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Inconsistency between process-based model and dose-response function in estimating biomass losses in Northern Hemisphere due to elevated O_3 ☆

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ABSTRACT

Tropospheric ozone (O_3) concentrations in the Northern Hemisphere have significantly increased since the pre-industrial era, with ongoing growth driven by emissions from industrial, agricultural, and transportation activities, further exacerbated by the warming temperatures and altered atmospheric circulation patterns associated with climate change. This study compared different methodologies for estimating biomass potential losses (BPL) in forests due to elevated O_3 using both concentration-based (AOT40) and flux-based (POD1) metrics. Moreover, to further assess the impact of O_3 on forest health and carbon uptake across the dominant forest types in the Northern Hemisphere, we also compared BPL estimates from dose-response functions with those derived from the process-based model ORCHIDEE.

Our analysis showed that deciduous forests, particularly boreal and continental types, are more sensitive to O_3-induced biomass loss compared to evergreen forests. Importantly, the study also revealed significant regional differences, with Europe and North America experiencing higher BPL than Asia and North Africa. Regression analysis between BPL and Gross Primary Production anomalies indicated that the relationship between O_3 exposure and forest productivity varied across forest types, with continental deciduous forests showing stronger correlations. The findings highlighted the importance of using flux-based metrics like POD1 in assessing O_3 impacts and that current dose-response functions may require further validation across diverse ecological settings to propose effective forest management and conservation strategies.

1. Introduction

Tropospheric ozone (O_3) concentrations in the Northern Hemisphere (NH) have experienced a significant increase since the pre-industrial era (Young et al., 2013). Presently, the concentrations are expected to rise from 0.5% to 2.0% per year, attributed mostly to alterations in the release of precursor compounds from industrial, agriculture and transport sources (Hartmann et al., 2013; Gaudel et al., 2018). Furthermore, the O_3 increase can be mainly attributed to a substantial rise in CH4 emissions, coupled with global warming and a weakened NO titration, which further exacerbates the formation and persistence of ozone in the atmosphere (Sicard et al., 2017). Considering future projections, the different Representative Concentration Pathway (RCP, van Vuuren et al., 2011) scenarios indicate varying degrees of expected increase in background O_3 concentrations across the Northern Hemisphere (e.g., Sicard et al., 2017; Crespo-Miguel et al., 2024).

The impact of elevated surface O_3 extends beyond atmospheric considerations, particularly regarding its phytotoxic effects on forests (Wittig et al., 2009; Feng et al., 2019). In particular, infiltrating in leaves through stomata, O_3 causes oxidative reactions that impair cell membranes, proteins, and deoxyribonucleic acid (DNA) (Omasa & Takayama, 2002; Leisner & Ainsworth, 2012). The damage to the photosynthetic apparatus disrupts leaf gas exchange, translating into reduced plant productivity (both as gross as net), stunted growth, and

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compromised carbon and biomass accumulation (Paoletti et al., 2007; Proietti et al., 2016; Ainsworth et al., 2012).

As plants have the capability to detoxify certain doses of O_3, thereby mitigating the impact of oxidative stress (Sachdev et al., 2021), process-based models have been developed accordingly to integrate the plant response to O_3. This protective mechanism is quantified through the Phytotoxic Ozone Dose (PODy) metric, which gauges the amount of O_3 entering the leaf surface while considering a detoxification threshold denoted by 'y' (Emberson, Büker, & Ashmore, 2007; Mills et al., 2011a; De Marco et al., 2015). Another approach to estimate the potential impacts of O_3 on vegetation is the AOT40, that is decumulated O_3 concentration over the threshold over 40 ppb during the growing season. In essence, while AOT40 is just based on O_3 concentration, PODy represents the cumulative O_3 amount that a plant cannot detoxify, thereby adversely affecting the plant eco-physiological processes (Mills et al., 2011b). Notably, this approach has demonstrated efficacy in modelling studies across diverse ecosystems (Sitch et al., 2007; Clark et al., 2011; De Marco et al., 2015; Anav et al., 2016). However, most of the studies examining O_3 damage to forests relied on observations at the site level, often constrained by the limited availability of monitoring stations that provide comprehensive data, including meteorological conditions, environmental factors, and physiological responses. (Fares et al., 2013; Yue & Unger, 2014; Yue et al., 2016; Verryckt et al., 2017). Consequently, comprehensive evaluations of the O_3 threat to forests over large scales necessitate the use of complex process-based models (Sitch et al., 2007; Lombardozzi et al., 2015; Yue and Unger, 2018). These models incorporate both biological, physical, and chemical processes representation that influence O_3 uptake subsequently influencing plant physiology (Evans, 2012). Alternatively, certain metrics have been devised to swiftly identify forest areas at O_3 risk (Musselman et al., 2006; Lefohn et al., 2018; Mills et al., 2018) and estimate the resulting plant response using straightforward dose-response relationships derived from field experiments (Mills et al., 2011a,b). However, the effectiveness of these metrics in pinpointing vulnerable forests, and their alignment with estimates derived from process-based models, still poses a challenge to our understanding. Thus, in this study, different methods of estimating forest BPL based on concentration or flux-based metrics were compared. Besides, BPL estimated using dose-response functions were evaluated against BPL estimated by the land surface model ORCHIDEE model (Krinner et al., 2005). The aim of this study is assess the consistency of two different approaches, i.e. process-based models versus empirical dose-response functions, used to estimate the biomass losses due to elevated O_3 concentrations at large scale in the whole Northern hemisphere. To facilitate a comprehensive understanding of the processes involved, please refer to the scheme depicted in Fig. 1.

1.1. Analysis

Dominant forest types across the NH were characterised using a methodology that integrates United States Geological Survey (USGS) land cover data with Koppen climate classifications, following Anav et al. (2016). This approach ensures consistency in defining vegetation types and parameterizations as outlined in chapter 3 of the Mapping Manual (CLRTAP, 2017), facilitating the computation of POD1 and its critical level derivation. Six distinct forest categories were identified (Fig. S2): boreal deciduous (BD), boreal evergreen (BE), continental deciduous (CD), continental evergreen (CE), (sub)tropical deciduous (TD), and (sub)tropical evergreen (TE) species, based on the classification proposed by Anav et al. (2022). The chosen study year is 2016.

Potential yield losses for each forest type were calculated using the dose-response functions (CLRTAP, 2017) in SI. Critical Loads (CLs) are defined as: "*concentrations, cumulative exposure or cumulative stomatal flux of atmospheric pollutants above which direct adverse effects on sensitive vegetation may occur according to present knowledge*" (CLRTAP, 2017). The parameter usually evaluated for estimating such adverse effect on forests is a 4% reduction in biomass except for evergreen species where

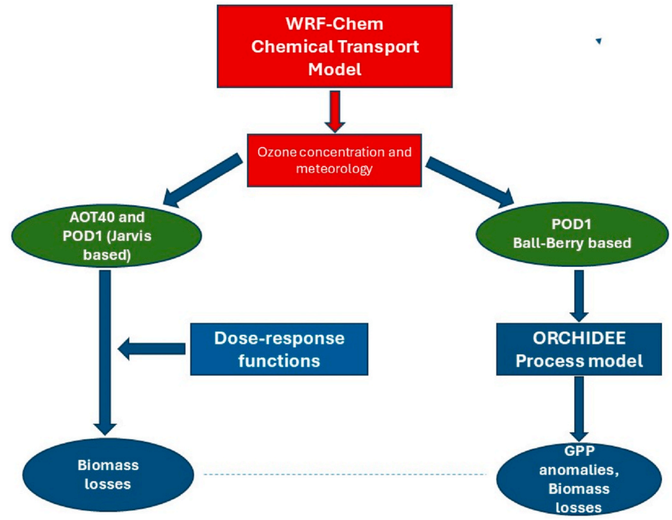

Fig. 1. Logical scheme illustrating the processes involved in assessing biomass loss and Gross Primary Productivity (GPP) due to elevated ozone (O_3) concentrations. This figure provides a visual framework for understanding the comparison between process-based models and dose-response across the Northern Hemisphere.

the biomass reduction is set to 2% (CLRTAP, 2017). Exceedances of O_3 CL were calculated for the two metrics AOT40 and POD1 as recommended by CLRTAP (2017), i.e., as difference between the estimated value in each grid cell and the CL obtained by literature data. We used different CLs depending on the metric, i.e.: for AOT40 we applied the European CL set to 5 ppm h^{-1} to protect all forest types (CLRTAP, 2015); for POD1, we used 5.2 mmol m^{-2} for BD and CD, 9.2 mmol m^{-2} for BE and CE, 14.0 mmol m^{-2} for TD and 47.3 mmol m^{-2} for TE, according to CLRTAP (2017).

To link the AOT40 and POD1 to the forest BPL, we applied the dose-response function to the different forests type (Fig. 2, 3). Considering the AOT40 metric, the continental deciduous (CD) forests showed the largest biomass loss with a BPL of 22.5%, followed by the boreal deciduous (BD) forests with a loss of 11.8%. The (sub)tropical deciduous forests, differently from BD and CD, which have high level of BPL (15–20% on average) showed a value of 3% BPL, thus less sensitive to O_3 injury. Similarly, all the evergreen forests were weakly affected by O_3, with BPL values around of 5% for boreal evergreen (BE), continental evergreen (CE) and (sub)tropical evergreen (TE). Conversely, the PBLs computed through the POD1 metric indicated that the most affected forest types were the deciduous species, in particular BD (18%), then CD and TD, with a respective BPL of 18.5%, 11%, and 8%. Evergreen species showed lower biomass reductions for all the three categories, i.e. BE, CE and TE, with a BPL of 1.5%. These values are remarkably in agreement with the values obtained by De Marco et al. (2020).

The relative BPL aggregated to the continents (Fig. 4) of the NH indicated that in North Africa the O_3 led to a potential biomass reduction lower than 5%, both using AOT40 and POD1 as metrics. In Asia, with the AOT40 the CD forests showed the largest BPL reduction, with a value close to 25%, followed by the BD and CE forests, with values of 12% and 8.5%, respectively. In BE, TD and TE, AOT40 caused a potential biomass reduction less than 5%. The BPL computed using the POD1 highlighted that in Asia the O_3 injury are prevalent on the deciduous forests, then it decreased progressively from B, C, to T with values of 15%, 10%, and 8%, respectively. For evergreen forests the potential biomass reduction was under 5% in all cases. It can be observed that for deciduous forests, in particular B and C, both Europe and North America have the same magnitude of the potential biomass reduction computed using the AOT40. In Europe values were 12% and 17% for BD and CD and in North America were 11% and 20%, respectively. In other cases, BE, CE, TD and

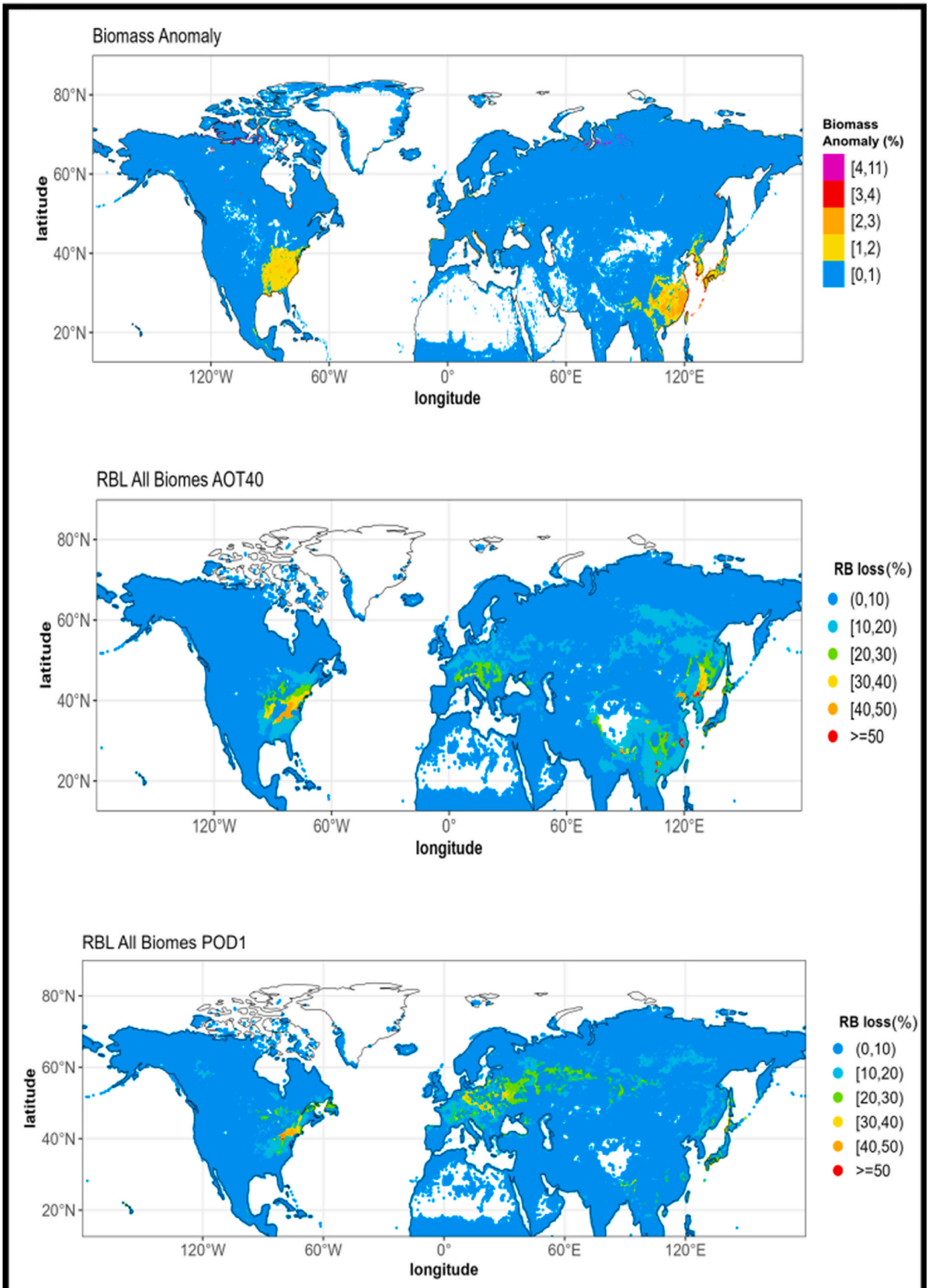

Fig. 2. Spatial variations of the biomass potential loss across the northern hemisphere based on different estimation methods.

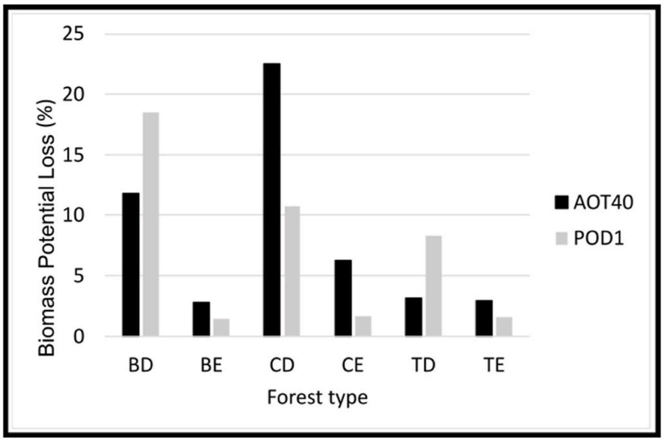

Fig. 3. Relative BPL due to AOT40 and POD1 in the six forest types: B, Boreal; C, Continental; T, (sub)tropical; D, deciduous; E, evergreen (Study year: 2016).

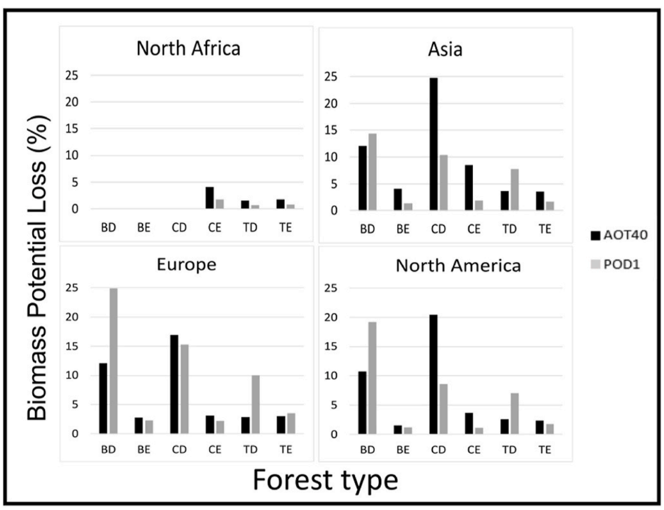

Fig. 4. Relative BPL due to AOT40 and POD1 in the six forest types: B, Boreal; C, Continental; T, (sub)tropical; D, deciduous; E, evergreen, in the four continents of the Northern Hemisphere (Study year: 2016).

TE both in Europe and North America values for potential biomass reduction due to AOT40 was less than 5%. Potential biomass reduction due to POD1 in Europe and North America was higher for deciduous forests as expected (Breil et al., 2023) with higher values for BD equal to 25% and 19%, followed by CD with values of 15% and 8.5% and TD equal to 10% and 7%, respectively. For evergreen forests the potential biomass reduction due to POD1 both in Europe and in North America was under 5% in all cases.

Considering O_3 critical levels, our results showed that the AOT40 were exceeded over 93%, 81%, 94%, 82%, 96% and 90% of the areas covered by BD, BE, CD, CE, TD and TE forest types, respectively (Fig. 5). The AOT40-based O_3 risk was higher for deciduous forests than evergreen forests, despite the shorter duration of the growing season. POD1 critical levels were exceeded over 100%, 15%, 85%, 21%, 78% and 5% of the areas covered by BD, BE, CD, CE, TD and TE forest types, respectively (Fig. 5).

1.2. Regression analysis

Finally, the regression analysis investigated AOT40-BPL with ORCHIDEE derived GPP anomaly and Biomass anomaly (Anav et al., 2022). Continental forests consistently exhibited higher coefficients of

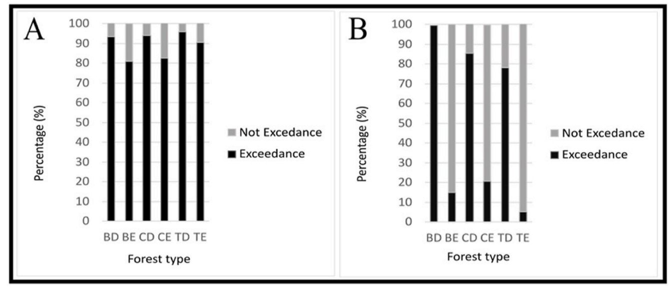

Fig. 5. Northern Hemisphere forests exposed to O_3 levels exceeding the critical levels for AOT40 (A) and POD1 (B). Forest types: B, Boreal; C, Continental; T, (sub)tropical; D, deciduous; E, evergreen.

determination (R^2) in both biomass and GPP anomaly relationships meaning that part of the GPP variability can be described by the AOT40 variability (Fig. 6). In contrast, subtropical forests and boreal evergreen forests consistently showed lower R^2 values in both biomass and GPP anomaly relationships and highlighting as the impacts of AOT40 on biomass and GPP anomalies varied significantly across different forest types. Continental forests appeared more responsive to AOT40-induced changes compared to subtropical and boreal evergreen forests, as indicated by their higher R^2 in the regression analyses. These findings underscore the complex and varied nature of O_3 exposure effects on ecosystem productivity, emphasizing the need for nuanced analyses across diverse ecological settings.

Deciduous forests consistently exhibited higher R^2 across all cases, indicating a stronger correlation between relative biomass and GPP anomalies as influenced by POD1 (Fig. 7). In contrast, boreal evergreen forests consistently demonstrated lower R^2 values in these relationships suggesting that POD1 is more robust for risk assessment for deciduous forests compared to boreal evergreen forests. Understanding these relationships is crucial for assessing how specific environmental factors, represented by POD1, affect ecosystem dynamics differently across forest types. Such insights can support targeted conservation and management strategies tailored to the ecological characteristics and sensitivities of different forest ecosystems.

2. Conclusions

When evaluating BPL using established dose-response functions, POD1 suggested higher losses for boreal deciduous forests compared to evergreen forests, where losses are relatively comparable. Furthermore, POD1 estimates revealed varying BPL across the NH, with Europe and the US experiencing higher losses compared to Asia and North Africa. Comparisons between ORCHIDEE model-derived BPL and critical levels derived from dose-response functions showed weak correlations for both the POD1 and AOT40 metrics. This finding underscores the recommendation for policymakers to consider adopting POD1 as the air quality standard to safeguard vulnerable forest ecosystems in future conservation efforts. It is important to note that current dose-response functions are primarily derived from local experimental data and may not fully translate across larger geographical regions. This is because forest ecosystems are sensitive to air pollutants and the injury to O_3 can vary significantly depending on various environmental and climatic factors. For example, forest ecosystems can have different microclimates, which influence the concentration of air pollutants and their interaction with plants. Forests in areas of high relative humidity may be more susceptible to the damaging effects of O_3 than those in arid regions, or higher temperatures may increase the formation of O_3 and other pollutants, making some forests, located in warm regions, more vulnerable to the effects of O_3. Therefore, further experimental observations are crucial to validate these functions on a broader scale and derive dose-response functions to apply at hemispheric level, ensuring accurate and effective management strategies for mitigating O_3-induced

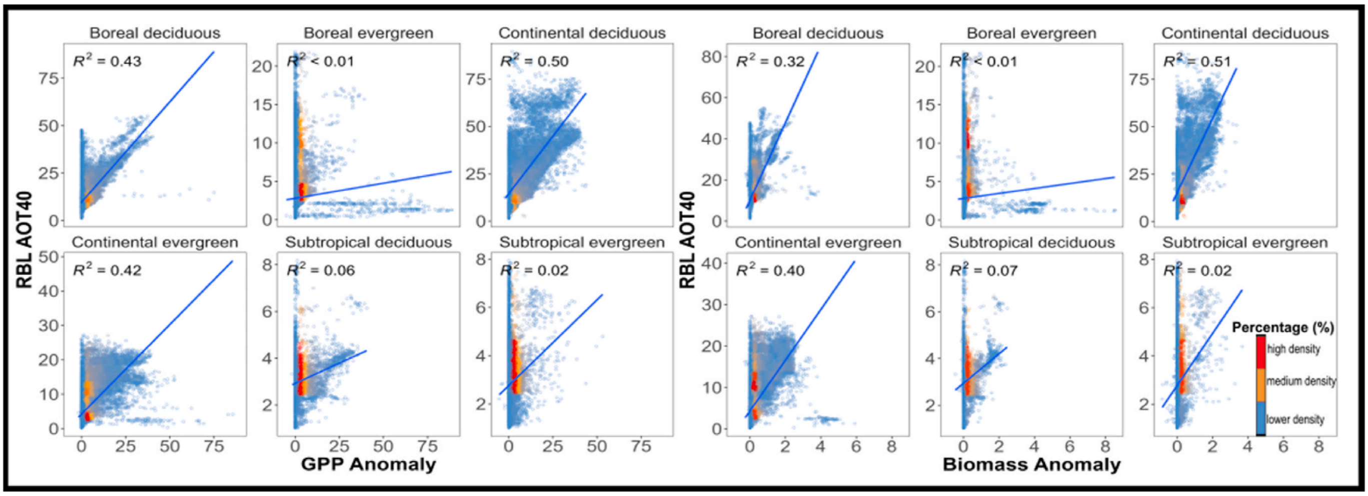

Fig. 6. Density maps of calculated AOT40-BPL with either ORCHIDEE derived GPP anomaly and Biomass anomaly for forest types: B, Boreal; C, Continental; T, (sub) tropical; D, deciduous; E, evergreen. R^2 values for linear regression analysis are showed in each panel.

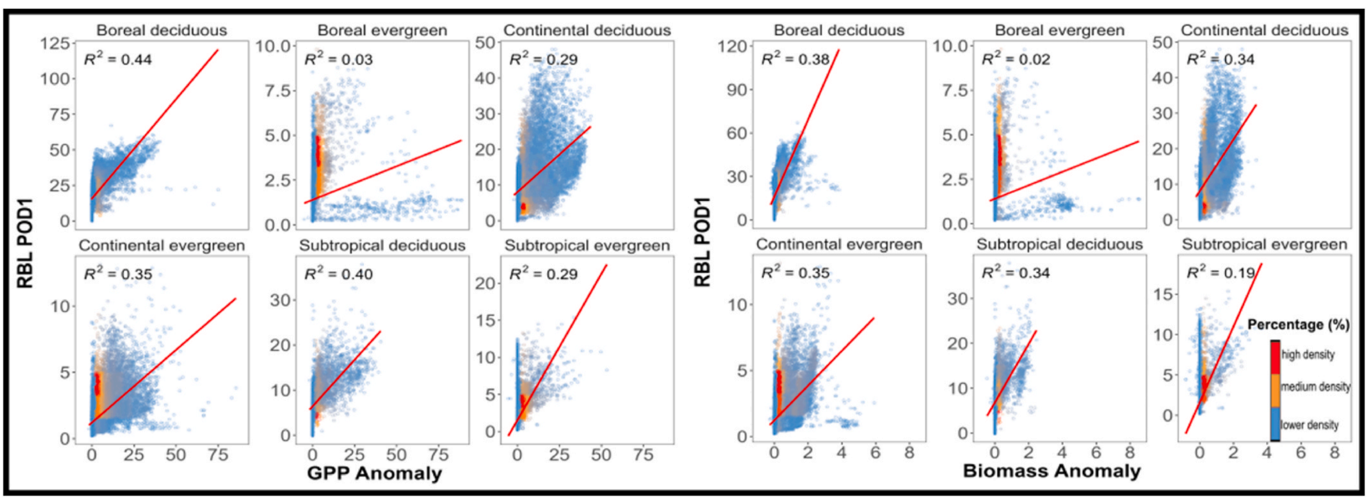

Fig. 7. Density maps of calculated POD1- BPL and either ORCHIDEE derived GPP anomaly and Biomass anomaly for forest types: B, Boreal; C, Continental; T, (sub) tropical; D, deciduous; E, evergreen. R^2 values for linear regression analysis are indicated in each panel.

impacts on forest health globally. Similarly, these new observations can be also useful to further improve process-based model, updating the vegetation sensitivity to ozone.

CRediT authorship contribution statement

Beatrice Sorrentino: Writing – original draft, Methodology, Formal analysis. **Alessandro Anav:** Writing – review & editing, Software, Methodology, Investigation, Data curation. **Vicent Calatayud:** Writing – review & editing, Software, Methodology, Formal analysis. **Alessio Collalti:** Writing – review & editing, Conceptualization. **Pierre Sicard:** Writing – review & editing, Formal analysis. **Stefan Leca:** Writing – review & editing, Validation. **Francesca Fornasier:** Writing – review & editing, Software, Formal analysis. **Elena Paoletti:** Writing – review & editing, Conceptualization. **Alessandra De Marco:** Writing – review & editing, Writing – original draft, Supervision, Resources, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alessandra De Marco reports administrative support was provided by ENEA National Agency for New Technologies Energy and Economic Sustainable Development. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.125379.

Data availability

Data will be made available on request.

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