Author Responses to Referees' Comments on

"Ozone Risk to Forests and Crops under Drought Modulation: A 15-Year Flux-Based and Economic Loss Assessment for Saxony, Germany"

by Engelhardt et al. (Preprint EGUsphere-2025-5542)

We sincerely thank the reviewers for their constructive and insightful comments, which have helped us to improve the clarity and quality of the manuscript. In the following document, the reviewers' comments are reproduced in green, followed by our responses in black. Reviewer comments and author responses are labelled as R#-C# (reviewer comment) and R#-R# (author response). Longer reviewer comments have been divided into individual points to ensure that each remark is addressed explicitly.

Page and line numbers referring to the original manuscript are indicated in blue. Text that has been revised or newly added in the manuscript is shown in purple to clearly identify the changes introduced during revision. Locations of modifications in the revised manuscript are indicated by page (P) and line (l) numbers.

Referee #1

R1-C1: Authors took advantage of long dataset from various O_3 concentration measurements in stations in Germany, some of them being in higher altitudes in mountainous regions. They calculated AOT40 and PODy for wheat and two forest tree species. In addition, they calculated the potential reduction of above ground biomass and corresponding economic loss.

R1-R1: We thank Referee #1 for the concise summary of the scope and objectives of our study.

R1-C2: The paper is written in bad and complicated English with vague sentences bearing no or little information. The text is highly redundant. In addition, the methodology is highly unclear and sometimes authors are writing contradictory information.

R1-R2: We thank Referee #1 for the careful and critical reading of the manuscript. We acknowledge that the original version required improvement in terms of language clarity, redundancy, and the consistency of the methodological description. In the revised manuscript we have therefore (i) revised the manuscript throughout to improve clarity and reduce redundant text (see responses R1-R6, R1-R13, R1-R25, R2-R4b), (ii) shortened or removed redundant passages (R1-R32, R1-R33, R1-R39a), and (iii) clarified and reorganised parts of the Methods and Results sections to present the analytical workflow and underlying assumptions more clearly (R1-R17, R1-R26, R1-R31, R1-R34-R1-R37, R2-R5b, R2-R19, R2-R20, R2-R21, and R2-R24).

R1-C3: Moreover, PODy calculation would highly benefit from calculation based on flux measurements, rather than only concentration with subsequent modelling, otherwise causing large uncertainties.

R1-R3: We thank the referee for highlighting the importance of direct flux measurements. We agree that $POD_Y SPEC$ calculations constrained by ecosystem-scale ozone flux measurements (e.g. eddy covariance or chamber-based approaches) would provide valuable additional constraints. Such measurements have been conducted at a limited number of forest research sites in Europe (e.g. Wieser et al., 2000; Gerosa et al., 2009). However, comparable long-term ozone flux measurements are not available for the Saxon monitoring stations used in this study.

Our approach therefore follows the current standard for local and regional O_3 risk assessment in Germany (VDI 2310 Sheet 6), developed by the VDI/DIN Commission on Air Pollution Prevention (Kommission Reinhaltung der Luft, KRdL), which provides standards and technical guidance for air pollution monitoring and environmental protection. This standard is based on the UNECE Mapping Manual methodology for vegetation flux modelling (Mills et al., 2017) and is designed to enable flux-based assessments of vegetation risk using data from stationary air-monitoring networks, in line with the requirements of the EU Air Quality Directive. Within this framework, stomatal O_3 flux and $POD_Y SPEC$ are estimated from observed O_3 concentrations and meteorological variables using Jarvis-type stomatal conductance parameterisations.

Using long-term, quality-controlled in situ O_3 and meteorological observations has two main advantages: (1) it captures the temporal variability at both lowland and mountain sites without introducing additional uncertainty from regional chemical transport models, and (2) it enables a consistent application of species-specific flux parameterisations across vegetation types and elevations over the 15-year study period. In line with VDI 2310, the analysis based on eight air-monitoring stations is intended to be representative of the evaluated ecosystems and to provide the required input data for flux-based risk assessment.

We acknowledge that flux modelling introduces uncertainties related to the parameterisation of stomatal conductance, soil water content and phenology. In the revised manuscript we therefore summarise these main sources of uncertainty for FO3REST, GRASSLANDO3 and CRO3PS. Accordingly, we have added the following text to the Methods section:

Revised manuscript, (P10, l255-260): In line with other flux-based O_3 risk assessments, the flux estimates used for FO3REST, GRASSLANDO3 and CRO3PS are subject to several sources of uncertainty. These include the parameterisation of stomatal conductance (e.g. species-specific responses to vapour pressure deficit and temperature), the representation of soil water content and drought in the flux model, and assumptions about phenology and growing season length. These uncertainties may affect the absolute magnitude of the calculated POD_YSPEC values, but relative patterns between years, sites and scenarios are expected to be robust because all sites were treated consistently within the same modelling framework.

R1-C4: Due to methodology flaws and bad non-scientifically written text, I recommend to reject the paper.

R1-R4: We thank the referee for the comment. We respectfully disagree that the study is methodologically flawed. The analysis is based on 15 years of hourly in situ O_3 and meteorological observations from eight monitoring stations and applies established flux-based risk assessment methods following the flux-based framework described in the UNECE Mapping Manual and implemented in VDI 2310 Sheet 6. However, we acknowledge that the original manuscript may not have clearly explained the methodological framework and its assumptions. In the revised version, we have improved the English language, reduced redundant text, and clarified the methodological descriptions to present the analysis and its scientific context more clearly.

R1-C5: Line 37: spruce does not have deeper rooting

R1-R5: We thank the referee for this remark. In the abstract, our use of "forests" was intended to refer to the mixed high-elevation forest stands (spruce and beech together), not to a specific rooting strategy of spruce alone. We agree that Norway spruce is generally considered a shallow-rooting species compared with beech, and that the phrasing "reflecting deeper rooting and higher drought tolerance" is misleading in this context and not directly supported by our POD_YSPEC-based analysis. In the revised abstract, and in the conclusions, we therefore remove the reference to "deeper rooting" and instead describe the sustained stomatal O_3 uptake at mountain sites in terms of higher effective water availability and the overall drought response of these high-elevation forest stands, which is what our modelling actually captures. Accordingly, we have adjusted the text.

Original manuscript, (P2, l37): "…forests at mountain sites sustained O_3 stomatal uptake even during prolonged droughts, reflecting deeper rooting and higher drought tolerance."

Revised manuscript, (P2, l31-32): "…forests at mountain sites sustained O_3 stomatal uptake even during prolonged droughts, consistent with higher effective water availability and a different drought response of these high-elevation stands."

R1-C6: line 64-65. The sentence seems abrupt.

R1-R6: We thank the referee for the remark. The sentences have been merged and rephrased to improve the logical flow.

Original manuscript, (P3, l64-67): "…With global population projected to grow approximately 20% by 2050 (United Nations Population Division, 2024). O_3-induced crop yield reduction poses an escalating challenge to food security (Lombardozzi et al., 2018; Mills et al., 2018). Understanding current O_3 impacts on vegetation is therefore essential for sustainable forest management, climate adaptation strategies, and ensuring food security (Emberson, 2020)."

Revised manuscript, (P3, l59-63): With global population projected to grow by approximately 20% by 2050 (United Nations Population Division, 2024), ensuring food security is an increasingly urgent challenge. In this context, O_3-induced crop yield reductions represent an additional pressure on food production (Lombardozzi et al., 2018; Mills et al., 2018). Understanding current O_3 impacts on vegetation is therefore essential for sustainable forest management, climate adaptation strategies and safeguarding food security (Emberson, 2020).

R1-C7: line 66: check dots or commas in the sentence.

R1-R7: We thank the referee for this remark. The punctuation has been corrected and the sentence has been revised in the updated manuscript to ensure proper grammar and flow (see R1-R6).

R1-C8: line 71: what kind of receptors?

R1-R8: We thank the referee for the comment. Here, "plant receptors" refers to the vegetation species or types for which POD_YSPEC is defined within the flux-based risk assessment framework. In this study, the considered receptors are beech, spruce, permanent grassland and wheat. This has been clarified in the manuscript.

Original manuscript, (P3, l71-72): "…In this context, flux-based approaches like the accumulated stomatal O_3 uptake over a threshold for specific plant receptors (POD_YSPEC)."

Revised manuscript, (P3, l67-68): In this context, flux-based approaches like the accumulated stomatal O_3 uptake over an instantaneous flux threshold (POD_YSPEC) for specific plant receptors, here represented by beech, spruce, permanent grassland and wheat.

R1-C9: line 126: in line 11 you have Easter Germany and here eastern Germany. Please be consistent.

R1-R9: We thank the referee for pointing this out. In the revised manuscript we use the form "eastern Germany" consistently at all occurrences. We have checked the full text to ensure that all instances are now harmonised to "eastern Germany" (Revised manuscript, P4, l107, P5 l123, P28, l752, and P30, l830).

R1-C10: 2.2 data set or dataset?

R1-R10: We thank the referee for this remark. In the revised manuscript we will consistently use "Dataset" in the section title and "dataset" (one word) throughout Section 2.2 and the rest of the manuscript. (Revised manuscript, P5, l121, P7 l163, P7 l164, P7 l176, P7, l180, P7, l183, and P14, l373, P4, l515, P32, l880).

R1-C11: line 167: it would be useful to add here instruments that measure O_3 concentration, which height above ground, length of inlet lines and how frequently they were calibrated.

R1-R11: We thank the referee for this helpful suggestion. Information on the O_3 measurement technique, measurement heights and inlet configuration has been added to Sect. 2.2 (Dataset).

Original manuscript, (P7, l166-172): "…2.2 Dataset. A data set of concentrations over 15 years, from 2006 to 2020, with a one-hour time resolution for the selected mountain and rural background stations in Saxony, is used for this study (Pausch and Mühlner, 2020): Tropospheric O_3 (µg m^{-3}), and meteorological variables: air temperature (T; ºC), relative air humidity (RH; %), air pressure (mbar), wind speed (WS, m s^{-1}) and global radiation (GR; W m^{-2}). were recorded at 3 m above ground level, while WS was measured at 10 m height at each station. Precipitation (P; mm) was obtained from the German Weather Service (Deutscher Wetterdienst DWD, n.d.) open data centre. All data are given in Central European Time (CET) with no daylight saving considered."

Revised manuscript, (P7 l164-l184): 2.2 Dataset. A dataset of concentrations over 15 years from 2006 to 2020, with a one-hour time resolution for the selected mountain and rural background stations in

Saxony, was used for this study (Pausch and Mühlner, 2020). Ozone (µg m^{-3}) and the meteorological variables air temperature (T, °C), relative humidity (RH, %), air pressure (mbar), wind speed (WS, m s^{-1}) and global radiation (GR, W m^{-2}) were recorded at 3 m above ground level, while WS was measured at 10 m height at each station. Precipitation (P, mm) was obtained from the German Weather Service (Deutscher Wetterdienst DWD, n.d.) open data centre. All data are given in Central European Time (CET) with no daylight saving considered.

Ozone was measured with UV-absorption analysers operated according to DIN EN 14625 within the LfULG air-quality monitoring network. Measurement heights for O_3 ranged between approximately 3.5 m and 15 m above ground (Carlsfeld 3.5 m, Schwartenberg 3.7 m, Zinnwald 5 m, Fichtelberg 15 m, Radebeul 3.5 m, Collmberg 3.7 m, Niesky and Schkeuditz 3.8 m), with short horizontal inlet lines following the network standard. These measurement heights were used as input in the $POD_Y SPEC$ models (FO3REST, GRASSLANDO3, CRO3PS), which explicitly include the measurement height of O_3 concentration in the flux parameterisation.

R1-C12: line 170. check dots within the sentence

R1-R12: We thank the referee for the remark. The punctuation in this sentence has been corrected in the revised manuscript (see R1-R11).

R1-C13: line 173: what should that mean that data were good? Be specific

R1-R13: We thank the referee for this remark. The phrase "data were good" has been removed, reorganizing the sentence with the quantitative description of the data coverage.

Original manuscript, (P7, l173 to 176): "…Within the dataset, the data available for the studied period (2006 to 2020) were good (> 97 %) at all stations except for the Fichtelberg site, which had a large data gap in 2019, from March to July. Given the significant data gap, the data set of 2019 for Fichtelberg was not used in this study. Only relatively small data gaps were present in the used data sets, typically ranging from 0.1 to 2.6 % missing values, with a maximum of 3 %."

Revised manuscript, (P7, l176-179): "Within the dataset, hourly data coverage for the study period 2006-2020 exceeded 97% at all stations, except for Fichtelberg, which had a large data gap in 2019 (March-July). Because of this gap, the 2019 data from Fichtelberg were excluded from the analysis. At the remaining station-year combinations, only relatively small gaps were present, typically 0.1-2.6% missing hourly values, with a maximum of 3%."

R1-C14: line 175: this is confusing. If that dataset was not used, why are mentioning that here? Why it is in Table 1, when later you do not use that? Please if you did not used this dataset, then delete that from Figure 1 and do not mention that anywhere in the manuscript.

R1-R14: We thank the referee for this comment. The text has been clarified to state that only the year 2019 at Fichtelberg was excluded due to the large data gap, while all other years from this station are used in the analysis. Therefore, Fichtelberg remains included in Table 1 and Figure 1. The revised description of the data coverage is provided in R1-R13 (revised manuscript P7, l176-179).

R1-C15: line 184-187: no need to mention that you tested other ways, if they are not present here. Although it might have taken you some portion of time, do not mention that here.

R1-R15: We thank the referee for this suggestion. The sentences referring to alternative imputation methods that were tested but not used have been removed, and only the description of the applied MICE-CART imputation approach is retained.

Original manuscript, (P7, l177 to 187): "…Complete hourly resolution data sets are a prerequisite for calculating vegetation risk using the PODySPEC metric, and any gaps with missing values must be filled to ensure uninterrupted time series. For the present study, missing data were filled using the imputation method Multivariate Imputation via Chained Equations (MICE) approach, implemented via the MICE package (van der Ploeg et al., 2015) in R (R Core Team, 2022). MICE is a flexible imputation framework that allows the use of different models to estimate missing values. For the datasets used in this study, the classification and tree-based regression trees (CART) method was selected, which can be considered a simple machine learning approach. CART is an algorithm that builds decision trees to predict missing values of a variable based on observed values of other variables.

Alternative imputation methods, including those recommended in the flux modelling guide from ICP vegetation (Mills et al., 2020) were also tested. Due to the relatively small proportion of missing data at the selected stations, the results across methods were similar. Nevertheless, the choice of imputation method ma y become more critical when dealing with larger gaps or less complete datasets.“

Revised manuscript, (P8, l180-184): Complete hourly-resolution datasets are a prerequisite for calculating vegetation risk using the POD_YSPEC metric, and any gaps with missing values must be filled to ensure uninterrupted time series. For the present study, missing data were filled using the Multivariate Imputation via Chained Equations (MICE) approach, implemented in R (van der Ploeg et al., 2015; R Core Team) MICE is a flexible imputation framework; for our datasets we used the classification and regression trees (CART) method, which predicts missing values of a variable based on observed values of other variables.

R1-C16: line 189: calculation of calculation--please rephrase

R1-R16: We thank the referee for pointing out this redundancy. The sentence has been rephrased in the revised manuscript.

Original manuscript, (P8, l189): “…The calculations of the accumulated stomatal ozone uptake metric POD_YSPEC calculations were conducted according.”

Revised manuscript, (P8, l186-188): ”…The accumulated stomatal ozone uptake metric (POD_YSPEC) was calculated following the flux-based framework described in the UNECE Mapping Manual and implemented in VDI 2310 Sheet 6 guideline for local and regional vegetation risk assessments (German Institute for Standardization, 2020)”.

R1-C17: line 212: Firstly, you calculated stomatal O_3 flux from concentration and later you summed to calculate PODy - so why here in methods you did not describe the process in this way? Please write the methods as you were processing the data.

R1-R17: We thank the referee for this comment. Section 2.3 has been reorganised to present the POD_YSPEC calculation in a step-wise manner, starting from stomatal conductance, followed by stomatal O_3 flux, and finally the accumulation of POD_YSPEC. To then explain the methodology about the protection goals, risk assessment and case scenarios.

Original manuscript, (P8 and P9, l188-l257): “…2.3 PODySPEC model

The calculations of the accumulated stomatal ozone uptake metric (POD_YSPEC) calculations were conducted according to the procedure implemented in the electronic appendix of the VDI 2310 Sheet 6 guideline for local and regional vegetation risk assessments (German Institute for Standardization, 2020). This standardized approach ensures consistency with current approaches for assessing O_3-induced damage to vegetation. For specific plant receptors, the model of FO3REST was used for beech and spruce, GRASSLANDO3 for grassland, and CRO3PS for wheat (German Institute for Standardization, 2020). A detailed explanation of FO3REST for beech is provided in (Grünhage et al., 2012), and of CRO3PS for wheat in (Grünhage et al., 2011).

Briefly, the O_3-induced damage for vegetation at selected mountain and rural background sites in Saxony was assessed using the accumulated stomatal O_3 uptake over an hourly threshold for specific plant receptors (POD_YSPEC) metric (Mills et al., 2017), which represents the sunlit-leaf stomatal uptake at canopy height accumulated over a specified period, minus a receptor-specific threshold below which O_3 fluxes are not considered damaging (Mills et al., 2017). The POD_YSPEC values were calculated based on hourly O_3 uptake exceeding this threshold for each plant receptor. The method follows the modelling framework established in the aforementioned VDI guideline. Eq. 1 provides the calculation for POD_YSPEC.

$$POD_YSPEC = \sum_{i=1}^{n} \left[max\left(F_{sunlit_{leaf},stom,O_3} - Y, 0\right) \cdot \Delta t \right]_i \qquad \textbf{Eq. 1}$$

In Eq. 1, POD_YSPEC is the accumulated phytotoxic O_3 dose above an threshold value (Y), expressed in nmol · m^{-2}. $F_{sunlit_{leaf},stom,O_3}$ is the stomatal O_3 uptake by sunlit leaves at the canopy top in nmol · m^{-2} · s^{-1}. The index n denotes the number of hours in the accumulation period, and Δt is the time step (1 hour). The variable y represents the receptor-specific threshold value for stomatal O_3 uptake in nmol · m^{-2} · s^{-1}, below which O_3 is not considered phytotoxic. The stomatal O_3 flux $F_{sunlit_{leaf},stom,O_3}$ and the threshold y are calculated with reference to the projected leaf area (PLA), although PLA itself not explicitly appear in the equation. PLA refers to the one-sided leaf surface area that is projected to the sun onto a horizontal plane, and all uptake values are normalized to this reference area. The threshold values y reflect the detoxification capacity of plant species (wheat, beech, and grassland) considered particularly sensitive to O_3. Their respective thresholds (in nmol · m^{-2} PLA · s^{-1}) are 6 for wheat and for the species beech, grassland 1. Another available known threshold is for spruce (1), a predominant tree in German forests (Buker et al., 2015; Mills et al., 2017).

To estimate the stomatal O_3 uptake, the $PODySPEC$ model applied in this study is based on the multiplicative Jarvis-Stewart weighting functions (Jarvis, 1976). Such functions represent mathematically the numerous physiological and atmospheric variations (e.g., plant phenology, the O_3 load, the light intensity, air temperature, the water vapour pressure deficit of the atmosphere, and the plant-available SWC) on which the stomatal O_3 uptake depends. The Jarvis-Stewart weighting functions require the hourly O_3 concentration and meteorological parameters (GR, WS, T, and RH), which must first be converted to their equivalent values at the canopy height of each receptor to estimate the stomatal O_3 uptake (German Institute for Standardization, 2020). Also, since vegetation is physiologically active during daylight and is most susceptible to damage, only the values during daylight hours with global irradiance above 50 W m^{-2} are included in the evaluation.

The yearly accumulated POD_YSPEC for each representative species was estimated by summing up the hourly exceedance values of the abovementioned O_3 stomatal uptake thresholds in the growing season of each representative specie (German Institute for Standardization, 2020). The growing season (accumulation period) of beech extends from April 1st to October 30th, for spruce is the whole year (January 1st to December 31st). For grassland, it ranges from April 1st to the end of September, and for wheat, from June 14th to August 26th. For each location, the start and end of the growing season for each representative species were adjusted using a Germany-fitted latitudinal model (German Institute for Standardization, 2020).

2.3.1 Protection goals

The O_3 effects on vegetation from the POD_YSPEC metric relates exclusively to specific protection goals such as biomass, yield, and reproduction parameters from the different plant receptor species (beech, winter wheat, spruce, and grassland), see Table S1 (Mills et al., 2017). For the risk assessment, yearly accumulated POD_YSPEC values are compared with critical dose-response parameters described in the UNECE LRTAP Convention Mapping Manual (Mills et al., 2017) to estimate the effects of O_3 on various biological endpoints Table S2. The POD_YSPEC approach enables quantitative yield and biomass loss estimates. Therefore, recommended PODySPEC threshold values for growth and yield reduction are defined as "critical levels" (CL PODySPEC), reflecting preindustrial O_3 exposure conditions, and "target values" (TV PODySPEC), corresponding to O_3 loads prior to 1980 (see Table S3) and can be understood as achievable targets that can be reached within a period that has yet to be defined (German Institute for Standardization, 2020).

2.3.2 Risk assessment

The percentage effect of the stomatal O_3 uptake on the biological endpoints for each representative species set by default within the models is regarded as the preindustrial O_3 exposure situation concerning the exceedance of the $CL_{PODySPEC}$. The mean preindustrial O_3 concentration is set at 10 ppb, and the resulting accumulated stomatal O_3 uptake due to O_3 preindustrial concentrations is denoted as Ref10POD_YSPEC (Mills et al., 2017). The percentage effect caused by O_3 can be calculated with Eq. 2.

The growth and yield reduction can also be compared to the O_3 exposure situation before 1980, calculated concerning the exceedance of the specific $TV_{PODySPEC}$.

$$\boldsymbol{potential\ maximum\ reduction\ rate}\ (\%) = \left(\boldsymbol{POD_ySPEC} - \boldsymbol{Ref10POD_ySPEC}\right) * \%\ \boldsymbol{reduction}\ (\boldsymbol{per\ mmol\ m^{-2}\ POD_ySPEC}) \quad \text{Eq. 2}$$

The O_3 risk assessment for the corresponding protection target is interpreted based on the exceedance of $TV_{PODySPEC}$ and $CL_{PODySPEC}$. The higher the POD_ySPEC values are, the higher the risk. The maximum possible protection is provided if the $CL_{PODySPEC}$ is not reached. If the $TV_{PODySPEC}$ is exceeded, there is a high risk. With POD_YSPEC values in the range between the $CL_{PODySPEC}$ and $TV_{PODySPEC}$, there is a moderate risk (German Institute for Standardization, 2020)

2.3.3 Best and worst-case scenarios

The lower the soil water content (SWC), the drier the soil becomes, which limits stomatal conductance and reduces O_3 uptake, potentially lowering the risk of O_3-induced vegetation damage. According to current guidelines for local and regional O_3 risk assessment, the standard approach is to assume a worst-case scenario in which SWC does not limit stomatal uptake; in other words, O_3 uptake remains optimal even during dry soil conditions (German Institute for Standardization, 2020). Based on this recommendation, PODySPEC was calculated under worst-case conditions for all studied representative species (beech and spruce) for forests, grassland, and wheat (crops). In addition, since the main focus of this study is on forest ecosystems, a best-case scenario was applied only for beech and spruce to allow a more realistic evaluation of O_3 risk under drought conditions. This scenario included modelled soil water content to assess its effect on POD_1SPEC. The soil moisture models used for this were taken from the guideline's appendix (German Institute for Standardization, 2020), with further details available in(Bender et al., 2015; Simpson et al., 2007)."

Revised manuscript, (P8, l185-285): 2.3 Flux-based O_3 uptake model (PODySPEC)

The accumulated stomatal ozone uptake metric (POD_YSPEC) was calculated following the flux-based framework described in the UNECE Mapping Manual and implemented in VDI 2310 Sheet 6, guideline for local and regional vegetation risk assessments (German Institute for Standardization, 2020). This standardized approach ensures consistency with current approaches for assessing O_3-induced damage to vegetation. For the specific plant receptors considered in this study, the model FO3REST was used for beech and spruce, GRASSLANDO3 for grassland, and CRO3PS for wheat (German Institute for Standardization, 2020). Detailed descriptions of FO3REST for beech and CRO3PS for wheat are given in (Grünhage et al., 2012; Grünhage et al., 2011), respectively.

In this framework, O_3-induced damage is quantified using the accumulated stomatal O_3 uptake over an instantaneous flux threshold Y for specific plant receptors (POD_YSPEC) (Mills et al., 2017). POD_YSPEC represents the sunlit-leaf stomatal O_3 uptake at canopy height accumulated over a defined period, minus a receptor-specific instantaneous flux threshold below which O_3 fluxes are not considered damaging

2.3.1 POD_YSPEC calculation

The POD_YSPEC calculation followed these steps:

a) Atmospheric input variables. Hourly O_3 concentrations and meteorological variables (T, RH, WS, GR) were obtained for each station. O_3, WS, T, and RH were transformed from measurement height to canopy height following the flux-based methodology of the UNECE Mapping Manual (Mills et al., 2017). O_3 concentrations were adjusted using the prescribed vertical gradient function, wind speed using a logarithmic wind profile accounting for displacement height and surface roughness, and T and RH according to the standard relationships described in the same framework.

Global radiation was used as measured and converted to photosynthetically active radiation (PAR). Vapour pressure deficit (VPD) was derived from T and RH. Receptor-specific canopy heights (e.g. 25 m for forest trees) were applied consistently across sites.

b) Stomatal Weighting (f_{Jarvis}): Environmental limitations on stomatal conductance were modeled using the Jarvis-Stewart multiplicative approach (Jarvis, 1976). The combined weighting term f_{Jarvis}, is defined as in Eq. 1,

$$f_{Jarvis} = [min(f_{phen}, f_{O_3})] \cdot f_{radiation} \cdot max(f_{min}, f_{Temp} \cdot f_{VDP} \cdot f_{PAW}) \qquad \text{Eq. 1}$$

The individual functions f_i represent the influence of phenology, O_3 concentration, radiation, temperature, and vapor pressure deficit. Where plant-available soil water (f_{PAW}) is not estimated, it is assigned a value of 1, assuming no soil-moisture limitation on stomatal opening (German Institute for Standardization, 2020).

c) Stomatal conductance (g_{sto}): The hourly stomatal conductance at canopy height was calculated by scaling a species-specific constant, the maximum stomatal conductance (g_{max}) by the multiplicative environmental weighting term f_{Jarvis} defined in Eq. 1, using Eq. 2

$$g_{sto} = g_{max} \cdot f_{Jarvis} \qquad \text{Eq. 2}$$

d) Hourly stomatal O_3 flux of the projected leaf area at canopy top ($\boldsymbol{F_{sunlit_{leaf},stom,O_3}}$): The $\boldsymbol{F_{sunlit_{leaf},stom,O_3}}$ (nmol m^{-2} s^{-1}), was derived by multiplying the calculated g_{sto} by the corresponding hourly O_3 concentration $[O_3]$:

$$F_{sunlit_{leaf},stom,O_3} = g_{sto} \cdot [O_3] \qquad \text{Eq. 3}$$

e) Yearly accumulated POD_YSPEC. The annual phytotoxic dose was determined by summing hourly exceedances of the receptor-specific instantaneous flux threshold for stomatal O_3 uptake (Y) (nmol m^{-2} s^{-1}) over the duration of the growing season. This accumulation only accounts for daylight hours with global irradiance exceeding 50 W m^{-2}, as vegetation is considered most physiologically active and susceptible to O_3 damage under these conditions (German Institute for Standardization, 2020). The instantaneous flux threshold Y represents the detoxification capacity of the plant, below which O_3 fluxes are not considered damaging:

$$POD_YSPEC = \sum_{i=1}^{n} max\left(F_{sunlit_{leaf},stom,O_3,i} - Y, 0\right) \cdot \Delta t \qquad \text{Eq. 4}$$

Where $F_{sunlit_{leaf},stom,O_3}$ is the hourly stomatal O_3 stomatal uptake by sunlit leaves at the canopy top, n is the number of hours in the specific accumulation period, and Δt is the 1 h time step.

$F_{sunlit_{leaf},stom,O_3}$ and POD_YSPEC, and the receptor-specific instantaneous flux threshold are expressed per projected leaf area (PLA), i.e. the one-sided leaf area projected onto a horizontal plane, and all uptake values are normalised to this reference area. The instantaneous flux thresholds Y reflect the detoxification capacity of O_3-sensitive plant species: their values (nmol m^{-2} s^{-1}) are 6 for wheat and 1 for beech, spruce and grassland (Buker et al., 2015; Mills et al., 2017).

The accumulation period for beech extends from 1 April to 30 October; for spruce it is the whole year (1 January to 31 December); for grassland it ranges from 1 April to the end of September; and for wheat from 14 June to 26 August. For each location, the start and end dates of the growing season for each receptor were adjusted using a Germany-fitted latitudinal model (German Institute for Standardization, 2020).

2.3.2 Protection goals and risk assessment

The effects of stomatal O_3 uptake on vegetation from the POD_YSPEC metric relate to specific protection goals such as biomass, yield and reproduction parameters for the receptor species beech, spruce, winter wheat and grassland (Mills et al., 2017); Table S1). For the risk assessment, annual POD_YSPEC values are inserted into established dose-response functions from the UNECE LRTAP Convention Mapping Manual (Mills et al., 2017) to estimate O_3 effects on various biological endpoints (Table S2).

The percentage effect of stomatal O_3 uptake on each biological endpoint is calculated relative to an assumed pre-industrial O_3 concentration of 10 ppb, for which the accumulated stomatal O_3 uptake is denoted Ref10POD_YSPEC (Mills et al., 2017). The percentage effect is derived using Eq. 5,

$$R=(POD_YSPEC\text{-Ref10}POD_YSPEC)\cdot S, \qquad \text{Eq. 5}$$

where R is the relative reduction in the biological endpoint (%) and S is the slope of the dose-response function in % per mmol m^{-2} POD_YSPEC. The parameters Ref10POD_YSPEC and S are species-specific coefficients derived from the dose-response relationships reported in the UNECE Mapping Manual (Mills et al., 2017) and are provided in Table S2.

Recommended threshold values for the accumulated flux metric POD_YSPEC for growth and yield reduction are defined as critical levels (CL_{POD_YSPEC}), above which adverse effects on vegetation are expected to occur, and target values (TV_{POD_YSPEC}), corresponding to O_3 loads prior to 1980 (Table S3). These TV_{POD_YSPEC} can be understood as an achievable policy target and reductions can also be evaluated relative to it. (German Institute for Standardization, 2020). The O_3 risk for a given protection target is interpreted from the exceedance of CL_{POD_YSPEC} and TV_{POD_YSPEC}. Maximum protection is achieved if CL_{POD_YSPEC} is not reached. Values between CL_{POD_YSPEC} and TV_{POD_YSPEC}indicate a moderate risk, whereas exceedance of TV_{POD_YSPEC} indicates a high risk (German Institute for Standardization, 2020).

2.3.3 Best-case and worst-case scenarios

Soil water content (SWC) influences stomatal conductance and thus O_3 uptake: low soil moisture reduces stomatal opening and may therefore decrease the risk of O_3-induced vegetation damage. In the European flux-based risk assessment framework (Mills et al., 2017), soil moisture effects are incorporated through a multiplicative limitation function (f_{PAW}) within the Jarvis-type stomatal conductance model.

Volumetric soil water content (θ) was first estimated using a simplified daily water balance model driven by observed precipitation and meteorological data, consistent with the implementation described in VDI 2310 Sheet 6 and (Bender et al., 2015). Rooting depth and soil hydraulic parameters were receptor-specific and followed the standard parameterisation provided in the VDI appendix (German Institute for Standardization, 2020).

Plant-available water (PAW), representing the fraction of soil water accessible to plants, was then calculated as:

$$PAW = \frac{\theta - \theta_{WP}}{\theta_{FC} - \theta_{WP}}, \qquad \text{Eq. 6}$$

where θ_{FC} is the soil water content at field capacity and θ_{WP} is the soil water content at permanent wilting point.

The soil moisture response function f_{PAW} (0-1) was implemented as a multiplicative limitation factor in Eq. 1, consistent with the DO_3SE modelling framework (Simpson et al., 2007; Mills et al., 2017). When PAW exceeds a species-specific critical fraction (PAW_{crit}), soil moisture does not limit stomatal conductance (f_{PAW}=1). If PAW falls below PAW_{crit}, f_{PAW} decreases linearly towards zero at the wilting point, thereby reducing stomatal conductance and stomatal O_3 flux (Mills et al., 2017).

In the regulatory framework, a worst-case scenario assumes that soil moisture does not limit stomatal conductance (f_{PAW} = 1 throughout the accumulation period), i.e. O_3 uptake remains optimal even under dry soil conditions. In this study, POD_YSPEC was first calculated under this assumption for all receptor species (beech and spruce in forests, grassland, and wheat).

Because the main focus of this study is on forest ecosystems, an additional best-case scenario was implemented for beech and spruce to provide a more realistic evaluation of O_3 risk under drought conditions. In this case, modelled plant-available water (PAW) reduces stomatal conductance via f_{PAW} during dry periods, thereby reducing stomatal O_3 uptake and the resulting $POD_Y SPEC$. The soil moisture parameterisation follows the DO_3SE framework (Simpson et al., 2007; Mills et al., 2017).

R1-C18: line 214: O3 load means O3 concentration?

R1-R18: We thank the referee for pointing out this ambiguity. In the original text, "O_3 load" referred to the ambient O_3 concentration used as input to the Jarvis-Stewart functions. To avoid confusion, the term has been replaced with "O_3 concentration". The revised description with the change to O_3 concentration is provided in R1-R17 Revised manuscript, P8 and P9, l185-285.

Original manuscript, (P8, l213-214):…"Such functions represent mathematically the numerous physiological and atmospheric variations (e.g., plant phenology, the O_3 load, the light intensity".

R1-C19: line 215: please add equations here

R1-R19: We thank the referee for this suggestion. The revised manuscript now includes the equations describing the Jarvis-Stewart stomatal conductance model, the calculation of stomatal O_3 flux, and the accumulation of $POD_Y SPEC$. The revised version is provided in R1-R17 Revised manuscript, P8 and P9, l185-285.

Original manuscript, (P8, l214-215): "...Such functions represent mathematically the numerous physiological and atmospheric variations (e.g., plant phenology, the O_3 load, the light intensity, air temperature, the water vapour pressure deficit of the atmosphere, and the plant-available SWC) on which the stomatal O_3 uptake depends."

R1-C20: line 217: Does it mean that you did not measure those variables at canopy height? It might differ a lot when measured at different height. How did you convert those variables?

R1-R20: We thank the referee for this important point. The variables were measured at the fixed instrument heights of the Saxon monitoring network and not directly at canopy height. Details on the measurement heights and instrumentation have been added in Sect. 2.2 (see R1-R11, Revised manuscript, P7 l164-l184). In addition, it is explained that these measurements are converted to canopy-top conditions using the standard correction procedures described in the UNECE Mapping Manual and implemented in VDI 2310 Sheet 6 (see R1-R17 Revised manuscript, P8 and P9, l185-285).

Original manuscript: (P8, l215 to 218): "...The Jarvis-Stewart weighting functions require the hourly O_3 concentration and meteorological parameters converted to their equivalent values at the canopy height of each receptor to estimate the stomatal O_3 uptake (German Institute for Standardization, 2020)."

Revised manuscript, (P8, l199-207): a) Atmospheric input variables. Hourly O_3 concentrations and meteorological variables (T, RH, WS, GR) were obtained for each station. O_3, WS, T, and RH were transformed from measurement height to canopy height following the flux-based methodology of the UNECE Mapping Manual (Mills et al., 2017). O_3 concentrations were adjusted using the prescribed vertical gradient function, wind speed using a logarithmic wind profile accounting for displacement height and surface roughness, and T and RH according to the standard relationships described in the same framework.

Global radiation was used as measured and converted to photosynthetically active radiation (PAR). Vapour pressure deficit (VPD) was derived from T and RH. Receptor-specific canopy heights (e.g. 25 m for forest trees) were applied consistently across sites.

R1-C21: line 221: should be specimen

R1-R21: We thank the referee for the remark. In this context the correct term is species, as the text refers to plant receptor species used in the flux-based risk assessment framework (e.g. beech, spruce, grassland and wheat). The grammatical error "specie" has therefore been corrected to "species" in the revised manuscript (see R1-R17 Revised manuscript, P8 and P9, l185-285).

Original manuscript, (P9, l221): "…O_3 stomatal uptake thresholds in the growing season of each representative specie."

R1-C22: section 2.3 make it shorter. You have here too many redundant passages and sentences are too long an vague.

R1-R22: We thank the referee for this suggestion. Section 2.3 has been substantially shortened by removing redundant explanations and restructuring the text into concise subsections describing the POD_YSPEC model, the calculation steps, the risk assessment procedure, and the scenario assumptions. The revised version is provided in (R1-R17 Revised manuscript, P8 and P9, l185-285).

R1-C23: line 230: table 2 - what should that mean?

R1-R23: We thank the referee for pointing this out. The reference to Table S2 in this sentence was unclear due to missing punctuation and wording. The sentence has been revised to clearly indicate that the dose-response parameters used for the risk assessment are summarised in Table S2. (see R1-R17 Revised manuscript, P8 and P9, l185-285).

Original manuscript, (P9, l229 to 231): For the risk assessment, yearly accumulated POD_YSPEC values are compared with critical dose-response parameters described in the UNECE LRTAP Convention Mapping Manual (Mills et al., 2017) to estimate the effects of O_3 on various biological endpoints Table S2.

Revised manuscript, (P8, l189-190): "…For the risk assessment, annual POD_YSPEC values are inserted into established dose-response functions from the UNECE LRTAP Convention Mapping Manual (Mills et al., 2017) to estimate O_3 effects on various biological endpoints (Table S2)."

R1-C24: line 232: this is in contradiction to what you have stated above (line 208), that the critical level is defined as the plant´s detoxification level. Moreover, how did you estimate the preindustrial stomatal ozone flux?

R1-R24: We thank the referee for pointing out this possible confusion. Two different quantities are referred to in the manuscript: (i) the O_3 stomatal instantaneous flux threshold Y, which represents the detoxification capacity of the plant and defines the flux above which O_3 is considered phytotoxic, and (ii) threshold values for the accumulated flux metric POD_YSPEC, the critical level (CL_{POD_YSPEC}) and the target value (TV_{POD_YSPEC}), which are accumulated POD_YSPEC values used for risk assessment and defined in the UNECE Mapping Manual.

To avoid confusion, the revised manuscript now explicitly distinguishes between the stomatal instantaneous flux threshold Y and the threshold values for the accumulated flux metric CL_{POD_YSPEC} and TV_{POD_YSPEC}. In addition, the derivation of the reference pre-industrial dose Ref10POD_YSPEC has been clarified. Following the UNECE Mapping Manual, Ref10POD_YSPEC is obtained by running the flux model with an assumed background O_3 concentration of 10 ppb over the growing season. The complete revised description of the flux calculation and risk-assessment framework is provided in R1-R17 (Revised manuscript, P8 and P9, l185-285).

Original manuscript, (P8, l208- 211): "…The threshold values y reflect the detoxification capacity of plant species (wheat, beech, and grassland) considered particularly sensitive to O_3. Their respective thresholds (in nmol · m^{-2} PLA · s^{-1}) are 6 for wheat and for the species beech, grassland 1. Another available known threshold is for spruce (1), a predominant tree in German forests (Buker et al., 2015; Mills et al., 2017)."

Original manuscript, (P8, l226-235): "…2.3.1 Protection goals

The O_3 effects on vegetation from the POD_YSPEC metric relates exclusively to specific protection goals such as biomass, yield, and reproduction parameters from the different plant receptor species (beech, winter wheat, spruce, and grassland), see Table S1 (Mills et al., 2017). For the risk assessment, yearly accumulated POD_YSPEC values are compared with critical dose-response parameters described in the UNECE LRTAP Convention Mapping Manual (Mills et al., 2017) to estimate the effects of O_3 on various biological endpoints Table S2. The POD_YSPEC approach enables quantitative yield and biomass loss estimates. Therefore, recommended POD_YSPEC threshold values for growth and yield reduction are defined as "critical levels" (CLPOD_YSPEC), reflecting preindustrial O_3 exposure conditions, and "target values" (TVPOD_YSPEC), corresponding to O_3 loads prior to 1980 (see Table S3) and can be understood as achievable targets that can be reached within a period that has yet to be defined (German Institute for Standardization, 2020)."

Revised manuscript, (P8, l189-190): "…Recommended threshold values for the accumulated flux metric POD_YSPEC for growth and yield reduction are defined as critical levels (CL_{POD_YSPEC}), above which adverse effects on vegetation are expected to occur, and target values (TV_{POD_YSPEC}), corresponding to O_3 loads prior to 1980 (Table S3). These TV_{POD_YSPEC} can be understood as an achievable policy target and reductions can also be evaluated relative to it. (German Institute for Standardization, 2020). The O_3 risk for a given protection target is interpreted from the exceedance of CL_{POD_YSPEC} and TV_{POD_YSPEC}. Maximum protection is achieved if CL_{POD_YSPEC} is not reached. Values between CL_{POD_YSPEC} and TV_{POD_YSPEC}indicate a moderate risk, whereas exceedance of TV_{POD_YSPEC} indicates a high risk (German Institute for Standardization, 2020).

Revised manuscript, (P9, l221-222): Yearly accumulated POD_YSPEC. The annual phytotoxic dose was determined by summing hourly exceedances of the receptor-specific instantaneous flux threshold for stomatal O_3 uptake (Y) (nmol m^{-2} s^{-1}) over the duration of the growing season.

Revised manuscript, (P9, l225): "…The instantaneous flux threshold Y represents the detoxification capacity of the plant, below which O_3 fluxes are not considered damaging".

R1-C25: line 237-238: please be consistent. Exposure means concentration?

R1-R25: We thank the referee for this remark. In the revised manuscript we now use the terms consistently: O_3 concentration is used only as input to the stomatal flux model, whereas vegetation risk is expressed in terms of stomatal O_3 flux and its accumulated dose POD_YSPEC. The wording in Sect. 2.3.2 has been revised accordingly. The complete revised section is provided in R1-R17 (Revised manuscript, P8 and P9, l185-285).

Original manuscript, (P9, l237-238) "…The percentage effect of the stomatal O_3 uptake on the biological endpoints for each representative species set by default within the models is regarded as the preindustrial O_3 exposure situation concerning the exceedance of the $CL_{PODySPEC}$."

Revised manuscript, (P10, l242-254): "…The percentage effect of stomatal O_3 uptake on each biological endpoint is calculated relative to an assumed pre-industrial O_3 concentration of 10 ppb, for which the accumulated stomatal O_3 uptake is denoted Ref10POD_YSPEC (Mills et al., 2017). The percentage effect is derived using Eq. 5,

$$R=(POD_YSPEC\text{-Ref10}POD_YSPEC)\cdot S, \qquad \text{Eq. 5}$$

where R is the relative reduction in the biological endpoint (%) and S is the slope of the dose-response function in % per mmol m^{-2} POD_YSPEC. The parameters Ref10POD_YSPEC and S are species-specific coefficients derived from the dose-response relationships reported in the UNECE Mapping Manual (Mills et al., 2017) and are provided in Table S2.

Recommended threshold values for the accumulated flux metric POD_YSPEC for growth and yield reduction are defined as critical levels (CL_{POD_YSPEC}), above which adverse effects on vegetation are expected to occur, and target values (TV_{POD_YSPEC}), corresponding to O_3 loads prior to 1980 (Table S3).

These TV_{POD_YSPEC} can be understood as an achievable policy target and reductions can also be evaluated relative to it (German Institute for Standardization, 2020). The O_3 risk for a given protection target is interpreted from the exceedance of CL_{POD_YSPEC} and TV_{POD_YSPEC}. Maximum protection is achieved if CL_{POD_YSPEC} is not reached. Values between CL_{POD_YSPEC} and TV_{POD_YSPEC}indicate a moderate risk, whereas exceedance of TV_{POD_YSPEC} indicates a high risk (German Institute for Standardization, 2020)."

R1-C26: What should then mean O_3 exposure situation concerning the exceedance of the CLPODySPEC how should be concentration being concerning the flux? It is very unclear here.

R1-R26: We thank the referee for pointing out that this formulation was unclear. As explained in R1-R25, the revised manuscript now consistently distinguishes between O_3 concentration, which is used only as input to the stomatal flux model, and vegetation risk expressed in terms of the accumulated stomatal flux metric POD_YSPEC.

To remove the ambiguity, the phrase *"*O_3 exposure situation concerning the exceedance of CL_{POD_YSPEC}*"* has been deleted. In the revised manuscript, the risk assessment is now described consistently in terms of the exceedance of the threshold values for the accumulated flux metric POD_YSPEC, namely the critical level CL_{POD_YSPEC}) and the target value TV_{POD_YSPEC}. The corresponding revised text is provided in R1-R25 and R1-R17 (Sect. 2.3.2, P8-P9, l185-285).

R1-C27: line 240: "is denoted as Ref10$PODYSPEC$" - this is very critical how you calculated possible stomatal O3 flux during preindustrial era. However, here you do not describe that at all! This is a major shortcoming.

R1-R27: We thank the referee for pointing out that the derivation of Ref10POD_YSPEC was not sufficiently explained in the original manuscript. In the revised manuscript we now clarify that Ref10POD_YSPEC represents the accumulated stomatal O_3 uptake calculated for a reference O_3 concentration of 10 ppb, which is assumed to represent pre-industrial background conditions in the UNECE Mapping Manual (Mills et al., 2017).

This reference value is obtained by applying the same stomatal flux parameterisation used for POD_YSPEC, but using the assumed background concentration of 10 ppb as model input and accumulating the stomatal O_3 flux above the receptor-specific threshold Y over the growing season. The resulting Ref10POD_YSPEC values are species-specific coefficients derived from the UNECE dose-response framework and are used as the reference level in Eq. 5 to estimate the relative reduction in biological endpoints. This clarification has been added to Sect. 2.3.2 of the revised manuscript. The corresponding revised text is provided in R1-R17 (Sect. 2.3.2, P8-P9, l185-285), R1-R25, and R1-R26.

Original manuscript, (P9, l240-242): "…The percentage effect caused by O_3 can be calculated with Eq. 2. The growth and yield reduction can also be compared to the O_3 exposure situation before 1980, calculated concerning the exceedance of the specific $TV_{PODySPEC}$."

R1-C28: line 240: "The percentage effect caused by O3" - you mean concentration or flux?

R1-R28: We thank the referee for highlighting this ambiguity. As clarified in R1-R25, the revised manuscript consistently distinguishes between O_3 concentration, which is used only as input to the stomatal flux model, and the vegetation response expressed in terms of stomatal O_3 uptake, quantified as the accumulated stomatal flux metric POD_YSPEC.

To avoid confusion, the phrase "percentage effect caused by O_3 " has been replaced by "percentage effect of stomatal O_3 uptake", indicating that the calculated effect is derived from POD_YSPEC rather than directly from ambient O_3 concentration. The revised wording is included in Sect. 2.3.2 and is shown in R1-R25 and R1-R17 (P8-P9, l185-285).

R1-C29: line 242: why you mix here comparison to 1980? Without any interconnection to the comparison before preindustrial era.

R1-R29: We thank the referee for this comment. In the UNECE flux-based framework two reference situations are considered for interpreting vegetation risk. The first is the pre-industrial reference level, represented by Ref10POD_YSPEC, which is derived assuming a background O_3 concentration of 10 ppb and is used in the dose-response function to calculate the relative reduction in biological endpoints. The second reference is the target value TV_{POD_YSPEC}, which represents the upper margin of O_3 exposure prior to the 1980s and is used as a policy-relevant benchmark for risk classification.

In the revised manuscript, this distinction between the pre-industrial reference used in the dose-response calculation and the target value used for risk interpretation has been clarified in Sect. 2.3.2..

R1-C30: line 243-245: This is completely unclear. You should write more clearly and describe abbreviations at their first use - as in line 242.

R1-R30: We thank the referee for this comment. The original wording did not clearly distinguish between the different reference concepts used in the UNECE flux-based framework. In the revised manuscript, we clarify that Ref10POD_YSPEC represents the pre-industrial reference level used in the dose-response calculation, whereas critical levels (CL_{POD_YSPEC},) and target values (TV_{POD_YSPEC}re threshold values applied to the accumulated stomatal flux metric POD_YSPEC for risk interpretation, with the target values corresponding to O_3 loads prior to the 1980s. The revised text in Sect. 2.3.2 now explicitly separates these concepts (see R1-R25-R1-R27 and revised manuscript in R1-R17, P8-P9, l185-285).

Original manuscript, (P9, l236- 246): "…2.3.2 Risk assessment

The percentage effect of the stomatal O3 uptake on the biological endpoints for each representative species set by default within the models is regarded as the preindustrial O3 exposure situation concerning the exceedance of the CLPOD_YSPEC. The mean preindustrial O3 concentration is set at 10 ppb, and the resulting accumulated stomatal O3 uptake due to O3 preindustrial concentrations is denoted as Ref10POD_YSPEC (Mills et al., 2017). The percentage effect caused by O_3 can be calculated with Eq. 2. The growth and yield reduction can also be compared to the O_3 exposure situation before 1980, calculated concerning the exceedance of the specific TVPOD_YSPEC.

$$\text{potential maximum reduction rate (\%)} = \left(\text{POD}_\text{y}\text{SPEC} - \text{Ref10POD}_\text{y}\text{SPEC}\right) * \text{\% reduction (per mmol m}^{-2}\text{ POD}_\text{y}\text{SPEC)} \quad \text{Eq. 2}$$

The O_3 risk assessment for the corresponding protection target is interpreted based on the exceedance of TVPOD_YSPEC and CLPOD_YSPEC. The higher the POD_YSPEC values are, the higher the risk. The maximum possible protection is provided if the CLPOD_YSPEC is not reached. If the TVPOD_YSPEC is exceeded, there is a high risk. With POD_YSPEC values in the range between the CLPOD_YSPEC and TVPOD_YSPEC, there is a moderate risk (German Institute for Standardization, 2020)."

R1-C31: line 255: before in the methods you wrote, that you did measure SWC, in here you write that you did model that. So what is true?

R1-R31: We thank the referee for pointing out this ambiguity. Soil water content (SWC) was not measured in this study, but estimated using a simplified soil water balance model, following the implementation described in VDI 2310 Sheet 6 and the approaches of Bender et al. (2015) and Simpson et al. (2007). The estimated volumetric soil water content (θ) was used to calculate plant-available water (PAW), which is incorporated into the Jarvis-type stomatal conductance model through the soil-moisture limitation function (f_{PAW}).

The worst-case scenario assumes that soil moisture does not limit stomatal conductance (f_{PAW}= 1), whereas the best-case scenario includes the modelled PAW limitation to reduce stomatal conductance and stomatal O_3 flux under dry conditions.

To avoid misunderstanding, the wording in the Abstract, Introduction and Sect. 2.3.3 has been revised to explicitly state that SWC is modelled rather than measured, and the soil-moisture parameterisation is now described in detail (see revised manuscript in R1-R17, Sect. 2.3.3).

Original manuscript, (P2, l32- 34): "…POD_1SPEC was applied to forests (spruce and beech) and grasslands, while POD_6SPEC was used for croplands (wheat). Risk estimations were conducted under two scenarios: a worst-case assuming unrestricted irrigation and a best-case incorporating modelled soil water content (SWC)."

Revised version, (P2, l32-35): Risk estimations were conducted under two scenarios: a worst-case assuming unrestricted irrigation (no limitation by SWC) and a best-case using modelled soil water content (SWC).

Original manuscript, (P4, l117-119): "…Two different scenarios are applied for the forest analysis, one assuming unrestricted irrigation and one incorporating modelled soil water content (SWC), with a specific focus on the role of drought and site elevation."

Revised version, (P4, l117-119): "Two different scenarios are applied for the forest analysis: one assuming unrestricted irrigation (no SWC limitation) and one incorporating modelled SWC from the VDI 2310/ICP Vegetation soil-moisture models, with a specific focus on the role of drought and site elevation.

Original manuscript, (P9, l247-257): "…2.3.3 Best and worst-case scenarios

The lower the soil water content (SWC), the drier the soil becomes, which limits stomatal conductance and reduces O_3 uptake, potentially lowering the risk of O_3-induced vegetation damage. According to current guidelines for local and regional O_3 risk assessment, the standard approach is to assume a worst-case scenario in which SWC does not limit stomatal uptake; in other words, O_3 uptake remains optimal even during dry soil conditions (German Institute for Standardization, 2020). Based on this recommendation, PODySPEC was calculated under worst-case conditions for all studied representative species (beech and spruce) for forests, grassland, and wheat (crops). In addition, since the main focus of this study is on forest ecosystems, a best-case scenario was applied only for beech and spruce to allow a more realistic evaluation of O_3 risk under drought conditions. This scenario included modelled soil water content to assess its effect on POD_1SPEC. The soil moisture models used for this were taken from the guideline's appendix (German Institute for Standardization, 2020), with further details available in (Bender et al., 2015; Simpson et al., 2007)."

R1-C32: 2.5 most of that is redundant

R1-R32: We thank the referee for this remark. Section 2.5 has been shortened by removing redundant explanatory text and retaining only the operational definition of AOT40, the accumulation periods used in this study, and the relevant regulatory thresholds. The revised section now briefly defines AOT40, specifies the calculation periods (May-July for general vegetation and April-September for forests), and lists the target value (9000 ppb h, 5-year mean) and critical level (5000 ppb h per year) used for comparison according to the EU Air Quality Directive and UNECE LRTAP Convention (European Parliament and Council, 2008)..

Original manuscript, (P10, l267-274): "…2.5 Cumulative ozone exposure (AOT40)

The accumulated Ozone exposure over a threshold of 40 ppb (AOT40) metric is the current European standard for the protection of vegetation (Lefohn et al., 2018). It represents the sum of all hourly O3 concentrations at the canopy top that exceeds 40 ppb during daylight hours between 08:00 and 20:00 for a given period in ppb h. Two periods are considered for the calculations of AOT40: May to July, when vegetation is most sensitive to O3, and April to September, when forests are to be protected. Based on the EU Air Quality Directive and the UNECE LRTAP Convention air quality standards for vegetation protection, the AOT40 TV for vegetation is 9000 ppb h, as a 5-year average. The CL for forests is 5000 ppb h per year (European Parliament and Council, 2008)."

Revised version, (P12, l298-304): 2.5 Cumulative ozone exposure (AOT40)

AOT40 (accumulated ozone exposure over a threshold of 40 ppb) is the European exposure-based standard for vegetation protection (Lefohn et al., 2018). It is defined as the sum of hourly O_3 concentrations above 40 ppb during daylight hours (08:00-20:00) over a given period. In this study, AOT40 was calculated for May-July (general vegetation) and April-September (forests). Thresholds used for comparison are 9000 ppb h (5-year mean target value for vegetation) and 5000 ppb h per year (critical level for forests) as defined in the EU Air Quality Directive and UNECE LRTAP Convention (European Parliament and Council, 2008).

R1-C33: 276-278: write better English - too complicated sentence

R1-R33: We thank the referee for this remark. The introductory sentences of Sect. 2.6 have been rewritten to improve clarity and readability. The previously long and complex sentence has been split into shorter statements, and the description of the drought metric has been clarified. In addition, the calculation of atmospheric water balance (AWB) and drought intensity is now presented explicitly with the corresponding equations. The revised text is shown below..

Original manuscript, (P12, l275-296): "…2.6 Drought events

As tropospheric O_3 and droughts have been shown to have combined effects on the tree growth decline of beech and Norway spruce in coniferous and deciduous forests in Europe (Eghdami et al., 2022), in this study, an analysis of droughts and their influence in O_3 stomatal uptake is carried out for forests at each studied site in Saxony. The duration of drought is a distinguishing characteristic of such events that can vary from days to years (Wilhite, 2000). SWC deficits are the leading cause of droughts on relatively short timescales of days in response to precipitation shortfalls (Bender et al., 2015; Kallis, 2008). This study assesses droughts considering the sum of dry days (the accumulation of daily negative atmospheric water balance (AWB), according to the Eq. 5.

$$Drought\ (mm) = Sum\ of\ daily\ negative\ AWB\ if\ PAW < 50\ \%\ of\ uFC \qquad \text{Eq. 5}$$

Dry days are days with negative atmospheric water balance (AWB; mm) for which the soil water supply decreases below 50 % of the useable field capacity (uFC) (Eghdami et al., 2020). The uFC is the difference between the field capacity and permanent wilting point estimated within the SWC models used to calculate the best-case scenario (see section 2.3.3) (Bender et al., 2015). In section 3.1: Risk assessment for coniferous and deciduous forests, the impact of droughts is addressed considering the number of dry days accumulated. Years with few dry days would have a higher O_3 uptake risk because water stress will not restrict leaf conductivity. In contrast, years with more dry days would lead to stomata closure, which protects the trees against increased water losses, and also reduces O_3 uptake.

The AWB is calculated from daily meteorological data as the difference between the sum of precipitation (P) and potential evapotranspiration (PET) according to Eq. 6.

$$AWB = P - PET \qquad \text{Eq. 6}$$

The daily PET can be calculated according to the Penman-Monteith method (Allen et al., 1998). To estimate the daily PET values of elevation, latitude, and daily weather data such as temperature, solar radiation, relative humidity, and mean wind speed were taken from the meteorological data of each station. The daily PET calculations were done through the fruclimadapt package from R (Miranda, 2023)."

Revised version, (P12, l305-330): l2.6 Drought events

Tropospheric O_3 and drought have been shown to interactively affect tree growth of beech and Norway spruce in European forests (Eghdami et al., 2022). Therefore, we analysed drought and its influence on stomatal O_3 uptake for forests. Drought duration can range from days to years (Wilhite, 2000), but on short timescales it is mainly driven by deficits in soil water content (SWC) caused by precipitation shortfalls (Bender et al., 2015; Kallis, 2008).

In this study, drought intensity at each site was quantified from the accumulation of daily negative atmospheric water balance (AWB, mm) during days classified as dry. This drought metric is independent of O_3 concentration and allows to analyse the co-occurrence of high O_3 exposure and water stress conditions. AWB was computed from daily meteorological data as:

$$AWB = P - PET \qquad \text{Eq. 9}$$

where P is daily precipitation and PET is daily potential evapotranspiration (mm d^{-1}). Dry days are days with negative AWB for which plant-available soil water (PAW) falls below 50% of the useable field capacity (uFC), following (Eghdami et al., 2020). The uFC is the difference between the field capacity and the permanent wilting point as estimated by the SWC models used in the best-case scenario, Sect. 2.3.3; (Bender et al., 2015). Drought intensity (D, mm) over a given period was then calculated as

$$D = \sum_{Dry\ days} (-AWB) \qquad \text{Eq. 10}$$

Potential evapotranspiration (PET) was calculated using the FAO Penman-Monteith equation (Allen et al., 1998):

$$PET = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad \text{Eq. 11}$$

where Δ is the slope of the saturation vapour pressure curve, R_n is net radiation, G is soil heat flux density, γ is the psychrometric constant, T is mean air temperature (°C), u_2 is wind speed at 2 m height (m s^{-1}), and $(e_s - e_a)$ is the vapour pressure deficit. The calculation follows the FAO-56 guidelines (Allen et al., 1998).

Daily PET was derived from meteorological observations at each station, including temperature, solar radiation, relative humidity, wind speed, elevation and latitude. All PET and AWB calculations were performed with the R package *fruclimadapt* (Miranda, 2023).

In Sect. 3.1 we relate the number of dry days to POD_YSPEC to evaluate how drought modulates O_3 uptake by trees. Years with few dry days are expected to show higher O_3 uptake and thus higher risk, because water stress does not substantially restrict stomatal conductance, whereas years with many dry days promote stomatal closure, lower transpiration losses and reduced O_3 uptake."

R1-C34: Eq 5. this is no equation. There must be physical variables.

R1-R34: We thank the referee for pointing this out. The original expression of Eq. 5 was written in a descriptive form rather than as a proper mathematical equation. In the revised manuscript, this has been replaced by explicit equations defining atmospheric water balance (AWB) and drought intensity, including the relevant physical variables precipitation (P) and potential evapotranspiration (PET). The revised section now first defines AWB as AWB = P − PET and subsequently expresses drought intensity as the accumulation of negative AWB values during dry days. The revised equations are provided in Sect. 2.6 (see revised manuscript in R1-R33).

Original manuscript, (P11, l282): "… according to the Eq. 5.

$$Drought\ (mm) = Sum\ of\ daily\ negative\ AWB\ if\ PAW < 50\,\%\ of\ uFC \qquad \text{Eq. 5}$$

."

R1-C35: Line 286: write better English

R1-R35: We thank the referee for this remark. The sentence has been rephrased to improve clarity and readability. In the revised manuscript, the relationship between the drought metric and the subsequent analysis of ozone uptake is now described more clearly. The revised wording is included in Sect. 2.6 (see revised manuscript in R1-R33).

Original manuscript, (P11, l286-287): "…In section 3.1: Risk assessment for coniferous and deciduous forests, the impact of droughts is addressed considering the number of dry days accumulated."

R1-C36: lines 293-296: how exactly did you calculate this? Please ass equation. Could you add comparison to eddy covariance measured data?

R1-R36: We thank the referee for this suggestion. In the revised manuscript, the calculation of potential evapotranspiration (PET) is now described with its corresponding equation in Sect. 2.6 (see revised manuscript in R1-R33).

Potential evapotranspiration (PET) is calculated using the FAO Penman-Monteith equation (Allen et al., 1998) based on daily meteorological variables from each station, including temperature, solar radiation, relative humidity, wind speed, latitude and elevation. The PET and AWB calculations were implemented using the ET_penman_monteith function of the R package fruclimadapt (Miranda, 2023).

Long-term eddy covariance flux measurements are unfortunately not available at the studied sites; therefore, a direct comparison with measured evapotranspiration or latent heat fluxes cannot be provided.

Original manuscript, (P11, l293-296): "…The daily PET can be calculated according to the Penman-Monteith method (Allen et al., 1998). To estimate the daily PET values of elevation, latitude, and daily weather data such as temperature, solar radiation, relative humidity, and mean wind speed were taken from the meteorological data of each station. The daily PET calculations were done through the fruclimadapt package from R (Miranda, 2023)."

R1-C37: line 305-309: so you did a pearson correlation test or PCA? Here you mix both together. very unclear what you have done.

R1-R37: We thank the referee for pointing out the lack of clarity. In the revised manuscript we now clearly distinguish between the two statistical approaches. Pearson correlation coefficients were calculated to quantify pairwise linear relationships between POD_1SPEC and individual environmental variables based on monthly data. In addition, a principal component analysis (PCA) was applied to yearly mean values of POD_1SPEC and the same environmental variables to analyse their joint dependence structure. The description of both analyses has been separated and clarified in Sect. 2.7.

Original manuscript, (P306-309): "…The Pearson correlation test was used to study the correlations of environmental variables with the POD1SPEC. To analyse the dependence among variables, e.g., yearly data POD1SPEC, daytime mean O_3 concentration, global radiation (GR), air temperature (T), soil water content (SWC), drought duration, atmospheric water balance (AWB), and the elevation of the sites, a principal component analysis (PCA) was developed."

Revised version, (P13, l331-343): "…2.7 Statistical analyses

The 15-year time series of environmental data used in this study exhibits non-normal distributions and extreme values. Therefore, non-parametric statistical tests were applied using a significance level of 5% ($p < 0.05$) and implemented in R.

To compare the distributions of observations under the two case scenarios (best-case and worst-case) for beech and spruce, the non-parametric two-sample Kolmogorov-Smirnov (KS) test was used(Massey, 1951; Teegavarapu, 2018). Short-term trends in POD_YSPEC, AOT40 and drought indicators were assessed using the Mann-Kendall test together with Sen's slope estimator (Teegavarapu, 2018). Differences in AOT40 between mountain and rural background sites were evaluated using the Mann-Whitney U-test (Teegavarapu, 2018).

Pearson correlation coefficients were calculated based on monthly data to quantify linear relationships between POD_1SPEC and individual environmental variables (daytime mean O_3 concentration, global radiation, air temperature, soil water content, drought duration, atmospheric water balance, and elevation). In addition, principal component analysis (PCA) with varimax rotation was applied to yearly mean values of POD_1SPEC and the same set of meteorological and site variables to examine their joint dependence structure and to identify the dominant gradients controlling O_3 risk."

R1-C38: line 316: Abbreviation should be defined at its 1st use, not again and again. Please check through the manuscript.

R1-R38:
We thank the referee for this remark. In the revised manuscript all abbreviations have been checked and

are now defined only at their first occurrence in the main text. After the first definition, only the abbreviated forms (e.g. POD_1SPEC, AOT40, SWC) are used consistently throughout the manuscript.

Original manuscript, (P12, l316-321): A comparison of POD_1SPEC from forests with the AOT40 metric (Accumulated Ozone exposure over a Threshold of 40 ppb) highlights differences in temporal behaviour and their implications for forest risk assessment. The analysis then explores the influence of environmental drivers on POD_1SPEC variability such as global radiation, O3 concentrations, and SWC, as well as elevation and climate. Finally, the role of drought is addressed by introducing the number of dry days as an indicator of droughts, and its interaction with daytime O3 concentrations is analysed to better understand vegetation risk under combined conditions.

R1-C39a: do not describe here what is in next sections! You should write shortly, not writing redundantly!

R1-R39a: We thank the referee for this remark. The introductory paragraph of Sect. 3 has been shortened and rewritten to remove the detailed description of the following subsections. The revised text now provides only a brief overview of the metrics and vegetation types considered.

Original manuscript, (P12, l311-327): "…Results and discussion

The results are structured to reflect the primary focus of this study: assessing the risk of ozone (O_3) deposition on forests. The analysis begins with a detailed evaluation of coniferous and deciduous tree species (spruce and beech) in section 3.1, for which both scenarios best-case (incorporates modelled soil water content (SWC)) and worst-case (assuming unrestricted plant irrigation) are considered. First, section 3.1 presents the temporal variation in POD_1SPEC under both scenarios, including intra-annual accumulation patterns under the best-case scenario and long-term trends from 2006 to 2020. A comparison of POD_1SPEC from forests with the AOT40 metric (Accumulated Ozone exposure over a Threshold of 40 ppb) highlights differences in temporal behaviour and their implications for forest risk assessment. The analysis then explores the influence of environmental drivers on POD_1SPEC variability such as global radiation, O_3 concentrations, and SWC, as well as elevation and climate. Finally, the role of drought is addressed by introducing the number of dry days as an indicator of droughts, and its interaction with daytime O_3 concentrations is analysed to better understand vegetation risk under combined conditions.

Section 3.2 focuses on grassland and cropland risk assessments. For grassland and wheat, O_3 risk was evaluated under worst-case scenario only. The potential economic losses associated with O_3-induced yield reductions in wheat are also estimated, assessing the implications for regional agriculture and food security.

While risk estimations under both scenarios and environmental driver analyses are applied in detail to forests, grassland and cropland assessments are limited to worst-case conditions, and economic impacts are quantified only for wheat using established dose-response functions. These differences in scope reflect the methodological priorities of the study."

Revised version, (P13, l345-351): This section presents the O_3 risk assessment for forests and vegetation in Saxony based primarily on the flux-based metric POD_YSPEC. For forests (beech and spruce), POD_YSPEC was analysed under a worst-case scenario, assuming unrestricted stomatal uptake, and under a best-case scenario, which includes soil-moisture limitation to account for drought effects on stomatal conductance. For grassland and crops O_3 risk is evaluated using the receptor-specific flux metrics POD_1SPEC and POD_6SPEC, respectively. For context, the flux-based results are compared with the concentration-based indicator AOT40. In addition, potential economic losses associated with O_3 induced yield reductions in wheat are estimated, and the influence of meteorological conditions and drought indicators on O_3 risk is examined.

.

.

R1-C39b: In here I stop reading, the above written issues are too major for this paper to be considered for publication.

R1-R39b: We thank the referee for the detailed comments provided on the earlier sections of the manuscript. These remarks were very helpful in improving the clarity and structure of the paper. In the revised version, the language has been carefully edited, redundant passages have been removed, and the methodological description has been clarified and streamlined, as detailed in our responses above. We hope that these revisions address the concerns raised and encourage a complete re-evaluation of the manuscript.

Referee #2

R2-C1: Authors Engelhardt et al. present an ozone risk assessment for forests and cropland for the German state of Saxony, based on in-situ ozone observations in cropland and mountainous regions. They consider exposure- and dose-based ozone impact metrics, and for the latter, they examine the impact of soil moisture. The choice of impact metric can affect the risk assessment, and therefore this topic is relevant for scientific and policy purposes related to air quality, but this manuscript unfortunately does not offer a large contribution to this topic. The methodology is not clearly described, the manuscript is poorly structured making it difficult to distill the key messages, and the presentation of the results is insufficient. Therefore, I cannot recommend publication of this article. Below, I list some key shortcomings that the authors may wish to address going forward.

R2-R1: We thank Referee #2 for the careful reading of the manuscript and for recognising the relevance of metric choice for ozone risk assessment. We acknowledge that the original version did not present the study design and key findings with sufficient clarity. In the revised manuscript, we have therefore improved the language and conciseness of the text, reduced redundant passages, and clarified the methodological description and analytical workflow. In particular, the Methods and Results sections were reorganised to ensure that definitions, assumptions and calculation steps are presented consistently. These revisions are detailed in the responses to Referee #1 (R1-R17, R1-R26, R1-R31, R1-R32, R1-R33, R1-R34-R1-R37) and further clarifications relevant to Referee #2 are provided in R2-R5b, R2-R19-R2-R21, and R2-R24.

We respectfully disagree, however, that the study does not provide a significant contribution. O_3 risk assessments that include Germany are often based on regional-scale models with coarse spatial resolution, e.g. (Schucht et al., 2021; Mills et al., 2018), which are not able to resolve fine-scale differences in meteorology, soil water properties and phenology (Mills et al., 2017). Moreover, such studies predominantly focus on rural and low- to mid-elevation forest areas, while mountain sites- despite often exhibiting higher O_3 concentrations and high conservation value remain underrepresented (Ehlers et al., 2016). The vegetation working group of the Tropospheric Ozone Assessment Report (TOAR) explicitly recommends expanding O_3 impact assessments to mountain ecosystems (Mills et al., 2018). To our knowledge, only very few studies have assessed O_3 risks for high-altitude forest sites in Germany based on long-term field observations, with (Baumgarten et al., 2009) being one of the rare examples and limited to a short time period.

Our study addresses this gap by analysing 15 years of in situ observations from both lowland and mountain sites using a consistent flux-based framework that also considers drought effects. This provides site-resolved evidence that complements existing regional modelling studies.

R2-C2a: Ozone flux calculation in the Methods section: the soil moisture function and the soil moisture models, key components of this study, are merely introduced by referring to another document. This document is not open-access and is written in German, so this is not accessible for the (English-speaking) reader. Therefore, this information must be included in this manuscript.

R2-R2a: We thank the referee for pointing out that the description of the soil-moisture parameterisation was insufficient in the original manuscript and relied on a non-open-access guideline.

In the revised manuscript, the calculation of the flux-based O_3 uptake is now described explicitly in Sect. 2.3, including the equations for stomatal conductance, stomatal O_3 flux and the accumulation of

POD_YSPEC (see R1-R17). The soil-moisture parameterisation and the derivation of plant-available water (PAW) are now presented in Sect. 2.3.3 together with the corresponding equations.

The soil-moisture limitation function f_{PAW} is implemented within the Jarvis-type stomatal conductance model following the UNECE Mapping Manual and the DO3SE framework (Simpson et al., 2007; Mills et al., 2017). By including these equations and parameter definitions directly in the manuscript, the methodology is now accessible without requiring consultation of the VDI guideline.

R2-C2b: Additionally, the authors acknowledge that the Jarvis (1976) formulation of stomatal conductance does not include the effect of SWC (line 215-216), but it is unclear how they apply this model to study the impact of soil moisture on ozone fluxes.

R2-R2b: We thank the referee for pointing out that the role of soil moisture within the Jarvis-type stomatal conductance formulation was not sufficiently clear in the original manuscript.

In the revised manuscript, this has been clarified by explicitly describing how soil moisture is incorporated into the Jarvis-type stomatal conductance model through a multiplicative soil-moisture limitation function f_{PAW} (Sect. 2.3.3). Plant-available water (PAW), derived from modelled volumetric soil water content, is used to regulate stomatal conductance: when PAW exceeds a species-specific threshold, stomatal conductance is not limited (f_{PAW}=1); below this threshold, f_{PAW} decreases linearly towards zero at the wilting point, thereby reducing stomatal conductance and the resulting stomatal O_3 flux.

In addition, the distinction between the worst-case scenario (no soil-moisture limitation, f_{PAW}=1 and the best-case scenario, in which modelled PAW dynamically limits stomatal conductance during dry conditions, is now described explicitly.

This clarification and the corresponding revisions to the manuscript are detailed in our response to R1-C31 (see R1-R31) and in the revised description of the soil-moisture parameterisation in Sect. 2.3.3 (see R1-R17).

R2-C3: Role of drought: the authors correctly identify that soil moisture may modulate ozone fluxes in the case of drought, and that ozone risk may be reduced in case of drought. However, droughts also affect vegetation productivity and crop yield. In turn, droughts may affect surface ozone concentrations by reducing stomatal uptake, e.g. (Lin et al., 2020) and by changing emissions of biogenic VOCs, e.g. (Peñuelas and Staudt, 2010). I would encourage the authors to consider the risks of drought and O_3 jointly in their analysis.

R2-R3: We thank the referee for this suggestion and agree that drought and O_3 should be considered jointly. In our analysis, drought was quantified independently of O_3 using atmospheric water balance (AWB) and the number of dry days (Sect. 2.6) and related to annual POD_YSPEC values in Sect. 3.1. Thus, the co-occurrence of high O_3 exposure and water stress conditions were already evaluated.

In the revised manuscript, we have strengthened the discussion in Sect. 3.1.3 to more clearly describe drought and O_3 as coupled stressors. While drought reduces stomatal conductance and may lower POD_γSPEC uptake, it simultaneously imposes direct physiological stress on vegetation. We also note that drought may influence atmospheric O_3 concentrations and biogenic VOC emissions, as reported by Lin et al. (2020) and Peñuelas and Staudt (2010). Accordingly, the following paragraph has been added to Sect. 3.1.3:

Revised version, (P26, l684-691): Overall, these findings indicate that drought and O_3 act as coupled stressors rather than independent drivers. While prolonged dry periods reduce stomatal O_3 uptake and may lower POD_1SPEC at rural sites, drought simultaneously imposes direct physiological stress that reduces growth and productivity independently of O_3. In addition, reduced stomatal uptake during drought may increase near-surface O_3 concentrations and alter biogenic VOC emissions, potentially reinforcing atmospheric O_3 formation at regional scales (Lin et al., 2020; Peñuelas and Staudt, 2010). Thus, drought may mitigate O_3 damage at the leaf level while exacerbating ecosystem-level risk through productivity losses and atmospheric feedbacks. These results highlight the need to consider drought and O_3 jointly when evaluating forest vulnerability under future climate conditions.

R2-C4a: The added value of the statistical assessment of the drivers of the ozone flux is unclear. The main conclusions merely seem to confirm pre-existing knowledge on the drivers of ozone uptake by vegetation.

R2-R4a: We thank the referee for raising this point. We agree that the physiological drivers of stomatal conductance and O_3 uptake are well established in the literature. The aim of the statistical analysis in this study is therefore not to re-establish these mechanisms, but to quantify how these known drivers manifest across the Saxon monitoring sites and how strongly they influence the variability of POD_1SPEC under recent climatic and pollution conditions.

In particular, the analysis allows us to (i) distinguish elevation-related climatic gradients from the direct O_3-radiation signal and (ii) identify differences in drought limitation between rural background and mountain sites. These aspects are relevant for interpreting the spatial variability of the flux-based risk estimates within the study region.

To clarify this purpose, the description and interpretation of the statistical analysis have been revised in the manuscript.

Revised version, (P20, l523-526): The aim of the statistical analysis is not to re-establish the physiological controls on stomatal conductance, but to quantify how these well-known drivers manifest across the Saxon sites and how strongly they influence POD_1SPEC under recent climatic and pollution conditions. In particular, the analysis helps distinguish elevation-related climatic gradients from the direct O_3-radiation signal and highlights differences in drought limitation between rural and mountain sites.

R2-C4b: As an example, the authors write: "Number of dry days as a key modulator of O_3 uptake" (l 575). This is incorrect, it is not the number of dry days that modulates ozone uptake, but rather the meteorological/environmental variables that affect stomatal conductance (in the Jarvis formulation: vapor pressure deficit and soil water content).

R2-R4b: We thank the referee for this clarification. We agree that stomatal O_3 uptake is directly controlled by environmental variables such as vapour pressure deficit and soil water content within the Jarvis formulation. In the revised manuscript, the wording in Sect. 3.1.3 has been corrected to describe the number of dry days as an indicator of drought stress, rather than a physiological driver of O_3 uptake.

The manuscript has been revised as follows:

Revised version, (P20, l523-526): The aim of this analysis is not to re-establish the general physiological controls on stomatal conductance, but to quantify how these drivers co-vary across the studied sites and how strongly they influence POD_1SPEC under current climate and pollution conditions. In particular, the PCA helps to distinguish the dominant O_3-radiation signal from elevation-related climatic gradients.

Revised version, (P23, l589): Section 3.1.3 Number of dry days as an indicator of drought stress influencing stomatal O_3 uptake

Revised version, (P24, l609-629): ***Number of dry days as an indicator of drought stress influencing stomatal O_3 uptake***

Overall, the number of dry days was higher at rural background sites than at mountain sites in Saxony between 2006 and 2020 (Figure S4). Years with a high number of dry days occurred throughout the time series at rural sites, except for 2007, whereas at mountain sites dry periods were less frequent and mainly observed in 2013 and from 2015 to 2019. These patterns help explain the stronger negative correlations between POD_1SPEC and drought duration at rural sites compared to mountain sites (Table S5).

It is important to note that the number of dry days is not itself a physiological driver of O_3 uptake, but represents an integrative indicator of sustained soil moisture deficit and elevated evaporative demand, which in turn constrain stomatal conductance. At rural background sites, years with more dry days were associated with lower annual POD_1SPEC accumulation during the growing season, particularly for beech (e.g., 2018). This indicates that prolonged drought conditions restrict stomatal O_3 uptake, consistent with previous studies showing reduced fluxes under sustained water stress (Buckley, 2019; Pirasteh-Anosheh et al., 2016).

This relationship was less pronounced at mountain sites. Despite extended dry periods, POD_1SPEC remained comparatively high for spruce and beech, especially at elevated locations such as Fichtelberg. This may reflect cooler temperatures, lower vapour pressure deficit, and generally higher soil moisture availability at high altitude, which mitigate drought stress and allow stomata to remain active. Species-specific physiological tolerance may further contribute. By contrast, at rural sites the increase in dry days during 2018 and 2019 coincided with reduced POD_1SPEC accumulation, reflecting stronger drought limitation of stomatal O_3 uptake (Gerosa et al., 2022).

To further explore these interactions, yearly accumulated POD_1SPEC and the number of dry days were analysed in relation to the 25th, 50th, and 75th percentiles of daytime O_3 concentrations (for hours with global radiation > 50 W m^{-2}), as well as their seasonal evolution (Figure 5 and Figure S5).

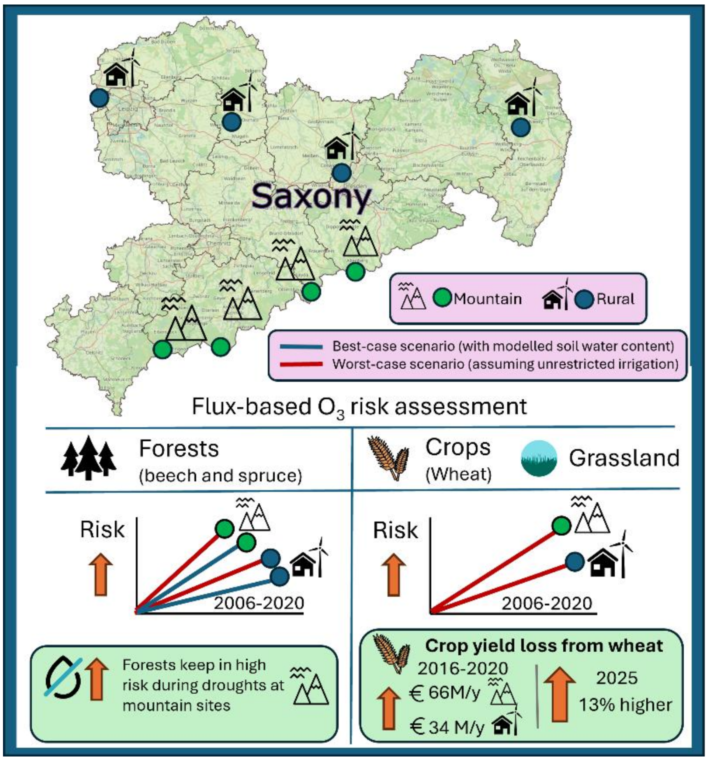
R2-C5a: Presentation of results. The graphical abstract unclear. I am unable to distill the key findings of the paper. What do the arrows and their colors indicate?

R2-R5a: We thank the referee for this comment. We agree that the original graphical abstract did not clearly convey the key findings and that the meaning of the arrows and colours was not sufficiently explained.

The graphical abstract has been revised to improve clarity. The results for forests are presented separately to the ones from crops and grassland, and a legend has been added. In the revised figure, blue lines represent the soil-moisture-limited ("best-case") scenario, whereas red arrows represent the non-limited ("worst-case") scenario. The upward line indicates increasing O_3 risk over the study period (2006-2020), and the circles distinguish mountain (green) and rural background sites (blue).

Key quantitative findings (e.g. crop yield losses and associated economic costs) are now also highlighted directly in the figure. The revised graphical abstract is provided below.

Revised version, (P1, l10-22):



R2-C5b: The different subsections in the Methods section are not well linked, making it difficult to understand how the different analysis steps relate to each other. As an example, the link between the use of the dose-response function and the economic impact analysis is unclear.

R2-R5b: We thank the referee for this comment. We agree that the methodological chain linking POD_6SPEC, the dose-response functions, and the economic loss calculations was not sufficiently explicit in the original version.

In the revised manuscript (Sect. 2.4), we clarify the analytical workflow. First, relative yield loss (RYL) is derived from the UNECE dose-response functions applied to POD_6SPEC. This RYL is then used to calculate crop production loss (CPL) and the associated economic cost loss (ECL). The corresponding equations and variables are now explicitly provided in the Methods section to make the sequence of calculations transparent.

Revised version, (P11, l286-297): 2.4 Economic loss

For wheat, the accumulated stomatal O_3 uptake metric (POD_6SPEC) was first translated into relative yield loss (RYL) using the established dose-response functions described in Sect. 2.3.2 and provided in the UNECE LRTAP Convention Mapping Manual (Mills et al., 2017). These functions quantify the percentage reduction in yield as a function of accumulated phytotoxic O_3 dose.

The estimated RYL was then used to calculate crop production loss (CPL) and the associated economic cost loss (ECL), following (Avnery et al., 2011; Sinha et al., 2015; Hu et al., 2020):

$$CPL = CP * \frac{RYL}{1 - RYL} \quad \text{Eq. 7}$$

$$ECL = CPL * MPP \quad \text{Eq. 8}$$

where CP is the annual wheat production in Saxony obtained from the Saxon State Ministry of Energy, Climate Protection, Agriculture and the Environment (Saxon Environment and Agriculture Ministry, 2021), and MPP is the German farm-gate producer price of wheat averaged over 2016-2020 (166.67 EUR t^{-1}) (German Ministry of Food and Agriculture, 2020). For policy context, an additional sensitivity evaluation was performed using projected farm prices for 2025 (189 EUR t^{-1}) (Dairy and Agricultural Economic Analysis Centre, 2025).

R2-C5c: The resolution of the figures is poor. This can be easily improved by saving the figures at a higher resolution.

R2-R5c: We thank the referee for this suggestion. In the revised manuscript, all figures have been exported at higher resolution to ensure clarity in both print and online versions.

R2-C5d: At various points in the manuscript, the text is highly redundant. Please consider writing more to the point.

R2-R5d: We thank the referee for this comment. In the revised manuscript, the text has been carefully edited to remove redundant phrases and repeated explanations, and several introductory and transition passages have been shortened to improve clarity and conciseness. These revisions were implemented throughout the manuscript, particularly in the Methods section (see also responses to Referee #1, R1-R17, R1-R32 and R1-R33).

R2-C6: Line 173: what does 'good' mean?

R2-R6: We thank the referee for this remark. We agree that the term "good" was vague. In the revised manuscript, this wording has been replaced by a quantitative description of data completeness. This clarification and the revised wording are provided in our response to Referee #1 (R1-R13).

R2-C7: Line 204-205: y is not defined. Do you mean Y?

R2-R7: We thank the referee for identifying this inconsistency. The symbol should indeed be the capital Y, as used in the definition of POD_YSPEC. In the revised manuscript, the notation has been corrected and Y is explicitly defined as the receptor-specific instantaneous stomatal flux threshold (nmol m^{-2} s^{-1}) below which O_3 is not considered phytotoxic. This correction and the corresponding clarification are described in our response to Referee #1 (R1-R17).

R2-C8: Line 215-216: Abbreviations for the meteorological variables are not defined.

R2-R8: We thank the referee for this remark. The abbreviations for the meteorological variables (T: air temperature, RH: relative humidity, WS: wind speed, GR: global radiation) are defined at their first occurrence in Sect. 2.2 (Dataset). We have checked the manuscript to ensure that these abbreviations are used consistently and defined only once, in accordance with the journal's guidelines. The definition of these variables and the description of the measurement setup were added in response to Referee #1 (R1-R11).

R2-C9: How do you convert these meteorological variables to their equivalent values at canopy height?

R2-R9: We thank the referee for this question. O_3 and meteorological variables are measured at fixed heights within the Saxon monitoring network (typically ~3-4 m for O_3, ~2 m for air temperature and relative humidity, and ~10 m for wind speed). In the flux-based models (FO3REST, GRASSLANDO3 and CRO3PS), these variables are converted to canopy-top conditions following the flux-based methodology described in the UNECE Mapping Manual and implemented in VDI 2310 Sheet 6. This includes the use of prescribed vertical gradients for O_3, a logarithmic wind profile for wind speed, and standard relationships for temperature and relative humidity. The procedure is now described explicitly in Sect. 2.3.1 of the revised manuscript. The corresponding clarification and revised text are provided in our response to Referee #1 (R1-R20, and R1-R17).

R2-C10: Equation 2: Please remove the units from the equations, and use more descriptive variable names (e.g. to replace 'potential maximum reduction rate').

R2-R10: We thank the referee for this suggestion. In the revised manuscript, units have been removed from the equation itself and are now provided only in the accompanying variable definitions. In addition, the previously ambiguous term "potential maximum reduction rate" has been replaced by the variable R, explicitly defined as the relative reduction in the biological endpoint (%). The parameter S is defined as the slope of the dose-response function (% per mmol m^{-2} POD_YSPEC). The equation and its variable definitions have been revised accordingly.

This correction and the corresponding clarification in the text are described in our response to Referee #1 (R1-R25).

R2-C11: Line 247: 'best-case' and 'worst-case' scenarios do not provide any information on what these scenarios actually mean. Please use more descriptive variable names.

R2-R11: We thank the referee for this comment. We agree that the terms "best-case" and "worst-case" may not have been sufficiently clear in the original manuscript. In this study, these labels are used as concise descriptors for scenarios with and without soil-moisture limitation of stomatal conductance within the flux-based modelling framework.

In the revised manuscript, the assumptions underlying these scenarios have been clarified in Sect. 2.3.3. The worst-case scenario assumes no soil-moisture limitation of stomatal conductance (f_{PAW}= 1) throughout the accumulation period), whereas the best-case scenario includes dynamic limitation of stomatal conductance based on modelled soil water content. This clarification makes the meaning of the scenario labels explicit.

The corresponding clarification in the manuscript is described in our response to Referee #1 (R1-R31).

R2-C12: Section 2.6: why don't you use soil moisture data from observations or from re-analysis datasets?

R2-R12: We thank the referee for this suggestion. In this study, soil moisture was not taken from observations or reanalysis datasets because the stomatal flux calculations follow the flux-based methodology implemented in VDI 2310 Sheet 6, where soil water content is estimated using a soil-water balance model consistent with the stomatal conductance parameterisation. Using this approach ensures internal consistency between the soil-moisture limitation function (f_{PAW}) and the stomatal flux calculations described in Sect. 2.3.3.

In addition, long-term continuous soil-moisture observations are not available for all stations over the full 15-year period analysed here. Reanalysis products would also introduce scale inconsistencies between grid-based soil-moisture estimates and the site-specific canopy-level flux calculations applied in this study.

R2-C13: Equation 5: this is not how an equation should be written.

R2-R13: We thank the referee for pointing this out. We agree that the original expression was descriptive rather than a formal mathematical equation. In the revised manuscript, drought intensity is now defined step-by-step through explicit equations for atmospheric water balance ($AWB = P - PET$), the dry-day criterion ($AWB < 0$ and $AWB <$ 50% of uFC), and the accumulation of negative AWB values during dry days. The revised equations and corresponding text are provided in our responses to Referee #1 (R1-R33-R1-R34).

Original manuscript, (P11, l282):

$$Drought\ (mm) = Sum\ of\ daily\ negative\ AWB\ if\ PAW < 50\ \%\ of\ uFC \quad \text{Eq. 5}$$

R2-C14: Line 336-338: where can I see the evidence for this?

R2-R14: We thank the referee for this remark. In the revised manuscript, the statements on the risk levels and temporal behaviour of POD_1SPEC are now explicitly supported by references to the corresponding figures and tables. Specifically, Fig. 2 presents the annual POD_1SPEC values for beech and spruce at rural and mountain sites together with the CL_{POD_YSPEC} and TV_{POD_YSPEC}, while Fig. S1 shows the station-specific time series for both scenarios. In addition, Table S4 provides the corresponding mean values, variability and trend statistics. These references have been added in Sect. 3.1.1 to make the evidence supporting the described risk levels and the decrease observed for beech at rural sites explicit.

To improve clarity, the entire subsection 3.1.1 (Temporal variability and vegetation risks) has also been rewritten to reduce redundancy, improve the english grammar and ensure that the interpretation of the results is directly supported by the referenced figures and tables.

Original manuscript, (P12, l328-486): "…Risk assessment for coniferous and deciduous forests

A summary of the accumulated POD1SPEC values for the representative species of coniferous and deciduous forests (beech and spruce) under their best and worst—case scenarios from 2006 to 2020 at mountain and rural background stations is presented in Figure 2. The time series of POD1SPEC values per station are shown in Figure S1. The mean values and annual trends of accumulated stomatal ozone flux (PODySPEC) per studied site types over the period 2006-2020 are shown in Table S4.

3.1.1 Temporal variability and vegetation risks

POD1SPEC trends for beech and spruce across scenarios and site types in Saxony

The POD_1SPEC for both representative species are mainly in the high-risk zone during the entire time serie of both scenarios, exceeding the critical levels (CL) and recommended target values (TV), except for the best-case scenario at rural sites, where POD_1SPEC are often below the TVs. For Beech, the yearly accumulated POD_1SPEC decreased from 2015, reaching the moderate risk zone at rural background stations for the best-case scenario. For spruce, the POD_1SPEC at rural background stations follows a similar pattern in both case scenarios. For the best-case scenario, the rural background sites Collmberg, Schkeuditz, and Niesky have been in the medium-risk category since 2018 (Figure S1). The exceedance in the CL of POD_1SPEC for coniferous and deciduous forests has been reported before in low-elevation sites in western and southern Germany (Eghdami et al., 2022a; Baumgarten et al., 2009).

The same pattern has been observed for forests in France, Italy, and Romania for 2017-2019 (Sicard et al., 2020; Gerosa et al., 2022).

The accumulated POD_1SPEC in Saxony is generally higher at mountain sites compared to rural background sites for the best-case scenario, decreasing by 34 and 42 % for the receptors beech and spruce, respectively (Figure 2). Spruce trees showed the more relevant differences (Table S4 and Figure S1), with the highest POD_1SPEC values for Fichtelberg, the most elevated mountain site among the others, with 1215 m.a.s.l. These results concord with what has been reported in previous studies for European forests at low and mid-elevation sites (Eghdami et al., 2022a; Wieser et al., 2000). At mountain sites, the higher O_3 concentrations and the lower temperatures could play a role in the higher POD_1SPEC accumulation. Also, it has been reported that, for spruce trees, O_3 stomatal uptake is higher at higher altitudes (Wieser et al., 2000).

The maximum potential loss for each biological endpoint per site type studied sites over the period 2006-2020 is shown in Table 2. For coniferous and deciduous forests, the mean potential maximum reduction rates (%) in the annual growth of the whole tree biomass in relation to exceeding the CL during the entire evaluated period (2006-2020) and for the best and worst-case scenarios range from 5.3 to 15.44 and from 1.56 to 4.84, for beech and spruce, respectively (Table 2).

Forests at mountain sites in Saxony were shown to have 60 and 70 % higher risk than at rural background sites for beech and spruce trees, respectively, under the best-case scenario concerning the critical level exceedance. Previous studies reported a decrease of 11% in tree biomass for spruce trees under elevated O_3 (an average of 64 ppb), compared with trees grown at ambient O_3 (Wittig et al., 2009). (FIGURE 2)

In Saxony, higher typical tropospheric O_3 concentrations occur in the Ore Mountains (~ 75 µg m^{-3}) than in rural background sites (~ 50 µg m^{-3}) (Wang et al., 2025) which supports the observed greater biomass reduction in these areas. This suggests that higher O_3 concentrations at elevation contribute significantly to the vegetation risk for both coniferous and deciduous trees. Over time, the decline in biomass production due to O_3 damage may also cause amplifying feedback. Since less atmospheric CO_2 from the air is sequestered into forest biomass, warming could accelerate in the short term due to reduced carbon uptake (Felzer et al., 2007).

Temporal patterns and scenario variations at rural and mountain sites

The mean of the accumulated POD_1SPEC (mean ± standard deviation; mmol O_3 m^{-2}) during the time series 2006 - 2020, at rural sites, for the best case and worst case scenarios for beech was 12.99 ± 3.12, and 16.61 ± 2.21 mmol O_3 m^{-2}, respectively, while at mountain sites, it was 19.58 ± 1.86, and 20.11 ± 2.42 mmol O_3 m^{-2} (Table S4), being 22 and 3 % lower for the best case than the worst case, respectively. For spruce, the mean of the accumulated POD_1SPEC at rural sites was 18.57 ± 3.04 and 19.85 ± 1.78 mmol O_3 m^{-2}, respectively, while at mountain sites, it was 31.68 ± 3.04 mmol O_3 m^{-2} and 31.72 ± 2.98 mmol O_3 m^{-2} (Table S4), being 7 % lower for the best case than the worst case, for rural sites. The results for spruce found in this study are similar to the ones reported for central European forests at mid-high altitude sites in Rhineland-Palatinate, Germany, with an average for all sites in the yearly accumulated POD_1SPEC of 22,18 mmol O_3 m^{-2} (Eghdami et al., 2022a).

Table 2

Maximum potential reduction rate (%) for each biological endpoint in all studied sites over the period 2006-2020, in comparison to a) preindustrial O3 exposure, b) O_3 exposure before 1980, and c) concerning the exceedance of the respective critical level (CL).

PODySPEC	Specie	Scenario	Site type	Biological endpoint	Potential max. reduction rate (%)		
					in comparison to "pre-industrial" O_3 exposure	In relation to the exceedance of CL	in comparison to O_3 exposure before 1980 (in relation

							to the exceedance of TV)
POD_1SPEC	Beech	Best-case	Rural	Annual growth of whole tree biomass	9.30	5.3	2
		Worst-case			14.1	10.1	2.9
		Best-case	Mountain		18	14	6.7
		Worst-case			19.4	15.4	8.2
	Spruce	Best-case	Rural	Annual growth of whole tree biomass	3.6	1.6	0.3
		Worst-case			4.2	2.2	0.9
		Best-case	Mountain		6.8	4.8	3.5
		Worst-case			6.8	4.8	3.6
	Grassland	Worst-case	Rural	Above-ground biomass	22	6.4	-
				Total biomass	8.8	-2.8	-
				Flower number	21.4	11.4	4.6
			Mountain	Above-ground biomass	24.7	9.2	-
				Total biomass	10	-0.1	-
				Flower number	26.0	16.0	9.2
POD_6SPEC	Wheat	Worst-case	Rural	Grain yield	11.94	6.93	0.39
			Mountain		21.18	16.17	9.63

In the POD_1SPEC time series of the different scenarios for spruce, and, with the exception of the last years (2014 - 2020), for the best-case scenario for rural sites, an even distribution of POD_1SPEC can be observed for spruce per site types (mountain and rural). Conversely, the POD_1SPEC distribution for beech within the time series is quite uneven across the years. Also, the two-sample Kolmogorov-Smirnov test indicated that the difference between scenarios is statistically significant for beech. It is possible that beech trees are more influenced by SWC than spruce (Hesse et al., 2024; Martinetti et al., 2025). Also, that deciduous tree species like beech, may be more sensitive to O_3 than evergreen coniferous species, like spruce, due to higher gas exchange rates or reduced detoxification ability (Emberson, 2020). These findings indicate that estimating the risk of vegetation damage due to O_3 for deciduous forests, using beech in a worst-case scenario setting produces overestimations.

00.0Furthermore, the mean of the last five years in the time series (2015 - 2020) at rural background sites for beech 10.9 ± 3.26 mmol O_3 m^{-2}, and spruce 16.3 ± 3.29 mmol O_3 m^{-2}, representing reductions of 16% and 12%, respectively, compared to the full-time series. Negative POD_1SPEC trends have been reported for European forests (Eghdami et al., 2022a), attributing it to SWC and drought duration. In our case, exploring the possible causes for the observed negative trend for POD_1SPEC for forests will be discussed in more detail in section 3.3 POD1SPEC drivers for coniferous and deciduous forests, where environmental variables and droughts are evaluated.

Intra-annual POD_1SPEC trends for beech and spruce (2006-2020)

The evolution in the mean accumulated POD_1SPEC for the best-case scenario of beech and spruce per day of the year during the accumulation period for mountain and rural background stations from 2006 to 2020 is shown in Figure 3. For both representative species, POD_1SPEC grows right from the beginning, during spring (from DOY ~ 60), having their higher evolution during summer (from DOY ~ 152). A plateau for beech is reached after the start of autumn (from DOY ~ 244), compared to spruce, which continues accumulating during that season, albeit much more slowly than before. POD_1SPEC for both species accumulates at a fast rate for mountain sites compared to what is observed for rural background sites (Figure 3)The steep growth and exceedance in the CL during spring observed for beech and spruce in Saxonian sites are occurring at around the same time as what is reported for Bavarian forests in Southern Germany (Baumgarten et al., 2009) and low-elevation forests in western Germany (Eghdami et al., 2022a). O_3 stomatal uptake for coniferous and deciduous forests in Germany is optimal during spring due to optimal environmental and phenological conditions for gas exchange, e.g., excellent nutrient conditions and sufficient soil water supply caused by higher precipitation during the winter months filling the water reservoirs. In Germany, O_3 stomatal uptake in coniferous species like spruce is reduced by lower air temperature (Wieser et al., 2000), which could explain why O_3 stomatal uptake decreases for our case study in autumn.

Comparison of AOT40 and POD_1SPEC: Differences in O_3 risk metrics across site types

Due to methodological differences, AOT40 and POD_1SPEC are not directly comparable. However, differences in their results for Saxony are evident, particularly regarding exceedances of their respective thresholds. For AOT40, the critical level

(**FIGURE 3**)

The evolution of AOT40 for the protection of forests and vegetation during (DOY) of the accumulation period is higher and increases faster at mountain sites than at rural background sites, reflecting the generally higher O_3 concentrations observed at mountain locations. Higher O_3 concentrations at mountain sites in Saxony are caused mainly by a lower circulation of polluted air masses, characterized by less O_3 destruction by NO and stratospheric intrusions (Herman et al., 2001; Wieser et al., 2009). These observations are consistent with the analysis by (Wang et al., 2025), who likewise reported elevated O_3 levels at Saxon mountain ridge stations (785-1214 m a.s.l.), together with evidence for enhanced free-tropospheric mixing, reduced deposition, and a declining 'rural decrement' over time.

The AOT40 for the protection of forests and vegetation, both showed faster increases at mountain sites compared to rural background sites (Figure 3). The AOT40 for the protection of forests for both site types grew fast, exceeding its CL right in spring, just 30 and 40 days after the start of the accumulation period (April 1st), reaching a first high by the DOY ~ 225, to later continue increasing more monotonically until the end of the accumulation period (30^{th} of September) (Figure 3). The AOT40 for vegetation protection growing rate was slow in the first part of its accumulation period, starting on the DOY ~ 121, reaching a first maximum on the DOY ~ 137 (May 17^{th}), to later grow slowly and exceed the TV 5-year AOT40 set in the Air Quality Directive (9000 ppb h) at mountain and rural background sites, on the DOY ~ 165 (~June 14^{th}) and 180 (~June 29^{th}), respectively (Figure 3) (Mills et al., 2017) (European Parliament and Council, 2008).

The differences in the growing behaviours for AOT40 to protect forests and vegetation can be explained by considering the average course in the daylight concentrations of O_3 between seasons, from which only the ones exceeding the 40-ppb threshold would have accumulated for the respective AOT40. As the accumulation period for AOT40 to protect forests starts earlier during spring, higher O_3 concentrations at lower temperatures cause such higher accumulation from the beginning, compared to AOT40 to protect vegetation. Such slow evolution in the AOT40 during the first part of the accumulation can be attributed to O_3 concentrations below the threshold of 40 ppb from the DOY 121 to later having different growth rate periods.

Compared to AOT40 for vegetation protection, POD_1SPEC for beech and spruce shows a steeper increase and higher accumulated values, which implies a more accurate risk assessment by POD_1SPEC

(Figure 3). This occurs because POD_1SPEC accounts for species-specific stomatal uptake, which continues whenever stomata are open, including at O_3 concentrations below the 40-ppb threshold that AOT40 requires. As a result, POD_1SPEC provides a more biologically relevant assessment of O_3 risk than AOT40, which is based solely on exceedances of an external concentration threshold. This pattern is consistent with established understanding that flux-based metrics such as PODySPEC provide a more biologically relevant assessment of O_3 risk than concentration-based indices like AOT40, as they account for species-specific stomatal uptake. Our results illustrate this difference for beech and spruce, where POD_1SPEC accumulates more strongly than AOT40 during the growing season. Similar contrasts between AOT40 and POD-based indices have also been reported in an Alpine larch forest (Finco et al., 2017), and a Holm oak forest in Rome, Italy (Gerosa et al., 2009).

Overall, using the AOT40 metric provides useful concentration-based index of O_3 exposure, but is has inherent limitations. Because it only accumulates concentrations above 40 ppb, it does not account for possible effects at lower concentrations, nor does it consider stomatal uptake or species-specific physiological responses (Matyssek et al., 2004). Thus, AOT40 generally mimics the temporal and spatial distribution of ambient O_3, whereas flux-based metrics such as PODySPEC additionally capture stomatal O_3 uptake and its modulation by environmental drivers, providing a more biologically relevant assessment (Mills et al., 2017)."

Revised version, (P14, l353-517): Risk assessment for coniferous and deciduous forests

A summary of the accumulated POD_1SPEC values for the representative forest species beech and spruce under the best-case and worst-case scenarios from 2006-2020 at mountain and rural background stations is shown in Fig. 2. Station-specific time series are presented in Fig. S1, while mean values and trend statistics for each site type are summarised in Table S4. The resulting estimates of potential reductions in forest growth associated with these flux levels are reported in Table 2.

3.1.1 Temporal variability and vegetation risks

POD_1SPEC trends for beech and spruce across scenarios and site types in Saxony

Across most sites and years. POD_1SPEC values for both species fall within the high-risk range, exceeding both the CL_{POD_YSPEC} and TV_{POD_YSPEC} (Fig. 2). An exception occurs for the best-case scenario at rural background sites, where POD_1SPEC frequently remains below the TV_{POD_YSPEC}. For beech, the annual accumulated POD_1SPEC at rural sites shows a decreasing tendency after 2015, reaching the moderate-risk range under the best-case scenario (Fig. 2; Fig. S1). Spruce shows a comparable temporal behaviour at rural sites under both scenarios, although several stations (Collmberg, Schkeuditz and Niesky) fall into the moderate-risk category under the best-case scenario after 2018 (Fig. S1).

Exceedance of flux-based critical levels for forest species has also been reported at other European sites, including low-elevation forests in western and southern Germany (Baumgarten et al., 2009; Eghdami et al., 2022a) and forest ecosystems in France, Italy and Romania (Sicard et al., 2020; Gerosa et al., 2022).

Accumulated POD_1SPEC values are generally higher at mountain sites than at rural background stations. Under the best-case scenario, mean values decrease by 34% for beech and 42% for spruce when moving from mountain to rural sites (Fig. 2; Table S4). The largest values occur at the high-elevation site Fichtelberg (1215 m a.s.l.), particularly for spruce (Fig. S1). Similar altitude-related increases in stomatal O_3 uptake have been reported for European forests, where elevated sites often experience higher O_3 concentrations and environmental conditions favourable for stomatal uptake (Wieser et al., 2000; Eghdami et al., 2022a).

The estimated potential reduction in forest growth associated with these flux levels is summarised in Table 2. For the period 2006-2020, the mean potential reduction in annual whole-tree biomass due to CL_{POD_YSPEC} exceedance ranges from 5.3-15.4% for beech and 1.6-4.8% for spruce, depending on site type and scenario.

Forests at mountain sites in Saxony show substantially higher estimated O_3 risk than rural background forests. Under the best-case scenario, the estimated reduction in biomass growth associated with the exceedance of CL_{POD_YSPEC} is approximately 60 % higher for beech and 70 % higher for spruce at mountain sites compared with rural background sites (Table 2). These differences are consistent with the higher average O_3 concentrations observed in the Ore Mountains (~75 µg m^{-3}) compared with rural background conditions (~50 µg m^{-3}) (Wang et al., 2025), which enhance stomatal O_3 uptake and associated vegetation risk. Previous studies have also reported reductions in tree biomass under elevated O_3 exposure, for example an average decrease of about 11 % in spruce biomass at elevated O_3 concentrations (~64 ppb) compared with ambient conditions (Wittig et al., 2009).

(FIGURE 2)

Long-term reductions in forest productivity caused by O_3 exposure may also have broader implications for ecosystem carbon balance. Reduced biomass accumulation implies lower carbon sequestration in forest ecosystems, potentially contributing to climate feedbacks through decreased CO_2 uptake (Felzer et al., 2007).

Temporal patterns and scenario variations at rural and mountain sites

For beech, the mean accumulated POD_1SPEC (mean ± standard deviation; mmol O_3 m^{-2}) over the period 2006-2020 at rural sites was 12.99 ± 3.12 under the best-case scenario and 16.61 ± 2.21 under the worst-case scenario. At mountain sites, the corresponding values were 19.58 ± 1.86 and 20.11 ± 2.42 mmol O_3 m^{-2}, respectively (Table S4). Thus, POD_1SPEC values for beech were 22% lower under the best-case scenario at rural sites and 3% lower at mountain sites compared with the worst-case scenario.

For spruce, the mean accumulated POD_1SPEC at rural sites was 18.57 ± 3.04 under the best-case scenario and 19.85 ± 1.78 mmol O_3 m^{-2} under the worst-case scenario. At mountain sites, the mean values were 31.68 ± 3.04 and 31.72 ± 2.98 mmol O_3 m^{-2}, respectively (Table S4). Under rural conditions, the best-case scenario produced 7% lower POD_1SPEC values than the worst-case scenario. The magnitude of the spruce fluxes observed in Saxony is comparable to values reported for central European forests at mid- to high-elevation sites in Rhineland-Palatinate, Germany, where the average annual accumulated POD_1SPEC was 22.18 mmol O_3 m^{-2} (Eghdami et al., 2022a).

Table 2

Relative reduction in biological endpoints (%) estimated from annual $\boldsymbol{POD_YSPEC}$ values for the period 2006-2020 at all studied sites and scenarios using the UNECE flux-based dose-response functions. Reductions refer to the biological endpoints listed in the table and are expressed relative to the pre-industrial reference flux Ref10$\boldsymbol{POD_YSPEC}$, and in relation to exceedance of the $\boldsymbol{CL_{POD_YSPEC}}$, and $\boldsymbol{TV_{POD_YSPEC}}$.

					Relative reduction in biological endpoints (%)		
$\boldsymbol{POD_YSPEC}$	**Specie**	**Scenario**	**Site type**	**Biological endpoint**	**Relative to Ref10 $\boldsymbol{POD_YSPEC}$**	**Relative to $\boldsymbol{CL_{POD_YSPEC}}$**	**Relative to $\boldsymbol{TV_{POD_YSPEC}}$**
POD_1SPEC	Beech	Best-case	Rural	Annual growth of whole tree biomass	9.30	5.3	2
		Worst-case			14.1	10.1	2.9
		Best-case	Mountain		18	14	6.7
		Worst-case			19.4	15.4	8.2
	Spruce	Best-case	Rural	Annual growth of whole tree biomass	3.6	1.6	0.3
		Worst-case			4.2	2.2	0.9
		Best-case	Mountain		6.8	4.8	3.5
		Worst-case			6.8	4.8	3.6

	Grassland	Worst-case	Rural	Above-ground biomass	22	6.4	-
				Total biomass	8.8	-2.8	-
				Flower number	21.4	11.4	4.6
			Mountain	Above-ground biomass	24.7	9.2	-
				Total biomass	10	-0.1	-
				Flower number	26.0	16.0	9.2
POD_6SPEC	Wheat	Worst-case	Rural	Grain yield	11.94	6.93	0.39
			Mountain		21.18	16.17	9.63

Inspection of the time series indicates that POD_1SPEC values for spruce are relatively evenly distributed across years and site types (mountain and rural), except for the later years of the best-case scenario at rural sites (2014-2020). In contrast, the temporal distribution of POD_1SPEC for beech shows greater interannual variability. The two-sample Kolmogorov-Smirnov test (Table S6) further indicates that the difference between scenarios is statistically significant for beech.

This behaviour may reflect differences in species sensitivity to soil water availability. Beech trees are reported to be more strongly influenced by soil water content than spruce (Hesse et al., 2024; Martinetti et al., 2025). In addition, deciduous species such as beech may be more sensitive to O_3 exposure than evergreen conifers due to higher gas-exchange rates or lower detoxification capacity (Emberson, 2020). These findings suggest that estimating O_3-induced vegetation risk for deciduous forests using only worst-case scenario conditions may lead to overestimation of damage.

Negative trends in POD_1SPEC are observed at rural background sites under the best-case scenario for both species (Sen's slope ≤ -0.34) and for spruce at mountain sites (Sen's slope ≤ -0.16) (Table S4). The mean values for the final five years of the time series (2015-2020) at rural background sites were 10.9 ± 3.26 mmol O_3 m^{-2} for beech and 16.3 ± 3.29 mmol O_3 m^{-2} for spruce, corresponding to reductions of 16% and 12%, respectively, relative to the full 2006-2020 period.

Declining POD_1SPEC trends have previously been reported for European forests and attributed to changes in soil moisture availability and drought duration (Eghdami et al., 2022a). In this study, the potential drivers of the observed POD_1SPEC trends are analysed further in Sect. 3.3, where environmental variables and drought indicators are examined in detail.

Intra-annual POD_1SPEC trends for beech and spruce (2006-2020)

The evolution of the mean accumulated POD_1SPEC for the best-case scenario of beech and spruce per day of the year during the accumulation period at mountain and rural background stations from 2006 to 2020 is shown in Fig. 3. For both species, POD_1SPEC begins to accumulate during early spring (from DOY ≈ 60) and increases rapidly towards summer (from DOY ≈ 152). For beech, accumulation approaches a plateau after the onset of autumn (from DOY ≈ 244), whereas spruce continues to accumulate during this period, although at a considerably slower rate.

For both species, the accumulation rate is consistently higher at mountain sites than at rural background sites (Fig. 3). The rapid spring increase and early exceedance of the critical level observed at the Saxon sites occur at similar times as reported for Bavarian forests in southern Germany (Baumgarten et al., 2009) and low-elevation forests in western Germany (Eghdami et al., 2022a).

High stomatal O_3 uptake during spring is consistent with favourable environmental and phenological conditions for gas exchange, including active leaf development, adequate soil water availability following winter precipitation, and suitable radiation conditions. In contrast, stomatal O_3 uptake decreases later in the season as environmental conditions become less favourable. For coniferous species such as spruce, lower air temperatures in autumn are known to reduce stomatal conductance and thereby limit O_3 uptake (Wieser et al., 2000).

Overall, these seasonal patterns indicate that the majority of stomatal O_3 uptake in Saxon forests occurs during spring and early summer, with consistently higher accumulation at mountain sites than at rural background locations.

Comparison of AOT40 and POD_1SPEC: Differences in O_3 risk metrics across site types

Because AOT40 and POD_1SPEC are based on fundamentally different approaches, their results are not directly comparable. AOT40 is a concentration-based exposure index, whereas POD_1SPEC represents accumulated stomatal O_3 uptake. Consequently, the two metrics differ in their accumulation periods and threshold definitions. For AOT40, the critical level (CL) for forest protection is defined for the April-September accumulation period, while the target value (TV) for general vegetation protection applies to May-July. In contrast, POD_1SPEC thresholds are defined for each receptor species, with species-specific accumulation periods applied in this study (Sect. 2.3).

Figure 3 compares the evolution of the mean accumulated AOT40 and POD_1SPEC values during the respective accumulation periods for mountain and rural background stations. For AOT40, accumulation rates are consistently higher at mountain sites than at rural sites, reflecting the generally elevated O_3concentrations observed at higher elevations. In Saxony, such enhanced O_3levels at mountain stations are associated with reduced titration by NO and a stronger influence of free-tropospheric air masses (Herman et al., 2001; Wieser et al., 2009). Similar patterns have been reported by Wang et al. (2025), who documented higher O_3 concentrations at Saxon mountain ridge stations (785-1214 m a.s.l.) together with increased free-tropospheric mixing and reduced deposition.

For the forest protection metric, AOT40 increases rapidly after the beginning of the accumulation period on 1 April, exceeding the CL approximately 30-40 days after the start of accumulation and reaching a first maximum around DOY ≈ 225 before continuing to rise more gradually until the end of September (Fig. 3). In contrast, AOT40 for vegetation protection (May-July) increases more slowly during the early part of the accumulation period and exceeds the regulatory target value of 9000 ppb h around DOY ≈ 165 (≈14 June) at mountain sites and DOY ≈ 180 (≈29 June) at rural sites.

These differences in accumulation behaviour largely reflect seasonal variations in daytime O_3concentrations. Because AOT40 only accumulates concentrations above the 40 ppb threshold, its growth rate depends strongly on how frequently this threshold is exceeded during the accumulation period. Early-spring concentrations exceeding this threshold lead to a rapid increase in the forest AOT40 metric, whereas lower concentrations during late spring slow the accumulation of the vegetation metric.

Compared with AOT40, POD_1SPEC for beech and spruce shows a steeper increase and higher accumulated values during the growing season (Fig. 3). This difference arises because POD_1SPEC accounts for stomatal uptake and therefore accumulates O_3 flux whenever stomata are open, including at concentrations below the 40-ppb threshold required for AOT40. Consequently, flux-based metrics capture plant exposure more directly than concentration-based indices. Similar contrasts between AOT40 and POD-based indices have been reported for European forest ecosystems, including an Alpine larch forest (Finco et al., 2017) and a Holm oak forest in Rome (Gerosa et al., 2009).

Overall, the comparison highlights that AOT40 primarily reflects the seasonal evolution of ambient O_3concentrations, whereas POD_1SPEC captures the biologically relevant stomatal uptake. For the Saxon sites analysed here, this results in systematically higher and earlier accumulation of POD_1SPEC compared with AOT40, indicating that flux-based metrics identify vegetation risk more consistently across the growing season.

R2-C15: Line 356-357: where can I see the evidence for this?

R2-R15: We thank the referee for this remark. The sentence has been clarified and now explicitly refers to Table 2, where the estimated reductions in biomass growth associated with CL_{POD_YSPEC} exceedance are reported for rural and mountain sites. The statement that the estimated risk is approximately 60 % higher for beech and 70 % higher for spruce at mountain sites is derived from the comparison of the corresponding rural and mountain values reported in Table 2 under the best-case scenario.

As explained in our response to R2-R14, the subsection has been revised to ensure that all statements are directly supported by the referenced figures and tables.

Original manuscript, (P13, l356-359): "…Line 352-359: Forests at mountain sites in Saxony were shown to have 60 and 70 % higher risk than at rural background sites for beech and spruce trees, respectively, under the best-case scenario concerning the critical level exceedance. Previous studies reported a decrease of 11% in tree biomass for spruce trees under elevated O3 (an average of 64 ppb), compared with trees grown at ambient O3 (Wittig et al., 2009)."

R2-C16: Line 357-359: this is a reference to a result from another study. I don't think this belongs in the Results section.

R2-R16: We thank the referee for this remark. As Sect. 3 combines Results and Discussion, the reference to Wittig et al. (2009) is used to place the magnitude of the estimated biomass reductions derived from the $POD_Y SPEC$ analysis into the context of previously reported O_3 effects on forest growth. The sentence has been revised to clarify that this citation provides contextual interpretation rather than a primary result. The revised wording can be found in the fully revised subsection 3.1.1 (Temporal variability and vegetation risks) (see R2-R14, Revised manuscript, P14, l353-517), and R2-R15.

R2-C17: Line 388: "the observed greater biomass reduction in these areas". What type of biomass observations were used here?

R2-R17: We thank the referee for pointing this out. No direct biomass observations were used in this study. The biomass reductions referred to in the text represent estimated potential reductions derived from the $POD_1 SPEC$ dose-response relationships, as described in Sect. 2.3.2 and reported in Table 2. The sentence has been revised to clarify that the values refer to model-derived estimates of biomass reduction associated with $CL_{POD_Y SPEC}$ exceedance, rather than observed biomass changes. The revised wording can be found in the fully revised subsection 3.1.1 (Temporal variability and vegetation risks) (see R2-R14, Revised manuscript, P14, l353-517).

Original manuscript, (P13, 387-392): "…In Saxony, higher typical tropospheric O3 concentrations occur in the Ore Mountains (~ 75 µg m-3) than in rural background sites (~ 50 µg m-3) (Wang et al., 2025) which supports the observed greater biomass reduction in these areas. This suggests that higher O_3 concentrations at elevation contribute significantly to the vegetation risk for both coniferous and deciduous trees. Over time, the decline in biomass production due to O3 damage may also cause amplifying feedback. Since less atmospheric CO2 from the air is sequestered into forest biomass, warming could accelerate in the short term due to reduced carbon uptake (Felzer et al., 2007).

R2-C18: Line 390-392: again, this is a reference to a result from another study. I don't think this belongs in the Results section.

R2-R18: We thank the referee for this remark. As Sect. 3 combines Results and Discussion, the reference to Felzer et al. (2007) is included to place the estimated reductions in forest productivity into a broader ecosystem context. The sentence has been revised and softened to clarify that this statement refers to potential implications for ecosystem carbon balance, rather than a direct result of the present study. The revised wording is included in the fully revised subsection 3.1.1 (Temporal variability and vegetation risks) (see R2-R14, Revised manuscript, P14, l353-517).

R2-C19: Caption of Table 2: "maximum potential reduction rate". Maximum reduction of what variable?

R2-R19: We thank the referee for pointing out that the wording in the original caption was unclear. In the revised manuscript, the caption of Table 2 has been rewritten to explicitly state that the values represent the relative reduction in biological endpoints (%), derived from the $POD_Y SPEC$ dose-response relationships. The biological endpoints considered (grain yield, whole-tree biomass, above-ground biomass, and flower number) are specified in the table and correspond to the receptor-specific protection goals described in Sect. 2.3.2.

Original manuscript, (P15, l402-405): "…Table 2 Maximum potential reduction rate (%) for each biological endpoint in all studied sites over the period 2006-2020, in comparison to a) preindustrial O3 exposure, b) O_3 exposure before 1980, and c) concerning the exceedance of the respective critical level (CL)."

Adjusted manuscript, (P16, l425-429): Table 2 Relative reduction in biological endpoints (%) estimated from annual $\boldsymbol{POD_Y SPEC}$ values for the period 2006-2020 at all studied sites and scenarios using the UNECE flux-based dose-response functions. Reductions refer to the biological endpoints listed in the table and are expressed relative to the pre-industrial reference flux Ref10$\boldsymbol{POD_Y SPEC}$, and in relation to exceedance of the $\boldsymbol{CL_{POD_Y SPEC}}$, and $\boldsymbol{TV_{POD_Y SPEC}}$.

R2-C20: Line 407-409: where can I see the evidence for this?

R2-R20: We thank the referee for this remark. The section has been revised to explicitly indicate the supporting evidence. The interannual behaviour of $POD_1 SPEC$ is shown in Fig. 2 and summarised in Table S4, which present the annual values and corresponding trend statistics across sites and scenarios. In addition, the statistical comparison between best-case and worst-case scenarios has now been explicitly reported. The results of the two-sample Kolmogorov-Smirnov (KS) test is provided in a newly added Table S6 in the Supplementary Material.

The KS test indicates a statistically significant difference between scenarios for beech at rural sites (D = 0.489, p < 0.001), while no significant differences were found for spruce or for beech at mountain sites. The manuscript text has been revised accordingly to explicitly refer to these figures and tables.

Original manuscript, (P16, l407-414): "…In the POD_1SPEC time series of the different scenarios for spruce, and, with the exception of the last years (2014 - 2020), for the best-case scenario for rural sites, an even distribution of POD_1SPEC can be observed for spruce per site types (mountain and rural). Conversely, the POD_1SPEC distribution for beech within the time series is quite uneven across the years. Also, the two-sample Kolmogorov-Smirnov test indicated that the difference between scenarios is statistically significant for beech. It is possible that beech trees are more influenced by SWC than spruce (Hesse et al., 2024; Martinetti et al., 2025). Also, that deciduous tree species like beech, may be more sensitive to O_3 than evergreen coniferous species, like spruce, due to higher gas exchange rates or reduced detoxification ability (Emberson, 2020). These findings indicate that estimating the risk of vegetation damage due to O_3 for deciduous forests, using beech in a worst-case scenario setting produces overestimations."

Revised manuscript, (Supplementary material, P7, l174-179): Table S6. Two-sample Kolmogorov-Smirnov test (KS) comparing annual POD_1SPEC distributions between best-case and worst-case scenarios (2006-2020).

Species	Site type	KS statistic (D)	p-value
Beech	Mountain	0.267	0.664
Beech	Rural	0.489	< 0.001
Spruce	Mountain	0.050	1.000
Spruce	Rural	0.267	0.075

R2-C21: Line 777-778: I don't see any results for crop yield loss in Figure 7.

R2-R21: We thank the referee for this remark. Figure 7 shows POD_6SPEC values and associated risk levels, but not crop yield loss directly. Relative yield loss (RYL) is derived from POD_6SPEC using the UNECE dose-response functions described in Sect. 2.3.2, and the resulting maximum potential reduction rates for grain yield are summarised in Table 2. The text has been revised to clarify this distinction and to explicitly refer to Table 2.

Original manuscript, (P28, l773-780): "… 3.2.3 Economic loss from crop risk

The amount of crop production in Saxony obtained from the Saxon State Ministry of Energy, Climate Protection, Agriculture and the Environment (Saxon Environment and Agriculture Ministry, 2021) was 1,407,000 t, and the mean producer price of wheat over 2016-2020 was €166.67/t (German Ministry of Food and Agriculture, 2020; German Agricultural Market Information Company (Ami), 2020). Considering the average wheat crop yield loss over the last five years of the time series (2016-2020) (Figure 7), and assuming a worst-case scenario (optimal irrigation), the yearly mean crop production loss (CPL) at rural background sites is approximately 201,180 t, resulting in an average economic cost loss (ECL) of €33.6 million. At mountain sites, the mean CPL is 397,080 t, leading to an average ECL of €66.2 million compared to pre-industrial times."

Adjusted manuscript, (P30, l812-823): 3.2.3 Economic loss from crop risk

The amount of wheat production in Saxony obtained from the Saxon State Ministry of Energy, Climate Protection, Agriculture and the Environment (Saxon Environment and Agriculture Ministry, 2021) was 1,407,000 t, and the mean producer price of wheat over 2016-2020 was €166.67 t^{-1} (German Ministry of Food and Agriculture, 2020; German Agricultural Market Information Company, AMI, 2020). Based on the accumulated POD_6SPEC values shown in Fig. 7, relative yield loss (RYL) was first estimated using the UNECE dose-response relationships described in Sect. 2.3.2. The mean RYL for the last five years of the time series (2016-2020) was then calculated and used to estimate the average annual crop production loss (CPL) and the associated average annual economic cost loss (ECL) under the worst-case scenario (optimal irrigation). Under these assumptions, the average annual CPL at rural background sites is approximately 201,180 t, resulting in an average annual ECL of €33.6 million. At mountain sites, the average annual CPL is 397,080 t, corresponding to an average annual ECL of €66.2 million relative to a reference scenario with pre-industrial ozone concentrations (10 ppb).

R2-C22: Line 778-779: It's unclear how you arrive at this CPL estimate.

R2-R22: We thank the referee for pointing out that the calculation pathway leading to the CPL estimate was not sufficiently clear in the original manuscript. In the revised version, the analytical workflow has been clarified in Sect. 2.4 (Economic loss). As explained in our response to R2-R5b, accumulated POD_6SPEC values are first translated into relative yield loss (RYL) using the UNECE dose-response relationships described in Sect. 2.3.2. The mean RYL for the last five years of the time series (2016-2020) is then used to calculate crop production loss (CPL) according to Eq. 7, and the associated economic cost loss (ECL) is obtained by multiplying CPL by the producer price of wheat according to Eq. 8. As also clarified in R2-R21, Fig. 7 presents the POD_6SPEC values from which RYL is derived, while the resulting reductions in grain yield are summarised in Table 2. These revisions make the calculation from O_3 exposure to economic loss explicit.

R2-C23: Line 780: "pre-industrial times". Was the crop yield the same in pre-industrial times as in the present? I think you refer to a scenario in which crop yield is the same as in the present, but ozone mixing ratios are kept at their pre-industrial values. It's important to be specific!

R2-R23: We thank the referee for this important clarification. In this study, the reference to "pre-industrial" does not refer to historical crop yields or agricultural practices. Instead, it refers to the reference ozone exposure level (10 ppb) used as the counterfactual baseline in the UNECE dose-response relationships (Sect. 2.3.2). Present-day wheat production levels in Saxony are maintained in all calculations, and yield loss is expressed relative to a scenario in which current crops are exposed to pre-industrial ozone concentrations.

As clarified in our response to R2-R21, Fig. 7 shows the accumulated POD_6SPEC values, from which relative yield loss (RYL) is derived using the UNECE dose-response functions. The mean RYL for the last five years of the time series (2016-2020) is then used to calculate crop production loss (CPL) and the associated economic cost loss (ECL) (Sect. 2.4).

The manuscript text has been revised accordingly to explicitly state that the reported CPL and ECL values represent losses relative to a reference scenario with pre-industrial O_3 concentrations (10 ppb) while maintaining present-day crop production levels (R2-R21, Revised manuscript, P30, l812-823).

R2-C24: Line 803-804: No information in the paper on how this is calculated.

R2-R24: We thank the referee for this remark. The biomass reductions reported in the Conclusions are model-based estimates derived from the UNECE dose-response relationships applied to POD_1SPEC, as described in Sect. 2.3.2 (Protection goals and risk assessment) and summarised in Table 2. The methodology leading to these estimates is now explicitly described in the revised Methods section (see R1-R17, Revised manuscript, P8, l185-285). The Conclusions have been revised to clarify that these values represent modelled maximum potential biomass growth reductions, rather than observed biomass changes.

Original manuscript, (P29, l800-805): "…4.Conclusions

The present study used 15 years of POD_YSPEC estimations to assess tropospheric ozone (O_3) risk to forests, grasslands, and crops across mountain and rural background sites in Saxony. The results show that persistent O_3 risk exists for both coniferous and deciduous forests at mountain sites, with critical levels frequently exceeded. Beech trees, in particular, showed potential biomass growth reductions of up to 14%. At rural background sites, lower risks and declining trends were observed, especially in recent years."

Adjusted manuscript, (P31, l844-849): The present study used 15 years of POD_YSPEC estimates to assess tropospheric O_3 risk to forests, grasslands, and crops across mountain and rural background sites in Saxony. The results show that persistent O_3 risk exists for both coniferous and deciduous forests at mountain sites, where critical levels are frequently exceeded. Beech trees, in particular, showed modelled maximum potential biomass growth reductions of up to ~19 % at mountain sites and ~14 % at rural background locations, derived from the UNECE POD_1SPEC dose-response relationships under worst-case assumptions. At rural background sites, lower risks and declining trends were observed, especially in recent years.

References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration: Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper, Food and Agriculture Organization of the United Nations, Rome1998.

Avnery, S., Mauzerall, D. L., Liu, J., and Horowitz, L. W.: Global crop yield reductions due to surface ozone exposure: 1. Year 2000 crop production losses and economic damage, Atmospheric Environment, 45, 2284--2296, 10.1016/j.atmosenv.2010.11.045, 2011.

Baumgarten, M., Huber, C., Buker, P., Emberson, L., Dietrich, H. P., Nunn, A. J., Heerdt, C., Beudert, B., and Matyssek, R.: Are Bavarian forests (southern Germany) at risk from ground-level ozone? Assessment using exposure and flux based ozone indices, Environ Pollut, 157, 2091--2107, 10.1016/j.envpol.2009.02.012, 2009.

Bender, J., Bergmann, E., Weigel, H. J., Grünhage, L., Schröder, M., Builtjes, P., Schaap, M. K., Wichink Kruit, R., Stern, R., Baumgarten, M., and Matyssek, R.: Anwendung und Überprüfung neuer Methoden zur flächenhaften Bewertung der Auswirkung von bodennahem Ozon auf die Biodiversität terrestrischer Ökosysteme, Umweltbundesamt, 2015, http://www.umweltbundesamt.de/publikationen/anwendung-ueberpruefung-neuer-methoden-zur.

Buckley, T. N.: How do stomata respond to water status?, New Phytol, 224, 21--36, 10.1111/nph.15899, 2019.

Buker, P., Feng, Z., Uddling, J., Briolat, A., Alonso, R., Braun, S., Elvira, S., Gerosa, G., Karlsson, P. E., Le Thiec, D., Marzuoli, R., Mills, G., Oksanen, E., Wieser, G., Wilkinson, M., and Emberson, L. D.:

New flux based dose-response relationships for ozone for European forest tree species, Environ Pollut, 206, 163--174, 10.1016/j.envpol.2015.06.033, 2015.

Dairy and Agricultural Economic Analysis Centre: Feed wheat price Cologne, Germany (weekly quotations), Italian agricultural market analysis organization (CLAL), 2025, https://teseo.clal.it/en/?section=cereals_price_eu.

Deutscher Wetterdienst DWD: [dataset], n.d., https://www.dwd.de/EN/Home/home_node.html.

Eghdami, H., Werner, W., and Büker, P.: Spatio-Temporal Variation of Ozone Concentrations and Ozone Uptake Conditions in Forests in Western Germany, Atmosphere, 11, 10.3390/atmos11111261, 2020.

Eghdami, H., Werner, W., De Marco, A., and Sicard, P.: Influence of Ozone and Drought on Tree Growth under Field Conditions in a 22 Year Time Series, Forests, 13, 10.3390/f13081215, 2022.

Ehlers, C., Klemp, D., Rohrer, F., Mihelcic, D., Wegener, R., Kiendler-Scharr, A., and Wahner, A.: Twenty years of ambient observations of nitrogen oxides and specified hydrocarbons in air masses dominated by traffic emissions in Germany, Faraday Discuss, 189, 407--437, 10.1039/c5fd00180c, 2016.

Emberson, L.: Effects of ozone on agriculture, forests and grasslands, Philos Trans A Math Phys Eng Sci, 378, 20190327, 10.1098/rsta.2019.0327, 2020.

European Parliament and Council: Directive 2008/50/EC of the Euopean Parliament and the council of 21 May 2008 on ambient air quality and clean air for Europe, 2008, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0050.

Felzer, B. S., Cronin, T., Reilly, J. M., Melillo, J. M., and Wang, X.: Impacts of ozone on trees and crops, Comptes Rendus. Géoscience, 339, 784--798, 10.1016/j.crte.2007.08.008, 2007.

German Institute for Standardization: manual Air Pollution Prevention Volume 1a: Maximum Immission Values, Volume 1 B: Environmental Meteorology, German Institute for Standardization and Association of German Engineers 2020, https://www.vdi.de/mitgliedschaft/vdi-richtlinien/details/vdidin-handbuch-reinhaltung-der-luft-band-1a-maximale-immissions-werte-band-1b-umweltmeteorologie.

German Ministry of Agriculture, F. a. H. A.: Welche Getreide produziert Deutschland?, 2021, https://www.bmel-statistik.de/landwirtschaft/bodennutzung-und-pflanzliche-erzeugung/getreide.

German Ministry of Food and Agriculture: Erntebericht 2020, Mengen und Preise, BMEL-Statistik, 2020, https://bmel-statistik.de/fileadmin/daten/1002050-2020.pdf.

Gerosa, G. A., Marzuoli, R., and Finco, A.: Interannual variability of ozone fluxes in a broadleaf deciduous forest in Italy, Elementa: Science of the Anthropocene, 10, 10.1525/elementa.2021.00105, 2022.

Grünhage, L., Lehmann, Y., Schröder, M., Braden, H., Bender, J., and Burkart, S.: Evaluation of the ozone-related risk for winter wheat at local scale with the CRO3PS model, JCR autoupdate, 71, 90--97, 2011.

Grünhage, L., Matyssek, R., Häberle, K.-H., Wieser, G., Metzger, U., Leuchner, M., Menzel, A., Dieler, J., Pretzsch, H., Grimmeisen, W., Zimmermann, L., and Raspe, S.: Flux-based ozone risk assessment for adult beech forests, Trees, 26, 1713--1721, 10.1007/s00468-012-0716-5, 2012.

Hesse, B. D., Hikino, K., Gebhardt, T., Buchhart, C., Dervishi, V., Goisser, M., Pretzsch, H., Haberle, K. H., and Grams, T. E. E.: Acclimation of mature spruce and beech to five years of repeated summer drought - The role of stomatal conductance and leaf area adjustment for water use, Sci Total Environ, 951, 175805, 10.1016/j.scitotenv.2024.175805, 2024.

Hu, T., Liu, S., Xu, Y., Feng, Z., and Calatayud, V.: Assessment of O(3)-induced yield and economic losses for wheat in the North China Plain from 2014 to 2017, China, Environ Pollut, 258, 113828, 10.1016/j.envpol.2019.113828, 2020.

Jarvis, P.: The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field, Philos Trans R Soc Lond B Biol Sci, 273, 593--610, https://doi.org/10.1098/rstb.1976.0035, 1976.

Kallis, G.: Droughts, Annual Review of Environment and Resources, 33, 85--118, 10.1146/annurev.environ.33.081307.123117, 2008.

Lefohn, A. S., Malley, C. S., Smith, L., Wells, B., Hazucha, M., Simon, H., Naik, V., Mills, G., Schultz, M. G., Paoletti, E., De Marco, A., Xu, X., Zhang, L., Wang, T., Neufeld, H. S., Musselman, R. C., Tarasick, D., Brauer, M., Feng, Z., Tang, H., Kobayashi, K., Sicard, P., Solberg, S., and Gerosa, G.: Tropospheric ozone assessment report: Global ozone metrics for climate change, human health, and crop/ecosystem research, Elementa: Science of the Anthropocene, 6, 28, 10.1525/journal.elementa.279, 2018.

Lin, M., Horowitz, L. W., Xie, Y., Paulot, F., Malyshev, S., Shevliakova, E., Finco, A., Gerosa, G., Kubistin, D., and Pilegaard, K.: Vegetation feedbacks during drought exacerbate ozone air pollution extremes in Europe, Nature Climate Change, 10, 444--451, 10.1038/s41558-020-0743-y, 2020.

Lombardozzi, D. L., Bonan, G. B., Levis, S., and Lawrence, D. M.: Changes in Wood Biomass and Crop Yields in Response to Projected CO2, O3, Nitrogen Deposition, and Climate, Journal of Geophysical Research: Biogeosciences, 123, 3262--3282, 10.1029/2018jg004680, 2018.

Martinetti, S., Molnar, P., Carminati, A., and Floriancic, M. G.: Contrasting the soil-plant hydraulics of beech and spruce by linking root water uptake to transpiration dynamics, Tree Physiol, 45, 10.1093/treephys/tpae158, 2025.

Massey, F. J.: The Kolmogorov-Smirnov Test for Goodness of Fit, Journal of the American Statistical Association, 46, 68--78, 10.1080/01621459.1951.10500769, 1951.

Mills, G., Harmens, H., Pleijel, H., Büker, P., González-Fernández, I., Hayes, F., and Sharps, K.: Scientific Background Document B of Chapter 3 of 'Manual on methodologies and criteria for modelling and mapping critical loads and levels of air pollution effects, risks and trends, UNECE Convention on

Long-range Transboundary Air Pollution, 2020, URL: https://icpvegetation.ceh.ac.uk/sites/default/files/Scientific%20Background%20document%20B%20June%202020.pdf.

Mills, G., Pleijel, H., Malley, C. S., Sinha, B., Cooper, O. R., Schultz, M. G., Neufeld, H. S., Simpson, D., Sharps, K., Feng, Z., Gerosa, G., Harmens, H., Kobayashi, K., Saxena, P., Paoletti, E., Sinha, V., and Xu, X.: Tropospheric Ozone Assessment Report: Present-day tropospheric ozone distribution and trends relevant to vegetation, Elementa: Science of the Anthropocene, 6, 47, 10.1525/elementa.302, 2018.

Mills, G., Harmens, H., Hayes, F., Pleijel, H., Büker, P., González-Fernández, I., Alonso, R., Bender, J., Bergmann, E., Bermejo, V., Braun, S., Danielsson, H., Gerosa, G., Grünhage, L., Karlsson, P. E., Marzuoli, R., Schaub, M., and Simpson, D.: Mapping Critical Levels for Vegetation, Chapter 3 of the Manual on Methodologies and Criteria for Modelling and Mapping Critical Loads and Levels and Air Pollution Effects, Risks and Trends, 2017, https://unece.org/fileadmin/DAM/env/documents/2017/AIR/EMEP/Final__new_Chapter_3_v2__August_2017_.pdf.

Miranda, C.: fruclimadapt: Evaluation Tools for Assessing Climate Adaptation of Fruit Tree Species (0.4.5), R package [code], 2023.

Pausch, A. and Mühlner, M.: Saxony air quality monitoring network (Luftmessnetz Sachsen), Saxon State Office for Environment, Agriculture and Geology (Landesamt für Umwelt, Landwirtschaft und Geologie), 2020, https://publikationen.sachsen.de/bdb/artikel/36866.

Peñuelas, J. and Staudt, M.: BVOCs and global change, Trends in Plant Science, 15, 133--144, 10.1016/j.tplants.2009.12.004, 2010.

Pirasteh-Anosheh, H., Saed-Moucheshi, A., Pakniyat, H., and Pessarakli, M.: Stomatal responses to drought stress, in: Water Stress and Crop Plants, 24--40, 10.1002/9781119054450.ch3, 2016.

R Core Team: R: A language and environment for statistical computing, R Foundation for Statistical Computing [code], 2022.

Air monitoring network: https://www.luft.sachsen.de/luftmessnetz-14996.html, last

Schucht, S., Tognet, F., and Létinois, L.: Wheat yield loss in 2019 in Europe due to ozone exposure, 2021, https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-report-17-2021-wheat-yield-loss-in-2019-in-europe-due-to-ozone-exposure.

Simpson, D., Ashmore, M. R., Emberson, L., and Tuovinen, J. P.: A comparison of two different approaches for mapping potential ozone damage to vegetation. A model study, Environ Pollut, 146, 715--725, 10.1016/j.envpol.2006.04.013, 2007.

Sinha, B., Singh Sangwan, K., Maurya, Y., Kumar, V., Sarkar, C., Chandra, B. P., and Sinha, V.: Assessment of crop yield losses in Punjab and Haryana using 2 years of continuous in situ ozone measurements, Atmospheric Chemistry and Physics, 15, 9555--9576, 10.5194/acp-15-9555-2015, 2015.

Teegavarapu, R.: Methods for Analysis of Trends and Changes in Hydroclimatological Time-Series, in: Trends and Changes in Hydroclimatic Variables: Links to Climate Variability and Change, 1 ed., edited by: Teegavarapu, R., Elsevier, 2018.

United Nations Population Division: World Population Prospects 2024: Summary of Results, UN DESA, 2024, https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/files/documents/2024/Jul/wpp2024_summary_of_results_final_web.pdf.

van der Ploeg, J. D., Franco, J. C., and Borras, S. M.: Land concentration and land grabbing in Europe: a preliminary analysis, Canadian Journal of Development Studies / Revue canadienne d'études du développement, 36, 147--162, 10.1080/02255189.2015.1027673, 2015.

Wang, Y., van Pinxteren, D., Tilgner, A., Hoffmann, E. H., Hell, M., Bastian, S., and Herrmann, H.: Ozone (O3) observations in Saxony, Germany, for 1997--2020: trends, modelling and implications for O3 control, 25, 8907--8927, 10.5194/acp-25-8907-2025, 2025.

Wilhite, D. A.: Droughts: A Global Assessment, Natural Hazards and Disasters Series, Routledge, London, 10.4324/9781315830896, 2000.

Wittig, V. E., Ainsworth, E. A., Naidu, S. L., Karnosky, D. F., and Long, S. P.: Quantifying the impact of current and future tropospheric ozone on tree biomass, growth, physiology and biochemistry: a quantitative meta-analysis, Global Change Biology, 15, 396--424, 10.1111/j.1365-2486.2008.01774.x, 2009.