienced two or more stand-replacing natural disturbances during the 2011-2023 period. As anticipated, these represent a negligible fraction (<3%) of the total disturbed area (Table S3), confirming that recurrent disturbance events do not substantially affect our continental-scale results. We have added a clarifying sentence to Section 2.4 [L. 159-166] acknowledging this assumption.

"We acknowledge that pixels experiencing a stand-replacing disturbance in the early period would, if disturbed again in the recent period, be assigned an age that no longer reflects their true post-disturbance condition. However, recurrent stand-replacing natural disturbance events were observed in fewer than 3% of forested pixels across the study domain (Table S3), consistent with the long return intervals documented for European forest disturbances (Schelhaas et al., 2003; Seidl et al., 2014). Furthermore, stands regenerating after a stand-replacing event in the early period would not reach the structural maturity required to become susceptible to bark beetle attack or windthrow within a 12-year window, given known minimum canopy development trajectories in European forests (Lindegaard et al., 2016; Suvanto et al., 2025). Together, these considerations confirm that repeat disturbance events do not substantially affect our continental-scale conclusions."

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 ≥ 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%**
Any disturbance	35,188,730	32,192,857 (91.49%)	2,995,873	**8.51%**

Comment 5: *The interpretation that disturbances increasingly affect high-biomass forests may partly reflect changes in the underlying forest structure. If disturbances occur randomly, an increasing fraction would be expected in high-biomass forests simply because such forests have become more widespread.*

Response: This is an important conceptual point that deserves explicit discussion. We note that our use of the fixed 2010 biomass baseline directly addresses the availability concern as described by the reviewers: by fixing all biomass values to 2010, we hold the landscape biomass distribution constant across both periods, ensuring that any observed shift in the biomass of disturbed stands reflects a change in selectivity rather than background biomass accumulation.

To further address the possibility that preferential disturbance of lower-biomass stands in the early period may have decreased their availability as hosts in the recent period, thereby driving subsequent disturbances toward higher-biomass cohorts by reducing the host pool rather than selectivity, we conducted an additional analysis using the fixed 2010 biomass baseline. For each 100 km hexagon, we compared the biomass distribution of all forested pixels against the residual landscape obtained by removing pixels disturbed by any agent during 2011-2016. If the early disturbance wave had substantially removed the pool of lower-biomass stands, the residual landscape would show a systematic shift toward higher biomass relative to the full landscape.

The results rule out a decrease in the host pool as an alternative explanation. Even in hexagons where up to 25% of the forested landscape was disturbed during 2011-2016, the biomass distribution of the residual landscape remained identical to that of the full landscape (r = 1.000;

maximum energy distance = 0.125 MgC ha-1, representing less than 0.1% of the study domain biomass range; Fig. S7). The regression line between full- and residual-landscape median biomass is indistinguishable from the 1:1 line across the full biomass range (50-250 MgC ha-1), confirming that disturbances between 2011-2016 did not meaningfully alter the biomass composition of the available host pool.

We have added the following statement to the Discussion [L. 627-630]: *"The persistence of the background landscape biomass distribution across periods (*Fig. S7*) confirms that the observed shift toward higher-biomass disturbed stands reflects an actual change in disturbance selectivity rather than a consequence of either biomass accumulation or the progressive loss of lower-biomass stands through the 2011-2016 disturbance activity"*

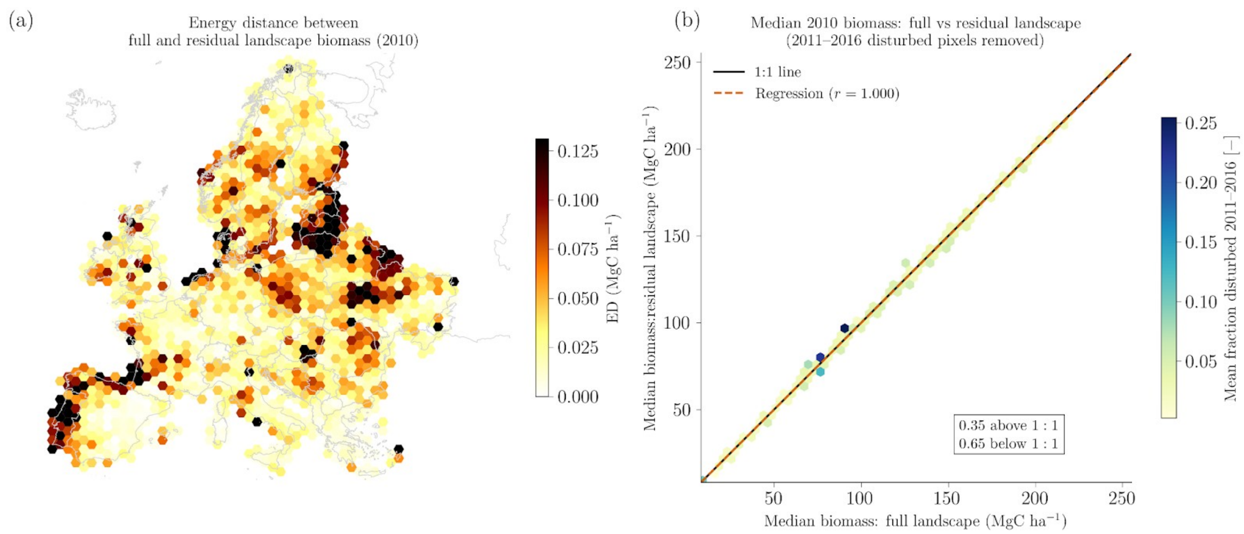


Fig S7: Persistence of the background landscape biomass distribution after removing 2011-2016 disturbed pixels. (a) Spatial distribution of energy distance (ED) between the biomass distribution of the full forested landscape and the residual landscape obtained by removing pixels disturbed by any agent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

Comment 6: *The manuscript refers to ~100 km hexagonal units as "forest stands", which is misleading. We recommend using "landscape unit" instead.*

Response: We thank the reviewers for catching this terminological inconsistency. We agree that "stand" has a specific meaning in forestry/forest ecology, typically a relatively homogeneous unit on the order of hectares, and that applying this term to 100 km hexagonal aggregation units is misleading. We have systematically replaced "stand" with "landscape unit" or "forest patch" (at pixel scale where appropriate) throughout the manuscript, and have revised the section heading 3.3 accordingly: *"Natural disturbances increasingly occur in structurally homogeneous landscapes."*

Comment 7: *It may bias the analysis towards regions with high disturbance activity. Clarifying how many hexagons are retained in each period would help assess robustness.*

Response: This is a valid point. We have added Table S4, which reports the number of hexagons retained for each disturbance type and period. For natural disturbances, 683 hexagons met the minimum pixel threshold in the early period (2011-2016) and 753 in the recent period (2017-2023). For harvest, 1,093 and 1,102 hexagons were retained, respectively. The modest increase in retained hexagons between periods for natural disturbances reflects the documented expansion of bark beetle outbreaks across Central and Northern Europe since 2017, which has brought more landscape units into the analysis. We also note that any bias introduced by the 50-pixel threshold would be consistent across periods, as the threshold is applied identically to both early and recent windows, and is therefore unlikely to systematically inflate differences between them.

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

Comment 8: *A more explicit discussion of the study's limitations, both in terms of data inputs and methodological choices, will be needed.*

Response: We agree. In addition to the limitations paragraph added in response to Comment 1, we have expanded the Limitations section to include the following:

"The analysis is also subject to several empirical and methodological limitations. The European Forest Disturbance Atlas primarily detects stand-replacing canopy loss events and may miss gradual or partial disturbances, such as progressive drought-induced dieback or low-severity insect damage. Our analysis, therefore, captures the most severe end of the disturbance spectrum, and patterns in lower-severity events may differ. The GAMIv3.0 age product carries inherent uncertainty, particularly in forests with complex management histories, which could propagate into the energy distance calculations and age-class comparisons. We address this by propagating uncertainty across the full 20-member age ensemble and reporting 5th-95th percentile ranges throughout. ESA CCI biomass data have inherent limitations for calibrating aboveground carbon estimates from remote sensing observations, as the sensitivity of satellite-derived retrievals decreases with increasing biomass, leading to disproportionately large uncertainty in high-biomass forests (Santoro et al., 2024). Biomass uncertainty is explicitly propagated through 20 independent realisations of the ESA CCI v6.0 product by introducing controlled perturbations to the mean estimates, scaled by the per-pixel standard deviation, ensuring that uncertainty is largest where retrieval uncertainty is greatest. All biomass-dependent results are reported as ensemble medians with 5th-95th percentile ranges." [L. 614-626]

Specific Comments

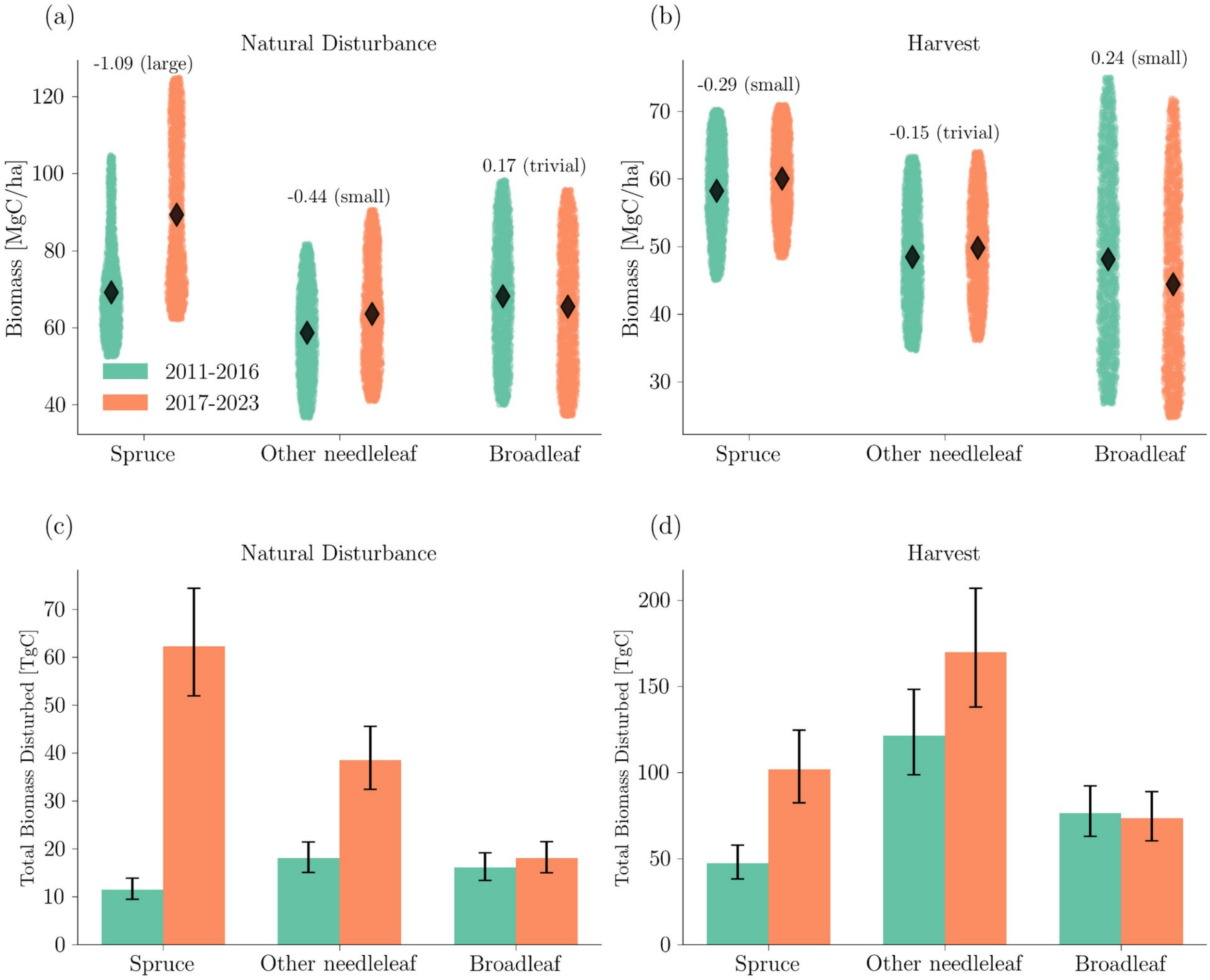
L 21, 147, 148, 397, 399: "species-specific" should be revised to reflect genus-level resolution: Agreed. We have revised all instances of "species-specific" throughout the manuscript to reflect the actual taxonomic and analytical resolution used. Where the text refers to patterns across the three functional groups (spruce, other needleleaf, broadleaf), we use "functional-group-specific." Where the text refers to the genus-level classification underlying those groups, we use "genus-level." This terminology more accurately reflects both the input data resolution and the analytical grouping applied in our study.

L 59-60: Jactel et al. (2017) focus on species diversity, not stand age or biomass: Agreed. We removed the reference.

L 70-71: Redundant with L 74; patterns are not "across dominant genera" but among three groups: The sentence at L 70-71 has been removed. The description at L.74 has been lightly revised to accurately reflect the three-group structure.

L 102-104: Using dominant genus may obscure compositional heterogeneity in mixed forests: We thank the reviewers for this comment. We agree that assigning a single dominant functional group to each 100 m pixel may underrepresent compositional heterogeneity, particularly in mixed forests. To address the related aggregation concern raised in comments L 148-150, we have rerun the analysis using the corrected aggregation order, reclassifying the eight original genus classes into three functional groups at the native 10 m resolution before applying the majority filter to aggregate to 100 m. This procedure is more robust than the original approach for two reasons. First, aggregating functional groups rather than individual genera reduces vote fragmentation in mixed pixels, producing more stable majority assignments under the projection transformation from EPSG:3035 to EPSG:4326. Second, it ensures that no-tree pixels are correctly treated as *nodata* before the majority filter operates, preventing them from distorting genus assignments in partially forested pixels.

We acknowledge that assigning a single dominant functional group to each 100 m pixel remains an inherent simplification and does not fully capture compositional heterogeneity within mixed forests. We have added the following caveat to Section 2.2 [L 122-124]: *"Assigning a single dominant functional group to each 100 m pixel may underrepresent compositional heterogeneity, particularly in structurally complex mixed forests. Results should therefore be interpreted as reflecting the dominant compositional signal of each pixel rather than its full taxonomic complexity."* The revised results, while differing from the original manuscript in absolute values for broadleaf categories, do not alter the main conclusions of the study, as discussed in our response to comments L 148-150.



Updated Figure 3: Structural and quantitative changes in aboveground carbon loss by species group for natural forest disturbances and harvests.

L 113-117: Add further description of forest age, biomass, and forest fraction products: Additional metadata (resolution, reference years, member counts) have been added for all three products in Section 2.3.

L 119: Disturbances prior to 2011 are not used, correct?: Correct. Disturbances prior to 2011 are not used in the structural selectivity analyses but in the trend-based forecasting analysis. We have added a clarifying sentence: *"The resulting dataset is stored in tabular format, with each row corresponding to a single forested pixel that was disturbed at least once between 1985 and 2023. Disturbance records prior to 2011 are retained in the dataset for trend-based forecasting (Section 2.7) but are not used in the structural selectivity analyses, which are restricted to the 2011-2023 period."*

L 122-123: Justify the ≥30% forest fraction threshold: Revised to include justification: *"A minimum forest fraction of 30% was applied to exclude pixels dominated by non-forest land cover while retaining partially forested cells representative of Europe's fragmented forest landscapes."*

L 122-123: Justify the ≥50% disturbance threshold: Revised to include justification: *"A minimum disturbance fraction of 50% was applied to focus the analysis on high-severity, largely stand-replacing events where structural attributes of the disturbed stand are most meaningfully characterised. This conservative threshold minimises the influence of partial disturbances."*

L 148-150: Aggregation inconsistency, collapsing eight classes to three after majority filtering may misclassify mixed pixels: We thank the reviewers for identifying this inconsistency. We agree that the correct aggregation order is to first reclassify the 10 m genus map into three functional groups and then apply the majority filter to aggregate to 100 m. We have rerun the full analysis following this corrected procedure. The revised results show meaningful differences from the original manuscript, particularly in broadleaf totals, which we attribute to two compounding issues in the original approach. First, collapsing eight classes to three after the majority filter allowed vote fragmentation among fine-grained classes to determine outcomes in mixed pixels, where no single genus reached plurality but a functional group would have done so clearly. Second, a nodata-handling inconsistency in the original resampling pipeline caused no-tree pixels to be included in the majority filter as a valid class rather than being excluded, thereby systematically distorting genus assignments for partially forested pixels. Reclassifying to three functional groups prior to spatial aggregation resolves both issues simultaneously: it reduces class fragmentation and ensures that no-tree pixels are correctly excluded before the majority filter operates. Importantly, the core findings of the manuscript are robust to this correction. The structural shift toward higher-biomass disturbed stands in spruce-dominated Central European landscapes remains the dominant signal (Cohen's $d = 1.0$), and the contrast between natural disturbance selectivity and harvest stability is preserved. All figures and tables have been updated to reflect the reanalysis, and the Methods section has been revised accordingly. All figures and tables have been updated to reflect the reanalysis. We have updated the methodology: *"Prior to spatial aggregation, these eight classes were reclassified at the native 10 m resolution into three functional groups based on known differences in disturbance susceptibility: spruce (Picea spp.), other needleleaf (Larix spp., Pinus spp., and other conifers), and broadleaf (Fagus spp., Quercus spp., and other broadleaf species). No-tree pixels were assigned to nodata at this stage and excluded from the subsequent majority filter. Spruce is retained as a distinct group given its documented preferential vulnerability to bark beetle outbreaks and its central role in Central European disturbance dynamics. This grouping is analytical rather than exhaustive and is not intended to provide equal taxonomic resolution across all genera. The reclassified 10 m map was then reprojected to EPSG:4326 and aggregated to 100 m resolution using a mode-based majority filter, assigning each 100 m cell the functional group that* *occurred most frequently among its underlying 10 m pixels. Reclassifying to three functional groups prior to spatial aggregation reduces class fragmentation during the majority filter, producing more robust and stable genus assignments under the projection transformation from EPSG:3035 to EPSG:4326."* [L. 110-119]

L 151: Specify which ESA CCI biomass years were used for each period: We thank the reviewers for this comment. We clarify that, consistent with our use of a fixed 2010 forest age baseline, all biomass analyses use the 2010 ESA CCI v6.0 biomass estimates exclusively. This design choice is intentional: by anchoring biomass values to a single reference year, we ensure that any observed shift in the biomass of disturbed stands between the early and recent periods reflects an actual change in disturbance selectivity rather than changes in forest biomass accumulation over time. We have clarified this in Section 2.5 [L. 197-200]: *"For all analyses, aboveground biomass was fixed to the 2010 ESA CCI v6.0 estimate, consistent with the fixed 2010 forest age baseline. This approach ensures that differences in the biomass of disturbed stands between the early and recent periods reflect changes in disturbance selectivity rather than background biomass accumulation across the landscape."*

L 173: Explain annual median CV calculation in more detail: Revised to: *"To assess continuous shifts, we computed the annual median CV of pre-disturbance biomass across all retained hexagons separately for each of the 20 biomass ensemble members, then derived the annual ensemble median and 5th-95th percentile range across members, yielding a temporal trajectory of structural heterogeneity with associated uncertainty bounds. For each disturbance type and genus, we fitted ordinary least-squares regressions of CV against year; slopes and significance levels summarised long-term changes in structural heterogeneity. Temporal coherence between harvest- and disturbance-related CV trajectories was evaluated using Pearson's r."* [L. 218-224]

L 249-251: Comparison between harvest and natural disturbances may be misleading, given the incomplete representation of natural disturbances: Agreed. We have revised this sentence to: *"The contrast between stable harvest selectivity and shifting bark beetle and windthrow patterns suggests that climate-amplified biotic agents, rather than management changes, drive the observed structural selectivity within the disturbance types and geographic regions captured by our analysis."* [L. 294-296]